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CONTRAST SENSITIVITY DETERMINED WITH THE SPATIAL BANDWIDTH EQUALIZATION TECHNIQUE: THRESHOLD, SUPRATHRESHOLD, AND SPATIOTEMPORAL MEASUREMENTS
(Reprint)

By
Roger W. Wiley
Thomas H. Harding
Michael G. Gribler
Albert W. Kirby

Sensory Neurosciences Research Group
SENSORY RESEARCH DIVISION

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Contrast Sensitivity Determined with the Spatial Bandwidth Equalization Technique: Threshold, Suprathreshold, and Spatiotemporal Measurements

ROGER W. WILEY*
Sensory Neurosciences Research Group, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama, and School of Optometry, University of Missouri-St. Louis, St. Louis, Missouri

THOMAS H. HARDING,† MICHAEL G. GRIBLER,‡ and ALBERT W. KIRBY†
Sensory Neurosciences Research Group, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama

ABSTRACT

Contrast sensitivity functions were obtained from normal subjects using a spatial bandwidth equalization (SBE) technique and the more conventional display method. Static sensitivity measurements obtained with the two methods were in good agreement. However, when the patterns were counterphase flickered, sensitivity to the lower spatial frequencies was enhanced using the conventional method while sensitivity measured with the SBE technique was slightly depressed. The SBE method also was used to investigate suprathreshold contrast perception with static and flickering gratings. In general, the perception of contrast was independent of spatial frequency content of the stimulus, especially with increasing contrast levels and flicker frequencies. These studies have shown that the SBE technique is an acceptable method to assess static contrast sensitivity and suprathreshold contrast perception.

Key Words: spatial bandwidth equalization, contrast sensitivity, suprathreshold contrast perception, spatiotemporal contrast sensitivity

In clinical practice, spatial vision usually is assessed by a minimal separation criterion of familiar objects having very high contrast. Unfortunately, this measure is rather one-dimensional and has limited quantitative and predictive value for the visual environment in which we are required to function. A more complete evaluation of spatial vision is provided by the contrast sensitivity function (CSF) which gives information concerning the minimum contrast necessary for detection of a series of grating patterns of various spatial frequencies. Studies using spatial frequency analysis techniques have provided important information concerning basic visual properties in the developing,[1,2] mature,[3-6] and aging,[7-9] visual system. In addition, CSF's have been used to examine quantitatively such visual dysfunctions as amblyopia[10-12] and certain pathologies which affect the eye[13] and visual system.[14,15] CSF's also have been used to examine vision with contact lenses,[16,17] efficacy of visual rehabilitation,[18] and, recently, the suggestion[19,20] has been made that exposure to discrete spatial frequencies could be used in the treatment of amblyopia, although this latter suggestion has been challenged.[21,22]

Despite the increasing number of investigations which demonstrate the importance of determining the CSF when visual function is assessed, this technique still has not found general application in clinical practice, probably because the conventional method of obtaining CSF's requires good patient cooperation and is rather time consuming. Several methods have been suggested to reduce collection time.[23] Typically, a grating pattern is generated electronically on a cathode ray tube (CRT) and the observer adjusts the contrasts until that pattern is perceived to be at threshold. This procedure is repeated with additional frequencies until a description of contrast as a function of spatial frequency is obtained. Because of normal variability, these measurements must be repeated until a statistically reliable estimate of threshold

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* Optometrist, Ph.D., Member of Faculty, F.A.A.O.
† Ph.D.
‡ Biomedical Engineer.

is achieved. The CSF is displayed then as the reciprocals of these threshold contrasts.

Dobson and Davison[24] developed an optional method of obtaining a CSF which they termed the SBE technique. This method appears to reduce some of the disadvantages of measuring the CSF in clinical practice. Similar to the conventional CSF technique, the SBE method requires the electronic generation of patterns on a CRT. However, instead of a single frequency display as with the conventional technique, the SBE method displays multiple spatial frequencies simultaneously on the screen. For this paper, spatial frequency is defined as the number of light and dark bars per unit visual angle. With the SBE method, spatial frequency varies in an orderly fashion along the horizontal dimension of the screen while contrast varies in the vertical dimension. The screen is divided into a number of vertical segments and the patient controls contrast of the patterns within these segments with separate potentiometers. A horizontal line bisects the screen into upper and lower halves, and the patient's task is to adjust the contrast within each screen segment so that the patterns contained therein appear to be visible above the horizontal bisection but are invisible below. Because all spatial frequencies are viewed simultaneously, a criterion shift between observation is prevented. Dobson and Davison were able to obtain results in reasonable agreement with those obtained with the conventional CSF but in a much shorter time.

In this report we present results using a variant of the SBE technique. Whereas the perceptual task is similar to that used by Dobson and Davison, the instrumentation has been modified to provide a temporal capability. We have repeated Dobson's and Davison's comparisons between CSF's obtained with the conventional and SBE techniques and have expanded the data base using the SBE to include suprathreshold contrast perception and spatiotemporal sensitivity measurements at threshold and suprathreshold levels.

METHODS

Stimulus Generation

The stimulus display with the SBE technique was similar, but not identical, to that used by Dobson and Davison.[24] The method of stimulus pattern generation in our system was significantly different, and the flexibility of our electronic control was expanded to include a temporal capability so that the spatial frequencies could be presented in counterphase (sine or square wave) fashion at predetermined temporal frequencies. The SBE stimulus consists of a series of sinusoids of increasing spatial frequency from left to right (Fig. 1) generated on the face of a CRT. The screen of the CRT was partitioned electronically into eight equally spaced compartments, and the contrast of the pattern within each of these compartments could be varied independently with the corresponding one of eight potentiometers in the observer's control box.

A block diagram of the electronic pattern generation system is shown in Fig. 2. The system also is capable of conventional grating generation according to the method of Campbell and Green.[3] Contrast reversal is provided by multiplier 2 whose Y input is either a sine or square wave of selectable frequency. For patterns of increasing spatial frequency, a sweep generation system is used whose primary component is a voltage-controlled oscillator. The frequency of the output of the oscillator is inversely proportional to applied positive voltage. For a linear increase in spatial frequency with distance across the CRT screen, a ramp of negative slope is required. However, in order to provide measurement resolution at low as well as high spatial frequencies, we took the antilog of the linearly decreasing ramp voltage and applied the transformed voltage to the oscillator. This transformation allowed for a positive acceleration of spatial frequency with horizontal distance on the CRT. Thus, the mean frequencies of each of the eight bands of spatial frequency were separated more or less equally on a log plot.

For gratings of a single spatial frequency, contrast was controlled by a single potentiometer whose dc voltage output was multiplied (multiplier 1) with a sine wave of constant amplitude. For patterns of increasing spatial frequency, the output of eight potentiometers were gated such that each potentiometer controlled the contrast in its corresponding spatial frequency compartment on the CRT. In order for contrast to increase linearly from the bottom of the screen to the top, the Y-axis triangle wave with an appropriate dc offset (minimum voltage value set to zero) was multiplied (multiplier 3) with the increasing frequency band. Contrast was always zero at the bottom of the screen and accelerated with vertical distance on the screen at a rate proportional to potentiometer voltage. The maximum contrast at the top of the screen for each of the eight bands depended upon the observer's potentiometer setting.

Psychophysical Procedures

In all experiments, the subjects were seated comfortably and their heads were supported with a chin and forehead rest which was affixed to a table. The control box was positioned on the table so that the subject could adjust grating

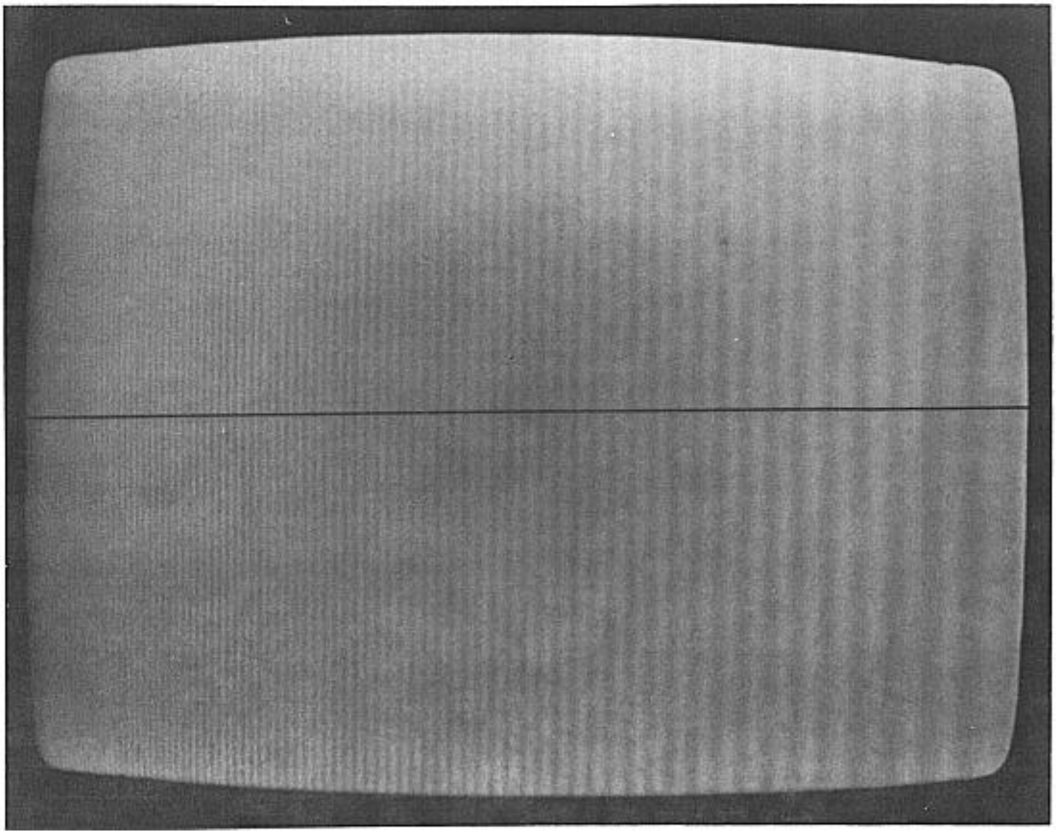

FIG. 1. Photograph of the SBE display. See text for explanation.

contrast[a] while viewing the screen. The CRT screen was at a viewing distance of 8 ft from the subjects' eyes and subtended a visual angle of 7.6° × 10.1°. The same eight spatial frequencies were used for all experimental conditions. These were: (in c/deg) 0.71, 1.62, 2.55, 4.20, 6.22, 10.47, 14.70, and 20.80. These spatial frequencies are also the center frequency of each of the eight bands of the SBE display. The ambient surround luminance was 0.01 cd/m^2 and the mean luminance of the CRT screen was 3.22 cd/m^2. The subjects' contrast settings were in units of voltage which were displayed on a digital voltmeter to an experimenter seated outside of the subjects' field of view. The modulation contrasts corresponding to the voltage settings were measured using a Photo Research model 1980 photometer.

Of the five male subjects used, three were well-corrected myopes and two were emmetropic; only one had previous experience in psychophysical experiments. Binocular viewing with natural pupils and accommodation was used at all times, and the subjects were allowed to fine tune their settings when necessary.

The method of adjustment with ascending contrast was used in all psychophysical procedures. For threshold measures with gratings of a single spatial frequency, the subjects were instructed to adjust the contrast of the pattern so that it was just detectable. For the SBE method, subjects were instructed to adjust contrast such that patterns were detectable above the horizontal bisector but were invisible below this line. For suprathreshold investigations, the experimenter set the contrast of the reference band, 2.55 c/deg, to levels determined for each of the subjects' previous thresholds, and the subjects were instructed to adjust the contrasts of the remaining seven spatial frequency bands so that they appeared to be of equal contrast with the reference band along the horizontal bisector. All the subjects were cautioned to make these observations on the basis of equal contrast rather than equal visibility. To reduce order effects, a balanced design using randomization was used for all studies.

[a] Contrast is defined by the following equation: $(L_{max} - L_{min}/L_{max} + L_{min})$, where L_{max} is the maximum luminance of the stimulus and L_{min} is the minimum luminance.

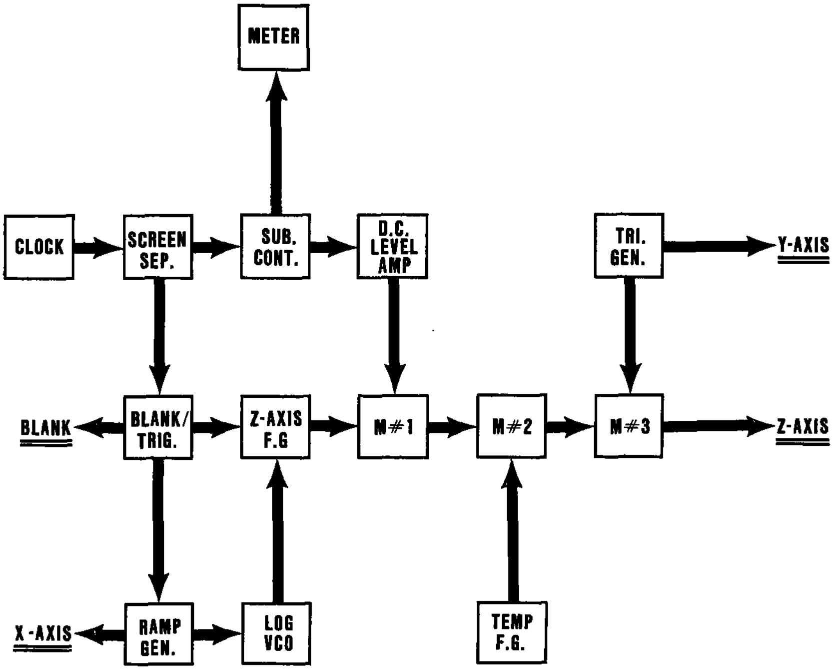

FIG. 2. Block diagram of the electronic system for stimulus generation. TEMP F.G., temporal function generator; M, multiplier; VCO, voltage controlled oscillator; SCREEN SEP., screen separation circuit; SUB. CONT., subject control box with potentiometers; TRI. GEN., triangle generator. See text for details.

RESULTS

Static Contrast Sensitivity

The primary purpose of these experiments was to compare CSF's obtained by the SBE technique with the more standard method of presenting sequential displays of uniform, discrete spatial frequencies. If the SBE method offers any advantages as a clinical tool, the results obtained with the two methods must be in reasonable agreement and the SBE technique should provide some time savings. Fig. 3 shows CSF's obtained by the two methods. These curves represent mean sensitivity measurements obtained from five observers, and, as shown in this figure, the two functions are in very good agreement. Although differences between corresponding points from the two curves were not significant, a systematic variation in the results of the two methods can be seen. Contrast sensitivity measurements obtained with the SBE method were higher at the lowest and highest spatial frequencies. This systematic variation perhaps is shown better in Fig. 4 in which the threshold results from each observer are plotted as sensitivity ratios, i.e., SBE/conventional, as a function of spatial frequency. Four of the five observers had ratios greater than 1.0 at the lowest and highest spatial frequencies, indicating a lower threshold or greater sensitivity with the SBE method. The other observer (GM) had a similar variation at the high spatial frequencies, while at low spatial frequencies he was more sensitive using the conventional method. A possible explanation for this systemic variation is that thresholds obtained with the SBE method actually represent a band of spatial frequencies and the data points are plotted at the center frequency of each of the eight bands. If the observers were setting the contrast threshold to the spatial frequency in that band at which they were most sensitive, their measurement actually would reflect a response to a spatial frequency slightly higher than the center spatial frequency at the lowest frequency bands and to a spatial frequency slightly lower than the center frequency at the highest frequency bands. Therefore, when the center frequency of each band is used in the graph, measurements at the extremes of the CSF would be slightly higher than that obtained with the standard method.

All of our subjects remarked that the threshold settings were faster and easier to make with the SBE procedure. However, the difference in times to obtain the measurements was not as great as originally expected. The time required to obtain threshold measurements with the SBE was 2.2 ± 1.4 min, whereas the time required with the conventional method was 3.8 ± 2.0 min. During each observation period, we repeated the threshold measurements five times for each of

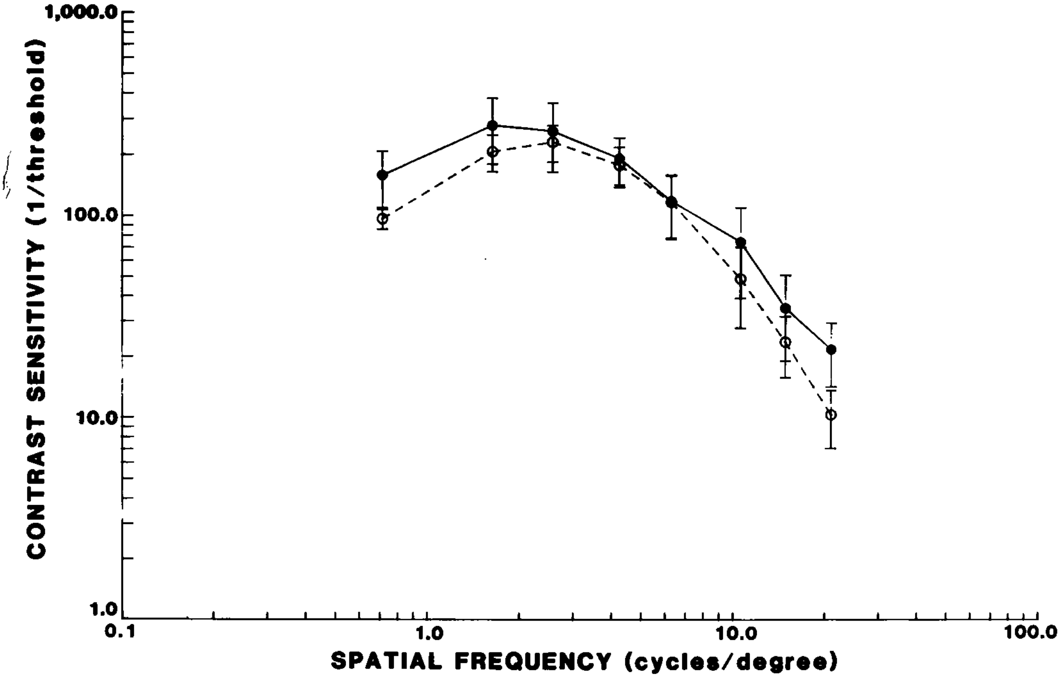

FIG. 3. Contrast sensitivity (1/threshold) functions obtained with the SBE (filled circles) and conventional (open circles) methods. Data points are the average of 25 observations (5 observations × 5 sessions) from each of 5 subjects. Brackets indicate ±1 SD.

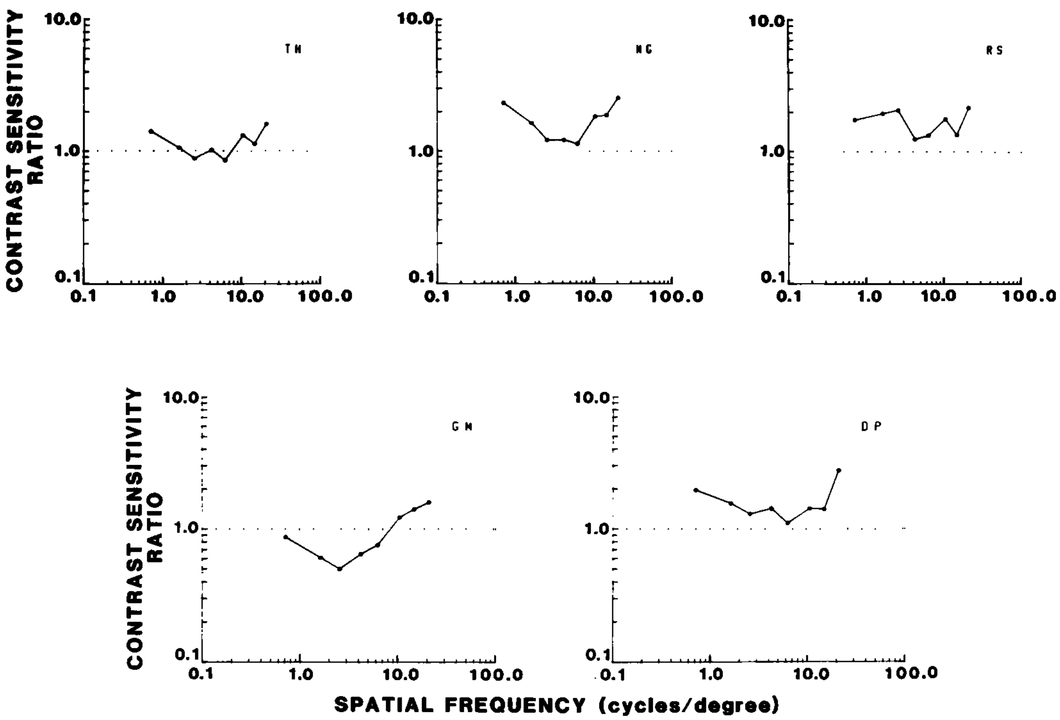

FIG. 4. Contrast sensitivity ratios (SBE/conventional) as a function of spatial frequency for each subject. A ratio of 1 (dotted lines) indicates equal thresholds with the two methods while ratios greater than 1 show greater sensitivity (lower thresholds) with the SBE method.

the two methods, which is similar to what might be accomplished in a clinical test. Thus, the total time savings using the SBE technique amounted to 8 min. Measurements of variability were essentially the same using the two methods.

Static Contrast Matches

After thresholds were determined, suprathreshold matches were investigated with the SBE technique. The contrast of the third frequency band (2.55 c/deg center frequency) was set at 2.5× or 10× threshold and used as a reference against which all of the remaining spatial frequency bands were matched in contrast along the horizontal bisector. The response patterns from all three observers were quite similar; Fig. 5 shows typical contrast matching functions for one observer. Several features of these functions merit comment. There is an obvious change in the general shape of the curves as contrast increases. The functions tend to flatten so that perceptual equality of contrast becomes more closely related to physical contrast equality. The perceived matching contrast of the highest spatial frequency band is a bit perplexing. As shown in Fig. 5, the matching contrasts at this spatial frequency are practically identical to the threshold contrast sensitivity even though the contrast of the reference spatial frequency was established at 2.5 and 10× threshold. Although we can offer no unequivocal explanation for this result, several investigations have shown similar results, and Graham[25] has suggested that they could be attributed to steeper stimulus-response functions at higher spatial frequencies. However, this explanation seems insufficient because data obtained by Georgeson and Sullivan[27] show steeper stimulus-response functions for higher spatial frequencies only at moderate suprathreshold levels. At high suprathreshold contrasts, the stimulus-response functions are the same for all spatial frequencies.

Spatiotemporal Contrast Sensitivity

Contrast sensitivity to flickering gratings, i.e., sine wave alternation of spatial phase, was compared with the conventional and SBE methods. Representative results from one of our observers are shown in Fig. 6. Previous investigations[28,29] have shown that adding flicker enhances contrast sensitivity to low spatial frequencies while leaving sensitivity to high spatial frequencies relatively unaffected. Similarly, our observers demonstrated an increased contrast sensitivity to the lowest spatial frequency when the grating was phase alternated. However, this result was only obtained with the conventional method. Threshold enhancement with flicker was not found using the SBE technique. This difference

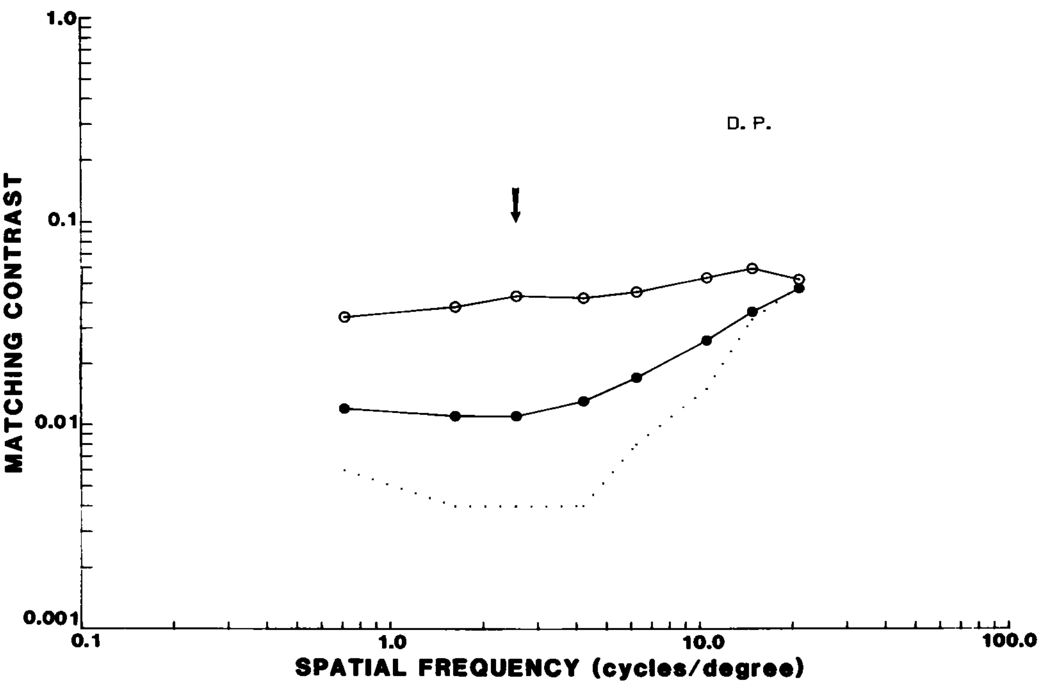

FIG. 5. Matching contrasts for one subject when the contrast of the reference spatial frequency (arrow) was set at 2.5× (filled circles) or 10× (open circles) above threshold. Threshold contrast (dotted line) is shown for comparison. Each datum point is the average of 25 observations (5 observations × 5 sessions).

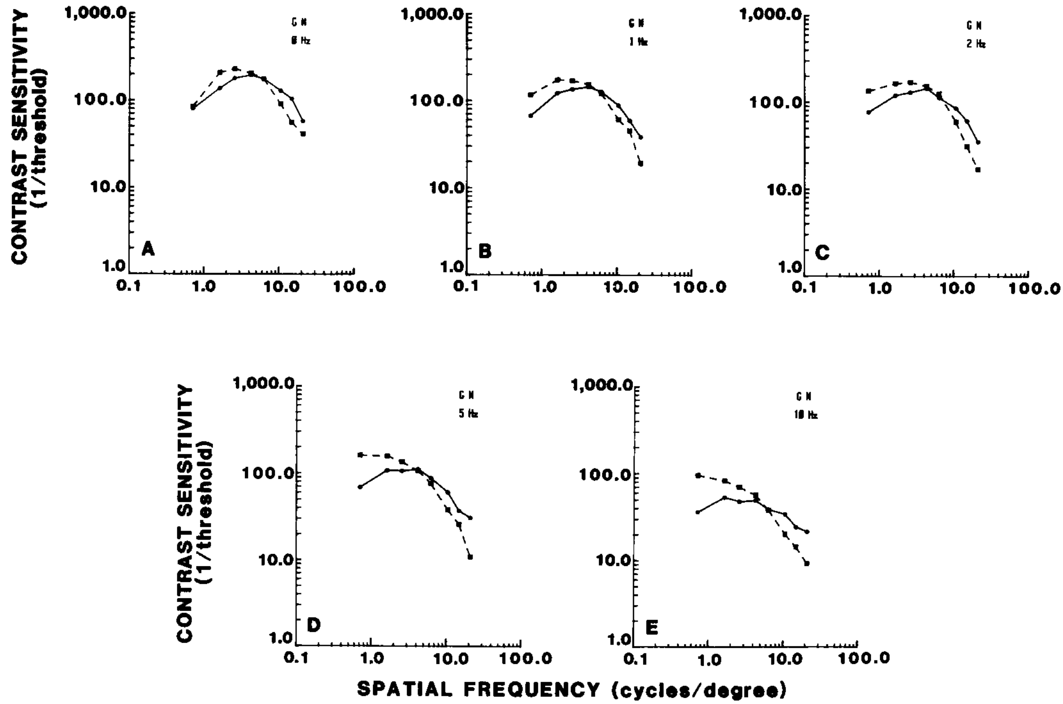

FIG. 6. Contrast sensitivity (1/threshold) functions obtained from one subject with the SBE (filled circles) and conventional (open squares) methods. Each datum point is the average of 25 observations. A, static sensitivity; B through E, CSF's when the patterns are counterphase flickered at 1, 2, 5, and 10 Hz, respectively.

between the two methods is more apparent in Fig. 7. In this figure, the contrast sensitivity ratios, i.e., flicker contrast sensitivity/static, are plotted as a function of temporal frequency. The three columns display the results for three spatial frequencies, 0.71, 4.2, and 20.8 c/deg, and threshold enhancement with flicker is shown at the lowest spatial frequency with the standard technique. Contrast sensitivities measured with the SBE method were generally depressed when the grating display was flickered at the various temporal frequencies. Only one of our subjects (MG) demonstrated an enhanced sensitivity with flicker at the lowest spatial frequency with the SBE method and only with a 5 Hz temporal modulation. In general, with the exception of the lowest spatial frequency band, the addition of flicker depressed the spatial contrast sensitivity with both the conventional and SBE method. Increasing temporal frequency tended to cause a slight reduction in sensitivity.

Contrast Matching with Flickering Patterns

Using the SBE technique, contrast matching with flickering spatial frequency bands was studied in three subjects. Representative results from one subject are shown in Fig. 8. A prominent feature is the flattening of these matching functions which becomes more pronounced with higher suprathreshold levels. The 2.55 c/deg reference spatial frequency (arrow) was the same for all observers and, as shown in Fig. 8, the matching contrasts for adjacent spatial frequency bands invariably were lower for static and counterphased patterns.

Similar to the previous static matching functions, flickering matching functions show that perceptual equality of contrasts become more closely related to physical contrast equality at suprathreshold levels independent of spatial frequency. This tendency is shown in Fig. 9 which presents the combined data from our three subjects. For this figure, the ratio of the matching contrast of the test band to the contrast of the reference band is shown as a function of counterphase frequency for the lowest and highest spatial frequency bands. The arrows indicate the relevant contrast ratios from the threshold data. As can be seen in Fig. 9, the suprathreshold contrast ratios were always lower than threshold contrast ratios and tended to decrease further with increasing temporal frequency.

DISCUSSION

In agreement with Dobson and Davison,[24] our studies show that, under static conditions, the SBE technique is an acceptable alternative to the conventional method of measuring contrast

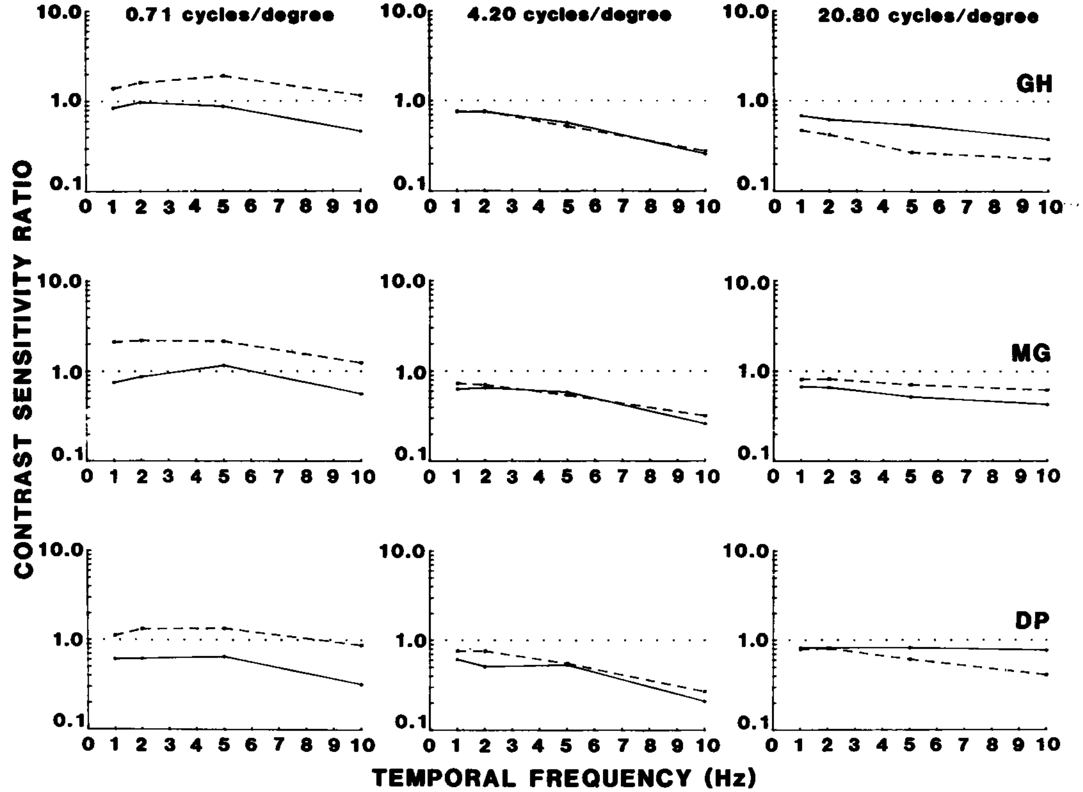

FIG. 7. Contrast ratios (sensitivity with flicker/static sensitivity) as a function of counterphase frequency for three spatial frequency bands (columns) from three subjects (rows). Squares (dashed lines) are data using the conventional method and the filled circles (solid line) show the data obtained with the SBE technique. A ratio of 1 (dotted lines) indicates that static sensitivity and sensitivity with flicker are equal. Note that the ratios for the lowest spatial frequency (left column) with the conventional method are greater than 1, indicating enhanced sensitivity with the added flicker.

sensitivity. Our contrast sensitivity measurements obtained with the SBE and conventional methods are in very good agreement (Fig. 3). Sensitivity measurements with the SBE method were usually somewhat higher for the lower and higher spatial frequencies.

The SBE method offers considerable flexibility for the clinical evaluation of patient contrast sensitivity. The method is time-efficient and the observer's task is easily understood and rapidly learned so that a greater range of patients can be evaluated. In addition, the SBE display allows a straightforward method to evaluate suprathreshold contrast perception. Whereas contrast sensitivity measures have been used to evaluate a variety of eye pathologies and visual dysfunctions, information relating to suprathreshold perception is limited. Several recent reports[30-32] have presented data suggesting that the perception of suprathreshold contrast is not affected in amblyopia, whereas amblyopes have significantly reduced contrast sensitivity, especially for higher spatial frequencies. In consideration of the normal suprathreshold contrast perception combined with subnormal contrast sensitivity, Loshin and Levi[32] concluded that the amblyopic eye has a higher contrast gain than the nonamblyopic eye. The concept of a variable contrast gain has been used in discussing results from suprathreshold contrasts measurements in subjects with normal vision. The several studies[26,27,33-35] which provide information concerning suprathreshold contrast perception have shown that perceived suprathreshold contrast is relatively independent of spatial frequency. That is, gratings which are perceived to be equal in contrast are, in fact, equal regardless of spatial frequency. Assuming that contrast detection (threshold) and contrast perception (suprathreshold) are related, Georgeson and Sullivan[27] termed this phenomenon contrast constancy and suggested that it represented a mechanism by which early stage optical and neural blurring was corrected by the visual system. Our suprathreshold measurements using the SBE technique are consistent with these previous reports. As shown in Fig. 5, differences in matching contrasts for the various spatial frequency bands

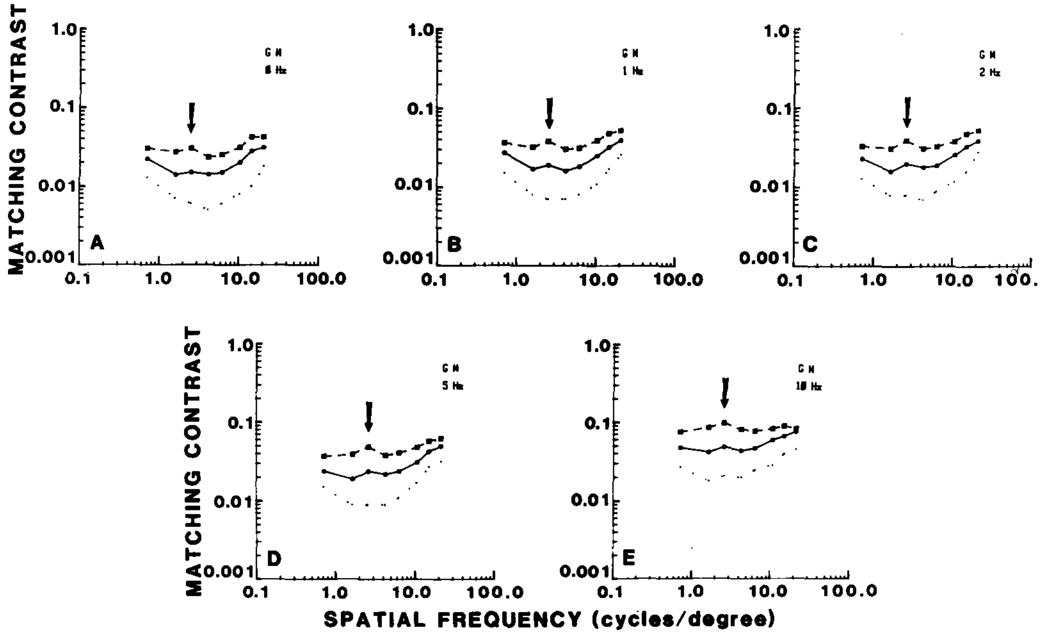

FIG. 8. Matching contrasts for one subject when the contrast of the reference band (arrow) was set at 2.5× (filled circles) or 5× (open squares) threshold. Each datum point is the average of 25 observations. A, matching contrasts with static patterns; B through E, matching contrasts when the patterns are counterphase flickered at 1, 2, 5, and 10 Hz, respectively. Corresponding threshold contrasts (dotted lines) are shown for comparison.

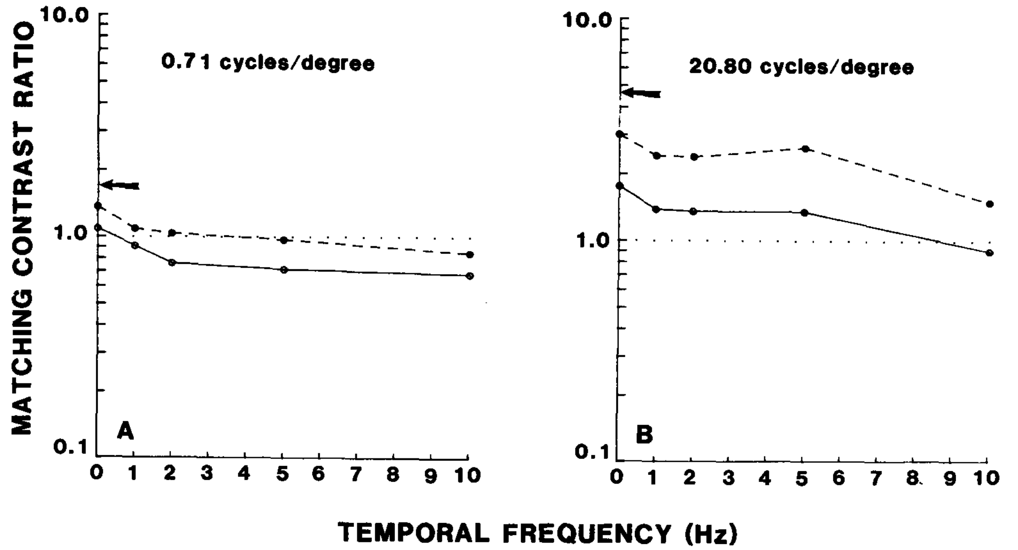

FIG. 9. Ratios (test spatial frequency band/reference band) of matching contrasts at 2.5× (filled circles) and 5× (open circles) threshold as a function of counterphase frequency for the lowest (A) and highest (B) spatial frequency bands. Results are the average from three subjects. The horizontal arrow indicates the corresponding static threshold contrast ratios.

are reduced at suprathreshold levels, a tendency which increases with increasing contrast above theshold. The addition of flicker reduces suprathreshold differences in perceived contrast (Fig. 8) and these differences become less with further increases in flicker frequency (Fig. 9). These results support the findings reported by Bowker[26] using a two-display contrast matching paradigm.

The influence of flicker on contrast sensitivity has been studied by other investigators.[28, 29] In general, these studies have shown that the introduction of flicker alters the filter characteristics of the visual system. With static displays, the visual system functions as a midrange bandpass filter having greater sensitivity to gratings of moderate spatial frequency with sensitivity roll-offs for lower and higher spatial frequencies. However, when the gratings are phase reversed, the system changes to resemble a low-pass filter. Sensitivity to lower spatial frequencies is increased. These effects are evident in Fig. 6 which shows that for thresholds obtained by the conventional method the addition of flicker differentially enhances the contrast sensitivity for low spatial frequencies while reducing the sensitivity for middle and higher spatial frequencies. Curiously, our results using the SBE technique did not show this effect. Flicker reduced the sensitivity for all spatial frequencies, although sensitivity to the lowest spatial frequency was most resistant to reduction, particularly when phase alternation was 5 Hz (Fig. 7). Although we can offer no unequivocal explanation for failure of the SBE technique to reproduce the spatiotemporal results using the standard technique, the limited horizontal extent of the grating display is probably a factor.[36, 37] A disadvantage of the SBE display is the reduced width of each spatial frequency segment. This severely limits the number of cycles for low spatial frequencies that can be displayed within one segment.

The expanding data base concerning contrast sensitivity with a variety of eye conditions[38] demonstrates the value of such measurements and ensures that routine assessment of contrast sensitivity will have more frequent application for clinical evaluations. The SBE technique offers an optional method to determine contrast sensitivity and, because of its flexibility for assessing suprathreshold contrast perception, has some advantage over the more conventional methods. Our studies have demonstrated that static measurements obtained with the SBE technique compare favorably with conventional measurements.

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AUTHOR'S ADDRESS:
Roger W. Wiley
School of Optometry
8001 Natural Bridge Road
University of Missouri-St. Louis
St. Louis, Missouri 63121