

The Effects of Astigmatism on Sensitivity to Sinusoidal and Square Wave Gratings

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Abstract

Contrast thresholds for different spatial frequencies were measured for four individuals with optimum optical correction and with 2 D of astigmatism induced at various meridians. Sensitivity for sine waves of low spatial frequencies was unaffected by the astigmatism; however, gross changes were found at high spatial frequencies when the astigmatism was induced with the power meridian perpendicular to the orientation of the stripes. For square waves, the results were comparable at high spatial frequencies, but astigmatism also produced a decrement at 0.2 cycles/degree. This latter effect can be predicted by assuming that astigmatism results in a loss of higher order harmonics in the response to square waves.

Key Words: spatial contrast thresholds, astigmatism

Although the effects of astigmatism on spatial contrast sensitivity have not been subjected to extensive investigation, results can be predicted from the optics of astigmatic systems and from the data on the effects of defocusing by spherical lenses. An astigmatic optical system focuses a point source as two focal lines, with contours parallel to the emmetropic meridian appearing blurred while perpendicular contours remain clear.^{1,2} Differential effects would be predicted for grid patterns oriented parallel to, or perpendicular to, the axis of astigmatism. The fact that defocusing affects primarily the high spatial frequencies has been realized since the original study of Campbell and Green.³

Thus, we would predict that astigmatism would produce decrements in contrast sensitivity for vertically oriented sine waves

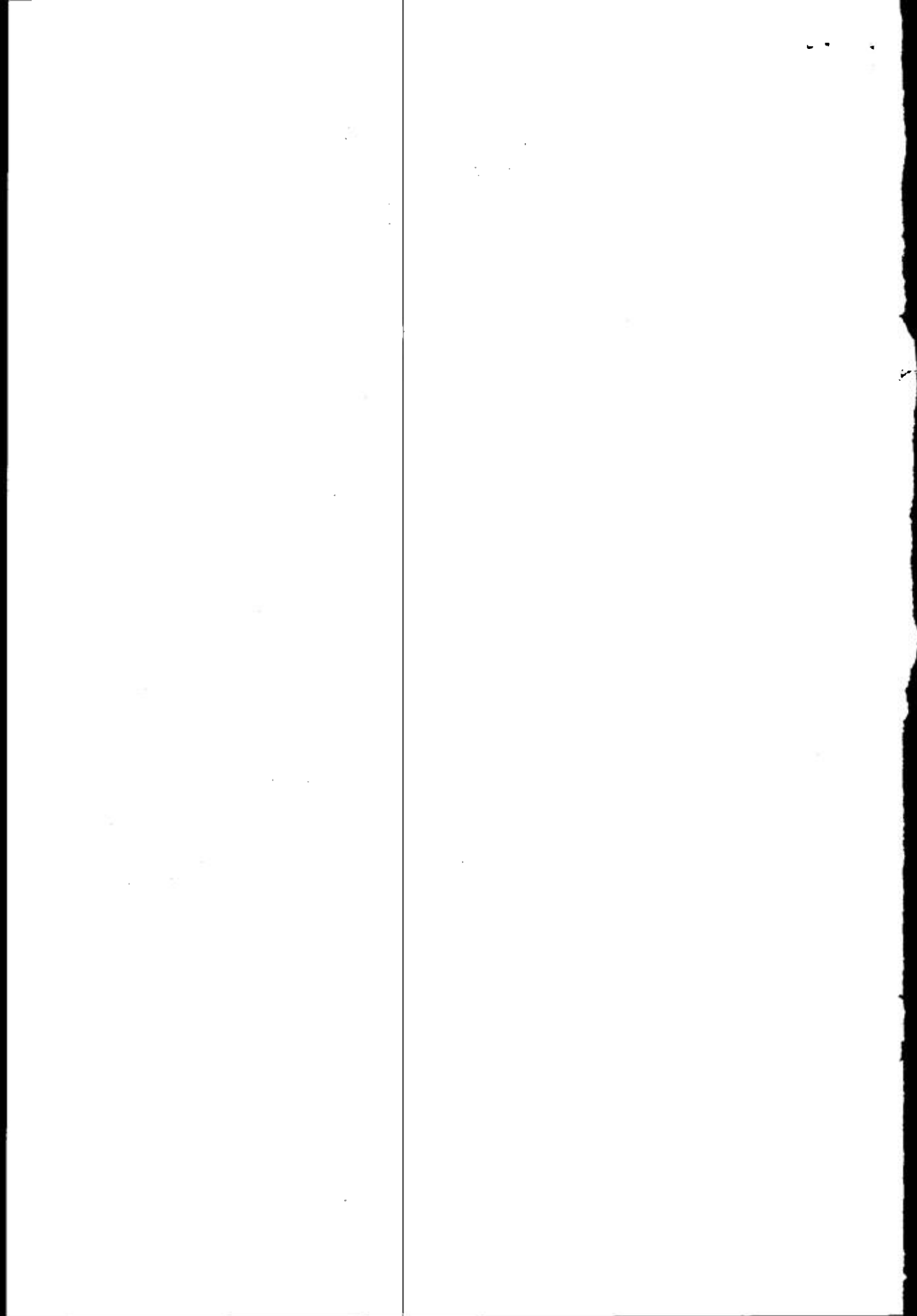
only at high spatial frequencies (the specific frequencies depending upon the amount of astigmatism) and that the decrements would be maximal for astigmatism with the power meridian horizontal. Furthermore, according to the multiple channel theory of contrast sensitivity, differential effects on the responses to sine waves and square waves should occur if the effects of astigmatism are sufficiently large to eliminate the higher order harmonics from participating in the response to square waves of low spatial frequency. This study gives an empirical test of these predictions by measuring contrast thresholds for vertical sine and square waves with subjects in whom 2 D of astigmatism was induced in different meridians.

METHODS

Sinusoidal and square-wave gratings, in a vertical dimension, were generated on a Hewlett-Packard 1311A CRT with a P31 phosphor by conventional techniques.⁴ The

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mean luminance of the oscilloscope was 4.5 cd/m^2 , and its angular subtense was 10.5×13.5 degrees at a viewing distance of 114 cm. The surround was dimly illuminated at 0.1 cd/m^2 . Five spatial frequencies, 0.2, 0.5, 2, 5, and 10 cycles/degree (cpd), were chosen to sample adequately visual sensitivity to different spatial frequencies.

Four subjects using binocular vision were employed. All were first corrected for the observing distance of 114 cm, by adding lenses of $+0.875 \text{ D}$ to their normal correction for infinity. This correction is hereafter referred to as the "no astigmatism" condition. For the other conditions, astigmatism was induced in each eye by the addition of a cylindrical lens of $+2 \text{ D}$. The astigmatism was induced at various meridians by orienting the cylinder axes at 90, 135, and 180 degrees, for use with the sine waves. Only the extreme conditions of no astigmatism

and a cylinder axis of 090 degrees were employed with the square waves.

Five levels of modulation were selected for each spatial frequency to range from zero to an easily perceptible grating. Each level was presented twice in a given session. All five levels at all five spatial frequencies were combined and randomized for a total of 50 judgments per session. The subject's task on each presentation was simply to state whether or not stripes were perceived. There were no temporal constraints; the stimulus continued to be visible until the subject responded. Two sessions were run for each condition of astigmatism so that final limens for each spatial frequency were based upon 20 judgments.

RESULTS

The mean data for the four subjects viewing sinusoidal gratings are given in Fig. 1.

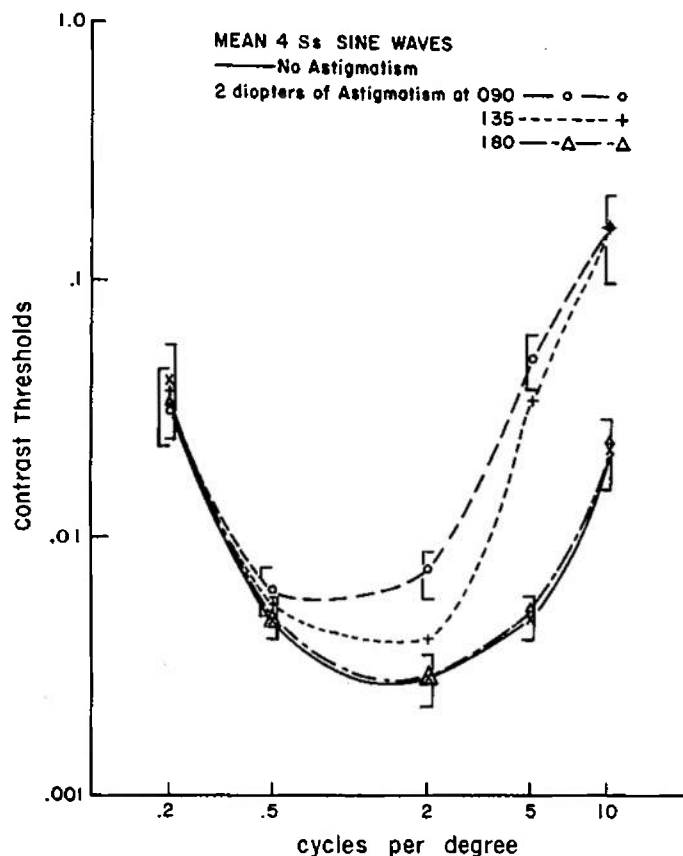


FIG. 1. Contrast thresholds for sine-wave gratings with subjects fully corrected or with 2 D of astigmatism at different meridians. The numbers refer to the axis of the cylinders. Mean of four subjects, with vertical bars indicating ± 1 SD for no astigmatism (○) and for astigmatism axis 90 degrees (○).

The shapes of the curves for all four individuals were the same, as were the differential effects of the axis of astigmatism. When fully corrected, contrast thresholds for all subjects are best at 2 cpd and rise rapidly in either direction; the curve is in agreement with many in the literature for these experimental conditions.⁵⁻⁷ With the 2 D cylinder at an axis of 180 degrees (that is, with the power meridian parallel to the orientation of the stripes), there is no change in contrast thresholds at any spatial frequency. With the cylinder at an axis of 90 degrees, thresholds for low spatial frequencies are unaffected whereas those for high spatial frequencies are poorer by almost a log unit. With an intermediate orientation of the stripes, the loss of sensitivity is intermediate.

The vertical bars show $\pm$ one standard deviation around the means for the no astigmatism and the axis 90-degree astigmatism conditions; there is complete overlap of standard deviations at the low spatial frequencies and none at high. Standard deviations for the other conditions, not shown to simplify the figure, were of comparable size.

Comparable data for the same four subjects, for square waves, are shown in Fig. 2 for the emmetropic condition and the worst orientation of induced astigmatism. For the astigmatic condition, contrast thresholds at frequencies of 2 cpd and higher are considerably poorer, whereas there is virtually no difference at 0.5 cpd; these results are thus comparable to those for sine waves. However, at 0.2 cpd, there is an apparent change: in contrast with the data for sine waves, astigmatism has produced a reduction in sensitivity resulting in a higher threshold for this low spatial frequency. The standard deviations around the means at 0.2 cpd barely overlap.

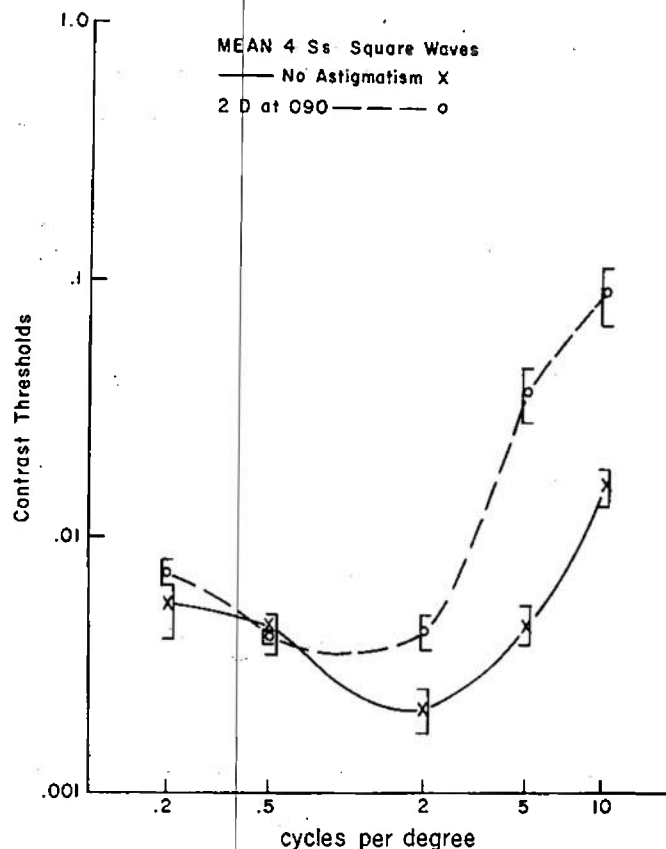


FIG. 2. Contrast thresholds for square waves for the same four subjects, either corrected or with 2 D of astigmatism at axis 90 degrees. Vertical bars are $\pm$ 1 SD.

This difference is further illustrated in Fig. 3 which shows the ratio of square wave to sine-wave sensitivity for individual subjects with and without astigmatism. The data are very similar to the original comparison by Campbell and Robson⁸ and do not deviate systematically from the theoretical prediction of 1.27 at frequencies of 0.5 cpd and higher.

At 0.2 cpd, however, there is a large increase in the sensitivity ratio, which averages 7.4 without astigmatism and 4.4 with it. The effect of astigmatism on this sensitivity ratio is much more apparent in the data of some subjects than others. At one extreme, the sensitivity ratio for SML is reduced from 8.8 to 3.7 by 2 D of astigmatism, whereas the comparable decrease for AR is only from 4.5 to 3.9

DISCUSSION

The effects of astigmatism on contrast sensitivity to sine and square waves are, in general, well predicted by theory and in good agreement with the data accumulated over the past 15 years of study of contrast sensitivity. Thus, the fact that astigmatism affects the high spatial frequencies stems from the defocusing of the image and occurs in all optical systems. The amount of deterioration depends, of course, on the amount of blurring. These data on astigmatism fit well, quantitatively, with data in the literature for blurring by spherical lenses. For example, Campbell et al.⁹ report 0.35 log unit at all frequencies above 5 cpd for 0.5 D of blur. Regan's¹⁰ measures show 0.6 log unit for 1 D of defocusing, and these data

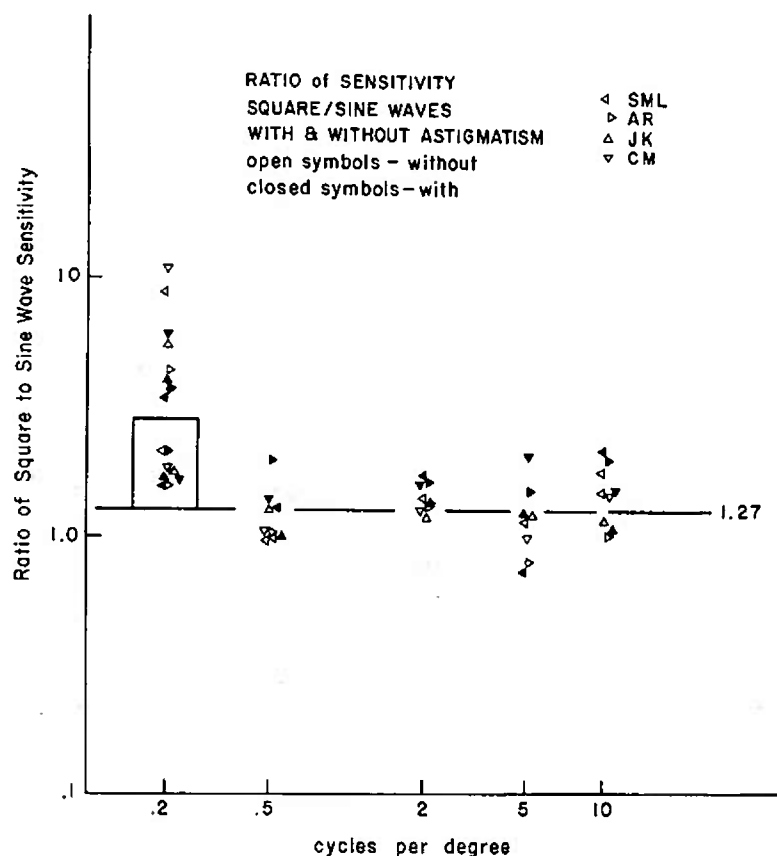


FIG. 3. Ratio of empirical sensitivity of square waves to sine waves for individual subjects. Open symbols refer to the fully corrected condition; closed, to the astigmatic. The ratios in the square are theoretical ratios as described in the text.

reveal a maximum of nearly 1.0 log unit for the 2 D of astigmatism in the worst meridian.

Moreover, the comparison of sensitivity to square waves and sine waves of the same spatial frequency is in general agreement with the original comparison of Campbell and Robson.⁸ With the subjects appropriately corrected, the difference between sensitivity to square waves and sine waves is as predicted from the theory. Thus, at 0.5 cpd and higher spatial frequencies, there are no differences between the two curves other than that of amplitude, and the factor of 1.27 adequately describes the data. This implies that there are no harmonics involved in the sensitivity to square waves, nor should there be any.

At the lowest spatial frequency, 0.2 cpd, however, there is a large increase in square-wave sensitivity over that of sine waves. This increase, an average ratio of 7, is greater than that reported by Campbell and Robson⁸ or by Furchner et al.¹¹ for square waves of 0.25 cpd. A likely explanation is the inclusion of responses by channels sensitive to higher order harmonics in the response to the square wave. Indeed, Fig. 1 shows that many of the higher order harmonics have the necessary sensitivity to be included in the response of square waves at 0.2 cpd^a with the greatest sensitivity shown for the first harmonic at 0.6 cpd. The fact that many higher order harmonics have the requisite sensitivity can be attributed to the specific experimental conditions employed which depress sensitivity to low spatial frequencies. Both the use of a long duration stimulus and a finite target size have this effect.¹²

Theoretical sensitivity to square waves, derived from the theory of probability summation among independent channels,^{13,14} is compared to the empirical data in the box

^a Fourier analysis (Nachmias¹⁵) of a square wave at a given spatial frequency yields 1.27 times the amplitude (A) of the fundamental, f (the sine wave at the same frequency), plus odd-numbered harmonics at regularly decreasing amplitudes: $\frac{1}{3}A(3f) + \frac{1}{5}A(5f) + \frac{1}{7}A(7f)$, etc. Thus, for a given harmonic to be involved in the sensitivity to a specific square wave, the sensitivity to it must be proportionally increased. At 3f for example, sinusoidal sensitivity must be 3 times as great as at f to produce equal contributions.

in Fig. 3. The new ratios in this box were calculated for each individual, using the hypothetical sine-wave response (of $\frac{1}{3}$ the sine-wave sensitivity to 0.6 cpd), either alone or together with $\frac{1}{5}$ the sensitivity to 1.0 cpd) compared to the empirical square-wave data. The ratios for emmetropic vision employ probability summation between channels at 0.6 and 1.0 cpd.^b Since astigmatism reduced the hypothetical sensitivity to 1.0 well below that of 0.6 cpd, for all subjects, only one channel was employed in these ratios.

This procedure eliminates both the large square-sine wave ratios at 0.2 cpd and the differences between the emmetropic and astigmatic conditions. Thus, concrete support is given to both the general theory of probability summation among independent channels and to the suggestion that astigmatism reduces sensitivity to low frequency square waves by removing the contribution of higher order harmonics. Nonetheless, all eight ratios are slightly above the theoretical value of 1.27, implying some additional factor is involved. This result is in general agreement with Furchner et al.¹¹ who found that patterns composed of very low spatial frequencies were more visible than predicted by probability summation.

The practical implications of this study are that astigmatism is detrimental to vision only for small targets (high spatial frequencies) or for the recognition of forms whose frequency composition requires good vision for high spatial frequencies. Thus, the astigmatic individual should see as well as the emmetrope if he is close enough to the target so that it is composed of only low spatial frequencies. This implication has recently been tested and found to be correct in accounting for the vision of astigmatic periscope operators using different amounts of magnification.¹⁷

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^b Quick's method¹⁶ for calculating the effects of probability summation for independent channels was employed to determine the sensitivity predicted from the use of all possible harmonics, but no further increase was obtained.

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