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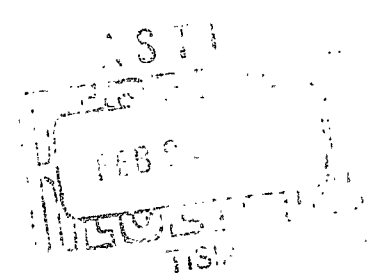
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Spectral Sensitivity of Small Retinal Areas

Contract Number
DA-49-193-MD-2327



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A B S T R A C T

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2. Title of Report: Annual Progress Report on "Spectral Sensitivity for Small Retinal Areas"
3. Principal investigator: John Krauskopf
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Measurements of the image forming properties of the eye in white and monochromatic light are discussed. The results show that the eye forms poorer images than an aberration free lens and that its departure from ideal performance increases with pupil size. Since imagery is no better with monochromatic light than with white light, it is concluded that spherical aberration (or more properly irregular variation in dioptric power over the pupil) is probably the main cause of the departure from ideal performance. The results agree with measurements of visual acuity which show that acuity is not significantly altered by the spectral composition of the stimulus. Experiments with annular as opposed to round pupils are briefly discussed.

Note: Copies of this report are filed with the Armed Services Technical Information Agency, Arlington Hall Station, Arlington 12, Virginia, and may be obtained from that agency by qualified investigators working under Government contract.

This progress report covers work done from August 1, 1962 to December 1, 1962. The principal work done during this period concerns the measurement of the image forming properties of the human eye. In earlier reports similar experiments with white light have been reported;¹ the present work concerns image formation with monochromatic targets.

The apparatus constructed for the experiments is a photoelectric ophthalmoscope. The observer views a vertical transilluminated slit, so that an image of this slit is formed on his retina. The light in the image is diffusely reflected by the retina and some passes out of the eye through the optics of the eye which form a second image in space. This image is in focus in the plane of the target slit, but by the use of a beam splitting pellicle part of the light coming out of the eye is reflected to one side and forms an image in the plane of a second vertical slit, behind which is located a photomultiplier. Before arriving at the second slit the light is reflected by a small mirror mounted on a galvanometer. This mirror is made to rotate back and forth in a saw-toothed fashion about a vertical axis. The image is thus scanned repeatedly over the slit in a linear fashion. The light falling on the sensitive surface of the photomultiplier and thus its electrical output is proportional to the energy distribution in the image in the horizontal direction. Hence, its spatial energy distribution is translated into a temporal voltage distribution.

The levels of the light falling on the multiplier are quite low and the output signal is noisy. To overcome this difficulty, the output for a number of passes through the image are recorded and averaged by the same methods as are used to improve the signal-to-noise ratio in evoked potentials.² In this way a record of the light distribution unobscured by noise fluctuations may be obtained.

This distribution, however, is a doubly degraded copy of the target as the light has passed through the optical system of the eye twice. In order to deduce the nature of the retinal image the sine-wave response theory of optical imagery must be applied.³ To apply this theory it must be assumed that the eye optics are reversible, i.e., that a ray traveling in one direction behaves the same way as a ray following the same path in the opposite direction. Furthermore it must be assumed that the retina is primarily a diffuse reflector. On these assumptions the eye optics may be considered as a filter of spatial sinusoidal patterns. Since the eye optics are traversed twice in the experimental situation they act as two filters of identical characteristics in cascade. If the target and the recorded light distribution are submitted to spatial Fourier analysis, the response of the cascaded system may be found by dividing the output coefficients of the various frequency terms by the input coefficients. Since these response terms represent the behavior of the cascaded system it is necessary to take their square roots to obtain the response terms for a single passage. When response is plotted as a function of spatial frequency it is found that the eye like other optical systems behaves like a low pass filter.

Theoretical calculations of the behavior of ideal, aberration-free lens have been published.⁴ In this case it is assumed that the system is limited solely by diffraction. These results show that the cut-off frequency of the lens is determined by the wavelength of the light used and the diameter of the lens. The cut-off frequency in cycles per minute of arc is given by $d / 3.44 \times 10^3 \lambda$, where d is the diameter of the lens in millimeters and λ is the wavelength of the light in millimicrons.

Response functions for the human eye were determined for various pupil diameters from 3 to 8 mm. In absolute terms the best imagery is

obtained with a 4-5 mm pupil. That is, the cut-off frequency of the eye is highest for pupils of this order. In relative terms, that is, comparing the behavior of the eye to an ideal system, the performance deteriorates with increasing aperture. The increasing departure of the response function from the ideal probably represents the increasing significance of spherical and chromatic aberration.

Experiments were therefore undertaken to evaluate the response functions of the eye at various apertures using monochromatic light. Measurements were also made with the same observers using white light so that the performance of the eye could be compared for the two light distributions under equivalent conditions. The results of these experiments indicate that the performance of the eye is not significantly different with monochromatic and white light.

Since the eye is known to have considerable chromatic aberration (the difference in power amounts to approximately 2 diopters from 400 to 700 mμ),⁵ this result seems at first surprising. However, when the spectral distribution of the white light source, the spectral reflectance of the retina and the spectral sensitivity of the photomultiplier are taken into consideration it is apparent that most of the energy measured in the white light experiments is concentrated in the central portion of the visual spectrum (approximately 500 to 600 mμ). Over this region the difference in dioptric power is only about .5 diopters. It seems reasonable to attribute the deviation of the properties of the eye from the ideal optical system to spherical aberration (or more correctly the variation in dioptric power over the pupil since the eye does not exhibit simple symmetric spherical aberration). The variation in focal length over the pupil appears to have such a large effect relative to the contribution of the chromatic aberration

that the difference in image quality between white and monochromatic light is not measurable.

These results are in good agreement with what is known about the effect of spectral composition on visual acuity. It has been generally found that acuity is of the same order with white and colored light when appropriate steps have been taken to equate luminances.⁶

One of the purposes of undertaking the measurements of image formation was to find those conditions under which the smallest images of point sources might be produced on the retina. This information is then to be used to determine the experimental conditions for microstimulation experiments being carried out under this contract. Furthermore the information will be helpful in interpreting the results of such experiments. Thus far the results indicate that it would be best to use a 4-5 mm pupil. However, there is a suggestion in the literature going back to observations by the astronomer Herschel, that finer point images may be obtained by use of annular pupils.⁷ Experiments are now in progress to evaluate imagery through such a system.

Footnotes

1. J. Krauskopf, Light distribution in human retinal images. J. Opt. Soc. Amer., 52, 1962, 1046.
2. Communication Biophysics Group of Research Laboratory of Electronics and W. M. Siebert, Processing Neuroelectric Data (The Technology Press, Cambridge, Massachusetts, 1959).
3. Fred. H. Perrin, Methods of appraising photographic systems, J. Soc. Motion Picture and Television Engrs., 69, 1960, 151, 249.
4. E. L. O'Neill, Transfer function for an annular aperature, J. Opt. Soc. Amer., 45, 1956, 285.
5. H. Hartridge, Recent advances in the physiology of vision, (Blakiston, Philadelphia, 1950) 87.
6. See reference 5 p. 39.
7. See reference 4.

Recent Publications Supported by Contract

1. Light distribution in human retinal images, J. Opt. Soc. Amer., 52, 1952, 1046.
2. Effect of target oscillation on contrast resolution, J. Opt. Soc. Amer., 62, 1962, 1306.
3. Student color mixer with monochromatic primaries, Amer. J. Psychol. (in press)
4. Effect of retinal image stabilization on the appearance of heterochromatic targets, J. Opt. Soc. Amer. (in press)
5. Effects of chromatic adaptation on normal and dichromatic red-green brightness matches (with Speelman) J. Opt. Soc. Amer. (in press).