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Research Article

Apparent Motion for Ultra-Small offsets as a Hyperacuity Phenomenon

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Keywords

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Abstract

two-LED testing instrument was developed to investigate the mechanisms of hyperacuity. Two point light sources are observed through the beam splitter cube. The luminance of each light point is approximately 4000 cd/m2, the angular size is 7 arc sec at a viewing distance of about three meters. The angular distance between light points is accurate to 1 arc sec, and controlled with a stepper motor. To eliminate the effect of eye movements, the 12 ms flash duration was selected.

Two experiments were performed:

1. Estimation of the discrimination threshold. Two light points were presented simultaneously. Subjects were asked whether they observed 1 or 2 points. The resulting thresholds were in the range 80 -100 arc sec for several subjects.

2. Measurement of the apparent motion thresholds. Two light points were presented with time delays 0, 20, 40 ms the subjects answered whether a movement was occurred, and assessed its direction. The following motion detection thresholds were obtained: for asynchrony 20 ms 60-80 arc sec, for 40 ms 30-40 arc sec. It is known that for stimuli with different spatial size the apparent motion detection thresholds are less than the two-point resolution. Our findings are in line with these results.

ABBREVIATIONS

MAR- Minimum Angle of Resolution

INTRODUCTION

The term visual acuity usually implies the ability of a subject to discriminate very small objects at a considerable distance. The commonly accepted approach to determine visual acuity is based on Hermann Helmholtz's metaphor: "the eye is like a camera". An optical system forms an image in the retinal plane that is converted into electrical signals by an array of photoreceptors. These signals are transformed by retinal neurons and then transmitted through the optic nerve to the brain for further analysis. Each of these processes affects the visual acuity.

It is customary to assume that the optical system of the eye essentially sets the upper limit of visual acuity. The diameter and spacing of the photoreceptors are in good agreement with the size of the point source diffraction image. The basic concept here is the resolving power of an optical system, characterizing its ability to produce separate images of two closely spaced light sources. To assess the quality of images on the retina, optical methods are used to identify an ophthalmic model of the eye.

The angular size of test stimuli which the observer can still distinguish with a given probability is usually taken as a measure of visual acuity. A wide variety of assorted stimuli is used in these experiments: points, lines, grids, various figures, letters, etc. For this purpose, appropriate psychophysical procedures have been developed.

Suppose we know how the optical system of the eye form images of a set of simple stimuli. Then, using transfer function linearity, it is always possible to calculate the image of any stimulus that can be expressed as their weighted sum. Thus, if visual acuity was determined only by eye optics, then using the ophthalmological model, one could calculate the sensitivity of the visual system to any stimulation. However, in a number of cases, the results of psychophysical experiments are poorly consistent with predictions based on the ophthalmic model. This refers to a lot of experimental facts known as "hyperacuity" [1]. The thresholds of detection or discrimination for certain stimuli are very low. This is true for Vernier visual acuity, abnormally low stereovision thresholds, apparent motion caused by closely spaced light sources, and the like. In such experiments, the subjects distinguish small details obviously better than it follows from the ophthalmic model.

It seems likely that the hyperacuity can be explained by the cooperative effects [2]. Extended stimuli activate more photoreceptors, whose signals can be processed together. Thus, the effects of accumulation and signal processing in the visual system allow us to perceive much smaller details of the stimulus than one would expect, applying the Rayleigh criterion for imaging on the retina. Despite the huge accumulated array of experimental data, at the moment there is no general psychophysical theory, which allows us to quantitatively predict detection and discrimination thresholds for arbitrary stimuli.

One also may speculate that oculomotor activity plays a large role in the operation of these mechanisms. At the same time, it is not completely clear how the eyes micro-movements are associated with an increase of the resolution in vision. Currently, this issue is being actively explored [3,4].

Thus, an experimental study is now required that could clarify the contribution of each component to the visual acuity:

- Optical system of the eye

- Effects of light field conversion in retina volume and light absorption.

- Eyes micro-movements

- Effects associated with processing signals in the retina and the visual fields of the brain

The solution of this problem is greatly simplified if we choose a stimulation that would allow us to separately investigate the influence of each of these factors. In particular, in order to exclude the cooperative effect discussed above, it is desirable to abandon the use of extended stimuli and use point stimulation. This allows minimizing the number of simultaneously activated photoreceptors. To eliminate the effect of eye movement, stimuli should be presented for a short time. Moreover, due to Bloch's law for temporal summation, the shorter is the presentation time, the higher brightness of the point stimulus is required for the confident detection.

Broadly speaking, experimental study of the detection of luminous points is challenging task. From Ricco's law, the detection threshold is proportional to the product of brightness and the area of the stimulus. This means that the smaller the stimulus size, the greater the brightness is required for the stimulus to be detected with confidence. To build up the small-sized point light stimulus of the angular size comparable with the diameter of a single photoreceptor at a distance of 2-6 meters from the screen (that is typical for laboratory experiments), only one pixel should be used. The brightness of a standard monitor is insufficient for this.

Probably for this reason, mainly two types of stimulation for visual acuity investigation can be found in the literature: point light stimuli with small angular size and relatively long presentation time (more than 100 ms), or area stimuli (more than 2 arcmin). At the same time, there are practically no experiments in which point stimuli whose angular size is smaller than the size of a single photoreceptor would be presented for a short time.

MATERIALS AND METHODS

Therefore, despite all the comforts, we must abandon the use of monitors in such experiments. We developed a visual testing instrument (Figure 1) that meets the requirements: extremely small angular dimensions, short-term presentation, and, consequently, high brightness. As sources of light, ultra-bright light-emitting diodes LED1 and LED2 are used. Light beams are formed by the diaphragms D1 and D2 and are merged at the beam splitter cube BS. LED2 is mounted on a movable carriage and is driven by a stepper motor with a corkscrew shaft. In this way, the optical separation between light sources can be adjusted. With an observation distance of about three meters, the angular diameter of the light source is 7 arc sec (Figure 1b). The angular distance between the light sources can be set with the step of 1 arc sec. The luminance of the light sources is approximately 4000 cd/m^2. All device parameters are controlled by microprocessor.

A similar design was used by [5], but instead of LEDs, laser light sources were employed. This can be the cause of the appearance of speckles – random patterns formed by the mutual interference of coherent waves, scattered on the optical elements of the eye. Speckles can mask the signal and affect the subject's detection of the stimuli. For this reason, we have refused to use coherent light sources.

Three subjects (**A.E., A.K., E.S.**) participated in the experiments. The distance from the visual testing instrument to the subject's eyes was 287 cm. Under these conditions, the point sources of light had angular diameter of 7.2 arc sec. To minimize the effect of eye movements, the exposure time of LED flashes was chosen equal to 12 msec. The angular separation between light sources varied randomly with 10 arc.sec step. The experiments were carried out in a laboratory room with standard illumination with fluorescent lamps of 200 lx.

We started with a single presentation of stimulus in each trial, but it was found that in the experiments described below it was difficult for subjects to make persistent judgments. To ensure that all experiments were conducted under the same conditions,

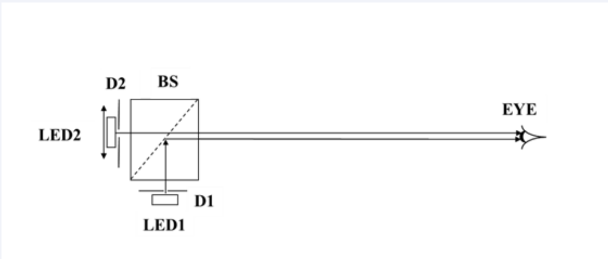

Figure 1a All device parameters are controlled by microprocessor.

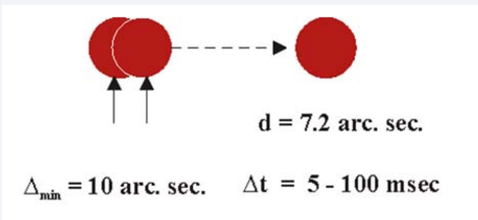

Figure 1b The angular diameter of the light source.

one test always included 5 stimulus repetitions with an interval of 750 ms.

The measurements were carried out by the method of constants.

Experiment 1

Psychophysical measurement of the resolving power of the eye with two-point discrimination. An estimation of the threshold for distinguishing two points was made by simultaneous presentation of pairs of light points, the distance between which varied.

Instruction: subjects were asked whether they saw 1 or 2 points.

The decision-making data are fitted by the logistic curves that are completely determined by the threshold values, where the probability of correct response is 50%, and the scale parameters.

Psychometric curves obtained for three subjects are presented in Figure 2.

The parameters of the fitted logistics for all experiments are tabulated in the Table 1.

The results correspond to the size of the photoreceptors and the diffraction limit of the optics of the eye and compare well with those obtained in other investigations. Let's give some examples.

[5] The minimum angle of resolution (MAR) was determined to be 1.58 to 2.74 arc.min. Time of presentation is not specified in the paper.

[6] The thresholds for the two-point resolution task were around 48 arc sec. Presentation time was 100 ms, angular size of the point source - 12 arc sec.

[7] MAR was about 105 arc sec., the angular size of the source (according to our calculations) is approximately 10 arc sec.

Since in our experiments the presentation time was 12 ms, it can be assumed that the effect of eye micro-movements, according to the data given in [8], can be neglected.

If the light points are not presented simultaneously, then an apparent motion is observed [9,10] first discovered experimentally that apparent motion is observed, even two light points do not differ with simultaneous presentation. The experimental setup of Exner formed two sparks at some distance from each other with a short time interval. Two sparks appeared to the observer as one moving spark. Exner argued that the apparent motion is a separate quality of perception.

There are several papers in which the apparent motion was examined using closely spaced light points, but only for peripheral vision. It has been repeatedly noted that the apparent motion is observed when the points do not differ [11-13]. But in these studies no direct measurements of the two-point resolution

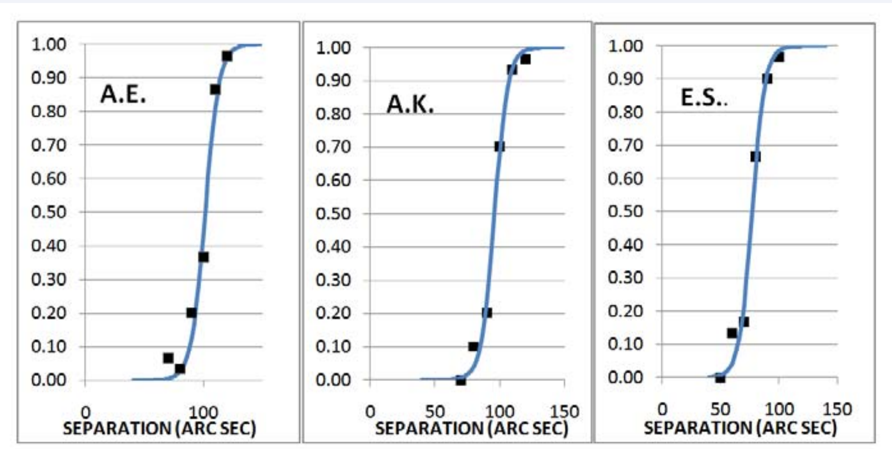

Figure 2 Scale parameters.

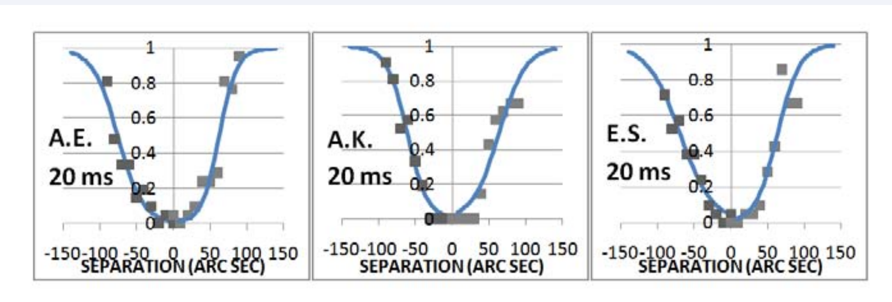

Figure 3a 20 ms turn-on delay.

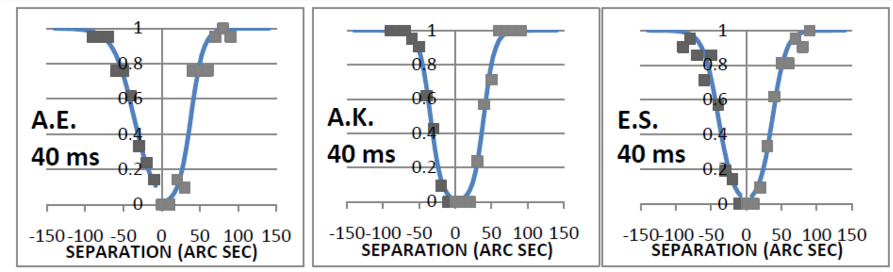

Figure 3b 40 ms turn-on delay.

Table 1: The parameters of the fitted logistics for all experiments have been summarized in the Table 1.

subject	A.E.		A.K.		E.S.	
two-point discrimination						
threshold	101		96		77	
slope	6		5		5	
apparent motion, 20 ms turn-on delay						
motion direction	←	→	←	→	←	→
threshold	76	62	62	64	70	63
scaling factor	17	12	14	18	22	15
apparent motion, 40 ms turn-on delay						
motion direction	←	→	←	→	←	→
threshold	37	38	34	39	40	37
scaling factor	13	8	8	7	11	10

were carried out. So, we measured the detection thresholds of apparent motion under the same conditions as in the Experiment 1, where direct measurements of two-point resolution had being conducted.

Experiment 2. The detection thresholds of apparent motion were measured. Subjects were presented with pairs of flashing points. Order of the flashes, the point offsets, and the turn-on delays (0, 20, 40 ms) were varied. Instruction: the subject had to press one of the three buttons, depending on whether he observed motion to the left, to the right, or did not observe the motion at all. With a single presentation of two flashing points, the subject often observed confidently the movement, but could not determine its direction. To make the results more sustainable, the subject made a decision after 5 consecutive presentations in each trial.

The results of each experiment are presented as two psychometric curves. The one on the right describes the dependence of the probability of the subject's answer "there is a movement to the right" depending on the turn-on delay, provided that the left point flashes before the right one. The left curve corresponds to the probability of the answer "there is a movement to the left", provided that the right point flashes before the left point.

Psychometric functions for all subjects fitted with logistics are shown in Figure 3a and 3b respectively for 20 and 40 ms turn-on delays.

RESULTS AND DISCUSSIONS

1. Based on measurements of two-point resolution and detection thresholds for apparent motion obtained under the same experimental conditions and for the same subjects, it can be asserted that motion detection occurs at a distance between points much less than necessary for distinguishing points. Thus, for foveal vision, the observation of Exner is confirmed.

2. We can assume that the apparent motion with closely spaced stimulus points belongs to the group of hyperacuity phenomena. The fact noted by Exner can be viewed as one of the phenomena of hyperacuity in the sense that the detection threshold of the apparent motion is less than the size of the photoreceptor.

3. To explain mechanisms of hyperacuity it is often attributed with the joint processing of signal from a number of activated photoreceptors. The use of small point stimuli makes it possible to minimize the contribution of this effect, and to study separately the influence of separate mechanisms on visual acuity.

4. It is possible to study separately motion detectors and evaluate the spatiotemporal characteristics of stimuli that can activate them, and also answer the question - where are the motion detectors located.

5. We constructed a testing instrument whose point size is much smaller than the size of the photoreceptor in the fovea. The device allows selectively stimulate small groups of receptors and can be employed for study of the microstructure of the retina

using a great variety of psychophysical and psychophysiological methods

6. The short presentation time allows investigating the influence of eye movements on visual acuity. It is possible both to eliminate the influence of the eye movements, reducing the time of stimulation, and to synchronize the stimulation with the movements of the eyes.

7. Visual acuity is the ability to respond to small stimuli. What type of stimulation is chosen to assess visual acuity? This is a matter of convention and the convenience of conducting an experiment. In this sense, local apparent motion is a very good method.

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