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Human contrast sensitivity for sinusoid gratings is examined over mean luminances ranging from 100 to 0.001 cd/m$^2$, i.e., into the scotopic region. In order to study the influence of the number of cycles of sinusoidal oscillation on contrast sensitivity of low-frequency gratings, a display of fixed physical size is used—the viewing distance and the number of cycles in the display are varied. At scotopic levels, although high-frequency attenuation in sensitivity occurs at much lower spatial frequencies than at photopic levels, there is a region over which contrast sensitivity depends largely on the number of cycles in the display.

## Introduction

The present study examines the influence of display size and/or number of cycles on threshold contrast for low-spatial-frequency sine-wave gratings as the mean luminance is decreased from photopic to scotopic levels. The primary question is whether the marked influence of number of cycles which those in our laboratory[1] and others[2,3] have found at various photopic luminances is also present at scotopic luminances.

## Methods

Figure 1 is a schematic illustration of the stimuli used. The apparatus generated three "zones" as shown in the top portion of the figure. Zones 1 and 2 were regions of uniform, independently adjustable luminance. Zone 3 was a sine-wave grating with vertically oriented bars. The boundaries of the regions (indicated by the letters A-K) were adjustable. For all experiments, Zone 3 was an 11 cm square centered in Zone 2. Zone 2 was a 17 cm square and had a uniform luminance equal to the mean luminance of the grating in Zone 3. The luminance of Zone 1 was zero and the rest of the room in which the subject and equipment were situated was also dark. The bottom portion of Fig. 1 is a luminance profile taken horizontally across the middle of the display when there was one cycle of sinusoidal oscillation in the grating.

Contrast threshold was measured for sine-wave gratings containing either 1, 2, 4, 8, or 16 cycles in sine phase with the beginning of the grating. The gratings were bordered on all sides by a region of uniform luminance equal to the mean luminance of the grating. The mean luminance of the grating and surround was varied from 100 candles per square meter (cd/m$^2$) to 0.001 cd/m$^2$ by a factor of 10 at each step. By varying the distance between the observer and the display from 18 to 640 cm, the size of the sine-wave grating was varied from a 32 by 32 degree square to a 1 by 1 degree square by a factor of 2 at each step. For each target, the subject made at least 10 contrast settings. For each setting, the contrast was initially well below threshold and the subject turned a 10-turn potentiometer to increase contrast until the sine-wave stimulus just appeared. *Contrast* is defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$, where $L_{max}$ and $L_{min}$ are the maximum and minimum luminances in the grating, respectively. *Contrast sensitivity* is defined as the reciprocal of threshold contrast.

The author, age 27, whose mild astigmatism was corrected with glasses, served as the principal subject. (A second subject was run at one of the high luminances and one of the low luminances and similar data were obtained). His head was positioned on a chin-rest. A very small piece of black tap affixed to the face of the display indicated the center of the grating. The subject restricted his gaze to a small region around this spot. At short distances, the black spot also served as a cue for monocular accommodation. For larger distances, the outline of the display device was a cue for accommodation. The gratings were viewed monocularly through an artificial pupil 4 mm in diameter. Thus, the retinal illuminance varied from $-2$ to $+3$ log photopic trolands. The 0.01 cd/m$^2$ gratings should be well into the scotopic region.[4] A scotopic matching experiment using different spectral compositions was used to confirm the point of transition from scotopic to photopic regions. Two color compensating gelatin filters (CC40Y and CC20B) were selected such that when they were placed side by side over the display, they caused the same (very slight) attenuation at scotopic luminances. As the luminance was increased, the filters became distinguishable in both color and amount of attenuation. This occurred at a screen luminance of 0.014 cd/m$^2$.

The stimuli were presented on a Hewlett-Packard 1317A high-speed graphics display, which is essentially a large cathode ray tube. Stimuli were calibrated photometrically using a Gamma Scientific telephotometer. The screen luminance was approximately 100 cd/m$^2$. For the highest luminance condition, the screen was viewed directly. For all other luminances, the screen was covered with large crossed polarizers adjusted to reduce the luminance to 10 cd/m$^2$. Wratten neutral filters of optical density 1.0, 2.0, 3.0, and 4.0 were taped over the artificial pupil to obtain the luminances of 1.0, 0.1, 0.01, and 0.001 cd/m$^2$, respectively.

## Results

The presentation of results will be divided into two parts. In the first part (Figs. 2 and 3) the display size is held constant and the luminance levels vary. This sort of data has been obtained previously.[5–9,*] In the second part (Figs. 4–6) the luminance is held constant and the display sizes vary. In all figures, error bars of plus-and-minus one standard deviation in contrast sensitivity are very nearly equal to the size of the symbols used to plot the data.

Figures 2 and 3 are graphs of contrast sensitivity versus spatial frequency for two of the six display sizes used, as the luminance is varied parametrically from 100 to 0.001 cd/m$^2$. The 1-degree display (Fig. 2) presents gratings with nominal spatial frequencies between 1 and 16 cycles per degree (cpd). The 8-degree display (Fig. 3) presents gratings with nominal spatial frequencies between 0.125 and 2 cpd. For the three highest luminances in Fig. 3, contrast sensitivity increases

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*Daitch and Green [*Vision Res.* 9: 947 (1969)] found similar results with stimuli presented 12 degrees perpheral to the fovea, except that the frequency of peak sensitivity increased to only 2 cpd at the maximum luminance they used.

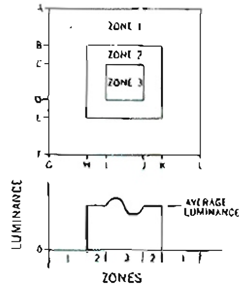


**Figure 1.** A schematic illustration of the stimuli used. Zone 3 is a vertical sine-wave grating. Zone 2 is a perimeter of uniform luminance equal to the mean luminance of the grating. The luminance of Zone 1 is zero for these experiments. The lower part of the figure is a luminance profile along the middle of the display for a 1-cycle grating. See *Methods* for further details.

monotonically with spatial frequency.† There is no high-frequency roll-off only because there are no data for the higher frequencies. For the same high luminances in Fig. 2 (where the highest frequencies are 8 and 16 cpd) there is a clear high-frequency roll-off, and the peak sensitivity is at 4 cpd. What about high-frequency attenuation at lower luminances? In Fig. 3 (the 8-degree display) a high-frequency attenuation is evident for the three lower luminances. For the 0.1 cd/m$^2$ data (filled circles) the peak is at 1 cpd; for the 0.01 cd/m$^2$ data (filled triangles) the peak is approximately 0.5 cpd. In Fig. 2, there are few data at the lower luminances because most of the 1-degree gratings were not visible at the highest contrast obtainable on our apparatus (0.33).

In summary, for a fixed size of display, varying the mean luminance yields results similar to previous reports. As luminance is decreased, contrast sensitivity decreases at all spatial frequencies and the nominal spatial frequency of maximum sensitivity decreases from about 4 cpd to less than 1 cpd.

Let us start the discussion of results for fixed luminance levels by examining the data of Figs. 4, 5*e*, and 5*f*, whose luminance of 0.1 cd/m$^2$ is near the middle of the range of luminances investigated. Figure 5*e* presents contrast sensitivity versus the nominal spatial frequency of gratings subtending 1, 2, 4, 8, 16, and 32 degrees. For gratings with nominal frequencies of 1 cpd or less there is a considerable increase in contrast sensitivity as display size increases, or, equivalently, as the number of cycles in the grating increases. Consider the five gratings with a nominal spatial frequency of 0.5 cpd, for example. As display size increases from 2 to 32 degrees, the number of cycles increases from 1 to 16 and the contrast sensitivity increases by a factor of 10. Thus, there is not a unique contrast sensitivity associated with each spatial frequency in this low frequency region. As was suggested earlier (in Fig. 3) the peak sensitivity for this luminance level occurs at about 1 cpd. Beyond the 1 cpd peak, gratings at a fixed frequency and with at least 4 cycles of oscillation have nearly equal contrast sensitivities. That is, a particular contrast sensitivity can be associated with each spatial frequency in the region of high frequency attenuation.‡ The two arrows in Fig. 5*e* indicate the data points to the right of the frequency of peak sensitivity.

Figure 4 presents the data of Fig. 5*e* replotted with the number of cycles of sinusoidal oscillation in the grating as the abscissa. There is a considerable amount of overlap of the

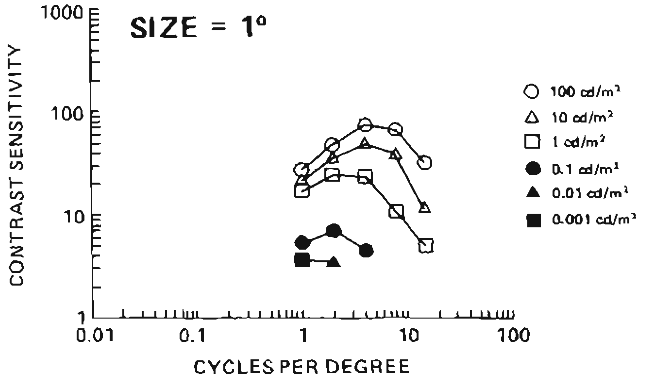


**Figure 2.** Contrast sensitivity vs. nominal spatial frequency for 1-degree wide gratings of various mean luminances. As luminance decreases, the frequency of peak sensitivity decreases and contrast sensitivity decreases at all spatial frequencies.

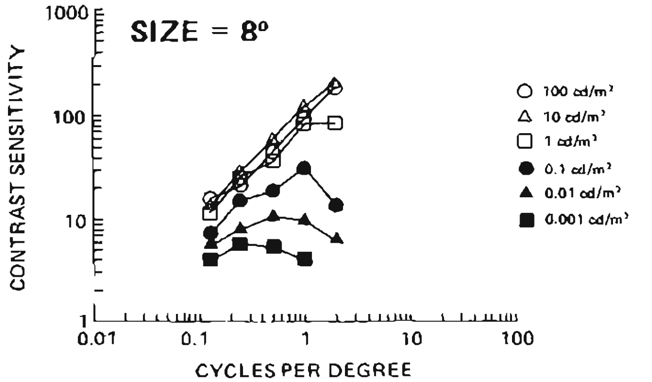


**Figure 3.** Data from an experiment similar to Fig. 2, but with 8-degree wide gratings. Because the physical size of the gratings on the cathode ray display are fixed, the spatial frequencies are lower than in Fig. 2. Again, as luminance is decreased, the frequency of peak sensitivity decreases and contrast sensitivity decreases at all spatial frequencies.

curves of various display sizes, but there are also many points with the same number of cycles but different contrast sensitivities. For many of these data points, the sine-wave gratings have nominal spatial frequencies beyond the peak sensitivity. That is, the decrease in contrast sensitivity for some points is due to high-frequency attenuation. In order to consider the influence of number of cycles, *per se*, see Fig. 5*f*. Figure 5*f* is identical to Fig. 4 except that the data points indicated in Fig. 5*e* as being in the region of high-frequency attenuation have been deleted. Now the influence of the number of cycles is most clear. Consider the gratings with one cycle, for example. As the display size increases from 1 degree to 32 degrees, the

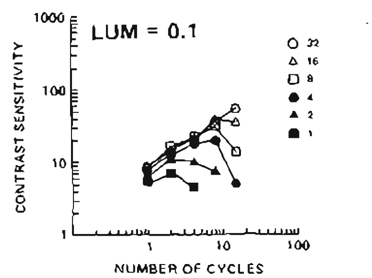


**Figure 4.** Contrast sensitivity vs. number of cycles for gratings of 1, 2, 4, 8, 16, and 32 degrees in width and mean luminance of 0.1 cd/m$^2$. Much of the data falls on a single line of slope 1. The points that do not fall on the line are in the region of high-frequency attenuation. See Figs. 5*e* and 5*f* and *Results* for further discussion.

†Since the display size is fixed, the number of cycles of sinusoidal oscillation is linearly proportional to the spatial frequency. Hence, one could equally well describe the high-luminance data of Fig. 3 by saying that contrast sensitivity increases monotonically with increasing number of cycles.

‡This last point is more clearly seen in Figs. 6*a*, 6*c*, and 6*e* which have higher mean luminances and high-frequency regions further to the right on the abscissa.

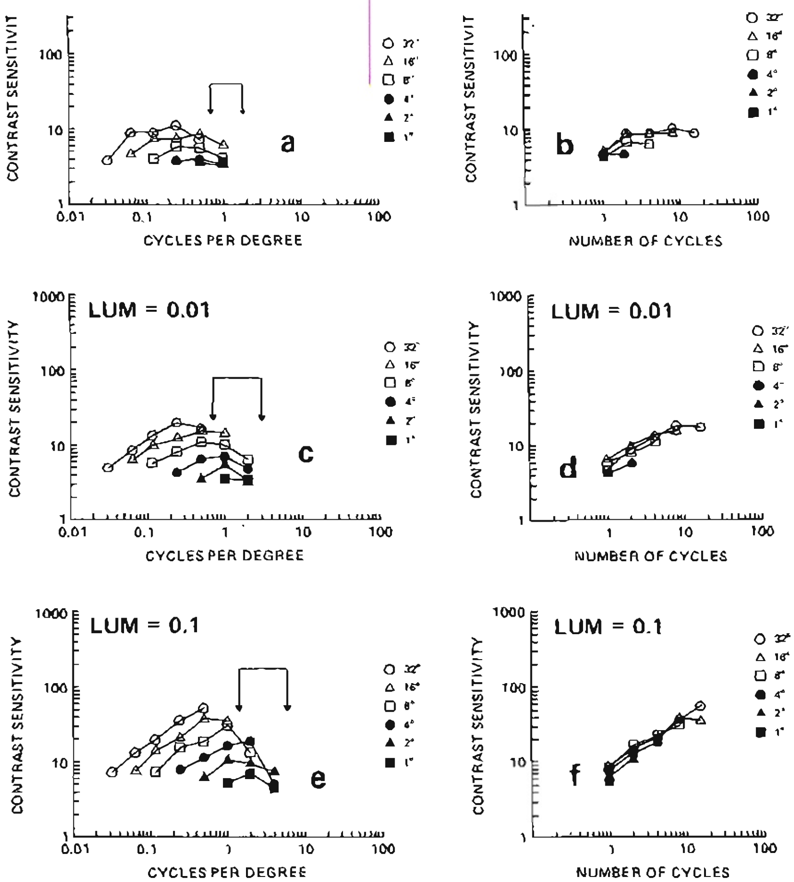


Figure 5. Results for the three lowest luminances. Figures 5*a*, 5*c*, and 5*e* plot contrast sensitivity vs. the nominal spatial frequency for gratings subtending 1, 2, 4, 8, 16, and 32 degrees. The two arrows indicate the data beyond the peak sensitivity at each luminance. Figures 5*b*, 5*d*, and 5*f* are replots of the data in Figs. 5*a*, 5*c*, and 5*e*, respectively, but with the number of cycles as the abscissa and with data points between the arrows deleted. It is clear in the three figures on the right that contrast sensitivity depends very strongly on the number of cycles in the grating, independent of display size (and hence independent of the nominal spatial frequency) for these low-frequency, low-number-of-cycle gratings.

nominal spatial frequency decreases from 1.0 to 0.03 cpd, a factor of 32. Yet the contrast sensitivity for these gratings varies by less than a factor of 2. In fact, for all the data in Fig. 5*f* the range of contrast sensitivities at a fixed number of cycles is less than a factor of 2.

The above discussion refers only to data of a single luminance level, 0.1 $cd/m^2$. These data are perhaps the most striking, of all the data in Figs. 5 and 6, in demonstrating a dependence of contrast sensitivity on number of cycles, independent of spatial frequency. However, the influence of number of cycles is clearly evident at other luminances.

Data for the two lower luminances, 0.01 and 0.001 $cd/m^2$, are shown in Figs. 5*a*, 5*b*, 5*c*,* and 5*d*. These graphs are similar to Figs. 5*e* and 5*f*. They show that contrast sensitivity for these low-frequency gratings depends on number of cycles independent of nominal spatial frequency.

Data for mean luminances of 1, 10, and 100 $cd/m^2$ are shown in Fig. 6. Here too, there is considerable overlap of much of the data when plotted on the number of cycles axis. In fact, for the three smaller display sizes (filled symbols) the data in Figs. 6*b*, 6*d*, and 6*f* coincide as much as the data in Figs. 5*b*, 5*d*, and 5*f*. However, as is first suggested for the 32 degree display at 1.0 $cd/m^2$ (Fig. 6*b*) and as is very clear for the largest displays at the highest luminance of 100 $cd/m^2$ (Fig. 6*f*), there is no longer a single contrast sensitivity for all the 1-cycle targets, or all the 2-cycle targets, as was the case at lower luminances. In Fig. 6*f*, the three smallest displays (filled symbols) all result in higher sensitivities than the larger displays (open symbols). That is, despite an equal number of cycles, there are substantial differences in contrast sensitivities and the larger displays result in the lower sensitivities. Thus, for the large displays at 100 $cd/m^2$ and for the 32 degree display at 1 and 10 $cd/m^2$, there is an attenuation due to low spatial frequency *per se*. However, the fact that there is still increasing sensitivity with increasing display size at fixed low frequencies indicates that number of cycles is still having some effect as well.

## Discussion

The importance of having enough cycles when measuring contrast thresholds was pointed out some time ago.[7] However, the marked dependence on the number of cycles, practically independent of the spatial frequency for low-number-of-cycle, low-frequency gratings, has recently led some people to suggest that the low-frequency attenuation long associated with contrast sensitivity functions might be due entirely to the influence of the smaller number of cycles present in low-frequency test gratings.[1,2] That interpretation of the data led to considerable discussion.[10–13] However, the present work indicates that for large displays, at luminances of 100 $cd/m^2$,

*There is no obvious peak in sensitivity as a function of spatial frequency in Fig. 5*a*. However, based on the clearer peaks in Figs. 5*c* and 5*e*, the data in Fig. 5*a* for 1 cpd gratings are in the region of high-frequency attenuation and have been deleted from Fig. 5*b*. If the 0.5 cpd data in Fig. 5*a* were also deleted, the Fig. 5*b* data would be even closer to a single function.

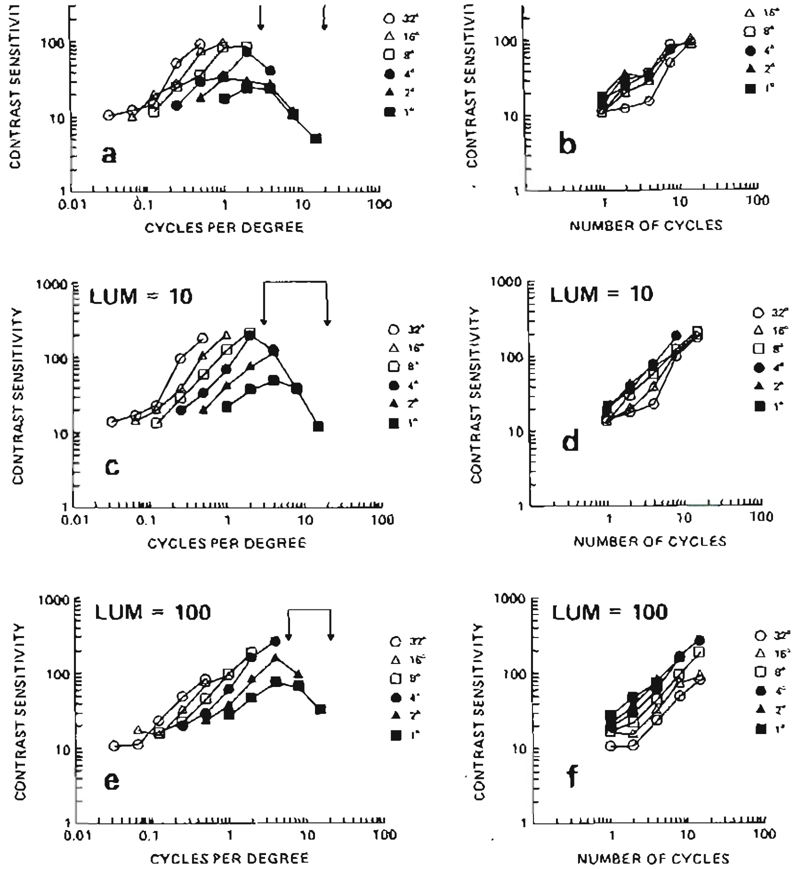


**Figure** 6. Results for the three highest luminances. Figures 6*a*, 6*c*, and 6*e* plot contrast sensitivity vs. the nominal spatial frequency for gratings subtending 1, 2, 4, 8, 16, and 32 degrees. The two arrows indicate the data beyond the peak sensitivity at each luminance. Figures 6*b*, 6*d*, and 6*f* are replots of the data in Figs. 6*a*, 6*c*, and 6*e*, respectively, but with number of cycles as the abscissa and with the data points between the arrows deleted. For the three smallest display sizes (filled symbols) there is a clear dependence on the number of cycles independent of the nominal frequency. For the larger displays (especially the 32 degree display) there is an attenuation in sensitivity which is due to the low spatial frequency as well as the low number of cycles.

there is a fall-off in sensitivity which is indeed due to low frequency, and not due solely to a small number of cycles. This last finding has been previously reported by Cohen, Carlson, and Cody.[3] Although their data are not precisely comparable to ours because of methodological differences, they did measure contrast sensitivities for gratings subtending 0.5, 1.0, 2.3, 6.5, and 60 degrees at a mean luminance slightly greater than 100 cd/m$^2$. The data for the four displays smaller than 60 degrees showed a clear dependence of contrast sensitivity on the number of cycles, but the 60-degree display showed an equally clear dependence on low spatial frequency *per se*. Cohen et al., used sine-wave gratings with nominal spatial frequencies as low as 0.25 cpd. The lowest frequencies is Figs. 5 and 6 are 0.03 cpd. The rate of decrease in sensitivity which is shown in Fig. 6*e* for these very low frequencies is somewhat slower than in the region investigated by Cohen et al.

In summary, experiments at scotopic luminances (0.001 and 0.01 cd/m$^2$) show that scotopic vision exhibits a dependence on number of cycles similar to that of photopic vision. For the four display sizes less than about 16 degrees in width, and for the five luminances less than 100 cd/m$^2$, contrast sensitivity for low-frequency sine-wave gratings with a small number of cycles depends upon the number of cycles, essentially independent of the nominal spatial frequency. Furthermore, for low luminances (0.1, 0.01, and 0.001 cd/m$^2$) the dependence on number of cycles also holds for gratings as large as 32 degrees wide (the largest used in this study). For the highest luminance used, 100 cd/m$^2$, the dependence on number of cycles is present for the smaller display sizes, but with the larger displays (especially the largest) there is a decrease in contrast sensitivity due to low spatial frequency itself, as well as the low number of cycles.

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