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Phenomenological Description of Local Extremes on Contrast Sensitivity Curves

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Previous studies have demonstrated that human contrast sensitivity curves have marked extremes [4]. This phenomenon has not yet been investigated. The present report describes studies of plots of frequency-contrast characteristics obtained using gratings with orientations of 0°, 90°, and 135°. The results showed that: 1) periodically located extremes were marked on the averaged curve obtained using gratings with an orientation of 0°, while use of gratings with orientations of 90° and 135° gave weak peaks; 2) on repeat testing, the amplitudes of extremes decreased sharply, to the level of disappearance by day 5 of testing. These data lead to the suggestion that the phenomenon of local extremes is not associated with random errors by the subjects but reflects the specific characteristics of information processing by the visual system.

KEY WORDS: contrast sensitivity curves, Fourier spectra.

Classical human visual system contrast sensitivity curves in the form in which they are usually presented in textbooks (Fig. 1, *A*) have a smooth, bell-like shape [2, 9]. However, more detailed analysis using larger numbers of optotypes has demonstrated periodically located extremes over the greater part of the curve (Fig. 1, *B*). This led to the suggestion that these local changes are not due to random errors by the subjects or methodological artifacts, but represent a phenomenon reflecting the ordered organization of the visual system [4]. However, the small number of subjects ($n = 2$) and some methodological features imposed restrictions on the interpretation of the results. At the same time, this is the only study we identified addressing local changes in contrast sensitivity.

In daily life, such variations in contrast sensitivity cannot influence perception. However, in threshold observation conditions (thick fog, turbid water, twilight), they can lead to degradation of the perception of individual objects of particular sizes. This shows the need for detailed study of this phenomenon. The aim of the present work was to describe the main features of local extremes of contrast sensitivity curves, using a representative sample set.

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METHODS

Visocontrastometry. Contrast sensitivity was measured using a programmable instrument including a personal computer with a high-resolution cathode ray tube monitor running the Ergotest 2.0 program, written at the I. P. Pavlov Institute of Physiology. Subjects were presented with stimuli using 15 sinusoidal gratings of different spatial frequencies – from 0.08 to 5.80 cycles per degree of the observer's visual field. One of the test stimuli is shown in Fig. 1, *C*. One of the 15 gratings is shown on the monitor at the beginning of presentation, when it had maximal contrast. The spatial frequency (number of pairs of light and dark bands per degree of the observer's visual field) of this grating was 1.66 cycles/degree. Its spatial orientation (the orientation of an imaginary line whose brightness changed in a strictly sinusoidal manner) was 0° (or 180°).

Gratings were presented in random order at a distance of 160 cm. The contrast of each grid ranged from 0 to 1 on a logarithmic scale. The subject's task was to press a mouse button at the moment at which he ceased to see the stimulus and release the button at the moment at which it was detected. Groups of three responses to each stimulus were averaged. Measurement results provided the frequency-contrast characteristic, i.e., the inverse of the threshold con-

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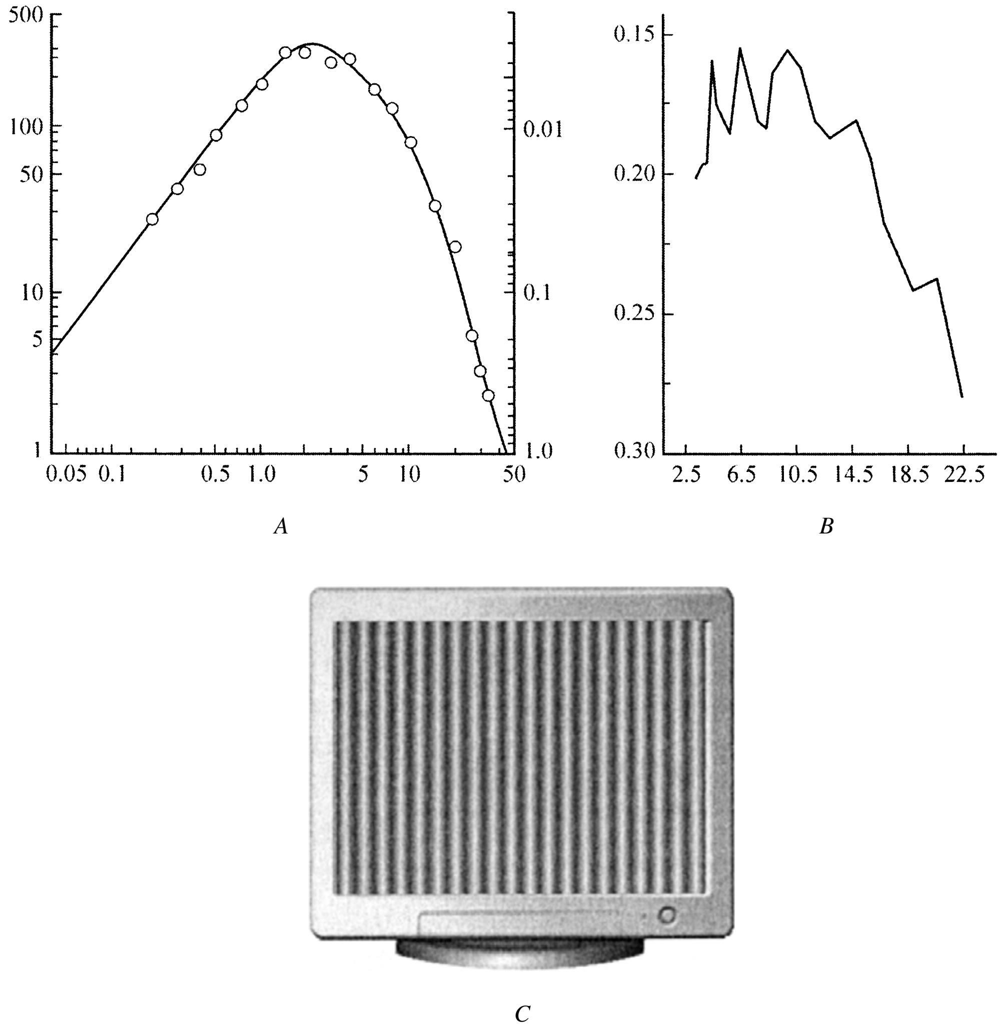


Fig. 1. Contrast sensitivity curves. *A*) Classical human contrast sensitivity curve [9]. The abscissa shows spatial frequency, cycles/degree; the left-hand ordinate shows contrast sensitivity, units; the right-hand ordinate shows test stimulus threshold contrast, units; *B*) averaged contrast sensitivity curve for two subjects at high resolution (the curves were not averaged in the original) [4]. The abscissa shows spatial frequency, cycles/degree; the ordinate shows threshold contrast, units; *C*) stimulation apparatus used for measurement of contrast sensitivity using the Ergotest method.

trast at which the stimulus was detected and the spatial frequency of the Gabor elements.

RESULTS

Three groups of subjects (n = 67) took part in the study; each subject was a member of only one group. Subjects of group 1 (n = 36) were presented with vertically oriented gratings, those of group 2 (n = 18) with horizontally oriented gratings, and those of group 3 (n = 13) with diagonally oriented gratings.

In group 1, local changes in contrast sensitivity differing in terms of depth (amplitude) and spatial frequency were seen in all subjects. These were also clearly visible in contrast sensitivity curves plotted for the mean values obtained from all subjects in the group (Fig. 2, *A*). This supports the hypothesis that the positions of peaks on the curve in most subjects are not random. Maxima were seen at the following spatial frequencies: 1.24, 2.49, 3.73, and 4.56 cycles/degree; the mean distance between maxima was 1.11 cycles. Minima were seen at the frequencies: 1.66, 3.31, 4.14, and 5.39 cycles/degree; the mean distance between them was 1.24 cycles. The mean distance between extremes was 0.59 cycles, i.e., close to the resolving ability of the method (the distance between experimental points), which was 0.41 cycles. Thus, if the number of experimental points had been 1.5 times fewer, most of the extremes would not have been detected.

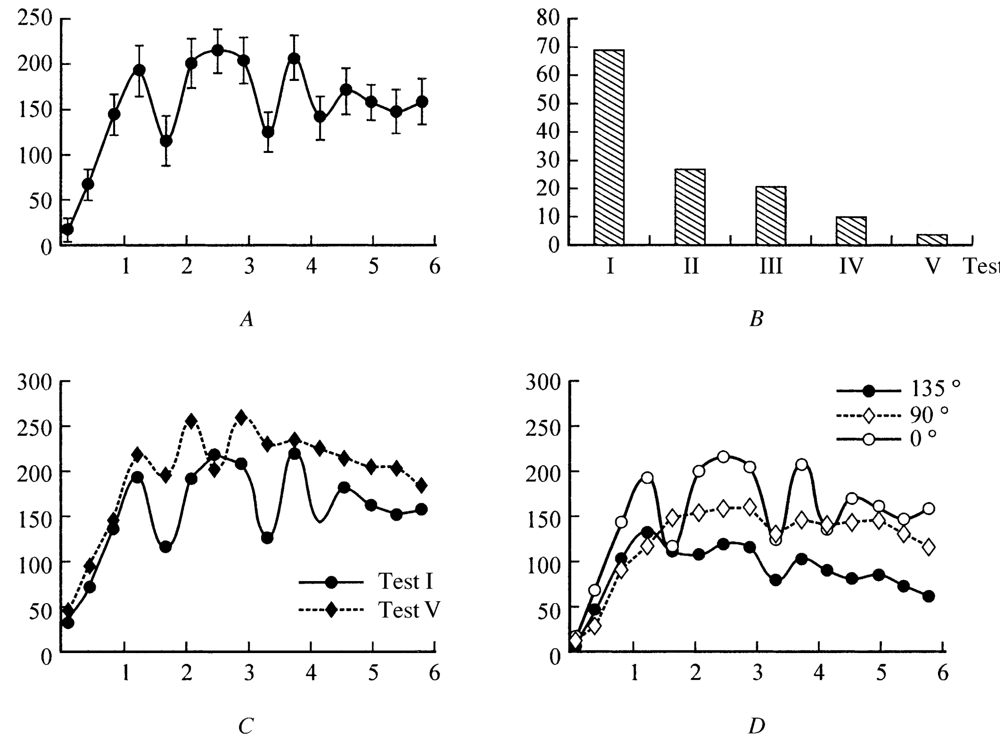


Fig. 2. Results from the first study. *A*) Averaged contrast sensitivity curves for 36 subjects. The abscissa shows spatial frequency, cycles/degree; the ordinate shows contrast sensitivity, units. The vertical bars show significant intervals at a significance level of 95%; *B*) changes in the mean heights of local extremes on repeat measurements; *C*) contrast sensitivity curves for the first and fifth tests. The abscissa shows spatial frequency, cycles/degree; the ordinate shows contrast sensitivity, units; *D*) contrast sensitivity curves obtained using gratings with different spatial orientations (0°, 90°, and 135°). The abscissa shows spatial frequency, cycles/degree; the ordinate shows contrast sensitivity, units.

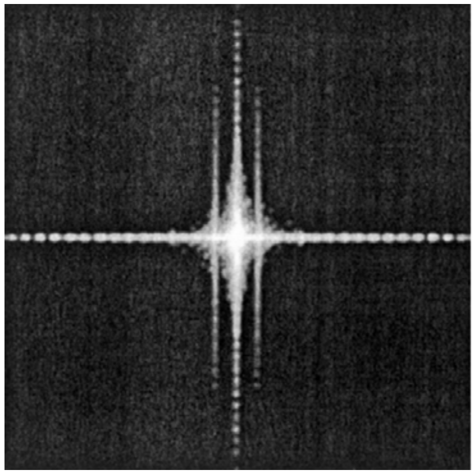
Four repeat tests were performed in 12 of the subjects in this group, with four-day intervals. In these experiments, the mean height of the extremes (mean difference in contrast sensitivity between maxima and minima) decreased sharply to the point of disappearing (Fig. 2, *B*, *C*), mainly because of increases in sensitivity in those ranges at which minima were present on first testing (Fig. 2, *C*). This indicates that the oscillating shape of the curve was initially due more to decreases than to increases in contrast sensitivity in individual spatial frequency ranges.

In group 2, measurements also revealed marked contrast sensitivity extremes in all subjects. However, the oscillations were very weak on the averaged plot (Fig. 2, *D*), because of significant variability in their positions on the curves for each individual subject. A similar result was obtained in group 3.

DISCUSSION

It is difficult to compare the results obtained here with results reported in [4] both because of the reasons identified in the Introduction and because of a number of methodological differences. Stimuli in the present study were presented using a computer monitor, while Evseev et al. [4] used an oscilloscope and an atlas containing photographs of gratings. Furthermore, the resolution of our method was almost twice as high as that used by Evseev et al. Nonetheless, it is possible to draw conclusions based on generalization of these different investigations. Comparison of the plots in Fig. 1, *A*, *B* and Fig. 2, *A* clearly shows that Evseev et al. studied the right-hand (descending) part of the contrast sensitivity curve, while our study addressed the left-hand (ascending) part. Local extremes were seen in both cases, which means that this phenomenon is present throughout the contrast sensitivity curve with the exception of the lowest frequencies.

Thus, local extremes did not result from random errors by the subjects; the positions of the extremes showed a clearly periodic character. But what is their cause? The authors are not inclined to conflate questions of phenomenology and etiology – the errors of this approach were demonstrated in the 1960s [1]. Nonetheless, an attempt to answer the purely phenomenological question of whether



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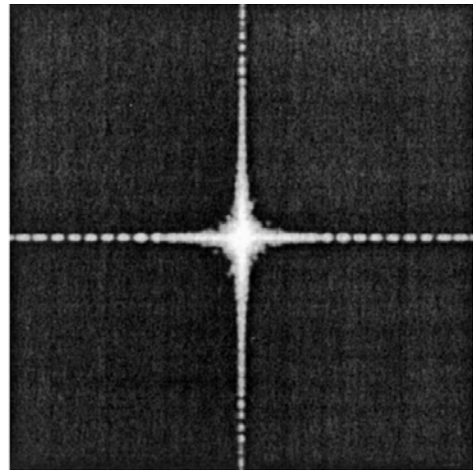

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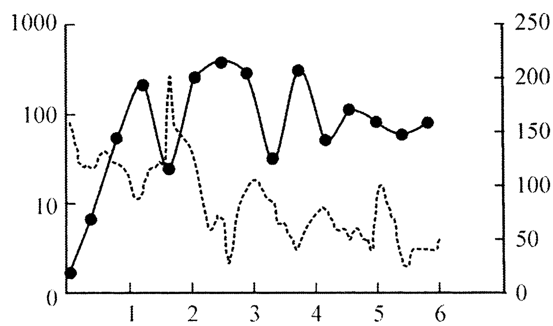

C

Fig. 3. Monitor panels as a possible source of the appearance of local extremes on contrast sensitivity curves. *A*, *B*) Two-dimensional amplitude-frequency Fourier spectra of the image of a monitor with a grating (taken from Fig. 1, *C*) and the same monitor without a grating. For explanation see text; *C*) one-dimensional profile of the spectrum of the monitor with a grating with an orientation of 0°. The abscissa shows spatial frequency, cycles/degree; the ordinate shows amplitude, units. The contrast sensitivity curve from Fig. 2, *A* is shown for comparison (right-hand ordinate, units).

the phenomenon observed is a methodological artifact leads to the need to discuss some aspects of its etiology.

The observed fact of a decrease in the amplitudes of local extremes on repeat testing, to the level of complete disappearance of extremes (Fig. 2, *B*, *C*), points to a qualitative difference in contrast sensitivity at spatial frequencies corresponding to local minima and maxima. Smoothing of the curve on repeated measurements occurred because of a nonuniform increase in contrast sensitivity in the areas of extremes, which was more marked at minima than at maxima.

Evseev et al. explained local extremes in terms of the existence of discrete visual spatial frequency channels. From this point of view, local maxima on the contrast sensitivity curve are seen at the frequencies corresponding to the optimum tuning of these filters. Sensitivity minima are seen at the spatial frequencies at the margins of the tunings of two neighboring filters and are beyond their optima [4].

This hypothesis cannot be accepted, because it contradicts both factual evidence and the concept of discrete spatial frequency channels. Firstly, as noted by Evseev et al., the distances between the extremes reported by them were three times smaller than the bandpass range of the individual spatial frequency channel measured in [10]. In our study, the distances between extremes were two times smaller than those reported in [4]. That is, the distances between extremes on contrast sensitivity curves were almost six times smaller than the widths of the hypothetical spatial frequency channels. Secondly, the channels concept cannot explain the fact of the absence of marked extremes on contrast sensitivity curves obtained using gratings in different orientations (Fig. 2, *D*). The anisotropy of contrast sensitivity has long been known. Contrast sensitivity is greater for horizontal and vertical than for diagonal orientations. This anisotropy is not associated with astigmatism and probably corresponds to the spectra of natural visual scenes [7]. However, in this case, anisotropy is fundamentally different in nature.

We will attempt to address the problem of the etiology of the phenomenon observed here using empirical generalizations. There is some factor which leads to the appearance of local extremes, because of the selective suppression of contrast sensitivity at particular spatial frequencies. Whatever it is, its influence can be described formally as the action of visual noise (interference) with a characteristic spatial frequency spectrum. A spatial frequency "portrait" of this noise can be constructed using the data obtained. The positions of maxima in its spectrum must be periodic, coinciding with the positions of minima on the contrast sensitivity curve. Furthermore, this noise is characterized by orientational anisotropy, i.e., the maxima in its spectrum are more marked in the horizontal orientation than in the diagonal or vertical orientations.

Finally, this spatial frequency "portrait" cannot yield a definitive spatial picture of the interference of interest. A multitude of different patterns can be synthesized whose spectra will resemble that of the "portrait." Nonetheless, one external factor can be identified for which the spectral similarity compared with the "portrait" is very significant. On testing, the subject's visual field contains, along with the stimuli themselves, other objects, which can be regarded as potential background noise. The background immediately surrounding the stimulus is the major item in the overall noise background. This is the monitor panel.

Figure 3, *A* shows the amplitude Fourier spectrum of a stylized image of the monitor (Fig. 1, *D*). The adjacent panel, Fig. 3, *B*, shows the spectrum of the image of this same monitor, but with the screen blank (without a grating). The spectra were obtained using a program written at the Vavilov State Optical Institute [11]. The spectra are presented in polar coordinates, i.e., the coordinate origin is located at the center. Each point on the spectrum corresponds to an individual Fourier component (Fourier components are the same gratings as used in visocontrastometry) and its spatial frequency is defined by the distance from the center, its contrast by its brightness, and its orientation by the angle relative to the coordinate origin. The spectra show a range of spatial frequencies (allowing for the distance of the subjects to the monitor during contrast sensitivity measurements) from 0.07 to 18.40 cycles/degree.

A characteristic feature evident on both spectra is the anisotropic distributions of amplitude in different orientations. In the horizontal orientation (0° and 180°) changes in amplitude with increases in spatial frequency were periodic. In the vertical orientation (90° and 270°), there was virtually no periodicity. This is because the left- and right-hand panels of the monitor (unlike the upper and lower) were of identical width. The Fourier components corresponding to each panel for a periodic spectral profile in the corresponding orientation and the differences in the upper and lower panels cause the amplitudes in the vertical orientation to lose this periodicity. As regards the diagonal orientation, amplitude in this case was very low, as the image of the monitor contained little in the way of diagonally oriented elements.

In Fig. 3, *C*, the horizontal profile of part of the spectrum of the image of the monitor is compared with the contrast sensitivity curve in Fig. 2, *A*. It is clear that the spatial frequencies of the maxima on this profile coincide with the spatial frequencies of the minima on the contrast sensitivity curve. Ultimately, this coincidence may be random, as the stylized image of the monitor is notably different from the design of the Sony Trinitron monitor used for presenting gratings in the study. However, the ability of monitors to influence the performance of various visual tasks has long been known. For example, the effects of display parameters such as screen brightness and angular size on the shape of the contrast sensitivity curve were described as long ago as the late 1970s [5]. However, the possible role of the monitor panel in producing local extremes on contrast sensitivity curves needs to be verified experimentally. At present, we can only say that there is a lack of factual evidence to contradict this hypothesis. The studies of Evseev et al. did not use a monitor; local extremes were detected both on curves constructed on presentation of gratings from an oscilloscope and on curves obtained by presentation of photographic images of gratings from an atlas. However, in the former case, the oscilloscope panel provides a source of interference, while the "field" of the atlas provides a source in the latter case.

In any case, even if this hypothesis is correct, there are no grounds to accept that the phenomenon of local extremes in contrast sensitivity is a purely methodological artifact. The monitor panels and screen are spatially separated, such that the panels cannot create interference for perception in the spatial area. They can only provide interference for the perception of gratings if "translated" from the "spatial" language to the "spatial frequency" language. And if the visual system uses spatial frequency analysis (this possibility has been discussed throughout the second half of the 20th century [2, 3, 6, 10, 12]), then the factor inducing the phenomenon of local extremes should be regarded as being not only the monitor panels, but also the specific features of information processing in the visual system.

Finally, the phenomenological description of local extremes in contrast sensitivity cannot be regarded as complete. It remains unknown whether this phenomenon occurs in natural perception conditions. There is also the need to assign a name, which cannot yet be done because its position among other known visual perception phenomena has not been identified. There is insufficient material for empirical generalization. One of our future reports will therefore provide a description of another phenomenon which, of the currently known visual perception phenomena, has the properties closest to that of local extremes in contrast sensitivity. As regards visual noise leading to the appearance of local extremes on the contrast sensitivity curve, other hypotheses as to what this noise could be will be presented in future reports.

REFERENCES

1. K. Belchugétsyanu, "Some questions on the classification and nomenclature of nervous diseases," *Zh. Nevropatol. Psikhiatr. im. S. S. Korsakova*, **63**, No. 6, 898–903 (1963).
2. V. M. Bondarko, M. V. Danilova, N. N. Krasil'nikov, L. I. Leushina, A. A. Nevskaya, and Yu. E. Shelepin, *Spatial Vision* [in Russian], Nauka, St. Petersburg (1999).
3. K. N. Dudkin, *Visual Perception and Memory* [in Russian], Nauka, Leningrad (1985).
4. E. A. Evseev, N. N. Pavlov, Yu. E. Shelepin, and V. D. Glukhovskii, "Automated evaluation of the periodicity of the contrast sensitivity of the eye," in: *Questions of Automation and Simulation of Psychophysiological Studies in Civil Aviation*, Moscow (1987), No. 266, pp. 81–90.
5. B. Klei, "Two-dimensional displays," in: *Optical Holography* [Russian translation], Mir, Moscow (1982), Vol. 2, pp. 452–485.
6. A. V. Merkul'ev, "Possible causes of failures of scientific studies in the development of machine vision systems," in: *Proceedings of the Jubilee Scientific-Applied Conference Celebrating the 30-th Anniversary of the 15th Central Normative Research Laboratory of the Navy* [in Russian], St. Petersburg (2007), pp. 197–206.
7. I. I. Tsukkerman, "Statistical structure of images and characteristics of visual perception," in: *Proceedings of the IV Symposium on the Physiology of Sensory Systems 'Information Processing in the Visual System'* [in Russian], Leningrad (1976), pp. 213–215.
8. Yu. E. Shelepin, L. N. Kolesnikova, and Yu. I. Levkovich, *Visocontrastometry (Measurement of Modulatory Transfer Functions)* [in Russian], Nauka, Leningrad (1985).
9. F. W. Campbell, "How much of information falling on the retina reaches the visual cortex and how much is stored in the visual memory?" in: *Pattern Recognition Mechanisms*, Springer, Berlin (1985), pp. 83–85.
10. F. W. Campbell and J. Robson, "Application of Fourier analysis to the visibility of gratings," *J. Physiol.*, **197**, No. 3, 551–561 (1968).
11. V. B. Makulov and V. N. Pauk, "Software for image processing on personal computers," *J. Optical Engineering*, **31**, No. 4, 782–788 (1992).
12. A. L. Ochs, "Is Fourier analysis performed by the visual system or by the visual investigator?" *J. Opt. Soc. Amer.*, **69**, No. 1, 95–98 (1979).