J.J. McCann and J. A. Hall, Jr.,

"Effects of average-luminance surrounds on the visibility of sine-wave gratings",

J. opt.Soc. Am., **70**, 212-219, 1980.

Effects of average-luminance surrounds on the visibility of sine-wave gratings

John J. McCann and John A. Hall, Jr.
Polaroid Corporation, Vision Research Laboratory, Cambridge, Massachusetts 02139
(Received 14 March 1979)

In the low-spatial-frequency region (below 2 c/deg) contrast sensitivity to sinusoids does not depend on spatial frequency, but does depend on the number of cycles of sinusoid. Contrast sensitivity to sinusoids can vary from 14 to 60 depending on the amount of average-luminance area or flank adjacent to the sinusoid. The influence of average-luminance flanks does not depend on the width of the flank, but does depend on the equivalent number of cycles of flank.

This work began with the interesting experimental result that two identical sine-wave targets had greatly different contrast thresholds depending on the nonsinusoidal areas in the field of view. This observation led to experiments which showed that the width of an average-luminance surround can have considerable effect on the contrast sensitivity of a sinusoidal grating of fixed dimensions.[1] Numerous experiments, such as increment threshold,[2,3] have shown that a variety of psychophysical tasks are influenced by the size of a surround adjacent to the stimulus parameter under study. In the case of sinusoidal gratings, the size, shape, and proportions of an average-luminance surround have had relatively little study. This paper describes numerous experiments on the influence of average-luminance areas on the visibility of sinusoidal gratings.

I. METHODS

A video system consisting of an oscillographic (X-Y) display and the electronics for its operation was designed and built in our laboratory by Bill Wray and John Hall for particular use in these experiments. We used this display system to generate luminance patterns for one sinusoidal portion and two concentric surrounds. The luminance of each of the three areas was independently adjustable. The electronics package uses an interlaced horizontal raster with any number of lines up to 1024. The raster has a line sweep period of about 33 μs. The top half of Fig. 1 is a diagram of the display and shows its three concentric zones. The positions on the display designated by letters A through L are zone division limits. Their positions are all adjustable using TTL digital circuitry. Once the number of lines that represent the total display is chosen, then the vertical dimensions, namely, the positions of limits A through F, are selected by assigning fractions of the total number of horizontal lines to the distances AB, BC, CD, etc. The zones of the display are further specified by limits G through L. A voltage applied to the X(horizontal) or Y(vertical) inputs moves the beam to a position defined by that voltage in either the X or Y direction. A Z-input voltage is used to control the intensity of the beam. The horizontal limits are independently set with continuously adjustable timing circuits. Every time the scan reaches a boundary limit (G through L), the automatic line-counting circuitry switches the Z input (intensity) to its appropriate signal. Zones 1 and 2 are both areas of uniform luminance produced by two independent Z-axis voltages. The luminance of zone 3 is controlled by a function generator; in these experiments we always used a sine-wave function. The frequency and phase

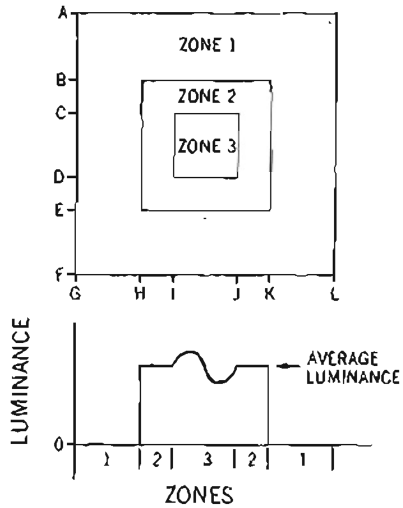


FIG. 1. Diagram of a cathode-ray-tube display (top half of figure). The positions of limits A through F are set by binary encoded line-counting switches, while the limits G through L are set by adjustable timing controls. The bottom half of the figure is a graph of a horizontal luminance trace through the center of this display. The graph is for the case of a target in which the luminance of zone 1 is 0, zone 2 is set to the average luminance, and zone 3 is a one-cycle sinusoid wave.

of this sine wave were adjustable so that one could choose the number of cycles to be displayed in zone 3. A synchronization circuit caused the sine wave to be in phase for all lines. The display system has a spatial-frequency range of 0.08 to 1.8 c/deg when the observer is seated 61 cm from the display.

After the experimenter chose all of the limits (A through L), he set the luminances of the uniform areas. Using a spot photometer, he set the average luminance of each target to 3 mL/cm^2 (9.4 c/m^2). By reversing the Z- and Y-axis inputs to the display tube he obtained a trace of the Z-axis voltage. Calibration measurements with a spot photometer showed that the luminous amplitude of the sine wave was a linear function of the voltage within the experimental range. Therefore, this voltage trace was proportional to a luminance trace of the target. The bottom half of Fig. 1 shows a diagram of the trace taken through the center of the target shown in the top half of Fig. 1. Similar traces were used for the setting of the phase and frequency of the sinusoid in zone 3.

The subject adjusted the amplitude of the sine wave in zone 3 with a ten-turn potentiometer. Each value of an experimental setting was recorded as a voltage. Voltages were transformed to contrast sensitivity using calibration curves of voltage versus target contrast as measured by the spot photometer.

We presented the targets in random order. When the experimenter set up a particular target, the observers made at least 20 observations per target which were averaged to be the result. Between each target a pause of 5 min was necessary for target set-up and calibration. At the beginning of each experiment, the observer sat in front of the display, which was set to zero contrast. When he turned the knob of the potentiometer, he increased the target's contrast, until he could detect the target. At this threshold, he set a switch and pressed a button to enter the reading into data-taking equipment; this operation took a few seconds. The observer was unaware of the value of the reading. Then the observer reset the contrast to zero and made another reading. All of the targets were static presentations; there was no time limit for an observation.

In all of the experiments described in this paper the observer was instructed to adjust the potentiometer to increase the contrast of the sine wave from below threshold to threshold. When the subject had completed a setting, he pressed a switch, and a voltage was measured across the potentiometer. This voltage was transferred to an auto-ranging digital voltmeter and then to paper tape. Each observer made a minimum of 20 settings per target. Several of the targets were common to more than one series of experiments. The comparison of the results from the same target at different times showed no significant variations.

All the observed data are reported in terms of sensitivity, that is, as the reciprocal of threshold contrast. Contrast sensitivity is defined as $(L\max + L\min)/(L\max - L\min)$ where $L\max$ and $L\min$ are the maximum and minimum luminances.[4] All measurements were monocular, unfixated vision with natural pupil, unless otherwise specified in the text. The result of each experiment is represented as the mean plus or minus one standard deviation, along with a two-dimensional diagram of the target.

The patterns generated by our electronics package were displayed on a Hewlett-Packard 1317A high-speed graphic display unit with a P4 phosphor. The entire display tube was 43.2 cm diagonally with a usable section of 34.3 by 26.0 cm. The resolution of the tube is 19.7 lines/cm with a 0.51-mm spot size.

II. INFLUENCE OF SINUSOID SIZE AND SHAPE ON CONTRAST SENSITIVITY: NO AVERAGE-LUMINANCE SURROUND

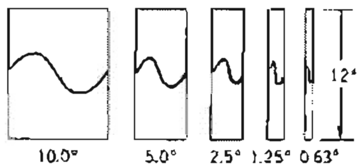
In the first experiment all targets were 12 deg high and each had a different width (10, 5, 2.5, 1.25, and 0.63 deg). All targets had only one cycle of sinusoid (in sine phase) along the horizontal direction and appeared on a black background. We define nominal spatial frequency as the number of cycles per degree that characterizes the sinusoid, irrespective of its width.[5] Since the width of the targets varied, the nominal spatial frequency of the sinusoid varied from 0.1 to 1.6 c/deg. The results are shown in Fig. 2.

Although the targets vary in width and nominal spatial frequency by a factor of 16, the observers report very little change in threshold contrast sensitivity. One observer reports contrast sensitivities of 14, 16, 15, 14, and 22; the second observer reports sensitivities of 11, 13, 13, 13, and 16 for targets that range from 12×10 to 12×0.63 deg.

In the second experiment the width of the sinusoid was constant (1.25 deg) and the height varied (12, 6.6, 3.9, 2.6, 1.9, 1.6, and 1.25 deg). The height was the direction perpendicular to the sinusoid. The diagram and associated average contrast sensitivities for these targets are shown in Fig. 3. Despite changes of target height by a factor of 10, observers show very little change in contrast sensitivity.

Previous experiments[4,6] measured the effects on contrast sensitivity of simultaneous changes in both the height and

VARY SINUSOID WIDTH
-BLACK SURROUND-

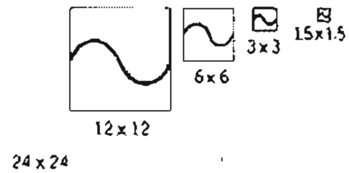


CONTRAST SENSITIVITY

OBS					
JAH	14±2	16±3	15±2	14±2	22±3
JMC	11±2	13±3	13±2	13±2	16±3

FIG. 2. Variation of the width of one-cycle sine-wave targets with a black surround. Except for a small increase in contrast sensitivity with the narrowest target, changing width and hence changing nominal spatial frequency by a factor of 16 has little effect on contrast sensitivity.

VARY SINUSOID HEIGHT AND WIDTH
-BLACK SURROUND-



OBS					
JAH	13±1	15±2	15±2	15±1	14±1
JMC	11±2	13±2	15±3	18±4	19±5

WITH 2.5mm ARTIFICIAL PUPIL

JAH	14±1	14±1	13±1	16±3	16±2
JMC	10±2	14±3	15±3	16±2	19±5

FIG. 4. Variation of both the height and width of one-cycle sine-wave targets. Contrast sensitivity remained essentially constant despite a 16 to 1 change in linear dimension and a 256 to 1 change in area. Nearly identical results were obtained both with and without a 2.5-mm artificial pupil.

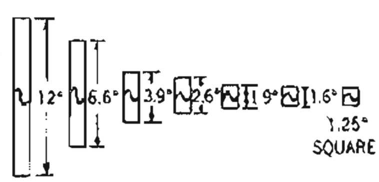
width of low-spatial-frequency sinusoids. These experiments found that the number of cycles was the critical parameter affecting observer contrast sensitivity, regardless of the size of the target on the observer's retina. The third experiment of this paper differed from previous ones because it was performed both with and without an artificial pupil. The targets varied from 24 × 24 deg to 1.5 × 1.5 deg, a factor of 16 in linear dimension and a factor of 256 in area. With such large changes in projected areas of the display on the retina, one must test the influence of any change in size of the natural pupil. The results are shown in Fig. 4. Since all the targets had only one cycle of sinusoid, the nominal spatial frequency varied from 0.04 to 0.7 c/deg. The introduction of a 2.5-mm artificial pupil did not produce any significant change in contrast sensitivity for any target tested. One observer reported no change in contrast sensitivity with change in size, while the other reported a change from 11 ± 2 to 19 ± 5, that is, a change by a factor of 1.7.

We can conclude that, within the range of retinal sizes tested, the observer's contrast sensitivity to one-cycle sine-wave targets is essentially independent of the nominal spatial frequency and independent of the height, width, and area of the display on the retina. This is quite an interesting property because the stimulus on any local region of the retina is considerably different when one cycle is spread across 24 deg of the retina instead of across 1.5 deg. It is not obvious how one might design an electronic system for which one cycle of sinusoid would have the same threshold independent of the width of the display and independent of the nominal spatial frequency.

III. INFLUENCE OF AVERAGE-LUMINANCE SURROUND ON CONTRAST SENSITIVITY

The first experiment in this section uses a series of targets in which the sinusoidal portion is held constant in size and shape while the width of one average-luminance flank is varied. The first target has no surround; it is 12 deg high and 1.25 deg wide. The observers report contrast sensitivities of 14 and 13. The subsequent targets in this series have 12 by 0.6-, 2.4-, and 9.4-deg average-luminance flanks to one side of the sinusoid. In general, observers report higher contrast sensitivities in the presence of the average-luminance flank (Fig. 5). With the widest (9.4-deg) flank the contrast sensitivity is

VARY SINUSOID HEIGHT
-BLACK SURROUND-

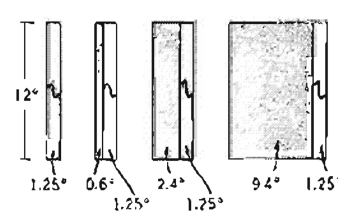


CONTRAST SENSITIVITY

OBS							
JAH	14±2	11±1	12±2	12±1	12±2	10±1	11±1
CGE	22±3	16±3	18±3	17±3	14±2	14±2	16±2

FIG. 3. Variation of the height of one-cycle sine-wave targets. Despite changes in height by a factor of 10, observers show very little change in contrast sensitivity.

VARY WIDTH OF ONE FLANK



CONTRAST SENSITIVITY

				OBS
14±2	15±2	27±3	34±3	JAH
13±2	13±2	23±4	33±5	JMC

□ AVERAGE-LUMINANCE AREA

FIG. 5. Variation of the width of one average-luminance flank adjacent to a 12 × 1.25 deg one-cycle sinusoid. The presence of a 9.4-deg average-luminance flank increases the observer's sensitivity to a one-cycle sinusoid two-and-one-half times.

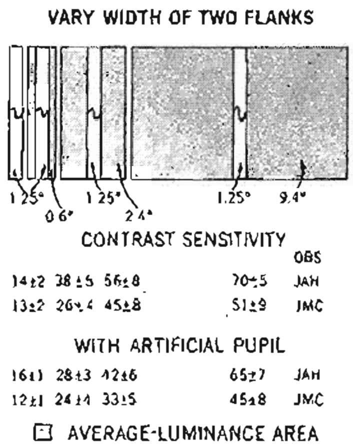


FIG. 6. Variation of the width of average-luminance flanks on both sides of a 12 × 1.25 deg one-cycle sine-wave target. Two 9.4-deg average-luminance flanks increase the observer's sensitivity to the sine wave by 4 times. Nearly identical results were obtained with and without a 2.5-mm artificial pupil.

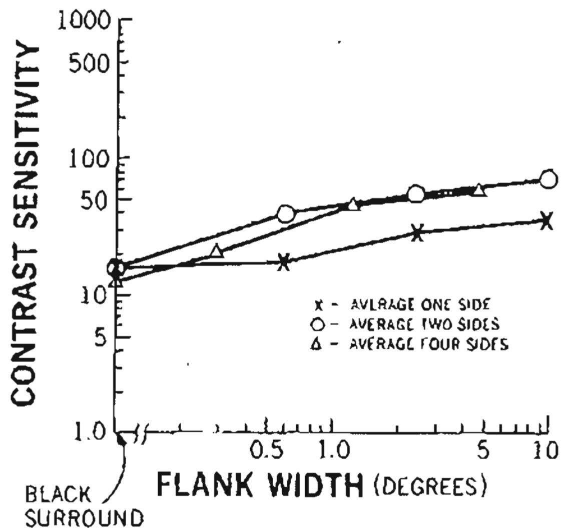


FIG. 8. Contrast sensitivity data for observer JAH from Figs. 5–7 plotted against the width of the average-luminance area. The X's are data from experiments with one flank, O's for two flanks, and Δ's for all four sides.

two-and-one-half times greater than that of the target without any average-luminance flank.

The next experiment uses two average-luminance flanks which vary in width. The average-luminance flanks are on each side of the sinusoid in the direction of the sinusoid The results are shown in Fig. 6. The first target has no surround, and observers report contrast sensitivities of 14 and 13. The addition of two 0.6-deg average-luminance flanks roughly doubles the contrast sensitivity. Further increases in the widths of both average-luminance flanks cause further increases in contrast sensitivity. With the addition of two 9.4-deg flanks, the observers are four times more sensitive to the 12 × 1.25 deg sinusoid than they are to the target without any average-luminance flanks. Since the area of the display changes from 12 × 1.25 deg to 12 × 20 deg, we again performed a parallel experiment with a 2.5-mm artificial pupil. By using an artificial pupil we ensured that any fluctuations in the size of the natural pupil with changes in projected display area on the retina did not account for our experimental results. Observers' contrast sensitivities do not change significantly with the use of a 2.5-mm artificial pupil. To summarize the results from Fig. 6, the sinusoid always subtended 12 × 1.25 deg; only the width of the average-luminance flank varied. With these changes in average-luminance flank, contrast sensitivities varied from 14 and 13 to 70 and 51.

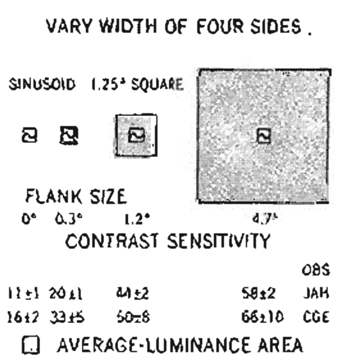


FIG. 7. Variation of the width of an average-luminance surround on all four sides of a 1.25-deg square sine-wave target. Here again, increasing the amount of average-luminance surround increased sensitivity to the sine-wave portion of the target.

In the next experiment we varied the size of an average-luminance flank on all four sides. For this experiment we used a 1.25 × 1.25 deg sinusoid. Here we again found a marked change in contrast sensitivity as a function of the width of the average-luminance surround (see Fig. 7). With a black surround the contrast sensitivities were 11 and 16. With a 4.7-deg average-luminance area on all four sides they were 58 and 66.

Figure 8 replots the data from Figs. 5–7 for one observer (JAH). This graph of contrast sensitivity as a function of the width of the average-luminance flank or surround provides a comparison of the influence of one flank, two flanks, and an average-luminance surround. All three curves are similar, but the results for targets with two and with four average-luminance flanks overlap over much of the graph. One can see from the displacement of the one-side data in Fig. 8 that a particular width of flank on one side does not increase contrast sensitivity as much as half that width on both sides of the sinusoid.

The experiments in Sec. II showed that in the presence of a black surround the height and width of the sinusoid do not substantially affect the contrast sensitivity. We now see that the width of the average-luminance flank along the direction of the sinusoid has a great effect. The next experiment tests the influence of average-luminance areas above and below the sinusoid, i.e., along the direction perpendicular to that of the sinusoid. In this experiment, as in the previous one, the sinusoid subtends 1.25 × 1.25 deg. The height of average-luminance areas at both the top and bottom of the sinusoid varied in four steps from 0 to 5.4 deg. The results (in Fig. 9)

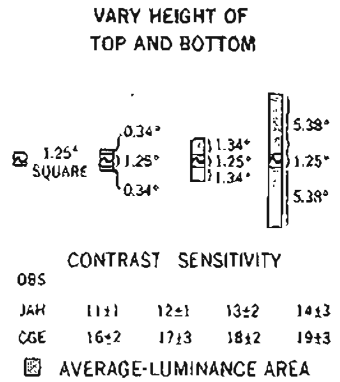


FIG. 9. Variation of the height of average-luminance areas above and below the sinusoid. The results show no significant change of contrast sensitivity.

show no significant effects on contrast sensitivity.

The final experiment in this series was designed to determine the effect of changes in height of the entire display. The sinusoid height was varied while the width was kept at 1.25 deg, with 0.35-deg average-luminance flanks. The heights were 12, 6, 3, and 1.5 deg. The contrast sensitivities for observer JAH were 25 ± 5, 26 ± 4, 26 ± 3, and 25 ± 4. The contrast sensitivities for observer CGE were 25 ± 3, 28 ± 4, 19 ± 2, and 17 ± 3. Display height showed little or no effect on contrast sensitivity.

In summary, we found that average-luminance flanks have a strong influence on contrast sensitivity. Two 9.4-deg average-luminance flanks increase an observer's contrast sensitivity to a 1.25-deg sine wave by a factor of 4 provided the flanks are added along the direction of the sinusoid. The effect of the average-luminance surround is limited to that of the left and right flanks (along the direction of the sinusoid). Changes in the size of average-luminance areas above and below (perpendicular to the direction of the sinusoid) do not produce substantial effects. Display height does not influence contrast sensitivity as long as the components along the direction of the sinusoid remain constant.

IV. INFLUENCE OF FLANK WIDTH VARIES WITH SINE WIDTH

McCann *et al.*[1] reported experiments in which the observer viewed a single target at different distances so that all parts of the display change size proportionally. They reported that one-cycle sinusoids with an average-luminance surround had contrast sensitivities of 21, 20, 19, 22, and 15 for 24-, 12-, 4-, 1.3-, and 0.4-degree target sizes. These results show contrast sensitivities that are nearly constant despite dramatic changes in size. The lack of dependence of contrast sensitivity on surround width is apparently inconsistent with the experiments just described. First, we have shown in Fig. 4 that contrast sensitivity remains the same despite changes in the size of sinusoids with a black surround. Second, we have shown in Figs. 6 and 7 that increases in width of average-luminance flanks cause a substantial change in contrast sensitivity. In the McCann *et al.*[1] experiments, the flank width varied from 0.7 to 4.2 deg with no significant increase in contrast sensitivity. Since changes of width of sinusoid do not alter contrast sensitivity, but changes of flank width do, we should expect a change in contrast sensitivity when the viewing distance is changed. Nevertheless, the experiments in McCann *et al.*[1] show that this is not the case. This series is of particular interest because both the width of the average-luminance surround and the width of the sine wave change proportionally.

McCann[7] reviewed the data from many different kinds of experiments and concluded that a great variety of perceptual responses to low-spatial-frequency targets was constant when the displays were held constant and the viewing distances were changed. The different experiments included contrast threshold and contrast matching, for both luminance gradients and low-number-of-cycle sinusoids, as well as lightness matching experiments with simultaneous contrast displays. Since these experiments show that contrast sensitivity is invariant with changes in viewing distance and hence changes in width of average-luminance flanks, we must hypothesize that the influence of average-luminance flanks varies with the size of the sinusoid.

The following experiment studies the changes in contrast sensitivity as a function of flank width using four different widths of sinusoid. In this section, flank width refers to the angle subtended by one of two equal flanks placed on either side of the sinusoidal portion of the display. The sinusoids were 12 × 5, 12 × 2.5, 12 × 1.25, and 12 × 0.63 deg. The flanks had widths of 0, 0.3, 0.6, 1.2, 2.4, 4.7, and 9.4 deg. Each data point is the average of mean contrast sensitivities of two observers, JAH and JMC. The data for all four sizes of sinusoid are plotted in Fig. 10 as contrast sensitivity versus flank width. The data from the four sizes of sinusoid form four similar curves that are displaced from each other, along the horizontal axis, by a factor of 2. Figure 11 replots the contrast sensitivity

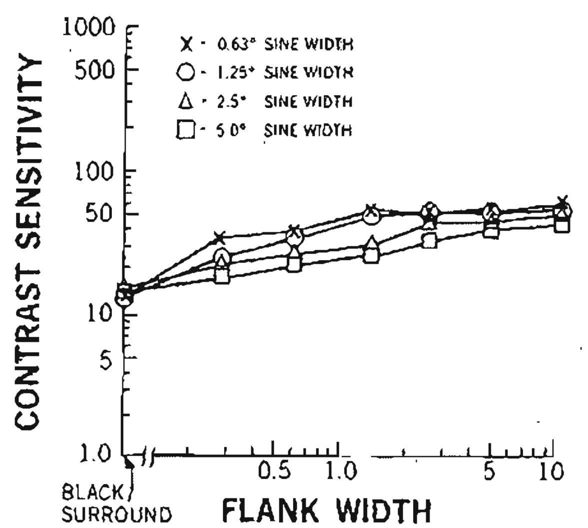


FIG. 10. Variation of both the sine and flank widths. Symbols to identify different sine-width data are X, O, Δ, and □, which represent 0.63, 1.25, 2.5, and 5.0-deg sine widths. The contrast sensitivity of four sets of sine widths is plotted as a function of flank width. The four distinct curves, one for each sine width, show that the effect of flank width varies with sine width. Each curve is displaced along the horizontal axis by roughly a factor of 2. The observers are JMC and JAH.

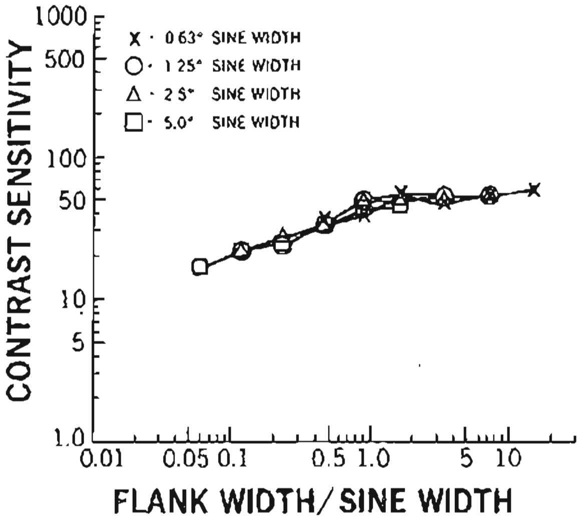


FIG. 11. Replot of the contrast-sensitivity data for observers JMC and JAH presented in Fig. 10 using flank width/sine width as the horizontal axis. This expression, which changes by a factor of 2 when the sine width is doubled, normalizes the variable effects of flank width on different sine-width targets. Different sine-width data are represented by the symbols X (0.63 deg), O (1.25 deg), Δ (2.5 deg), and □ (5.0 deg). Since all the targets replotted here have only one cycle of sinusoid, the expression flank width/sine width is equivalent to expressing flank width in terms of the number of cycles.

values from Fig. 10 using flank width/sine width as the horizontal axis. The coincidence of the four curves in the graph shows that this expression normalizes the variable effect of flank width on different sizes of low-frequency sinusoidal displays.

For one-cycle sinusoids the expression flank width/sine width may be thought of as the number of equivalent cycles of average-luminance flank. The data in Fig. 11 show that contrast sensitivity is influenced by the proportion of average-luminance flank rather than the absolute width of the flank. Another way of expressing this proportional relationship is to say that contrast sensitivity depends on the number of cycles of flank width.

In summary, in Sec. III we found that contrast sensitivity was greatly increased by the addition of average-luminance flanks when the dimensions of the sinusoidal portion of the display were constant. In earlier experiments in which observer viewing distance is the only variable, we did not find a significant dependence of contrast sensitivity on the absolute width of the average-luminance area. However, in those experiments the width of the sinusoid changes, and the extent of the average-luminance area is not a constant proportion of the whole target. The experiments in Sec. IV have shown that for one-cycle displays, the effect of the average-luminance flank is proportional to the width of the sinusoid. Displays have a constant visibility at different viewing distances because the flank and sinusoid are changing proportionally. This is equivalent to saying that contrast sensitivity is influenced by the number of cycles of average-luminance flank, rather than the absolute width of the flank.

V. INFLUENCE OF THE NUMBER OF CYCLES

McCann *et al.*,[8] Hoekstra *et al.*,[9] McCann *et al.*,[6] Savoy and McCann,[4] and Estevez and Cavonius[10] have all reported that increasing the number of cycles of sinusoid on a black surround causes an increase in the observer's contrast sensitivity. Thus far, we have reported results of experiments on targets containing only one cycle of sinusoid. In this section we designed experiments to quantify the relative contributions to visibility of average-luminance surrounds and the number of cycles of sinusoid. These experiments studied targets with 1, 2, 4, 8, and 16 cycles of sinusoid. Again, there were two observers (JAH and RLS); however, they were a different pair from those used in the data in Fig. 11. The targets were all 12 deg high by 20 deg wide. The sinusoids had widths of 0.63, 1.25, 2.5, 5, and 10 deg. All the sinusoids were centered on the 20-deg-wide target. With increasing number of cycles, the spatial frequency of the sinusoids eventually exceeded the upper limit of the display-device electronics (1.8 c/deg). This is the reason that there is only one 16-cycle target, two 8-cycle targets, etc. Nevertheless, the data from the 15 targets in this series allow us to study the contribution of the number of cycles of sinusoid relative to the number of cycles of average-luminance flank. The results of these experiments are plotted in Fig. 12. The axes are N_F (number of cycles of flank) versus contrast sensitivity.

The experiments in Sec. IV showed that for one-cycle sinusoids a particular number of cycles of flank was associated with a particular increase in sensitivity. If the influence of additional cycles of sinusoid was in some manner caused by changes in the number of cycles of flank, then we would expect a single curve for a plot of contrast sensitivity versus N_F. The data in Fig. 12 show that this is not the case. Despite the normalizing influence of the number-of-cycles-of-flank parameter, the data form a series of distinct curves that are displaced along the horizontal axis. This displacement shows that both N_S (number of cycles of sinusoid) and N_F (number of cycles of flank) independently affect contrast sensitivity.

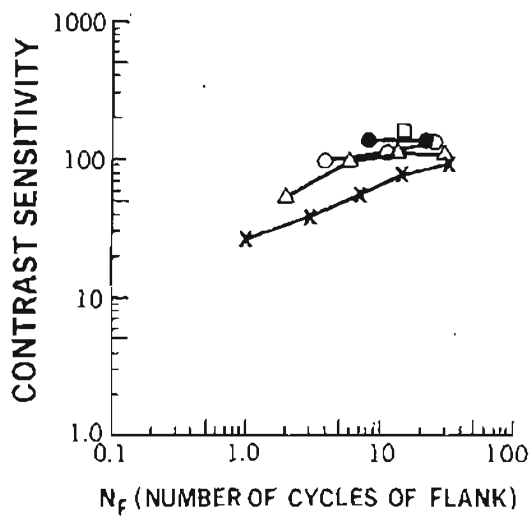


FIG. 12. Plot of the contrast sensitivity versus N_F (number of cycles of flank) for targets that have one or more sinusoid cycles, as well as variable sine and flank widths. The symbols X, Δ, O, ●, and □ represent targets containing N_S of 1, 2, 4, 8, and 16 cycles. This figure allows us to study the contribution of the number of cycles of sine relative to the number of cycles of average-luminance flank. As we saw in Fig. 11, plotting these results as a function of N_F normalizes the effects of variable width of flanks. The fact that the contrast sensitivity is greater with higher number of cycles of sinusoid shows that both N_S and N_F affect contrast sensitivity. The observers were JAH and RLS.

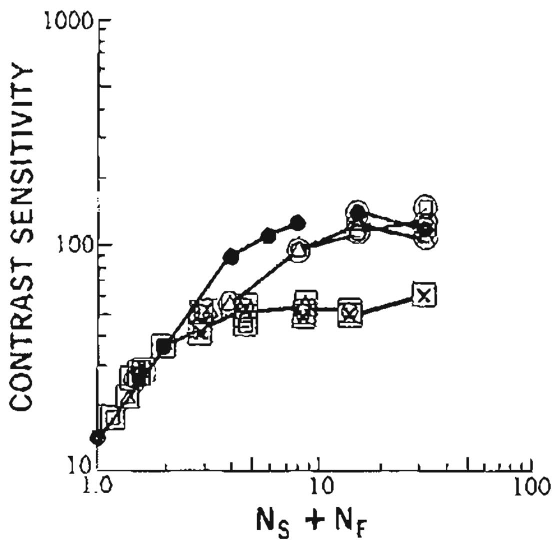


FIG. 13. Data from 45 experiments with different flank widths and sine widths and number of cycles of sinusoid. The results of Fig. 12 have shown that both N_S (number of cycles of sinusoid) and N_F (number of cycles of flank) independently affect contrast sensitivity. This graph plots contrast sensitivity versus the sum $N_S + N_F$. The Fig. 11 data, which represent all the experiments with one-cycle sinusoids, are plotted here inside open squares. Figure 12 data, which represent all the higher numbers of cycles of sinusoid experiments, are plotted here inside open circumscribing circles. Sinusoids on a black background are plotted with the symbol ●. The no-flank data and data from average-luminance flank targets with an N_F less than or equal to 1.0 coincide. For values of N_F greater than 1.0, the sum of sinusoid and flank cycles no longer provides a unique description of the contrast sensitivity. The solid lines identify data from targets with constant numbers of sinusoid cycles.

In order to consolidate all the experimental results into a single description of contrast sensitivity in the low-spatial-frequency region, we must express the results as a function of both N_S and N_F. In Fig. 13, the horizontal axis is $N_S + N_F$. If we take a display with a 5.0-deg one-cycle sinusoid, and the surround subtends 7.5 deg on each side or 15 deg of flank in all, then there are 3.0 cycles of flank. The value along the horizontal axis is 4.0.

The data from Fig. 11 show the results of one-cycle sinusoidal targets with various widths of average-luminance flanks for observers JAH and JMC. The data from Fig. 12 describe the results of many-cycle sinusoidal targets with various average-luminance flanks for observers JAH and RLS. Figure 13 replots the data from Figs. 11 and 12 along with data for various numbers of cycles of sinusoid on a black background. The Fig. 11 data are replotted in Fig. 13 using the original symbols inside open squares. The Fig. 12 data are replotted in Fig. 13 using the original symbols inside an open circumscribing circle. One-cycle Fig. 12 data are averaged into the Fig. 11 data for this presentation. Data circumscribed by a square are all from one-cycle targets, while circled data are from higher number of cycles targets. The data for sinusoids with different numbers of cycles on a black background without any average-luminance flank are plotted as filled circles.

In the black-surround experiments the one-cycle sinusoid subtended 1.25 deg, while the displays with 2, 4, 6, and 8 cycles were multiples of the one-cycle width. All displays were 12 deg high. The contrast sensitivities are the average for observers JAH and RLS.

The data fall along a set of curves. The series of displays that increases only the number of cycles on a black surround shows the most rapid increase of contrast sensitivity as a function of the total number of cycles. The other extreme is the data for one cycle of sinusoid with increasing flank width. The data for 2-, 4-, 8-, and 16-cycle targets fall between the one-cycle and the black-surround curves. When we compare the various curves plotted in Fig. 13, we can see that between one and two cycles the observers' contrast sensitivity is increased equally by adding either one cycle of average-luminance flank or one cycle of sinusoid. With more cycles of sinusoid, the additon of more average-luminance cycles produces smaller increases in sensitivity than those from extra cycles of sinusoid. We conclude that the effect of an average-luminance flank is qualitatively the same as that caused by the addition of more cycles of sinusoid, but the magnitude of the effect is less.

Using the data in Fig. 13 we can look for an empirical relationship that will describe all of the two-flank data. Regardless of the size of sinusoidal display, the low-frequency side of a contrast-sensitivity curve[1] (log contrast sensitivity versus log spatial frequency) has a slope very near 1.0. In Fig. 8 we saw that log contrast sensitivity versus log flank width for two-flank targets has a much lower slope. The data from that figure suggest that a graph of log contrast sensitivity versus log number of cycles of flank has a slope of about one-third that of contrast sensitivity versus number of cycles of sinusoid. Based on this and other data in Fig. 13, we used the expression (number of cycles of flank to the 0.3 power) to describe the effect of flank width. We incorporate all data from Fig. 13 in Fig. 14 by plotting contrast sensitivity versus $[N_S$ (number of cycles of sine) + $(N_F)^p$ (number of cycles of flank to the p power)]. If N_F was less than 1.0, we set $p = 1.0$. If N_F was greater than 1.0, we set the power $p = 0.3$. The data show some spread but, in general, form a simple curve which can be used to describe all 45 experiments. The significance of this result, beyond the convenience of having a unifying empirical relationship, is that increases in the number of equivalent average-luminance flank cycles have a similar but weaker effect on contrast sensitivity to increases in the number of cycles of sinusoid.

VI. DISCUSSION

By far the most important variable in the high-spatial-frequency region of a contrast-sensitivity curve is the nominal spatial frequency. Nevertheless, the influence of nominal spatial frequency apparently disappears at low frequencies. Many experiments use a fixed display size; thus the number of cycles of sinusoid is proportional to the nominal spatial frequency. When measurements of contrast sensitivity are made with a fixed size of display, the low-spatial-frequency measurements exhibit a dependence on the number of cycles. Earlier papers by McCann *et al.*,[8] Hoekstra *et al.*,[9] and McCann *et al.*[6] showed a marked dependence of contrast sensitivity on the number of cycles of sinusoid. The early experimental results have all been repeated and substantiated.[1] Additional observations[1] resolved differences between early results and those of Estevez and Cavonius.[10] The

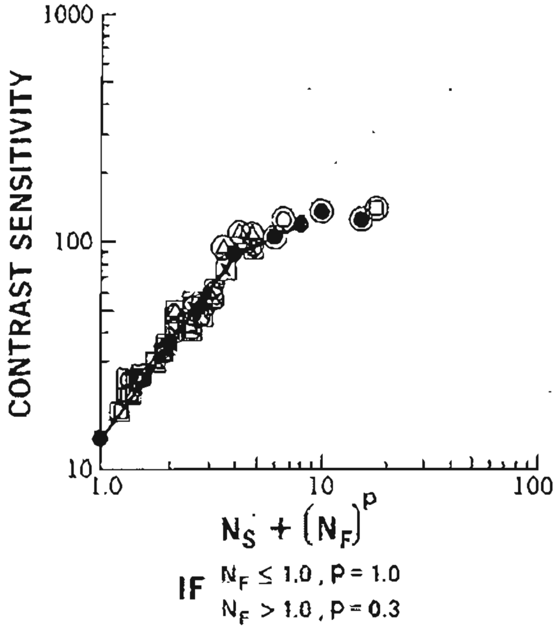


FIG. 14. Data from Fig. 13 replotted with a different horizontal axis. Here we replace N_F (number of cycles of flank) with $(N_F)^p$. The data in Fig. 13 showed that when N_F is small, namely, less than 1.0, increases in N_F have the same effect as increases in N_S (number of cycles of sinusoid). For this reason, we set $p = 1.0$ when N_F was less than or equal to 1.0. For values of N_F greater than 1.0, the effect of increasing N_F is less than increasing N_S by the same amount. Numerous experiments have shown that the slope of the log-contrast-sensitivity curve versus log N_S is always close to 1.0 in the low-spatial-frequency region.[1] The data in Fig. 8 show that the effect of increasing N_F, which in this case is proportional to flank width, is much less than a slope of 1.0. In fact, the slope is approximately 0.3. For this reason, for values greater than 1.0, we set $p = 0.3$. The data from all 45 targets form a single curve which can be used as an empirical description of any low-number-of-cycle target with average-luminance flanks.

new result derived from the experiments in this paper is that an average luminance flank mimics the effect of increasing the number of cycles. The absolute amount of flank is not as important as the proportion of flank to sinusoid width. The finding that the proportion of flank width to sine width determines the contrast sensitivity is consistent with results describing the ability of the visual system to generate the same lightness and threshold sensations regardless of very large changes in spatial properties of the stimuli.[7]

As reported earlier, we find no dependence of contrast sensitivity on the nominal spatial frequency in the low-spatial-frequency region. The region of this independence from spatial frequency is considerable. On the high-frequency side it is bounded by the peak of the contrast-sensitivity curve. On the low-spatial-frequency side it is bounded by the size of the display. Cohen *et al.*[11] found that the dependence on number of cycles does not hold for a 60-deg target. McCann *et al.*[1] showed that it does hold for a 20-deg display. Savoy[12] measured the extent to which contrast sensitivity depends on the number of cycles for displays of different sizes and luminances. The extent varies somewhat because the peak of the contrast sensitivity versus frequency curve varies with luminance. Above the peak of this curve, nevertheless, the phenomenon is found at all levels of luminance and all sizes of displays up to a size limit of between 20 and 30 deg.. Koenderink *et al.*[13] also report a lack of dependence on number of cycles at 50 deg eccentricity with 8 × 12 deg targets.

It is important to remember that contrast sensitivity measures the aggregate of all processes that analyze the display. Obviously, the individual processes that analyze the display will be specific for certain sizes in the space domain, or for certain frequencies in the Fourier domain. Each of these processes will be optimal for detecting a certain size of object or spatial frequency of object in the image. Each, individually, will have a specific size or a low-spatial-frequency attenuation that is spatial-frequency specific. What is fascinating is that the eye has a pattern of image-processing elements such that all the individual reports, which must depend on size or spatial frequency, are in the aggregate essentially independent of size or spatial frequency.

ACKNOWLEDGMENTS

The authors wish to thank William Wray for the design of the electronics used in these experiments. Observers Robert L. Savoy and Charles Elliot were also of invaluable aid in the experimentation necessary for these findings. Jon Frankle, W. Alan Stiehl, and Marie A. Watson have been very helpful in the preparation of the text.

[1] J. J. McCann, R. L. Savoy, and J. A. Hall, Jr., "Visibility of low-frequency sine-wave targets: dependence on number of cycles and surround parameters," Vision Res. 18, 891–894 (1978).

[2] B. H. Crawford, "The effect of field size and pattern on the change of visual sensitivity with time," Proc. R. Soc. (Lond) B 129, 94–106 (1940).

[3] G. Westheimer, "Spatial interaction in human cone vision," J. Physiol. (London) 190, 139–154 (1967).

[4] R. L. Savoy and J. J. McCann, "Visibility of low-spatial-frequency sine-wave targets: dependence on number of cycles," J. Opt. Soc. Am. 65, 343–350 (1975).

[5] The Fourier spectra of these targets cannot be inferred from the nominal spatial frequencies of the sinusoid-wave portions. The Fourier spectra of such targets with a black surround are dominated by the black-to-average-luminance edge. For a discussion of this problem see R. L. Savoy, "Visibility of low-spatial frequency targets: Dependence on number of cycles and implications for spatial frequency channels," M. S. Thesis, Massachusetts Institute of Technology, and Ref. 6.

[6] J. J. McCann, R. L. Savoy, J. A. Hall, Jr., and J. J. Scarpetti, "Visibility of continuous luminance gradients," Vision Res. 14, 917–927 (1974).

[7] J. J. McCann, "Visibility of gradients and low spatial frequency sinusoids: evidence for a distance constancy mechanism," Photogr. Sci. Eng. 22, 64–68 (1978).

[8] John J. McCann, Robert L. Savoy, and John A. Hall, Jr., "Visibility of low-spatial-frequency sine-wave targets: dependence on number of cycles," J. Opt. Soc. Am. 63, 1297– (1973).

[9] J. Hoekstra, D. P. J. van der Goot, G. van den Brink, and F. A. Bilsen, "The influence of number of cycles upon the visual contrast threshold for spatial sine patterns," Vision Res. 14, 365–368 (1974).

[10] O. Estevez and C. R. Cavonius, "Attenuation in detection of gratings: sorting out the artefacts," Vision Res. 16, 497–500 (1976).

[11] R. Cohen, C. R. Carlson, and G. Cody, "Image descriptors for displays," ONR Tech. Report, Contract No. N00014-74-C-0184 (1976).

[12] R. L. Savoy, "Low spatial frequencies and low number of cycles at low luminances," Photogr. Sci. Eng. 22, 76–79 (1978).

[13] J. J. Koenderink, M. A. Bouman, A. E. Bueno de Mequita, and S. Slappendel, "Perimetry of contrast detection thresholds of moving spatial sine wave patterns. III. The target extent as a sensitivity controlling parameter," J. Opt. Soc. Am. 68, 854–860 (1978).