Apparent contrast of suprathreshold gratings varies with stimulus orientation

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Human contrast sensitivity is known to vary with both stimulus spatial frequency and orientation. Previous research has indicated, however, that the apparent contrast of a sinusoidal grating is independent of spatial frequency at suprathreshold levels. We have found that the apparent contrast of suprathreshold gratings is not independent of its orientation. Observers adjusted the apparent contrasts of vertical and oblique gratings to match a 40% standard. Contrast match deviations were found at a number of spatial frequencies, indicating a lack of contrast constancy with stimulus orientation. The apparent contrast of gratings in different orientations could not be predicted in any simple fashion from either contrast threshold differences or ratios.

Human spatial contrast sensitivity for detecting the presence of sine-wave gratings is known to vary with both stimulus spatial frequency and orientation. Most observers are maximally sensitive to stimulus patterns with frequencies between approximately 3 and 6 cycles/deg (Campbell & Green, 1965). Sensitivity drops for frequencies above and below this range. Moreover, human observers typically show lower contrast thresholds for gratings oriented vertically or horizontally than for gratings oriented obliquely (Campbell, Kulikowski, & Levinson, 1966; Freeman & Thibos, 1975; Mitchell, Freeman, & Westheimer, 1967). This orientation-dependence of contrast sensitivity increases with spatial frequency.

Since a number of studies have shown the apparent contrast of suprathreshold gratings to remain relatively constant across a wide range of stimulus spatial frequencies (Blakemore, Muncey, & Ridley, 1973; Georgeson & Sullivan, 1975; Hamerly, Quick, & Reichert, 1977; Watanabe, Mori, Nagata, & Hiwatashi, 1968), the question arises as to whether or not the meridional differences in contrast sensitivity are related to meridional differences in apparent contrast at suprathreshold levels. It could be that the visual system compensates for these sensitivity differences so that, at suprathreshold levels, gratings of different orientations will have the same apparent contrast when they are of the same physical contrast. This may be referred to as the contrast constancy hypothesis.

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Several other hypotheses are possible. First, the suprathreshold contrast appearance of gratings in different orientations could be predicted by their absolute differences found at threshold. By this hypothesis, the contrast of a suprathreshold vertical grating ($C_{S:Vert}$) would appear to match the contrast of a suprathreshold oblique grating ($C_{S:Obl}$) when the two contrasts bore the following relationship to threshold:

$$C_{S:Obl} - C_{S:Vert} = C_{T:Obl} - C_{T:Vert},$$

where $C_{T:Obl}$ is the contrast threshold of an oblique grating of a given spatial frequency and $C_{T:Vert}$ is the contrast threshold of a vertical grating of the same spatial frequency. In other words, for $C_{S:Obl}$ and $C_{S:Vert}$ to match in apparent contrast, their difference must equal the difference between their respective thresholds. For example, if the contrast threshold of a grating was 10% when vertically oriented and 15% when obliquely oriented, a suprathreshold oblique grating would always have to be set at a modulation amplitude 5% higher than a vertical grating for the two to match in apparent contrast.

Another possibility is that meridional differences in suprathreshold contrast appearance are predictable from the *relative* differences in contrast threshold in different orientations. This relationship is expressed by the equation:

$$C_{S:Obl}/C_{S:Vert} = C_{T:Obl}/C_{T:Vert},$$

which states that for two gratings to match in apparent contrast, their suprathreshold contrasts must be in the same proportion as their contrast thresholds. So, for example, if an observer's contrast threshold

for an oblique grating was twice that for a vertical grating of the same spatial frequency, this observer would have to set the contrast of an oblique grating to be twice that of a suprathreshold vertical grating for the two to match.

The contrast constancy hypothesis discussed earlier is expressed by the equation:

$$C_{S:Obl} - C_{S:Vert} = 0.$$

This states simply that there should be no differences in apparent contrast between stimuli in different orientations at suprathreshold levels.

In the experiment discussed below, observers matched the apparent contrast of two gratings: one vertical and one oblique (45 deg). One of the gratings was presented at a standard contrast of 40% and the second grating was of variable contrast. Contrast match deviations between gratings in the two orientations were then compared with the relative differences in the contrast thresholds for these same orientations.

METHOD

Subjects

The subjects were the two authors, D.O.B. and M.B.M., both of whom are highly trained in psychophysical observation. Both observers are well-corrected myopes and have acuities of 20/17 or better as measured by a Bausch and Lomb Vision Tester.

Stimuli

Sinusoidal grating patterns were generated on two Tektronix 606 oscilloscopes with a variation of the method reported by Campbell and Green (1965) and Schade (1956). A sinusoidal grating is a pattern with a sinusoidal luminance distribution extending in one dimension. The spatial distribution of luminance in this dimension is expressed by the formula:

$$L(x) = L_0[1 + M\sin(2\pi fx + \phi)],$$

where L_0 is the space-average luminance of the pattern, M is the contrast of the pattern, f is the spatial frequency of the pattern, and ϕ is the initial phase angle of the modulation.

The contrast (M) of the pattern is defined as

$$(L_{\max} - L_{\min}) / (L_{\max} + L_{\min}),$$

where $L_{\max}$ is the maximum luminance found in the modulating pattern and $L_{\min}$ is the minimum luminance found in the pattern. The spatial frequency (f) of the pattern refers to the number of cycles present in the grating per degree of visual angle.

These gratings were produced by sending a phase-locked 640-kHz triangular waveform into each oscilloscope's Y amplifier and a sinusoidal waveform into the Z amplifier. The Z input was synchronized to the time base of the oscilloscope. The triangular waveform was generated by a Wavetek 182 (a MHz function generator) oscillator, and the sinusoidal Z input was produced by a Wavetek 136 (VCA/VCG generator) oscillator with voltage-controlled frequency and amplitude input ports. These voltage-controlled input ports were fed by a PDP-8A (Digital Corporation) computer through a series of 10-bit digital-to-analog converters. This allowed the experimenter to manipulate the frequency and modulation amplitude of the Z input to each oscilloscope and thereby vary the grating's spatial frequency and contrast. The D/A converters were linear in their response char-

acteristics and had essentially identical output functions. The stimulus space-average luminance (L_0) was calibrated to 17.1 cd/m² using a Spectra spotmeter (Photo Research Corporation Model 1505-UB).

The oscilloscopes were locked into rotating jigs that allowed display orientation to be adjusted manually by the experimenter. A locking pin arrangement in the jig guaranteed that the same display orientation could be reliably set time after time. The front of the entire apparatus was masked off except for two circular openings (3.82-deg diameter, 15.56-deg center-to-center separation), through which only the central portion of each oscilloscope face was visible. The observers viewed the displays binocularly through natural pupils, and the observation distance was held constant at 114 cm by means of a chinrest.

Contrast Matching Procedure

Sinusoidal gratings were displayed simultaneously on the two oscilloscopes. One of these gratings was vertically oriented, and the other was oriented at 45 deg. The side of stimulus orientation was counterbalanced between sessions. On each trial, one of the gratings (the standard) was displayed at a contrast of 40% and the second (the test) was displayed at either a higher or lower contrast level. The computer randomly set the initial test contrast value to one of 13 values about the standard contrast of 40%. Six of these contrasts were higher (up to 55%), six were lower (down to 25%), and one was identical to the standard value. Gratings were then displayed for a 3-sec duration or until the observer pressed one of three hand-held buttons. One button increased the test contrast by 2.5%, one decreased the test contrast by the same amount, and the third ended the trial, causing the computer to record the final match value. To make the adjustment task less predictable to the observer, the two contrast adjustment buttons were effective on a randomly determined basis 70% of the time, having no effect the other 30% of the time.

Contrast matching sessions contained 10 adjustment trials, 5 of which required matching the left contrast to the right, 5 of which required matching the right contrast to the left. The side of the standard was alternated on a trial-by-trial basis and was signaled to the observer prior to each trial by auditory tones. The inter-trial interval was 7 sec.

Contrast Threshold Procedure

Contrast threshold data were obtained with the Wetherill tracking procedure (Wetherill & Levitt, 1965). During the threshold determinations, both oscilloscopes were rotated to the same orientation, either vertical or oblique. On any given trial, a sinusoidal grating stimulus was presented on either the right scope face or left scope face. The stimulus was displayed on one of the oscilloscopes until the observer pressed one of two hand-held switches. The left switch indicated that the stimulus was on the left screen, and the right switch indicated its presence on the right screen. A faint beeping tone indicated that the stimulus was on and the observer was free to respond. This tone was off when no stimulus was present. Each button press was followed by a 2-sec interval in which only the space-average luminance was displayed on both scopes. The side of the next stimulus was then randomly determined by the computer.

Stimulus contrast for each trial was determined by the computer using a modified version of the Wetherill tracking procedure. The initial contrast level of the stimulus was set by the experimenter to be slightly higher than the observer's threshold. Each time the observer was correct as to the side of stimulus presentation, the contrast value was decremented. This procedure continued until the observer made his first error. At this point, the computer switched to the tracking algorithm. Contrast values were incremented for each error and decremented following three consecutive correct responses. These increments varied with stimulus condition. Increments were chosen to give a reasonable resolution about the observer's contrast threshold. This procedure was continued until 6 transition points ("peaks and valleys") were counted. The mean of these 6 points was computed and the

next stimulus was presented as close to this value as possible. The increment of change was halved, and the procedure was continued until 6 more transition points were counted. Means and standard deviations for the 12 transition points were computed and the mean of the 12 values was taken as a threshold estimate. According to Wetherill and Levitt (1965), this algorithm should generate threshold estimates corresponding to 79.4% correct on a psychometric function.

RESULTS

Contrast matches were made between vertical and oblique gratings at a number of spatial frequencies (4.0, 6.8, 8.8, 10.4, 12.0, and 16.0 cycles/deg) for the two observers (D.O.B. and M.B.M.). Average contrast match deviations are shown, along with absolute threshold differences, in Figures 1 (Observer D.O.B.) and 2 (Observer M.B.M.). Average contrast match deviations were obtained by pooling data on the degree to which an oblique grating's contrast had to be set above the standard vertical grating's contrast with data on the degree to which a vertical grating's contrast had to be set below the standard oblique grating's contrast. This pooling of data was justified by the insignificant difference between the two sets of measures (paired t statistic = $-.521$, $df=10$). Threshold differences were obtained by subtracting the vertical contrast thresholds from the oblique contrast thresholds. The horizontal lines in Figures 1 and 2 indicate the expected values if there were no contrast match deviations or threshold differences. Points above the line indicate that vertical gratings either had a higher apparent contrast or a lower threshold than oblique gratings. Points below the line indicate the opposite cases.

The threshold data are represented in these figures by filled circles. For both observers, thresholds at all frequencies are higher for oblique gratings than for vertical gratings (see Table 1). In addition, this absolute threshold difference increases with spatial frequency. Incidentally, if one were to plot the relative threshold differences ($C_{T:Obi}/C_{T:Vert}$) instead of the absolute threshold differences, this frequency dependency would remain for both observers.

The contrast match deviations, plotted as the open circles, show different relationships to spatial frequency for the two observers. For M.B.M. (Figure 2), vertical gratings always appear to have a higher contrast than oblique gratings. This effect increases with spatial frequency, so much so that deviations could not be obtained at 16 cycles per degree for this observer. At this frequency, the deviations were greater than the 15% contrast difference available. So, for observer M.B.M., contrast match deviations followed roughly the same relationship to spatial frequency as did threshold differences.

For Observer D.O.B. (Figure 1), the matching function is more complicated. At low frequencies,

Figure 1. Differences in contrast thresholds (filled circles) and suprathreshold contrast matches (open circles) between vertical and oblique (45-deg) sinusoidal gratings as a function of spatial frequency. Contrast match differences obtained by averaging between 20 and 60 contrast adjustment values. Contrast match deviations above horizontal line represent cases in which vertical gratings appeared to have a higher contrast than oblique gratings. Points below the line represent cases in which oblique gratings appeared as higher contrast than vertical gratings. Contrast threshold differences obtained by subtracting vertical thresholds from oblique thresholds. Error bars are standard errors of the means. Observer D.O.B.

Figure 2. Same as Figure 1. Observer M.B.M.

Table 1
Contrast Thresholds for Observers D.O.B. and M.B.M.

Spatial Frequency	D.O.B.		M.B.M.	
	Vertical	Oblique	Vertical	Oblique
4.0	.431	.551	.359	.411
6.8	.509	.970	.328	.638
8.8	.715	.999	.530	1.117
10.4	.971	1.855	.737	1.421
12.0	1.254	2.940	.986	2.145
16.0	2.193	7.671	1.167	2.521

Note—Spatial frequency is given in cycles per degree.

the apparent contrast of oblique gratings was actually greater than that of vertical gratings. This is particularly interesting, as this observer is more sensitive to vertical gratings. Additional sessions were run at these frequencies, and the effect was reliably found in all instances. At higher spatial frequencies, the function crosses over the zero deviation line, indicating that, at these frequencies, vertical gratings have a higher apparent contrast than oblique gratings. This is in closer agreement with the threshold data.

DISCUSSION

From the data presented in Figures 1 and 2, several conclusions may be drawn concerning the hypotheses stated in the introduction. First, contrast constancy does not exist between different orientations. If this hypothesis were indeed true, the contrast matching functions would be expected to correspond to the zero deviation line. These functions clearly do not correspond to this line, indicating that gratings in different orientations have different apparent contrasts. Second, meridional differences in contrast appearance are not predictable from absolute differences in contrast thresholds between orientations. If this were true, the contrast matching functions in Figures 1 and 2 would be expected to correspond to the threshold difference functions. However, match deviations tend to be substantially larger than the threshold differences. Finally, meridional differences in contrast appearance are not predictable from the threshold ratios. Although we have not provided figures with ratios plotted for matching and threshold data, an examination of these data indicated the threshold ratios to be significantly larger than the match ratios for both observers. Obviously, the fact that at low frequencies, D.O.B. shows opposite effects for threshold and matching data indicated that suprathreshold contrast appearance is not predictable from threshold data by any simple relationship.

In summary, the "oblique effect" (see Appelle, 1972) for contrast sensitivity, that is, the reduced sensitivity of the visual system to obliquely oriented targets, seems to have consequences at suprathreshold levels. Just as oblique gratings are less visible

than vertical gratings at threshold, so are they less salient at suprathreshold levels. In addition, the differences in apparent contrast between vertical and oblique targets are greatest at high spatial frequencies and are reduced or absent at low spatial frequencies. Thus, the spatial frequency dependency of the "oblique effect" in apparent contrast is similar to those reported for meridional variations in contrast sensitivity (Campbell, Kulikowski, & Levinson, 1966; Freeman & Thibos, 1975; Mitchell, Freeman, & Westheimer, 1967) and spatial frequency discrimination abilities (Bowker, 1980).

REFERENCES

- APPELLE, S. Perception and discrimination as a function of stimulus orientation: The "oblique effect" in man and animals. *Psychological Bulletin*, 1972, **78**, 266-278.
- BLAKEMORE, C., MUNCEY, J. P. J., & RIDLEY, R. M. Stimulus specificity in the human visual system. *Vision Research*, 1973, **13**, 1915-1931.
- BOWKER, D. O. Spatial frequency discrimination thresholds in different orientations. *Journal of the Optical Society of America*, 1980, **70**, 462-463.
- CAMPBELL, F. W., & GREEN, D. G. Optical and retinal factors affecting visual resolution. *Journal of Physiology*, 1965, **181**, 576-593.
- CAMPBELL, F. W., KULIKOWSKI, J. J., & LEVINSON, J. The effect of orientation on the visual resolution of gratings. *Journal of Physiology*, 1966, **187**, 427-436.
- FREEMAN, R. D., & THIBOS, L. N. Contrast sensitivity in humans with abnormal visual experience. *Journal of Physiology*, 1975, **247**, 687-710.
- GEORGESON, M. A., & SULLIVAN, G. D. Contrast constancy: Deblurring in human vision by spatial frequency channels. *Journal of Physiology*, 1975, **252**, 627-656.
- HAMERLY, J. R., QUICK, R. F., JR., & REICHERT, T. A. A study of grating contrast judgment. *Vision Research*, 1977, **17**, 201-207.
- MITCHELL, D. E., FREEMAN, R. D., & WESTHEIMER, G. Effect of orientation on the modulation sensitivity for interference fringes on the retina. *Journal of the Optical Society of America*, 1967, **57**, 246-259.
- SCHADE, O. H. Optical and photoelectric analog of the eye. *Journal of the Optical Society of America*, 1956, **46**, 721-739.
- WATANABE, A., MORI, T., NAGATA, S., & HIWATASHI, K. Spatial sine-wave responses of the human visual system. *Vision Research*, 1968, **8**, 1245-1263.
- WETHERILL, G. B., & LEVITT, H. Sequential estimation of points on a psychometric function. *British Journal of Mathematical and Statistical Psychology*, 1965, **18**, 1-10.

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