Dimesimeter – Light and Activity Measurement System Description and Calibration

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Overview

The Dimesimeter is a small, epoxy encapsulated, battery powered data logging device (diameter approximately 2 cm; slightly larger than the size of a US $.10 coin), used to record light and activity levels continuously over many days. A docking station and software client facilitate the communication necessary to start and stop logging sessions and control the downloading of data. The Dimesimeter can be worn by research participants in a variety of ways. The device pictured in Figure 1 is fitted with a pin for attaching to a shirt collar, lapel, or hat. Other versions include a wristband, a pendant, a badge and a glasses clip.

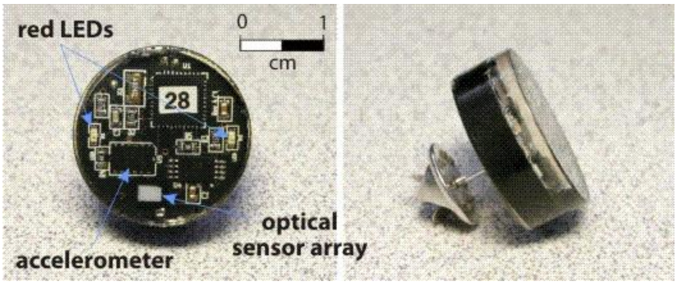

Figure 1: Front and side views of Dimesimeter #28. The optical sensor array and the monolithic accelerometer are indicated along with the two red LEDs used for interfacing the Dimesimeter with the docking station (not shown) and to indicate, by flashing at different rates, that the Dimesimeter is performing as expected.

Docking Station and Software Client

The docking station and software client are used to communicate with the Dimesimeter. The docking station has two optical sensors and one LED package containing three light emitting diodes (LED) with dies having λ_{peak} = 470, 520, and 640 nm . When the docking station's two optical sensors are aligned with the two red LEDs on the Dimesimeter (Figure 1), it can signal commands to and retrieve data from the Dimesimeter. A USB connection links the docking station to a personal computer.

A software client on the computer controls the docking station and allows the researcher to issue commands to the Dimesimeter and retrieve data. From the software client the researcher can specify a logging interval, start a logging session, stop a logging session, and download logged data. When specifying the logging interval, the researcher has a choice of one of five logging intervals, 30 s, 60 s, 90s, 120 s or 180 s. These logging intervals define both the Dimesimeter's logging interval and the duration of deployment without exceeding on-board memory capacity. For a prescribed logging interval of 180 s, the Dimesimeter can continuously record data for approximately 33 days; for a 30 s logging interval it can continuously record data for approximately 5.5 days.

When commands are issued from the software client, unique sequences of light pulses generated by the docking station LEDs are read by the Dimesimeter's optical sensor array (Figure 1) to "start logging," "stop logging," or "download data." When a "start logging" command is issued, all data on the Dimesimeter's on-board memory is erased, the specified logging interval is saved to memory, a time stamp derived from the personal computer's clock is saved to memory, the devices battery voltage is determined and saved to memory, and finally the device is put in logging mode. When a "stop logging" command is issued from the software client, the Dimesimeter stops recording data by exiting logging mode, and switches to a low-power, standby mode without affecting the on-board memory. When a "download data" command is issued, the Dimesimeter sends a copy of all the contents of its on-board memory to the software client which saves it to a text file. The saved data include the logging interval, time stamp, battery voltage, light data, and activity data. After the data are downloaded, a separate software post process decodes the downloaded data and applies calibration factors to the data sets. The post processed data sets include log time, photopic illuminance (lux), CL_A, CS, and activity.[1]

Data Processing and Logging

The Dimesimeter's microprocessor (Texas Instruments MSP430) initializes and communicates with its optical sensor array and the accelerometer, provides timing signals, performs calculations required to measure and process light and activity data, and controls data storage and retrieval functions. In addition to keeping track of the time relative to the time-stamped start logging time, the microprocessor clock is used to enter and exit low-power modes when needed. The accuracy of the clock is typically ±20 parts per million (ppm), or a drift of less than ± two seconds per day. Data are stored on the device in a 1Mbit Serial Electrically Erasable Programmable Read Only Memory (EEPROM) (Atmel AT24C1024B).

Power Supply

The Dimesimeter is powered by a 3.0 V lithium BR2032 coin cell battery with a rated capacity of 190 milliampere-hour (mAh). The expected operating time for the Dimesimeter is at least 10 weeks while recording data and more than one year in standby mode. Since the Dimesimeter is sealed in epoxy, the battery cannot be easily replaced; therefore, the useful life of the device is limited to its battery life.

Light Sensor

Light sensing is performed with an integrated circuit (IC) sensor array (Hamamatsu model S11059-78HT) that includes optical filters for four measurement channels: red (R), green (G), blue (B), and infrared (IR). According to the manufacturer, the R, G, B, and IR photo-elements have peak spectral responses at 615 nanometers (nm), 530 nm, 460 nm, and 855 nm, respectively. The optical sensing area is approximately two millimeters square (mm^2), consisting of a mosaic of 40 alternating R, G, B and IR filtered photo-elements. The R, G, B and IR channels include an integrating digital-to-analog converter, and an inter-integrated circuit (I^2C) communication interface for relaying data to the microprocessor. A single analog-to-digital converter sequentially transforms raw analog signals from each channel into 16-bit digital counts.

Raw signal values in every channel are based upon a 50 millisecond (ms) integration period unless the number of counts within the specified logging interval is less than 25 counts, in which case the integration period is automatically increased to 250 ms. R, G, B and IR signal values are measured once per second when in the 50 ms integration mode, and once every three seconds when in the 250 ms integration mode. The signal value generated by the IR channel is automatically subtracted from each of the R, G, and B signal values to reduce their out-of-band spectral response. The 50 ms and 250 ms integration periods correspond to a resolution of approximately 1 lux and 0.2 lux, respectively, with an absolute measurement range from approximately 0.2 lux to 65,000 (2^{16}) lux. At the end of each logging interval, previously set by the researcher, the average 16-bit R, G, B signal values for the logging interval are stored in the on-board memory.

The spectral and spatial response characteristics of the optical sensor array were modified for the Dimesimeter. Even after the automatic IR signal subtraction, the R, G, and B sensors exhibit a significant sensitivity to near-IR radiation. To minimize this artifact an IR-blocking filter (Schott BG39) was permanently affixed to the top of the optical sensor array. As reported by Van Derlofske et al.,[2] the spatial distribution of light incident on the retina is closely approximated by a three-dimensional cosine response. For this reason, an opal glass diffuser also was mounted to the optical sensor array, on top of the IR-blocking filter, so that the directional response of the Dimesimeter sensor package closely followed a three-dimensional cosine sensitivity distribution to incident light (below).

Spectral Response

To determine the typical spectral response characteristics of the optical sensor package, three Dimesimeters were, in turn, examined. Each Dimesimeter was placed in the exit beam of a double monochromater (Acton Research Corporation Spectra Pro 2300i). A 75W Q/CL tungsten halogen lamp illuminated the input slit of the monochromater. The pass band of the monochromater, defined by its center wavelength and fixed bandwidth of approximately 8 nm full-width half-maximum (FWHM), was controlled by custom LabVIEW software (National Instruments; Austin, TX). The software incrementally moved the wavelength at fixed time intervals so that the readings from each of the device’s R, G, and B sensors could be associated with the center wavelength that corresponds to the reading. Figure 2 illustrates the spectral response of one Dimesimeter’s optical sensor package equipped with the IR blocking filter and the opal glass diffuser. All three Dimesimeters examined had similar spectral response characteristics; the variation in the area under the spectral response envelope for a given channel was always less than 2.5% when normalized to the spectral peak. Note that the addition of the IR blocking filter and opal glass diffuser shift the sensitivities of the R, G, and B channels to 595 nm, 535 nm, and 470 nm, respectively.

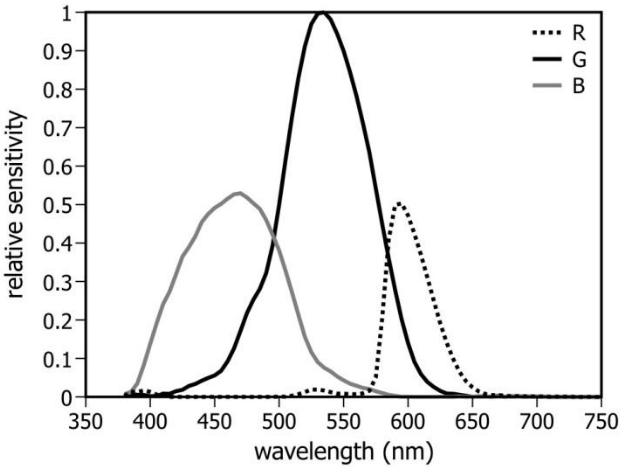

Figure 2: The spectral response characteristics of the R, G, and B channels of a typical Dimesimeter after addition of the opal diffuser and IR-blocking filter.

Spatial Response

A 750 W tungsten-halogen lamp operated at a color temperature of 2856 K (closely approximating CIE standard illuminant A)[3] was used to characterize the spatial response of a selected Dimesimeter. The Dimesimeter logging interval was set to 60 s and then mounted on a flat metal plate attached to a goniometer controlled with custom LabVIEW software. The goniometer rotated the Dimesimeter about the axis perpendicular to the line between the center of its front surface and the center of the calibrated light source. After 15 minutes for lamp stabilization, the Dimesimeter was rotated in one plane from -90 to 90 degrees in increments of five degrees every five minutes. The timing of the logged Dimesimeter measurements was used to determine the five-minute average values recorded for each selected angle from each of its R, G, and B channels. These average values were then normalized to the maximum average reading. Figure 3 shows the spatial response characteristics of the R, G, and B channels from a typical Dimesimeter together with an ideal cosine response function.

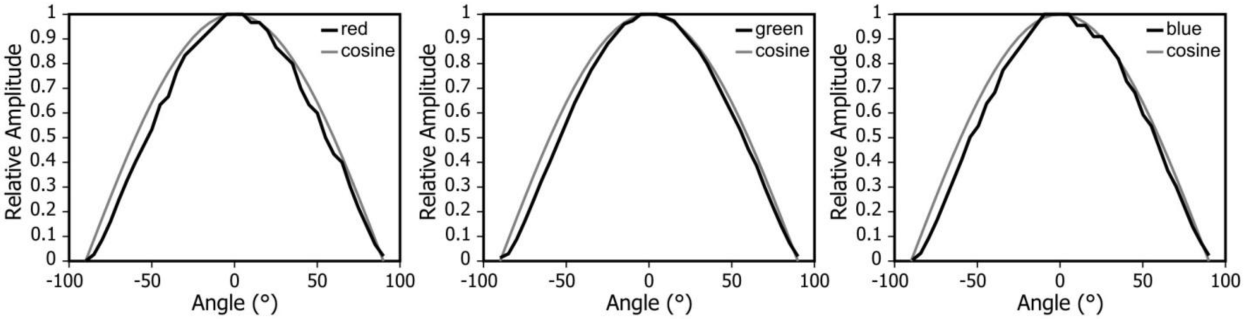

Figure 3: Spatial response of a Dimesimeter’s R, G, and B channels.

Absolute Response

The linearity of response to light by a typical Dimesimeter was measured using a laser (Wicked Lasers; 532 nm; 35W) and an integrating sphere. The laser was shone into an input port of the integrating sphere while a calibrated photosensor recorded the amount of flux exiting a second port at 90 degrees. The Dimesimeter was set to a 60 s logging interval and placed at a third port, opposite the second port. Neutral density filters were placed between the laser and the input port to systematically vary the amount of light entering the sphere. Each filter was in place for five minutes. Calibrated sensor readings from the second port were recorded at the beginning and end of each 5-minute block. The timestamps recorded by the Dimesimeter were used to link the Dimesimeter recorded values from the G channel to the calibrated sensor values. The average of three sample measurements recorded by the Dimesimeter near the middle of the measurement period was determined. The relationship between the calibrated sensor measurements and the Dimesimeter measurements are plotted in Figure 4, showing a linear response by the G channel over approximately four orders of magnitude. Since the R and B channels differ from the G channel only in terms of the spectral response, a linear response characteristic like that shown in Figure 4 would be applicable to all three channels and their combinations.

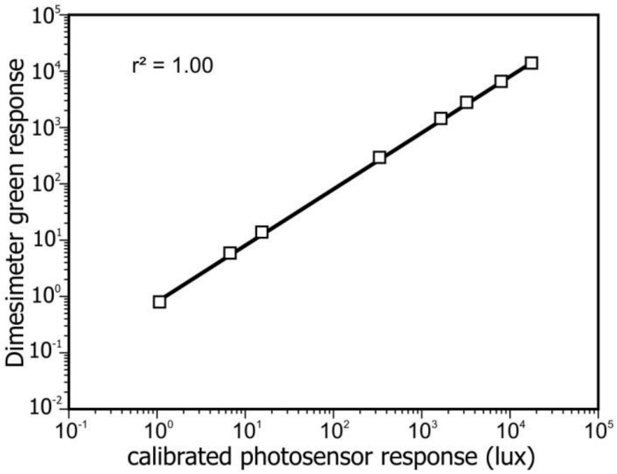

Figure 4: Absolute response characteristic of the Dimesimeter’s G (green) channel. Standard deviations are smaller than the size of the symbols.

Activity Sensor

The Dimesimeter measures activity using three orthogonal accelerometers contained within a single electronic sensor package (Analog Devices, model number ADXL345). The sensor outputs digital data via an I2C interface that enables communication with the Dimesimeter microcontroller (Texas Instruments, model number MSP430F2274). The output from each accelerometer channel is a 16-bit digital value, or count, proportional to the measured acceleration. The data sheet for the accelerometer states that a one g (1 g = 9.8 m/s2) difference in acceleration corresponds to a difference in counts between 232 and 286, corresponding to calibration factors of 0.0043 and 0.0035 in units of g per count, respectively. The sensor is configured to measure acceleration using a 3 Hz low pass filter at a rate of 6.25 samples per second over a range of ± 4 g for each accelerometer channel (x, y, and z direction).

Accelerometer values are continuously acquired at the 6.25 Hz sampling rate, and then for each logging interval the sum of squared differences from the mean value over the logging interval is computed for each accelerometer channel. Activity index (AI) combines the logging interval values from the three channels using the following formula:

$$\text{Activity Index} = k\sqrt{\frac{\left(SS_x + SS_y + SS_z\right)}{n}} \text{ ,}$$

where SSx, SSy, and SSz are the sum of the squared deviations from the mean of each channel over the logging interval, n is the number of samples (375 samples for a 60-second logging interval), and k is a calibration factor equal to 0.0039 g per count. In other words, AI is the root-mean-square (RMS) deviation in acceleration in three dimensions for each logging interval.

Calibration

Dimesimeters are individually calibrated to provide photopic illuminance (lux) values. Each Dimesimeter and a calibrated illuminance meter are placed at the same fixed distance from the same 750 W lamp used for the spatial characterization. The flat sensors of the Dimesimeter and of a calibrated illuminance meter are oriented orthogonal to the direction of flux generated by the light source. The Dimesimeter records light for five minutes and the measured values from the R, G and B channels obtained during that time interval are each averaged to determine R’, G’, and B’ calibration constants. Each of these three calibration constants are equal to the ratio of the calibrated illuminance meter reading to the average Dimesimeter output from that channel. These calibration constants are in units of lux per average channel output.

Photopic

Since it is important to measure illuminance levels from light sources other than illuminant A (e.g., fluorescent or daylight), it is necessary to optimize the relative outputs from the three channels such that their combined output would be in units of lux for a wide variety of practical light sources. This optimization provides a second set of three, dimensionless constants, W_R, W_G, and W_B for V(λ). The values for these constants are W_R 0.334060, W_G 0.645098, and W_B -0.013336. The three Dimesimeters tested for spectral response characteristics were used to estimate these three constants. The values of these three constants were optimized to a V(λ) response using a simplex search algorithm (*fminsearch* in MATLAB 7.10.0 by Mathworks) to minimize the f1’ error.[4] The error f1’ characterizes the degree to which the relative spectral response of a light measurement system matches V(λ) . This optimization procedure resulted in a typical f1’ error of approximately 25%. Figure 5 shows the weighted channel response that minimizes the f1’ error for the three Dimesimeters. Since the Dimesimeter responds linearly to light intensity (Figure 4), the outputs generated by the three Dimesimeter channels (C_R, C_G, C_B) can be multiplied by these two sets of constants and added together to estimate photopic illuminance (E_λ) for any arbitrary light level and light source as shown in Equation 2.

$$E_{Dime}\ [\text{lux}] = R' * W_R * C_R + G' * W_G * C_G + B' * W_B * C_B \qquad \textbf{(Equation 2)}$$

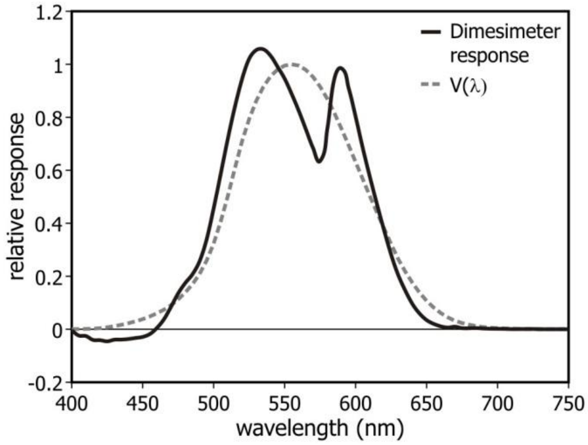

Figure 5: Weighted response that minimizes the f1' error for the Dimesimeter, compared with V(λ)

Because in the natural environment people will be exposed to a wide variety of light sources with different spectral power distributions, one final, minor adjustment was undertaken to improve the overall photometric accuracy of the Dimesimeter. The f1’ channel adjustments to match V(λ) are based upon a formal optimization of the overall spectral sensitivity to Illuminant A. To further maximize measurement accuracy, the spectral power distributions of a variety of practical, broadband light sources (Table 1) were used to determine a factor F that minimized the overall measurement error. The factor F defined in Equation 3 was applied to each of the calibration constants R’, G’, and B’. The value of F does not affect the f1’ error since it is applied equally to the R’, G’, and B’ constants.

$$F = \sum_{i=1}^{9} W_i * \frac{\int SPD(\lambda)_i * V(\lambda) * d\lambda}{E_{Dime_i}}$$

(Equation 3)

where $SPD(\lambda)_i$ is the spectral power distribution of source *i*, $V(\lambda)$ is the photopic luminous efficiency function, $E_{Dime\ i}$ is the photopic illuminance in Equation 2, and W_i is the weighting given to light source *i*. Table 1 shows the weighting factors applied to the different light sources used for determining F. These factors were chosen based upon the expected frequency with which they would be encountered in homes, offices, and outdoors. Figure 6 illustrates the expected relative errors in the photopic illuminance values generated by the Dimesimeter based upon Equations 2 and 3. For most commonly used white light sources the expected photometric errors would be less than 5%.

Table 1. Weighting coefficients for various light sources in the Dimesimeter photopic calibration.

Source	Weighting
CIE Illuminant A	9/31
CIE D65	9/31
3500 K Sylvania Octron T8 fluorescent	3/31
4100 K Sylvania Octron T8 fluorescent	3/31
6500 K Sylvania Octron T8 fluorescent	3/31
Luxeon 5200 K white LED	1/31
Agilent 4300 K white LED	1/31
CIE Illuminant A + 450 nm LED (8550 K)	1/31
Nichia 5400 K white LED	1/31

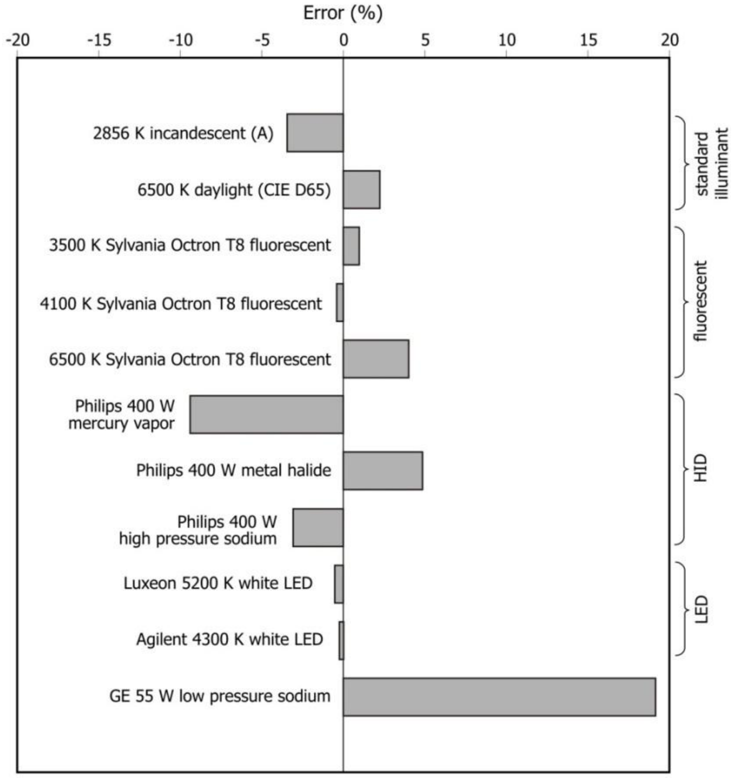

Figure 6: Expected errors (in %) when making photopic measurements of various sources with the Dimesimeter

CL_A Calibration

The same technique that was used to optimize the spectral response of the Dimesimeter to the photopic response, V(λ), is also used to optimize responses that approximate the different photoreceptor spectral sensitivities that are used for calculating CL_A.[1] CL_A is spectrally weighted corneal irradiance based upon the spectral sensitivity of the human circadian system. The equations for calculating CL_A are shown below.

If $S_{mac} > k * V_{mac}$ **(Equation 4)**

$$CL_{A_{Dime}} = A * \left[M + a_{b-y} * (S_{mac} - k * V_{mac}) - a_{rod} * 683 * \left(1 - e^{\left(\frac{-V\prime}{6.5 * 683}\right)}\right)\right]$$ **(Equation 5)**

else

$$CL_{A_{Dime}} = A * M$$ **(Equation 6)**

where *M*, S_{mac}, V_{mac}, and *V'* are the approximated photoreceptor response values given by Equation 7 and Table 2.

The weighting values obtained from the curve-fitting optimization are given in Table 2. Values for the photoreceptor response curves used for calculating CL_A are given in Table 4 at the end of this document. The photoreceptor curves are given by the following general equation:

$$Approximated\ photoreceptor\ response = w_R * C_R * R' + w_G * C_G * G' + w_B * C_B * B'$$ **(Equation 7)**

Table 2. Photoreceptor response curve weighting values.

Photoreceptor response curve	Symbol	w_R	w_G	w_B
S_{cone}/macula	S_{mac}	0.004902	-0.077333	0.293393
V(λ)/macula	V_{mac}	0.300981	0.736231	0.021824
Melanopsin	M	-0.009224	0.097292	0.320870
V'(λ)	V'	-0.028144	0.390077	0.199808
V(λ)	V	0.334060	0.645098	-0.013336

The optimized photoreceptor responses are then used in the CL_A model to determine a Dimesimeter estimation of CL_A (denoted $CL_{A\ Dime}$) and the constants in the model a_{b-y}, a_{rod}, k, and A (shown in Table 3) are re-optimized to minimize the error between the actual CL_A determined from the model and that estimated by the Dimesimeter using the *fminsearch* algorithm. The error being minimized is given by the following equation:

$$Error = \sum_{j=1}^{7} \sum_{i=1}^{9} W_i * \left|\left(CL_{A(Dime)i,j} - CL_{Ai,j}\right)/CL_{Ai,j}\right|$$

(Equation 8)

The subscript *j* specifies one of seven light levels (10, 31.6, 100, 316, 1000, 3160, and 10000 lux) and the subscript *i* specifies one of nine spectrum (incandescent, daylight, three fluorescent, and four phosphor-converted white LEDs). W_i specifies the weighting factors given in Table 1.

The following values are obtained for the constants in the model:

Table 3. $CL_{A_{Dime}}$ calculation constants.

a_{b-y}	a_{rod}	k	A
0.447	3.13	.253	2.46

Table 4. Tabulated values for the photoreceptor response curves used for calculating CL_A.

Wavelength (nm)	S_{cone}/macula	V/macula	Melanopsin	V'	V
380	0.000000	0.000000	0.001595	0.000000	0.000000
382	0.000000	0.000000	0.002760	0.000000	0.000000
384	0.000000	0.000000	0.003925	0.000000	0.000000
386	0.000000	0.000000	0.005090	0.000000	0.000000
388	0.000000	0.000000	0.006255	0.000000	0.000000
390	0.002901	0.000118	0.007420	0.002209	0.000120
392	0.015315	0.000149	0.011903	0.002939	0.000152
394	0.027730	0.000188	0.016386	0.003921	0.000192
396	0.040144	0.000242	0.020870	0.005240	0.000247
398	0.052559	0.000312	0.025353	0.006980	0.000319
400	0.108826	0.000650	0.029836	0.009290	0.000396
402	0.134866	0.000791	0.042752	0.012310	0.000473
404	0.161878	0.000975	0.055669	0.016190	0.000572
406	0.189837	0.001258	0.068585	0.021130	0.000725
408	0.218760	0.001664	0.081502	0.027300	0.000941
410	0.248773	0.002179	0.094418	0.034840	0.001210
412	0.294731	0.002805	0.119967	0.043900	0.001531
414	0.342319	0.003609	0.145517	0.054500	0.001936
416	0.393544	0.004683	0.171066	0.066800	0.002455
418	0.449441	0.006119	0.196616	0.080800	0.003118
420	0.508646	0.008083	0.222165	0.096600	0.004001
422	0.565490	0.010797	0.257443	0.114100	0.005160
424	0.626527	0.014204	0.292721	0.133400	0.006547
426	0.688422	0.018118	0.327999	0.154100	0.008088
428	0.750208	0.022493	0.363277	0.176400	0.009770
430	0.815529	0.027477	0.398555	0.199800	0.011602
432	0.845751	0.032675	0.433760	0.224300	0.013585
434	0.876930	0.038404	0.468964	0.249600	0.015718
436	0.908833	0.044700	0.504169	0.275500	0.018011
438	0.941463	0.051571	0.539373	0.301700	0.020458

Wavelength (nm)	S_{cone}/macula	V/macula	Melanopsin	V'	V
440	0.975135	0.058917	0.574578	0.328100	0.023005
442	0.978968	0.066985	0.603092	0.354300	0.025615
444	0.982965	0.075750	0.631607	0.380300	0.028357
446	0.987883	0.085562	0.660121	0.406000	0.031317
448	0.993795	0.096607	0.688636	0.431000	0.034528
450	1.000000	0.108967	0.717150	0.455000	0.038008
452	0.996493	0.122404	0.743779	0.479000	0.041776
454	0.992829	0.137364	0.770409	0.502000	0.045852
456	0.982230	0.152958	0.797038	0.524000	0.050254
458	0.964579	0.168924	0.823668	0.546000	0.054991
460	0.946599	0.186063	0.850297	0.567000	0.060012
462	0.906442	0.199248	0.869698	0.588000	0.065290
464	0.867527	0.213094	0.889099	0.610000	0.070925
466	0.827966	0.227409	0.908499	0.631000	0.077031
468	0.788048	0.242293	0.927900	0.653000	0.083683
470	0.749637	0.258497	0.947301	0.676000	0.090998
472	0.685812	0.275160	0.957841	0.699000	0.099065
474	0.624761	0.293200	0.968381	0.722000	0.107906
476	0.572134	0.315839	0.978920	0.745000	0.117555
478	0.526025	0.343633	0.989460	0.769000	0.128018
480	0.480000	0.372895	1.000000	0.793000	0.139047
482	0.440242	0.403234	0.992360	0.817000	0.150499
484	0.400557	0.435656	0.984720	0.840000	0.162750
486	0.359606	0.469685	0.977080	0.862000	0.176278
488	0.317857	0.505524	0.969440	0.884000	0.191311
490	0.276793	0.545274	0.961800	0.904000	0.208061
492	0.248893	0.581675	0.942587	0.923000	0.226779
494	0.222157	0.621663	0.923373	0.941000	0.247530
496	0.193517	0.654697	0.904160	0.957000	0.270238
498	0.164412	0.680513	0.884946	0.970000	0.295109
500	0.137982	0.710742	0.865733	0.982000	0.323064
502	0.118311	0.730540	0.838002	0.990000	0.354756
504	0.101006	0.753603	0.810271	0.997000	0.389364
506	0.085251	0.773481	0.782540	1.000000	0.425714
508	0.070992	0.789912	0.752881	1.000000	0.463486
510	0.058397	0.807379	0.721292	0.997000	0.503099
512	0.049622	0.825937	0.686921	0.990000	0.544620
514	0.041761	0.843914	0.652550	0.981000	0.587081
516	0.034555	0.856932	0.618179	0.968000	0.629479
518	0.027979	0.864567	0.583808	0.953000	0.671008
520	0.022071	0.868496	0.549437	0.935000	0.710140
522	0.019524	0.888215	0.516973	0.915000	0.745611

Wavelength (nm)	S_{cone}/macula	V/macula	Melanopsin	V'	V
524	0.017107	0.903349	0.484509	0.892000	0.777990
526	0.014797	0.914606	0.452045	0.867000	0.808270
528	0.012591	0.922273	0.419581	0.840000	0.836472
530	0.010495	0.926865	0.387117	0.811000	0.862170
532	0.009314	0.941451	0.360157	0.781000	0.885137
534	0.008158	0.953117	0.333197	0.749000	0.905622
536	0.007024	0.962127	0.306236	0.717000	0.923917
538	0.005914	0.968646	0.279276	0.683000	0.940108
540	0.004826	0.972877	0.252316	0.650000	0.954189
542	0.004267	0.981489	0.232298	0.616000	0.966198
544	0.003713	0.988021	0.212280	0.581000	0.976215
546	0.003162	0.992527	0.192263	0.548000	0.984287
548	0.002616	0.995124	0.172245	0.514000	0.990508
550	0.002073	0.996118	0.152227	0.481000	0.995147
552	0.001835	0.998809	0.138823	0.448000	0.998296
554	0.001598	1.000000	0.125419	0.417000	0.999946
556	0.001360	0.999648	0.112016	0.386400	1.000054
558	0.001123	0.997658	0.098612	0.356900	0.998523
560	0.000886	0.993877	0.085208	0.328800	0.995197
562	0.000826	0.987259	0.077103	0.301800	0.989938
564	0.000766	0.978905	0.068998	0.276200	0.982918
566	0.000706	0.968959	0.060892	0.251900	0.974276
568	0.000646	0.957461	0.052787	0.229100	0.964047
570	0.000587	0.944379	0.044682	0.207600	0.952188
572	0.000528	0.930558	0.040177	0.187600	0.938685
574	0.000469	0.915222	0.035671	0.169000	0.923640
576	0.000410	0.898503	0.031166	0.151700	0.907186
578	0.000351	0.880463	0.026660	0.135800	0.889380
580	0.000293	0.861051	0.022155	0.121200	0.870172
582	0.000292	0.839105	0.019829	0.107800	0.849560
584	0.000292	0.816055	0.017503	0.095600	0.827745
586	0.000291	0.792125	0.015178	0.084500	0.804954
588	0.000291	0.767478	0.012852	0.074500	0.781346
590	0.000290	0.742344	0.010526	0.065500	0.757150
592	0.000290	0.718242	0.009384	0.057400	0.732567
594	0.000290	0.693799	0.008242	0.050200	0.707636
596	0.000290	0.669011	0.007099	0.043800	0.682354
598	0.000290	0.643961	0.005957	0.038160	0.656804
600	0.000290	0.618784	0.004815	0.033150	0.631125
602	0.000232	0.593595	0.004288	0.028740	0.605434
604	0.000174	0.568416	0.003760	0.024870	0.579752
606	0.000116	0.543236	0.003233	0.021470	0.554071

Wavelength (nm)	S_{cone}/macula	V/macula	Melanopsin	V'	V
608	0.000058	0.518124	0.002705	0.018510	0.528457
610	0.000000	0.493262	0.002178	0.015930	0.503099
612	0.000000	0.468776	0.001945	0.013690	0.478125
614	0.000000	0.444625	0.001711	0.011750	0.453493
616	0.000000	0.420773	0.001478	0.010070	0.429165
618	0.000000	0.397190	0.001244	0.008620	0.405112
620	0.000000	0.373624	0.001011	0.007370	0.381075
622	0.000000	0.349919	0.000900	0.006300	0.356898
624	0.000000	0.326374	0.000788	0.005380	0.332883
626	0.000000	0.303349	0.000677	0.004590	0.309399
628	0.000000	0.281045	0.000565	0.003913	0.286650
630	0.000000	0.259869	0.000454	0.003335	0.265052
632	0.000000	0.240148	0.000398	0.002842	0.244938
634	0.000000	0.221676	0.000342	0.002421	0.226097
636	0.000000	0.204132	0.000286	0.002062	0.208203
638	0.000000	0.187454	0.000230	0.001757	0.191193
640	0.000000	0.171612	0.000174	0.001497	0.175035
642	0.000000	0.156556	0.000161	0.001276	0.159678
644	0.000000	0.142316	0.000148	0.001088	0.145155
646	0.000000	0.128954	0.000135	0.000928	0.131526
648	0.000000	0.116480	0.000122	0.000792	0.118803
650	0.000000	0.104928	0.000109	0.000677	0.107021
652	0.000000	0.094326	0.000094	0.000579	0.096208
654	0.000000	0.084595	0.000079	0.000496	0.086282
656	0.000000	0.075628	0.000063	0.000425	0.077136
658	0.000000	0.067380	0.000048	0.000365	0.068724
660	0.000000	0.059819	0.000033	0.000313	0.061012
662	0.000000	0.052910	0.000026	0.000269	0.053966
664	0.000000	0.046629	0.000020	0.000231	0.047559
666	0.000000	0.040950	0.000013	0.000199	0.041767
668	0.000000	0.035856	0.000007	0.000172	0.036571
670	0.000000	0.031380	0.000000	0.000148	0.032006
672	0.000000	0.027533	0.000000	0.000128	0.028082
674	0.000000	0.024230	0.000000	0.000110	0.024713
676	0.000000	0.021379	0.000000	0.000095	0.021805
678	0.000000	0.018908	0.000000	0.000083	0.019285
680	0.000000	0.016671	0.000000	0.000072	0.017003
682	0.000000	0.014550	0.000000	0.000062	0.014840
684	0.000000	0.012586	0.000000	0.000054	0.012837
686	0.000000	0.010854	0.000000	0.000047	0.011070
688	0.000000	0.009349	0.000000	0.000041	0.009535
690	0.000000	0.008051	0.000000	0.000035	0.008212

Wavelength (nm)	S_{cone}/macula	V/macula	Melanopsin	V'	V
692	0.000000	0.006948	0.000000	0.000031	0.007087
694	0.000000	0.006020	0.000000	0.000027	0.006140
696	0.000000	0.005240	0.000000	0.000023	0.005344
698	0.000000	0.004586	0.000000	0.000020	0.004677
700	0.000000	0.004023	0.000000	0.000018	0.004103
702	0.000000	0.003520	0.000000	0.000016	0.003590
704	0.000000	0.003073	0.000000	0.000014	0.003135
706	0.000000	0.002685	0.000000	0.000012	0.002739
708	0.000000	0.002347	0.000000	0.000010	0.002394
710	0.000000	0.002051	0.000000	0.000009	0.002091
712	0.000000	0.001789	0.000000	0.000008	0.001825
714	0.000000	0.001559	0.000000	0.000007	0.001591
716	0.000000	0.001358	0.000000	0.000006	0.001385
718	0.000000	0.001181	0.000000	0.000005	0.001204
720	0.000000	0.001027	0.000000	0.000005	0.001047
722	0.000000	0.000893	0.000000	0.000004	0.000911
724	0.000000	0.000778	0.000000	0.000004	0.000793
726	0.000000	0.000677	0.000000	0.000003	0.000691
728	0.000000	0.000588	0.000000	0.000003	0.000600
730	0.000000	0.000510	0.000000	0.000003	0.000520

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