Spectral sensitivity function measured by a rapid scan flicker photometric procedure

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A rapid scan flicker photometric procedure is described whereby continuous spectral sensitivity functions are measured from unpracticed observers in 30 min. The 30 min includes instructions, practice, and data collection. Data are presented from four unpracticed observers age 12 to 42 years. Three practiced observers had their spectral sensitivities measured by both the conventional and rapid scan methods. The conventional method took 1.5 hr, measuring at 25 wavelengths and repeating each three times. The agreement between the rapid scan and conventional methods is satisfactory. Comparison with Judd's correction of CIE V(\lambda) yields the same deviations as expected with conventional flicker photometry. The rapid scan procedure is shown to yield acceptably consistent data. The advantages of the rapid scan method for basic and applied vision research is discussed.

Key words: spectral sensitivity, flicker photometry, cone, fovea, retina

This paper describes a rapid scan flicker photometric procedure whereby continuous spectral sensitivity functions are obtained from unpracticed observers in 30 min. The 30 min includes instructions, practice, and actual data collection. A practiced observer can collect the same data in 15 min. These times do not include the radiometry necessary for the calculation of a sensitivity function. However, the radiometry does not require the presence of the observer.

The temporal requirements of conventional flicker photometry make it difficult to use when the observer’s time is limited and when more than one complete function per day may be desired. For example, research conducted on volunteer patients in ophthalmological clinics frequently requires that the test procedures be conducted with sufficient speed so that the patients are not unduly detained. Conventional flicker photometric procedures make it difficult to assess spectral sensitivity on such patients. The procedure described below overcomes this temporal obstacle, thus freeing this psychophysical assessment for a wider range of purposes.

Flicker photometry provided most of the data used to establish the 1924 CIE standard photopic luminosity function (V(\lambda)). This procedure is usually carried out as follows. A reference light (frequently white) is temporally alternated with a chromatic light. The chromatic light is variable in wavelength and radiance. A convenient flicker frequency is found that, with an appropriate chromatic radiance, meets the criterion of minimal perceptible flicker. When the radiance is increased or decreased from this point, the perceived flicker increases. This procedure is carried out on a convenient number of wavelengths (frequently ranging from as few as 10

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Fig. 1. Schema of apparatus. L₁ to L₆, Lenses for channeling light to the observer; S₁, source of the reference white light. See text for complete description.

to perhaps 30) and repeated at each wavelength a number of times depending on the required precision (usually from three to 15 repetitions per wavelength). Depending on the number of wavelengths sampled and the number of repetitions at each wavelength, conventional flicker photometry can take from 1 to several hours with unpracticed observers.

The rapid scan procedure described herein uses a variant of the tracking method von Bekesy¹ introduced for audiometry. Łakowski and his colleagues²–³ have used a tracking procedure to determine dark adaptation functions in color-deficient subjects and patients with glaucoma. Cavonius and Estévez⁴ used the von Bekesy tracking method to measure the spectral sensitivities of red, green, and blue mechanisms but provide a cursory description of how their procedure was conducted and present highly processed data. Estévez et al.⁵ provide a good description of this scanning procedure for measuring spectral sensitivities of human color mechanisms from contrast-evoked cortical potentials. They validate the electrophysiological measures with psychophysical measurements using the same optical apparatus. It is unclear when their psychophysical data were collected while the wavelengths were continuously
scanned and when the wavelengths were presented discretely. They report that the data were collected both ways. In their procedure they monitor the position of a neutral density wedge on the ordinate of an X-Y plotter and wavelength on the abscissa. They show that the psychophysical responses provide an adequate match with the electrophysiological responses and that the latter agree well with Stiles’ π1, π4, and π5 mechanism.

Below, I show that scanning rapidly through the spectrum yields the same flicker photometric function as the conventional flicker photometric method.

Thus the procedure of Estévez et al. can be extended to psychophysically determined functions. In addition, it is shown that the scan rate can be reduced from the 15 min for a single complete scan of 400 to 700 nm required for evoked potentials to 6 min for the flicker procedure.

**Materials and methods**

Fig. 1 shows a schematic representation of the apparatus. Monochromatic light was obtained by passing light from a xenon arc through an automatic scanning high-intensity grating monochromator (Model GM 250, Schoeffel Instrument Corp., Westwood, N. J.). The chromatic radiance was varied by an Inconel neutral-density wedge driven by a reversible 1.5 rpm synchronous motor. A cover slip acted as a beam splitter to divert part of the chromatic light to a United Detector Technology (UDT 500) photocell. The voltage from this photocell passed through a log amplifier and to the ordinate of an X-Y plotter. The reference white disc was used to measure the flicker frequency. Attached to the monochromator was a synchronous motor and variable-ratio gear mechanism to automatically change the wavelength at a predetermined rate. Attached to the drive mechanism of the monochromator was a highly linear potentiometer which provided an analog readout of wavelength, monitored by a digital voltmeter and fed into the abscissa of the X-Y plotter. The alternating fields were presented to the observer by rear projecting them on a ground glass screen. A white mask provided a 2° aperture with a dimly lit (0.2 cd · m⁻²) surround. The reference white field measured from the ground glass screen, had chromaticity coordinates of x = 0.337, y = 0.391, and had a luminance of 1.4 cd · m⁻².

The maximum wavelength range over which it was possible to obtain a function depended on the observer’s sensitivity and the luminance of the reference field. I realize that 1.4 cd · m⁻² is a low photopic level. Therefore sensitivity functions on two practiced and one unpracticed observer were also obtained at 5.2 and 10.4 cd · m⁻². No change in shape of the sensitivity function resulted. As the luminance of the reference light increased, the only result was a progressively narrower range of wavelengths able to be scanned.

The procedure for the rapid scan method is slightly different from the standard method described above. Instead of adjusting the radiance of the chromatic light for minimum perceptible flicker, the observer varied it to alternate between the perception of flicker and the disappearance of flicker by pushing one of two switches which activated the reversible motor. This motor rotated the neutral-density wedge in the chromatic channel. One switch caused the wedge to rotate clockwise, thus increasing the amount of chromatic light; the other switch caused the wedge to rotate counterclockwise, thus decreasing the amount of chromatic light. The observer, placed in a chin rest, viewed the ground-glass screen monocularly while wearing normal prescription spectacles (if not tinted). If the glasses were tinted, the observer was provided with appropriate trial lenses. The observer was told to push one switch if flicker was perceived and the other switch if no flicker was perceived. The observer’s task was to continuously change the amount of chromatic light causing flicker to appear and then to disappear. While the observer was producing and eliminating flicker, the wavelength automatically changed at a rate of 50 nm/min. At this rate it took 5.3 min to traverse all the wavelengths in the spectrum from 410 to 675 nm. Unpracticed observers found it difficult to concentrate for 5 continuous minutes on these flicker judgments. However, when three to five short rests (about 30 sec each) were given, the task became relatively easy. The spectrum was traversed twice, once in each direction, to compensate for possible chromatic adaptation effects. The flicker frequency was adjusted for each observer but was never lower than 17 Hz or higher than 20 Hz.

Alternating between flicker and no flicker rather than determining the range of no flicker was done because the latter method was too slow. We tested both methods and found the first method to be faster. The second method is similar to the conventional method discussed above. But in the
Fig. 2. Relative amount of chromatic light (volts) required to alternate between the perception of flicker and no flicker, with the rapid scan tracking method. D. M. B., P. K. K., and S. N. are practiced observers. The solid dots represent data by conventional flicker photometry.
Fig. 3. Relative amount of chromatic light (volts) required to alternate between the perception of flicker and no flicker, with the rapid scan tracking method. A. W., D. K., and L. H. are unpracticed observers.
rapid scan procedure, time is important because wavelength is continually changing. Furthermore, when alternating between flicker and no flicker, one is not bothered by the varying range of no flicker as a function of wavelength as is encountered by conventional flicker photometry. As will be seen below we compared the conventional flicker method with our rapid scan procedure and do not find any consistent differences.

Results

Fig. 2 shows the functions obtained from three observers who have had previous experience in psychophysical vision experiments. Observers S. N. and D. M. B. had a moderate amount of experience with flicker photometry but no experience with the rapid scan procedure. Observer P. K. K. was highly experienced with both methods. All three observers performed the rapid scan method and conventional flicker photometry. Fig. 2 shows the lines of best fit through the rapid scan raw data and data by the conventional method (black dots). Strictly speaking, these were not sensitivity functions. The photocell that provided the input to the ordinate of the X-Y plotter deviated from being a spectrally flat detector by as much as 0.13 log units. In order to plot a true sensitivity function, one must perform the necessary radiometric measurements (see below). For most basic research this would be imperative. However, in clinical application all that would be required is to know the shape of the curve showing the relative volts as a function of wavelength for the normal observer. This function can then be used as a template with which to compare patients with known or suspected pathological conditions. It took 1.5 hr for each observer to produce the conventional data. Each dot is the mean of three trials at the indicated wavelengths. The rapid scan method took less than 25 min for Observers S. N. and D. M. B. Observer P. K. K. took less than 15 min. The conventional flicker method was normalized at 550 nm and plotted over the raw rapid scan curves. There were slight differences between the conventional and rapid scan method; however, the differences fell within experimental error.

Fig. 3 contains the records of three unpracticed observers using the rapid scan method: a 12-year-old male (D. K.), a 30-year-old male (A. W.), and a 35-year-old female (L. H.). Each observer required 30 min to produce this data. The lines through these records are the visually best fit lines through the raw data.

Fig. 4 shows the functions of a 42-year-old unpracticed male observer. In this figure we
have reproduced the lines of best fit for his right and left eyes. Refraction in this observer's right eye was corrected to +1.50 +3.00 x 95 (20/20) and in the left eye to +2.00 +3.50 x 88 (20/40). In 1964 he was diagnosed as having a bilateral presumed ocular histoplasmosis syndrome with peripheral lesions in both eyes. There were juxtapapillary lesions as follows: right eye: superior to disc, macular not involved; left eye: temporal between disc and macula, macular edema, worst vision 20/60. His current fields were right: normal; left: scotoma from blind spot encircling fixation 3° to 5°, sparing central 3°. His color vision was right: normal; left: mild red-green and yellow-blue defect as measured with AO/HRR plates and an increased Nagel matching range. Finally, eccentric fixation in the left eye has been known since childhood. It took approximately 1 hr to collect these two functions (Fig. 4). It can be seen that the left eye exhibited a clearly higher sensitivity in the short wavelength end of the spectrum than did the right eye. I believe that this was attributed to the fact that his left eye was amblyopic and he had difficulty maintaining good central fixation. This observer reported that he did have difficulty fixating with that eye. Since the density of the macular pigment decreases as one moves away from the fovea centralis, I interpret the higher sensitivity in the blue end of the spectrum to represent the fact that the observer was fixating slightly eccentrically with the left eye. However, with his good right eye, he was able to achieve good central fixation where the density of the macular pigment was maximum. Support for this interpretation is derived from curves published by Marré and Marré who showed an elevated sensitivity in the short wavelength end of the spectrum by amblyopic observers using extrafoveal fixation. In addition, Wald has shown that normal observers have a similar elevation in sensitivity under extrafoveal fixation.

Thus far we have seen that the rapid scan procedure yields data similar to those from conventional flicker photometry, unpracticed observers can use the technique, and an unpracticed observer with known pathological conditions yields interpretable results. Two
questions have not been answered. Does this method yield consistent results? How does it compare with other sensitivity functions? To test the consistency question, two observers performed the task eight times. We present here the data (Fig. 5) for one of two observers. The other observer showed even less scatter than shown in Fig. 5. Each open circle represents where the line of best fit occurred at the indicated wavelengths for each of the eight trials. The data were normalized at 550 nm. The solid line connects the median data points at each wavelength.

As indicated above, the raw data are not true sensitivity functions. However, our photocell was a reasonably flat detector. The dashed curve in Fig. 5 is a true sensitivity function. That is to say, the amount of chromatic light was adjusted so that it produced the median voltage value as shown, and the radiance associated with this amount of chromatic light was measured at the ground-glass screen, normalized to 550 nm, and plotted over the original data. It was seen that the correspondence between the true sensitivity functions (dashed line) and that represented by the relative volts (solid line) was reasonably close. The sensitivity function (dashed line) described a slightly broader curve than the raw data.

The second question was answered with reference to the Xs in Fig. 5 which represent the spectral sensitivity of Judd's correction of the CIE photopic standard observer. One can see the reasonably close correspondence of P. K. K.'s spectral sensitivity (dashed line) to that of the CIE photopic standard observer with Judd's correction applied to 450 nm and below.

Discussion

Clearly the data obtained by the rapid scan method are comparable to those obtained by the conventional approach. These differences (Fig. 2) fall within experimental variability (Fig. 5). It is also seen that P. K. K.'s spectral sensitivity (Fig. 5) coincides quite well with Judd's correction of the CIE V(A). This is typical for this observer whose sensitivity function has been measured many times.

Since the equivalence of results obtained by the rapid scan procedure and the slower conventional method has been demonstrated, the former can now be used under those conditions where data collection speed is important.

In the past several years considerable emphasis has been placed on the "application of psychophysics to clinical problems." Indeed, a symposium with just this title was recently sponsored by the Committee on Vision of the National Research Council-National Academy of Science. As I understand it, usually clinical researchers are able to collect psychophysical data only when they can persuade a cooperative patient to spend an extended period of time in the laboratory. The rapid scan method now permits one to be tested for sensitivity function as part of a routine visit to an ophthalmology clinic.

The question can be rightfully asked: What for? A few reports show that severe cone pathology results in abnormal spectral sensitivity functions. These abnormal functions are usually associated with rather severe pathological conditions which also can manifest themselves as color-defective vision. Such color deficiencies may result from inherited or acquired disorders. One could make a case for being able to monitor the spectral sensitivity of patients with acquired deficiencies from the time of first consultation. This would be valuable for research clinicians interested in following the progress of a traumatically induced pathological disorder that usually results in acquired color-defective vision.

This procedure would be of value to the basic vision scientist as well. It is not uncommon to adjust stimuli for equal luminance by means of photometer. When a physical photometer is used, assumptions are necessary with regard to the correspondence between an observer's spectral sensitivity and the sensitivity of the photometer. The spectral sensitivity of the photometer is usually adjusted to approximate that of the CIE photopic standard observer. But most observers do not have the same spectral sensitivity as the CIE photopic standard ob-
Some observers do not even have the same spectral sensitivity as Judd's correction of the CIE V(λ). This lack of correspondence in sensitivity functions with the standard CIE observer will cause errors in the measurement of light. Thus, for critical work, it would be of value to assess the spectral sensitivity of one's observers. Now that this can be accomplished rapidly, it becomes a more feasible procedure in many basic experiments.

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REFERENCES