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IMAGES AND AFTERIMAGES OF SINUSOIDAL GRATINGS

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Abstract—To measure the contrast sensitivity function for afterimages, sinusoidal gratings of various contrasts and spatial frequencies were presented briefly to observers, who were asked to report the presence or absence of a primary image, a positive afterimage, and a negative afterimage. It proved possible for subjects consistently to distinguish between primary images and positive afterimages, suggesting that stimulus offset is signalled independently of perceived structure. At low spatial frequencies, negative afterimages were more detectable than positive afterimages, whereas at higher spatial frequencies, the reverse was true. This suggests that positive and negative afterimages are mediated by neural channels with different spatial characteristics.

INTRODUCTION

Psychophysical curves describing the contrast sensitivity of the visual system as a function of the spatial frequency of sinusoidal gratings are known as describing, or modulation-transfer functions (MTFs). MTFs have been measured under a variety of conditions, many of which differentially affect their shape (Patel, 1966; Robson, 1966; Kelly, 1969; Corwin, 1971). In particular, stimulus duration influences MTF shape under certain conditions, particularly at low spatial frequencies. On the basis of a series of stabilized-image experiments, Koenderink (1972) has suggested that contrast sensitivity is jointly determined by a summation of the positive and negative afterimages of a stimulus target. This hypothesis could account for differences in MTF shapes as a function of stimulus duration, since for continuously presented targets, positive and negative afterimages are both present simultaneously and hence capable of interacting, whereas for flashed targets the negative afterimage appears only after stimulus offset, thereby reducing the opportunity for interaction.

Recently, Ditchburn and Drysdale (1973) measured the contrast thresholds of afterimages of square-wave gratings of various spatial frequencies, presented as very brief (1 msec), intense flashes. Targets of various contrasts were presented, and subjects were asked to report the presence of positive and negative afterimages. MTFs were obtained for the two types of afterimage, and were compared in shape to MTFs measured under conventional steady-state conditions. All three curves had similar shapes, with peak sensitivities occurring at approx 5 c/deg. At all spatial frequencies, more contrast was required to detect a negative afterimage than to detect a positive afterimage. Steady-state contrast thresholds were lower than those of either afterimage. Both of these findings contradict the hypothesis that the shape of the conventionally measured MTF is significantly affected by the presence of stimulus afterimages. First, if all three curves have the same shapes and peak sensitivities, any linear combination of them will also. Second, if the visual system is more sensitive to the primary image of a grating than to its afterimages, then detection will presumably be based on the primary image rather than the relatively weaker afterimages.

Thus, Ditchburn and Drysdale show no evidence that afterimages play a role in determining the shape of the MTF as conventionally measured. One reason for this failure may be that subjects in their experiments were not asked to respond differentially to primary images and positive afterimages.

However, if the primary image of a stimulus flash is in fact distinguishable from the positive afterimage of that stimulus, it becomes possible to measure the relative contribution of each to conventionally measured contrast sensitivity functions. The purpose of the present study, therefore, was to design an experiment to separate the components of the MTF. This involved measurement of afterimage responses, using flashes of moderate average luminance and purely sinusoidal gratings, the Fourier spectra of which are not contaminated by harmonic components.

METHODS

Apparatus

Stimuli were presented by an Iconix 4-channel tachistoscope (Model 6137) controlled by a solid-state preset counter-timer (Model 6255).

Stimuli

Stimulus gratings were achromatic patterns varying sinusoidally in average reflectance horizontally, and of constant average reflectance vertically. Thus, to the subjects the gratings appeared as vertical striations. The stimuli subtended $8 \times 7°$ of visual angle from the subject's viewing distance of 1 m; viewing was binocular. The patterns were computer-generated "dot plots", composed of a rectangular array of approx 7,200,000 dense black dots (diameter = 0·4 mm) drawn by a Calcomp x–y plotter. Each dot

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subtended 1·5′ of arc at the viewer's eye, and under the present experimental conditions the gratings were not noticeably grainy. Dot density was modulated sinusoidally under program control. This technique has the advantage of producing accurately linear sinusoids of uniform contrast. A total of 25 gratings were produced; five spatial frequencies (0·33, 0·67, 1·33, 3·33 and 6·67 c/deg) at each of five physical contrasts (5, 10, 20, 40 and 100%). All gratings had an equal overall density of approx 50%.

Subjects

Two subjects were used. Both were well-practiced psychophysical observers with normal uncorrected visual acuity. One subject (LCV) was aware of the rationale of the study, but the other (VG) was not.

PROCEDURE

Each experimental session was preceded by 5 min of adaptation to a homogeneous white field. Following this adaptation period, stimulus presentations began, initiated by the subject using a hand-held microswitch. Switch closure caused the adaptation field to be replaced for 100 msec by a test grating of equal area and mean luminance. The adaptation field reappeared immediately after each trial. Both test and adaptation fields were matched for mean luminance of 58 cd/m^2. Fields were calibrated with a Spectra brightness spotmeter (Model 1505 UB). Each of the 25 target gratings was shown, in random order, five times in an experimental session lasting approx 1 hr. An inter-stimulus interval of at least 15 sec separated each trial. Each subject participated in five sessions, producing a total of 25 responses to each target.

On each trial, subjects were asked to report on three aspects of stimulus appearance: (1) the presence of structure during stimulus presentation (primary image), (2) the presence of structure perceived as persisting after stimulus termination (positive afterimage), and (3) the presence of structure reappearing after a period of no perceived structure (negative afterimage). Thus, three yes/no responses were required after each trial.

Subjects were familarized with the range of stimulus frequencies and contrasts to be used in an initial practice session. They expressed no difficulty in understanding and complying with the response instructions. At the luminance level used, no afterimage was reported to persist more than approx 1 sec after stimulus termination, so that the 15 sec inter-trial interval was sufficiently long to ensure negligible interaction between consecutive stimulus presentations.

RESULTS

In reporting perceived events in the stimulus the agreement between subjects' responses was in general close, and was within the limits of experimental error. For stimuli of relatively high spatial frequency, subjects were reliably able to report the presence of negative afterimages despite the fact that they were not able to perceive contrast phase-reversal (although at low spatial frequencies the phase-reversal characteristic of negative afterimages was apparent).

This was possible because a clear indication of the separation between positive and negative afterimages is obtained from the blank period occurring between them. Obviously, for the contrast to reverse it has to pass through zero, and the subjects could readily detect that the perceived grating faded to zero and then reappeared in the form of the negative afterimage.

Of particular interest is the apparent ease with which subjects could respond differentially to the primary image and the positive afterimage of the briefly presented grating. For all spatial frequencies, detection of the primary image occurred at lower contrast than that required to detect either afterimage.

Contrast thresholds for primary images fell below 10% contrast, except at the highest spatial frequency. On the other hand, none of the 5% contrast targets yielded a detectable image. Consequently, it was not possible to determine with any degree of accuracy the overall shape of the MTF for primary images, because the contrast increments were not sufficiently fine in the set of stimulus gratings available. Contrast thresholds for positive and negative afterimages were obtained by interpolation from frequency-of-detection curves plotted as direct functions of stimulus contrast. Examples of such curves for two spatial frequencies are shown in Fig. 1. The upper pair of graphs shows the results for each observer for targets of low spatial frequency, and the lower pair of graphs show corresponding data for targets of high spatial frequency. In no case was an afterimage more readily detected than a corresponding primary image. On the other hand, the relative detectability of the two types of afterimage reversed as a function of spatial frequency. This result is illustrated in Fig. 2, which shows MTFs derived from the detection curves exemplified in Fig. 1. The points in Fig. 2 are the data

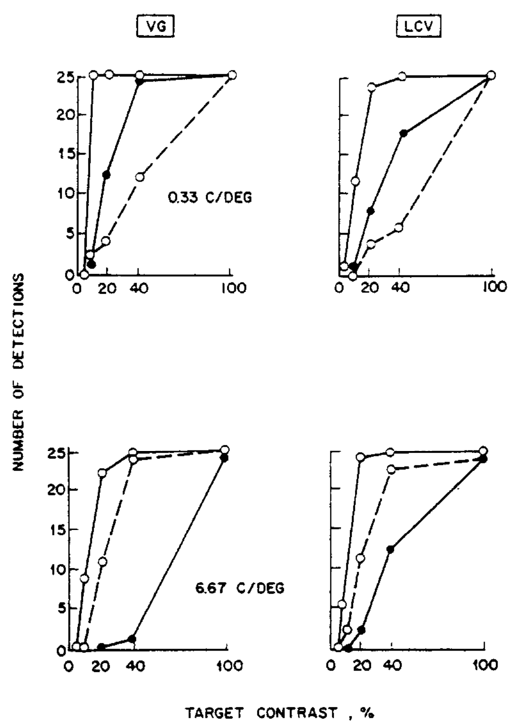

Fig. 1. Frequency-of-seeing curves based on 25 target presentations at each of five contrasts. Data show number of detections of primary images (solid lines and open circles), positive afterimages (dashed lines and open circles), and negative afterimages (full lines and filled circles). Top pair of graphs is for 0·33 c/deg grating target, bottom pair is for 6·67 c/deg target. Pair of graphs at left are of observer VG; graphs at right are data of observer LCV.

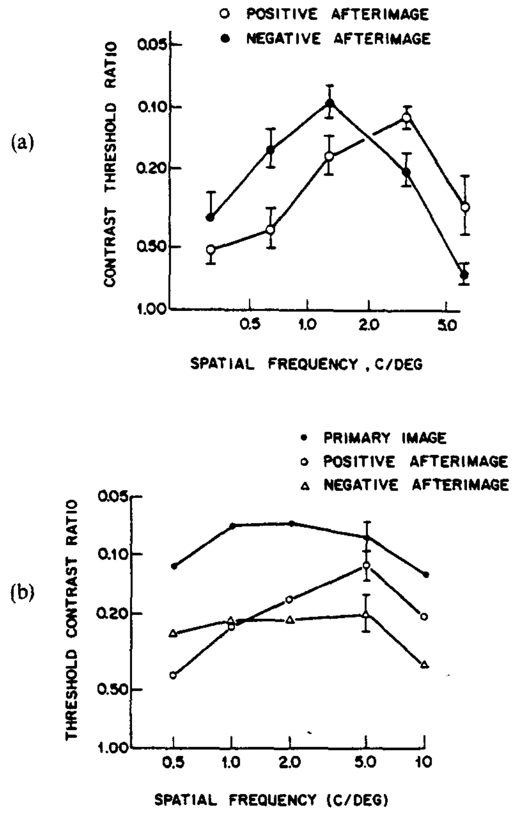

Fig. 2. (a) Contrast sensitivity functions at 100 msec for positive afterimages (open circles) and negative afterimages (filled circles) for observer VG derived from psychometric functions illustrated in Fig. 1. The method was not sufficiently sensitive to determine the form of the primary image function for this subject. Threshold values and standard deviations are based on a least-squares linear fit to each relative frequency-of-seeing curve. Standard deviations for each point derived as described in text. (b) Similar data for observer LCV, showing sensitivity for the primary image (solid points), the positive afterimage (open circles) and the negative afterimage (triangles). The mean standard deviation for each type of image is shown.

for observer VG; the other observer's data are essentially the same. Contrast sensitivity is defined as the reciprocal of stimulus contrast yielding a 50% frequency of detection, and is plotted as a function of spatial frequency on double logarithmic coordinates. Standard deviations of the thresholds, indicated by crossbars in Fig. 2, were determined by finding the contrasts corresponding to the 16 and 84% points on individual relative-frequency-of-seeing curves, based on a least-squares linear fit to each set of data points plotted on probability coordinates.

Three relationships of interest are apparent from Fig. 2. (1) Negative afterimages are relatively more detectable than positive afterimages at low spatial frequencies, whereas the converse is true at higher spatial frequencies; (2) negative afterimages have a shallower low-frequency falloff than positive afterimages; and (3) negative afterimages have a steeper high-frequency falloff than positive afterimages. These three relationships hold true for both subjects.

DISCUSSION

A surprising result was that subjects were able to distinguish the primary image of a briefly presented grating from its positive afterimage. How were they able to do so? At first sight it is not easy to identify the basis for such a discrimination, since both the primary image and the positive afterimage have the same spatial structure. A discrimination would be possible, however, if subjects were able to detect spatial structure and stimulus offset independently. This capability would allow them to respond differentially to perceived structure occurring before and after stimulus offset, which could be the case if the temporal and spatial aspects of a visual stimulus were processed by parallel neural mechanisms. It is, of course, also possible that there is a perceived structural change (such as a sudden loss of contrast) which serves as an unambiguous signal to the observer that the primary image of a flashed stimulus has been replaced by a positive afterimage.

Figure 2 shows that positive and negative afterimages have distinctly different MTF shapes. Under the assumptions of linear systems analysis, these shapes reflect underlying spatial-organization mechanisms in the visual system (Ratliff, 1965). By performing an inverse Fourier transform of the MTF, a "spatial weighting function" is obtained, the form of which is characteristic of visual receptive fields. For MTFs with non-monotonic shapes, the spatial weighting function is characterized by a central region of spatial summation flanked by a region of spatial inhibition, analogous to the well-known antagonistically organized center/surround neural receptive field. The excitatory area of the spatial weighting function is inversely related to the slope of the high-frequency falloff of the MTF. Similarly, the inhibitory area is inversely related to the slope of the low-frequency falloff (see Ratliff, *op. cit.*, p. 157). Figure 2 therefore suggests that positive and negative afterimages are detected by sets of antagonistically organized neural receptive fields of differing spatial configurations. Possibly the two sets are characterized by the nature of their transient responses, one being of the on-center/off-surround variety, and the other being of the off-center/on-surround variety. In any case, the analysis leads to the conclusion that cells which generate positive afterimages have narrow excitatory centers and wide inhibitory surrounds, compared to cells generating negative afterimages, which have wider centers and narrower surrounds. This organization may occur only transiently after each stimulus presentation. Koenderinck (1972), in measuring the MTFs of afterimages, found that negative afterimages have a steeper high-frequency falloff than positive afterimages. This is in agreement with the present results, and is reasonable in view of qualitative observations that the negative afterimage of a target is more "blurred" than its corresponding positive afterimage. An alternative interpretation of the different organizations underlying the two afterimage functions is that they are mediated by cones and rods, respectively. This hypothesis can be tested by observing the afterimages to colored stimulus presentation. If the rods are responsible for the second afterimage, it should appear entirely colorless. The test was performed by inserting a long-wavelength gelatin filter in front of the test grating, and

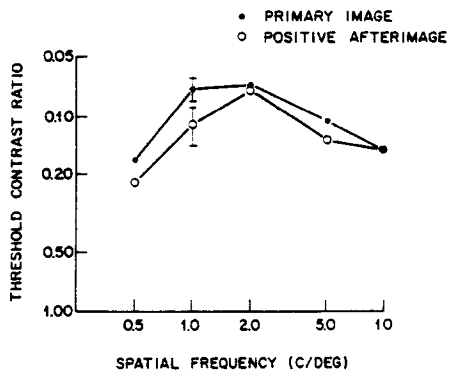

Fig. 3. Contrast sensitivity functions for the primary image and positive afterimage to a 50-msec presentation for subject LCV. No negative afterimage was visible in this condition.

adjusting the blank-field luminance level to equal brightness. Both the positive and negative afterimages appeared strongly pink in color at a range of spatial frequencies. The rod system therefore cannot be producing the negative afterimage. It is also unlikely that the rod system is operative at all at the photopic levels of illumination used in this study.

On the other hand, the low frequency portions of Fig. 2 do not agree with the data of either Koenderink (who found no low-frequency falloff for either afterimage) or of Ditchburn and Drysdale (1973) (who found approximately equal low-frequency falloffs for both types of afterimage). In the latter study, it is likely that the use of a very brief stimulus flash accounts for the discrepancy.

Evidence in favor of this interpretation was obtained by repeating the contrast sensitivity measurements represented in Fig. 2 for observer LCV, using a shorter 50 msec stimulus instead of the original 100 msec target presentation. All other aspects of the experimental situation remained as described earlier, including the mean stimulus luminance (58 cd/m^2). The replication of the 100 msec condition confirmed the original observations. Possibly because of the reduced stimulus energy, no negative afterimage was ever reported for the 50 msec presentation. Moreover, there was a sufficiently large number of trials in which no spatial structure was detected to produce a contrast sensitivity curve for primary image detection.

Although the observer was able to comply with the original instructions to report the presence of both a primary image and a positive afterimage, his confidence in these judgments appeared to be reduced. The contrast sensitivity curves for the detection of the primary image and the positive afterimage were essentially parallel, with the afterimage sensitivity curve shifted slightly downward (Fig. 3). The curves thus have the same form as those of Ditchburn and Drysdale. Comparing this result to those of the original experiment suggests that contrast sensitivity for positive afterimages is spuriously elevated at short duration flashes, due to a reduction in the observer's ability to respond differentially to a target and its positive afterimage. For short flashes, transient visual responses to stimulus onset and offset may not be perceptually discriminable events. Consequently, the observer is unable to discriminate between a primary image and a positive afterimage. If this is the case, then the data attributed by Ditchburn and Drysdale to "positive afterimages" may in fact reflect a combined response to a primary image and a positive afterimage as defined in the present study. This could account for the fact that the contrast sensitivity for Ditchburn and Drysdale's "positive afterimages" was always higher than that for their negative afterimages, whereas in the present study, negative afterimages were in fact more detectable than positive afterimages at low spatial frequencies.

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RÉSUMÉ

Pour mesurer la fonction de sensibilité au contraste, on a présenté des réseaux de divers contrastes et diverses fréquences spatiales brièvement aux observateurs, en les demandant d'indiquer la présence soit l'absence d'une image primaire, d'une image rémanente positive et d'une image rémanente négative. Il s'est montré possible aux observateurs de distinguer régulièrement entre les images primaires et les images rémanentes positives, d'où il découle que la fin du stimulus serait signalée indépendamment de la structure perçue. Aux faibles fréquences spatiales, les images rémanentes négatives étaient plus décelables que les images rémanentes positives, soit l'inverse pour les fréquences spatiales plus élevées. Ceci laisse supposer que les images rémanentes positives et négatives seraient amenées par des canaux neuraux avec caractéristiques spatiales différentes.

ZUSAMMENFASSUNG

Zur Bestimmung der Kontrastschwellenfunktion von Nachbildern wurden Versuchspersonen Sinusgitter verschiedenen Kontrastes und unterschiedlicher Ortsfrequenz kurzzeitig dargeboten. Sie hatten die Gegenwart oder Abwesen beit des Primarbildes, sowie des positiven und negativen Nachbildes anzugeben. Es zeigte sich, dass die Versuchspersonen durchweg in der Lage waren, zwischen Primabild und positivem Nachbild zu unterscheiden, was eine von der wahrgenommenen Struktur unabhangige Signalisierung des Reizendes nahlegt. Bei Reizung mit niedrigen Ortsfrequenzen waren negative Nachbilder leichter zu erkennen als positive, während für höhere Ortsfrequenzen das Umgekehrte galt. Dies lasst vermuten, dass positive und negative Nachbilder über neuronale Kanale unterschiedlicher Ortscharakteristik vermittelt werden.

РЕЗЮМЕ

Для измерения функции контрастной чувствительности в случае остаточных изображений кратковременно представлены синусоидальные решетки различного контраста и различной пространственной частоты наблюдателям с просьбой указать присутствие или отсутствие первичного изображения, позитивного остаточного изображения, негативного остаточного изображения. Наблюдателям оказывалось закономерно возможным отличать первичное изображение от позитивного остаточного изображения, откуда следует, что конец стимула сигнализируется независимо от воспринимаемой структуры. При пониженных пространственных частотах негативные остаточные изображения являлись более обнаружимыми нежели позитивные остаточные изображения, тогда как при повышенных пространственных частотах имело место противоположное. Отсюда следует, что позитивные и негативные остаточные изображения посредничаются нервными каналами с различными пространственными свойствами.