Luminous efficiencies of 2° and 10° fields for brightness perception obtained from Japanese subjects

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Luminous efficiencies for brightness are tabulated at every 10 nm step that were obtained for 2° field from 18 Japanese subjects and for 10° field from 9 Japanese subjects. The data were provided by various Japanese laboratories and analyzed in the Research Committee on the luminous efficiency functions in the Illuminating Engineering Institute of Japan. The efficiencies were all determined by the direct comparison method against a reference at some photopic retinal illuminance level. The mean luminous efficiency function of the 18 subjects for the 2° field is fairly close to that presented in a technical report of the CIE Technical Committee TC-1.4, Vision.

1. Introduction

The luminous efficiency function is definable for every visual task, at least in principle, such as for detection of fine detail, flicker, a minute of light, for perception of brightness, contrast, or others. We have no guarantee, therefore, that the existing CIE $V(\lambda)$ represents all the functions corresponding to these visual tasks. We will be just lucky if the $V(\lambda)$ determined for specific one or two visual tasks can represent all the visual tasks. Indeed, it has been pointed out from time to time that the $V(\lambda)$ comes short, in particular when it is applied to the brightness perception, which is no doubt one of the most important visual tasks for incoming light. When the luminous efficiency is determined for the brightness by means of heterochromatic direct comparison, it deviates considerably from the $V(\lambda)$ by showing almost double peaked curve at around 540 nm and 600 nm.

To overcome this problem the CIE Technical Committee TC-1.4, Vision, suggested an establishment of a new function for the brightness perception and presented tentatively a table tabulating averaged luminous efficiencies at every 10 nm covering wavelengths from 400 nm through 700 nm¹⁾. The table, however, was based only on seven American research groups (five US groups and two Canadian groups) and an appeal was made

by Kinney²⁾, the chairperson for the TC-1.4 at that time, to provide more data for 2° and 10° fields by the direct comparison method.

Meanwhile, the Technical Committee TC-1.4 established a subcommittee, the luminous efficiency functions, under the chairmanship of the present author to meet the appeal and to provide reliable data of the luminous efficiencies for brightness. To respond to such an international activity, the Research Committee on the luminous efficiency function affiliated to the Illuminating Engineering Institute of Japan surveyed relevant data obtained in domestic laboratories of Japan. Data of 18 subjects were found available for the 2° field and those of 9 subjects for the 10° field. The present report tabulates all the individual data so that they may be employed in establishing international standards of the luminous efficiency functions for brightness.

The Research Committee was consisted from 15 members, M. Ikeda (chairman), H. Yaguchi (secretary), M. Akita, K. Ikeda, M. Ishino, Y. Ohta, S. Kawai, K. Sagawa, H. Shimozono, T. Takeuchi, T. Hasegawa, T. Hatada, M. Fuwa, S. Yamaguchi, and T. Yamanaka.

2. Sources and experimental conditions for 2° field

Laboratories that provided data for the 2° field and experimental conditions are listed in Table 1.

Table 1 Sources and experimental conditions for 2° field.

Laboratories	Size	Level	Ref.	Duration	Subjects	No. Sub.
Tokyo Inst. Tech. ^{3),4)}	2°	100 td.	white	4 sec	HY, TN, KK, SR, MA	5
Tokyo Inst. Tech. ⁵⁾	2°	76 td.	570 nm	110 ms	KU, HU, SO	3
Electrotech. Lab. ⁶⁾	2°	50 td.	white	continuous	KM, TS, YS, MF, KK, HK	6
NHK Lab. ⁷⁾	2°	170 td.	white	continuous	HSG, WTN, YSN	3
Ind. Prod. Res. Inst. ⁸⁾	1°	80 td.	white	continuous	KS	1

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Subjects totalled 18 altogether. All laboratories but NHK employed a circular bipartite field. Hasegawa (NHK) used a circular field of 2° arc as a test stimulus surrounded by a reference field

Table 2 Individual data of luminous efficiencies determined by the direct comparison method for 2° field. Values are in logarithmic unit with normalization at 570 nm. Values in parentheses are interpolated. Subject's initials, age and sex are listed at the top of each column.

Wave-length	Tokyo Inst. Tech.										Electrotech. Lab.										NHK Lab.		No. of subjects	Mean	Wave-length
	Ref. 3			Ref. 4			Ref. 5				Ref. 6						Ref. 7		IPRI						
	HY (28M)	TN (22M)	KK-- (24M)	SR (23M)	MA (22F)	KU (28M)	HU (27F)	SO (24M)	KM (20F)	TS. (20M)	YS (36M)	MF (39H)	KK (45M)	HK (55M)	HSG (39M)	WTN (23F)	YSN (23F)	KS (30M)							
400																				4	-2.10	400			
410																				13	-1.68	410			
420	-1.57	-1.24	-1.19	-1.65	-1.52	-1.25	-1.00	-1.22	-1.24	-1.55	-1.76	-1.97	-2.34	-2.50	-1.84	-1.54	-1.50	-1.56	-1.72	18	-1.38	420			
430	(-1.39)	(-1.06)	(-1.01)	(-1.42)	(-1.51)	-1.18	-0.85	-0.67	-0.91	-1.25	-1.35	-1.59	-1.38	-2.09	-1.55	-1.21	-1.10	-1.29	-1.61	18	-1.20	430			
440	-1.21	-0.88	-0.83	-1.18	-1.49	-1.06	-0.73	-0.70	-0.94	-1.02	-1.19	-1.44	-1.17	-1.73	-1.45	-1.04	-0.96	-1.02	-1.49	18	-1.06	440			
450	(-1.13)	(-0.83)	(-0.76)	(-1.12)	(-1.31)	-1.06	-0.65	-0.66	-0.91	-0.91	-0.85	-1.18	-0.88	-1.33	-1.07	-0.83	-0.75	-0.82	-1.39	18	-0.97	450			
460	-1.04	-0.77	-0.68	-1.06	-1.12	-0.99	-0.66	-0.70	-0.74	-0.77	-0.77	-1.16	-0.58	-1.20	-0.91	-0.67	-0.55	-0.77	-1.25	18	-0.87	460			
470	(-0.88)	(-0.68)	(-0.57)	(-0.95)	(-0.97)	-0.80	-0.58	-0.60	-0.63	-0.63	-0.62	-0.96	-0.46	-0.95	-0.75	-0.64	-0.46	-0.48	-1.01	18	-0.72	470			
480	-0.71	-0.58	-0.45	-0.83	-0.82	-0.62	-0.52	-0.53	-0.51	-0.51	-0.51	-0.73	-0.33	-0.83	-0.61	-0.56	-0.39	-0.43	-0.85	18	-0.60	480			
490	(-0.56)	(-0.45)	(-0.35)	(-0.68)	(-0.62)	-0.52	-0.42	-0.45	-0.43	-0.43	-0.39	-0.71	-0.23	-0.71	-0.46	-0.47	-0.33	-0.41	-0.70	18	-0.49	490			
500	-0.41	-0.32	-0.24	-0.52	-0.41	-0.28	-0.26	-0.24	-0.14	-0.24	-0.24	-0.48	-0.22	-0.40	-0.33	-0.30	-0.17	-0.23	-0.53	18	-0.32	500			
510	(-0.21)	(-0.12)	(-0.06)	(-0.32)	(-0.26)	-0.18	+0.06	-0.02	-0.02	-0.08	-0.08	-0.15	+0.07	-0.10	-0.06	-0.05	-0.04	-0.12	-0.28	18	-0.11	510			
520	-0.01	+0.08	+0.12	-0.11	-0.11	-0.07	+0.19	+0.10	+0.09	+0.02	+0.02	-0.02	+0.17	+0.02	+0.05	+0.05	+0.08	-0.01	-0.11	18	+0.03	520			
530	(+0.06)	(+0.09)	(+0.14)	(-0.05)	(-0.05)	+0.03	+0.22	+0.13	+0.17	+0.12	+0.12	+0.11	+0.30	+0.14	+0.07	+0.05	+0.07	+0.04	0	18	+0.09	530			
540	+0.10	+0.10	+0.16	+0.01	+0.01	+0.03	+0.26	+0.14	+0.19	+0.12	+0.12	+0.13	+0.24	+0.11	+0.07	+0.11	+0.17	+0.08	+0.04	18	+0.12	540			
550	(+0.08)	(+0.10)	(+0.11)	(+0.02)	(+0.02)	+0.03	+0.16	+0.10	+0.18	+0.08	+0.08	+0.17	+0.17	+0.13	+0.09	+0.10	+0.15	+0.07	+0.08	18	+0.10	550			
560	+0.06	+0.10	+0.06	+0.02	+0.03	+0.04	+0.14	+0.07	+0.10	+0.04	+0.04	+0.06	+0.11	+0.09	+0.02	+0.04	+0.06	+0.05	+0.05	18	+0.06	560			
570	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	570			
580	-0.01	+0.04	+0.01	-0.02	-0.09	-0.05	+0.05	0	+0.01	-0.01	-0.01	-0.07	-0.05	-0.01	-0.04	+0.01	-0.01	-0.03	-0.02	18	-0.02	580			
590	(-0.03)	(0)	(+0.10)	(-0.04)	(-0.12)	-0.12	+0.08	-0.07	0	-0.08	-0.08	-0.05	-0.10	-0.06	-0.04	-0.02	-0.03	-0.06	-0.09	18	-0.04	590			
600	-0.05	-0.04	+0.18	-0.06	-0.14	-0.19	-0.11	-0.11	-0.01	-0.09	-0.09	-0.16	-0.13	-0.10	-0.11	-0.07	-0.06	-0.11	-0.19	18	-0.07	600			
610	(-0.12)	(-0.09)	(+0.09)	(-0.16)	(-0.16)	-0.30	-0.05	-0.14	-0.11	-0.17	-0.17	-0.25	-0.23	-0.12	-0.20	-0.12	-0.14	-0.15	-0.22	18	-0.15	610			
620	-0.19	-0.13	0	-0.26	-0.17	-0.46	-0.08	-0.41	-0.19	-0.24	-0.24	-0.45	-0.28	-0.21	-0.26	-0.12	-0.19	-0.28	-0.30	18	-0.23	620			
630	(-0.33)	(-0.26)	(-0.41)	(-0.26)	(-0.26)	-0.49	-0.27	-0.53	-0.25	-0.31	-0.31	-0.55	-0.48	-0.40	-0.36	-0.25	-0.32	-0.27	-0.48	18	-0.35	630			
640	-0.47	-0.38	-0.12	-0.56	-0.34	-0.67	-0.36	-0.59	-0.43	-0.46	-0.46	-0.75	-0.61	-0.57	-0.61	-0.40	-0.57	-0.45	-0.63	18	-0.50	640			
650	(-0.70)	(-0.58)	(-0.36)	(-0.79)	(-0.54)	-0.79	-0.53	-0.71	-0.67	-0.76	-0.76	-0.98	-0.90	-0.83	-0.74	-0.63	-0.72	-0.74	-0.87	18	-0.71	650			
660	-0.92	-0.78	-0.60	-1.01	-0.74	-1.08	-0.77	-1.00	-0.96	-0.98	-0.98	-1.14	-1.05	-1.00	-1.00	-0.85	-0.88	-0.67	-1.11	18	-0.92	660			
670	(-1.22)	(-1.07)	(-0.82)	(-1.31)	(-1.10)	-1.36	-1.05	-1.22	-1.27	-1.27	-1.20	-1.45	-1.30	-1.40	-1.44	-0.94	-0.97	-0.74	-1.33	18	-1.18	670			
680	-1.51	-1.36	-1.03	-1.61	-1.46	-1.58	-1.26	-1.50	-1.47	-1.62	-1.62	-1.84	-1.62	-1.53	-1.68	-1.11	-1.35	-1.17	-1.60	18	-1.46	680			
690									-1.93	-1.94	-1.94	-2.14	-2.01	-1.83	-1.96			-1.51	-1.85	8	-1.80	690			
700									-2.17	-2.18	-2.18	-2.35	-2.33	-2.11	-2.10				-2.04	6	-2.04	700			
710									-2.46	-2.49	-2.49	-2.83	-2.48	-2.58	-2.54				-2.39	6	-2.39	710			
720									-2.74	-2.71	-2.71	-3.05	-2.87	-2.91	-2.89				-2.69	6	-2.69	720			
730									-3.15	-3.05	-3.05	-3.34	-3.12	-3.17	-3.15				-2.99	6	-2.99	730			

of 6° arc of visual angle. Sagawa (IPRI) employed a small field of 1°, but this is considered essentially indifferent from 2° field in providing luminous efficiency function⁹⁾ and included in the table. The method of adjustment was used by all authors.

3. Results for 2° field

Individual data are presented in Table 2. Subject's initials, age and sex are provided for each column. Efficiencies are normalized for 570 nm and values are given in logarithmic unit. The values in parentheses are not experimental but interpolated by the neighboring two values. The column of mean shows the means calculated in logarithm. When the number of subjects decreases towards ends of spectrum, the mean luminous efficiency function may abruptly change causing an irregular bending point. This artifact-irregularity may cause misinterpretation about the nature of the luminous efficiency function, and was avoided by plotting the function near the irregularity with a curve based only on the reduced number of subjects. For example, geometric mean of eight subjects at 690 nm is -1.90 . The means of these same subjects are -1.57 at 680 nm and -1.27 at 670 nm yielding differences of -0.11 and -0.09 respectively when compared with the averages of all eighteen subjects at these wavelengths. Therefore, we add $+0.10$ to the geometric mean of the reduced number of subjects so that the final average is -1.80 at 690 nm. A similar modification was performed to all extreme wavelengths. The mean values at the column of mean, therefore, may differ from the average of raw data when the number of subjects decreases.

The mean luminous efficiencies of the 18 subjects are presented by open circles in Fig. 1. They show a curve of familiar shape having double peaks at 540 nm and at about 600 nm. Triangles are based upon the TC-1.4 Technical Report No. 41 and the present results do not appreciably differ from them. A continuous line is the CIE $V(\lambda)$ modified by Judd. A word or so must be mentioned in relation to the Technical Report. The present author, as the chairman of the subcommittee in the Technical Committee TC-1.4, reanalyzed the raw data included in the Technical Report No. 41 and found some inappropriate data to employ. Recalculation was conducted to obtain the average for the remaining subjects of 19 and the revised TC-1.4 report was proposed¹⁰⁾, which appears as open triangles in Fig. 1. Indifference between the triangles and the open circles encourages us as we may simply average all the international data for

Fig. 1 Luminous efficiencies for brightness. $\circ$: 2° field, 18 Japanese subjects, $+$: 10° field, 9 Japanese subjects, $\triangle$: 2°, revised TC-1.4 report, solid curve: the CIE $V(\lambda)$ as modified by Judd. All efficiencies are normalized relative to 570 nm.

a final standard function.

4. Sources and experimental conditions for 10° field

Three laboratories provided relevant data for the 10° field luminous efficiency function as summarized in Table 3. Subjects totalled 9 altogether. Sagawa (IPRI) again used a smaller field size than 10°, but his data may be included. The method of adjustment was used by all authors.

5. Results for 10° field

Table 4 summarizes individual data with the mean values at the last column. A modification of the mean values was similarly conducted as in the 2° field when the number of subjects reduced towards the ends of spectrum. The averages appear as crosses in Fig. 1.

6. Discussion

One reason for reluctance to develop a standard function of luminous efficiency for brightness is certainly a large variance observed among subjects. This can be illustrated by plotting two extreme subjects in one figure as Fig. 2. The subject KK (24 M) denoted by filled circles shows clear double peaks of about the same efficiency and mostly deviates from the CIE $V(\lambda)$, the Judd's modification, of the continuous line. Another ex-

Table 3 Sources and experimental conditions for 10° field.

Laboratories	Size	Level	Ref.	Duration	Subjects	No. Sub.
Tokyo Inst. Tech. ¹¹⁾	10°	100 td.	white	continuous	HY, SK	2
Tokyo Inst. Tech. ¹²⁾	10°	100 td.	white	continuous	HS, TG	2
Electrotech. Lab. ⁶⁾	10°	200 td.	white	continuous	KM, TS, MF, KK	4
Ind. Prod. Res. Inst. ⁸⁾	8°	50 td.	white	continuous	KS	1

Table 4 Individual data of luminous efficiencies determined by the direct comparison method for 10° field. Values are in logarithmic unit with normalization at 570 nm. Values in parentheses are interpolated. Subject's initials, age and sex are listed at the top of each column.

Wave-length	Tokyo Inst. Tech.				Electrotech. Lab.				IPRI	No. of subjects	Mean
	Ref.11		Ref.12		Ref.6				Ref.8		
	HY (29M)	SK (24M)	HS (23M)	TG (26M)	KM (20F)	TS (20M)	MF (39M)	KK (45M)	KS (30M)		
400			-1.44						-2.05	2	-1.81
410			(-1.20)						-1.65	2	-1.49
420	-1.23	-1.18	-0.97	-1.31	-1.34	-1.20	-0.97	-1.69	-1.37	9	-1.25
430	-0.92	-0.90	(-0.78)	(-1.13)	-1.12	-1.09	-0.86	-1.18	-1.20	9	-1.02
440	-0.80	-0.67	-0.59	-0.95	-1.00	-0.87	-0.70	-0.87	-1.13	9	-0.84
450	-0.74	-0.70	(-0.51)	(-0.85)	-0.86	-0.73	-0.44	-0.75	-1.07	9	-0.74
460	-0.64	-0.48	-0.43	-0.75	-0.73	-0.60	-0.40	-0.61	-0.93	9	-0.62
470	-0.47	-0.38	(-0.42)	(-0.59)	-0.53	-0.48	-0.25	-0.47	-0.73	9	-0.48
480	-0.42	-0.31	-0.42	-0.43	-0.43	-0.43	-0.12	-0.43	-0.57	9	-0.40
490	-0.35	-0.32	(-0.24)	(-0.35)	-0.29	-0.33	-0.08	-0.38	-0.32	9	-0.30
500	-0.16	-0.10	-0.07	-0.27	-0.19	-0.16	+0.02	-0.24	-0.19	9	-0.15
510	-0.03	+0.02	(+0.04)	(-0.13)	-0.07	-0.03	+0.17	-0.08	-0.06	9	-0.02
520	+0.10	+0.10	+0.15	+0.01	+0.04	+0.03	+0.31	+0.06	+0.05	9	+0.09
530	+0.16	+0.14	(+0.17)	(+0.05)	+0.08	+0.09	+0.29	+0.10	+0.10	9	+0.13
540	+0.18	+0.17	+0.20	+0.04	+0.10	+0.09	+0.27	+0.19	+0.14	9	+0.15
550	+0.16	+0.12	(+0.14)	(+0.04)	+0.11	+0.08	+0.20	+0.16	+0.09	9	+0.12
560	+0.07	+0.03	+0.08	+0.03	+0.06	+0.02	+0.13	+0.10	+0.07	9	+0.07
570	0	0	(0)	(0)	0	0	0	0	0	9	0
580	-0.05	+0.04	-0.08	-0.03	-0.01	+0.03	+0.02	+0.01	-0.05	9	-0.01
590	-0.05	-0.01	(-0.07)	(-0.10)	-0.05	-0.09	+0.04	-0.01	-0.10	9	-0.05
600	+0.02	-0.06	-0.07	-0.16	-0.11	-0.12	+0.05	-0.09	-0.19	9	-0.08
610	-0.05	-0.10	(-0.08)	(-0.33)	-0.14	-0.18	-0.01	-0.19	-0.22	9	-0.14
620	-0.17	-0.12	-0.10	-0.49	-0.31	-0.15	-0.10	-0.23	-0.31	9	-0.22
630	-0.26	-0.23	(-0.22)	(-0.66)	-0.40	-0.23	-0.26	-0.33	-0.39	9	-0.33
640	-0.42	-0.45	-0.35	-0.82	-0.61	-0.49	-0.42	-0.48	-0.57	9	-0.51
650	-0.62	-0.54	(-0.66)	(-1.12)	-0.85	-0.62	-0.53	-0.83	-0.79	9	-0.73
660	-0.85	-0.82	-0.98	-1.41	-1.12	-0.82	-0.97	-0.96	-1.05	9	-1.00
670	-1.12	-1.06	(-1.18)		-1.33	-0.93	-1.18	-1.35	-1.32	8	-1.23
680	-1.35	-1.34	-1.39		-1.65	-1.32	-1.47	-1.54	-1.64	8	-1.51
690			(-1.67)		-1.97	-1.63	-1.83	-1.84	-1.93	6	-1.82
700			-1.96		-2.18	-1.93	-2.09	-2.17		5	-2.11
710					-2.46	-2.22	-2.23	-2.37		4	-2.33
720											
730

Fig. 2 Luminous efficiencies of two extreme subjects determined by the direct comparison method. ● : KK (24M), ○ : YS, a smooth curve: the CIE $V(\lambda)$ as modified by Judd. 2° field. Normalized at 570 nm.

treme is represented by the subject YS denoted by open circles. In this subject the luminous efficiency

for brightness almost coincides with the CIE $V(\lambda)$. In other words his visual system may have the same spectral efficiency for the brightness perception and for the flicker detection.

With such a large variance among subjects we might regard it almost meaningless to propose a standard luminous efficiency function unless we are provided with data from enormous number of subjects. It is encouraging to see, however, that there is not much difference between the revised TC-1.4 report based on only 19 American subjects and the present report based on only 18 Japanese subjects as seen by triangles and circles in Fig. 1. We may, therefore, expect that a fairly reliable luminous efficiency function for brightness can be derived before too long to represent the CIE standard observer at least for the 2° field.

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