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Some Observations and Theory on the Variation of Visual Acuity
with the Orientation of the Test Object*

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ABSTRACT

The superiority of visual acuity obtained with a grating test object oriented vertically or horizontally over values obtained with oblique orientations is demonstrated for various combinations of pupil diameter and retinal illuminance level. This superiority, which has an average value of 7% of the mean threshold angle of resolution for all meridians, increases with pupil diameter but is not affected systematically by illuminance level.

The data are discussed with reference to the assumptions that meridional differences in acuity are a result of dioptric or of retinal factors. The systematic effect of pupil diameter points to the dioptric origin of some of the observed meridional differences. The influence of retinal or post-retinal factors as well is suggested by the persistence of the effect at a high illuminance level and with large pupil diameters, a condition where a slight decrease in retinal image contrast is shown not to lower acuity.

INTRODUCTION

Differences in visual acuity as a function of the angle of orientation of the test object have previously been reported for grating acuity,¹⁻⁵ Landolt C,⁶ and vernier acuity.⁷ The present paper presents

additional evidence of these meridional differences in order to:

- (a) determine the effect of the variables of pupil diameter and luminance level on the magnitude of the effect with a grating, and (b) investigate the origin of the phenomenon.

THE EFFECT OF PUPIL DIAMETER AND LUMINANCE LEVEL

In a previous experiment,⁸ the effect of artificial pupil diameter on grating acuity was determined at various levels of retinal illuminance. In order to determine luminance values of the acuity test field which would give the same retinal illuminances for the various artificial pupils employed, the acuity test field, as viewed through each artificial pupil, was matched with a reference field of fixed luminance viewed by the other eye through a 2.0 mm pupil. Visual acuity for a grating was then determined as a function of pupil size at five levels of retinal illuminance and for a fixed observation distance. The observed variations in acuity as a function of pupil size were assumed to reflect only the combined effects of aberrations and diffraction on acuity.

In the original study, four orientations of the grating test object were employed [horizontal (H), vertical (V), 45° clockwise from vertical (R), and 45° counterclockwise from vertical (L)] and the average of the values obtained in all four positions were presented. These data have now been analyzed to isolate the effect of orientation and are presented in Table I as the threshold angle of

resolution in seconds of arc. Each value is the mean of 6 determinations for subject L and of 12 for subject S.[†]

The results show meridional differences up to 17.4 seconds of arc and up to 26.9% of the average angle of resolution. Comparison between values for the H and V positions reveals no significant trends, and this is also true for the R and L positions. However, if the H and V data are averaged and compared with the average of the R and L positions, the superiority of HV over RL is marked. This superiority occurs without exception for all conditions of observation, and has an average value of approximately 7% of the average angle of resolution.

The averaged HV and RL data are presented graphically in Fig. 1 as log visual acuity vs. log pupil diameter. The shapes of the curves do not differ from those for the combined data for all four meridians.⁸ The effect of orientation is to shift these functions to higher acuity values for the horizontal and vertical orientations, and to lower acuity values for the oblique orientations.

Since these data are presented on a logarithmic plot, the separation between the HV and the RL curves is a measure of the percentage HV - RL superiority. This superiority increases with pupil diameter at all luminance levels. The effect of luminance level, determined by comparing the HV superiority over RL for a given pupil diameter, shows no consistent trends.

DISCUSSION

The results of the present study may be used to evaluate two of the explanations which have been offered for the phenomenon under discussion. These explanations attribute meridional differences either to dioptric or to retinal factors. (A third hypothesis based on involuntary eye movements⁹ has been shown to be untenable.⁴)

If dioptric factors are influential in producing the observed meridional differences in resolving power, it would be expected that any experimental condition which increases the effectiveness of the dioptric aberrations would also accentuate these differences. Since the effectiveness of the aberrations increases as the pupil is made larger,⁶ the tendency shown here for meridional differences to increase for a grating under these same conditions points to the importance of the image forming properties of the eye in producing the phenomenon under discussion.

The second hypothesis is that the density of the retinal elements (either anatomically or functionally) is not uniform, and that the observed variations in acuity are a result of similar variations in the fineness of the mosaic provided for resolution of the retinal image.^{3,6} The plausibility of such an argument may be examined with the aid of a procedure described by Shlaer.³ He has reasoned that under conditions of large pupil diameter and high retinal illuminance such that acuity is not improved by increasing the value of either factor,⁷ resolving power may be limited by either (a) the ability of the retina to dis-

criminate differences in intensity between the maxima and minima of the retinal image of a grating, or (b) the size of the retinal elements. (The maximum intensity difference between adjacent retinal elements will occur when adjacent maxima and minima are centered on adjacent receptors. If the image of the grating were made finer than this, each element would be covered by a fraction of the image of the light and dark stripes.) If the latter factor were limiting, a small decrease in the intensity difference between the maxima and minima without changing their periodicity should produce no change in acuity.⁵

Such a condition was realized by substituting a special grating in which the width of the opaque bars is only one-fourth the distance between the centers of adjacent bars (designated as the $1/4$ grating) in place of the conventional grating in which the opaque bars are one-half the distance between adjacent bars (designated as $1/2$). A third grating with bars one-half the width of those in the $1/4$ grating was also used and is designated as $1/8$. These three gratings were used at the highest luminance levels in a single session for subject L and in two sessions for subject S. The data representing the average of four acuity determinations for each point for subject L and eight for subject S are presented in Table II and Fig. 2. (For all gratings, the threshold angle of resolution was computed on the basis of one-half the visual angle subtended by the centers of adjacent opaque bars.)

The data show that a decrease in the width of the bars as produced by the $1/4$ grating does not reduce acuity for the largest pupil

diameters used. This is taken to indicate that the fineness of the retinal mosaic and not the ability of the retina to discriminate the difference between adjacent maxima and minima is limiting acuity under these conditions.¹¹ This conclusion is supported by the agreement between histological measurements of cone size and the acuity values obtained.^{3,13}

Under conditions where a small reduction in retinal image contrast does not affect acuity, it would be expected that slight variations in the image forming properties of the eye, such as have been suggested to account for meridional differences in acuity, would be ineffective. Thus, for the largest pupils at the highest luminance level it would be expected that acuity would be the same in all meridians if the observed differences as a function of orientation were due to purely dioptric factors. However, the data obtained show that meridional differences persist under these conditions. This is evidenced by the data of Table I and also by the more extensive data obtained at the highest luminance level and 4.75 mm pupil diameter for eight orientations of the grating in Table III. These data plotted in Fig. 3 demonstrate the superiority of the HV over the RL positions even under conditions where slight variations in retinal image contrast do not lower acuity. These data suggest that meridional differences originate in part from factors of retinal or post-retinal origin. Additional evidence comes from the experiment of Hamblin and Winsor² who determined the best grating acuity for 18 equally spaced meridians under conditions

of optimum refraction. Their report of the persistence of meridional differences under these conditions further demonstrated the importance of non-dioptic factors in producing meridional differences in acuity.

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NOTES

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† The data originally reported for subject S were obtained using luminance values of the acuity test field which produced equal retinal illuminance as determined by him in a preliminary binocular matching experiment. Acuity data were also obtained using the luminance values obtained by subject L, and are included here since the acuity functions were the same under both conditions.

‡ Further increase in luminance above the highest values reported in this study produced no change in acuity as would be predicted from the acuity luminance function which reaches a limiting value between 10 and 100 millilamberts. Maximum acuity was obtained under these conditions for pupil diameters between 2.77 and 3.86 mm.⁸ Shlaer³ reported maximum acuity with a 2.35 mm pupil, a value which he had predicted from computations based on Abbe's diffraction theory for objects of periodic structure viewed in transmitted light.

§ The assumptions underlying Shlaer's procedure do not take into account the possible effect on acuity of eye movements or post retinal factors.¹⁰⁻¹²

// It may be argued that the reduction in retinal image contrast by the narrow bar grating is less than that produced by the assumed dioptric effects, and that the latter factor was still effective. However, in using the 1/4 grating, acuity remained constant for all orientations indicating that despite the combined deteriorative effects of the narrow grating and the assumed aberrations, cone size was still limiting acuity.

TABLE I. Threshold angle of resolution for a grating in seconds of arc for photometrically equated test fields as a function of pupil diameter and at four orientations of the test object. The luminance of the test field was previously adjusted to match a reference field of constant luminance viewed by the other eye through a 2-mm pupil.

Sub- ject	Refer- ence Lumi- nance (ml)	Orien- tation	Threshold angle of resolution (seconds of arc)						
			Pupil diameter (mm)						
			1.0	1.4	1.6	2.0	2.77	3.86	4.75
L	100	H	65.6	43.4	38.2	33.6	29.8	27.1	27.7
		V	62.6	45.1	39.0	33.1	29.2	29.0	29.6
		R	64.1	47.0	40.7	34.5	32.4	31.9	32.4
		L	65.6	45.5	40.9	34.2	31.9	33.1	31.6
	10	H	66.5	46.8	41.4	34.6	29.8	29.2	31.5
		V	66.2	51.5	42.7	34.7	30.9	30.7	31.7
		R	67.5	48.5	43.9	37.3	33.5	34.5	36.1
		L	66.5	51.1	43.6	37.1	33.4	33.4	34.9
	1.0	H	74.2	54.7	45.1	39.3	38.0	39.1	42.4
		V	71.8	55.2	49.7	41.2	39.1	39.1	41.2
		R	77.6	58.1	50.3	43.4	40.9	41.6	43.8
		L	71.6	57.1	49.4	40.7	40.9	40.7	44.6
	0.1	H	81.3	59.1	54.0	49.7	51.0	51.0	55.7
		V	79.8	61.4	56.1	49.2	50.9	53.9	57.4
		R	93.6	61.9	65.7	57.9	52.8	57.8	59.2
		L	79.6	65.8	57.8	52.2	50.6	53.9	58.4
	0.01	H	113.8	99.8	91.0	92.1	83.8	88.7	101.4
		V	108.2	98.0	83.8	82.4	87.1	92.3	96.0
		R	119.7	108.7	94.7	99.8	92.3	104.0	109.4
		L	111.2	101.0	85.9	95.3	85.9	92.1	97.3
S	100	H	65.6	45.0	39.0	35.5	30.7	28.7	—
		V	63.0	45.5	40.2	34.0	29.7	27.7	—
		R	65.0	46.5	42.1	37.4	34.5	30.5	—
		L	67.9	45.3	41.0	36.6	33.8	33.3	—
	10	H	66.2	45.6	40.5	33.9	29.9	29.0	29.8
		V	63.2	46.4	41.9	34.1	30.6	29.4	31.4
		R	63.8	48.6	42.8	37.6	35.3	34.7	36.5
		L	66.2	47.5	43.7	36.4	33.7	33.1	34.4
	0.1	H	83.4	60.5	55.6	49.2	49.0	51.3	52.6
		V	78.4	63.7	57.9	53.3	48.9	53.5	49.0
		R	84.8	66.3	62.5	58.6	56.1	61.4	62.8
		L	83.4	64.6	62.2	57.3	55.1	58.0	60.6

TABLE II. Threshold angle of resolution in seconds of arc as a function of pupil diameter for gratings in which the width of the opaque bars is one half, one fourth, and one eighth the distance between the centers of adjacent opaque bars. The test field luminance had previously been matched to equal a reference luminance of 100 millilamberts viewed by the other eye through a 2-mm pupil. Each value is the average of two acuity determinations in each of four meridians for subject L, and of four determinations for subject S.

		Threshold angle of resolution (seconds of arc)							
		Pupil diameter (mm)							
Subject	Grating	1.0	1.4	1.6	2.0	2.77	3.86	4.75	
L	1/2	65.2	47.6	41.4	34.3	31.5	30.4	30.5	
	1/4	67.1	49.3	42.5	35.7	32.1	30.7	30.3	
	1/8	69.3	51.5	44.8	37.5	33.1	32.4	33.1	
S	1/2	—	45.7	39.4	33.2	29.9	29.0	—	
	1/4	—	46.8	40.5	33.7	30.4	28.8	—	
	1/8	—	50.0	42.7	35.7	32.8	32.0	—	

TABLE III. Threshold angle of resolution for a grating test object in seconds of arc for various meridians at a test field luminance of 100 millilamberts and with a 4.75 mm diameter pupil. All data are for subject L and each represents the means of 11 threshold determinations.

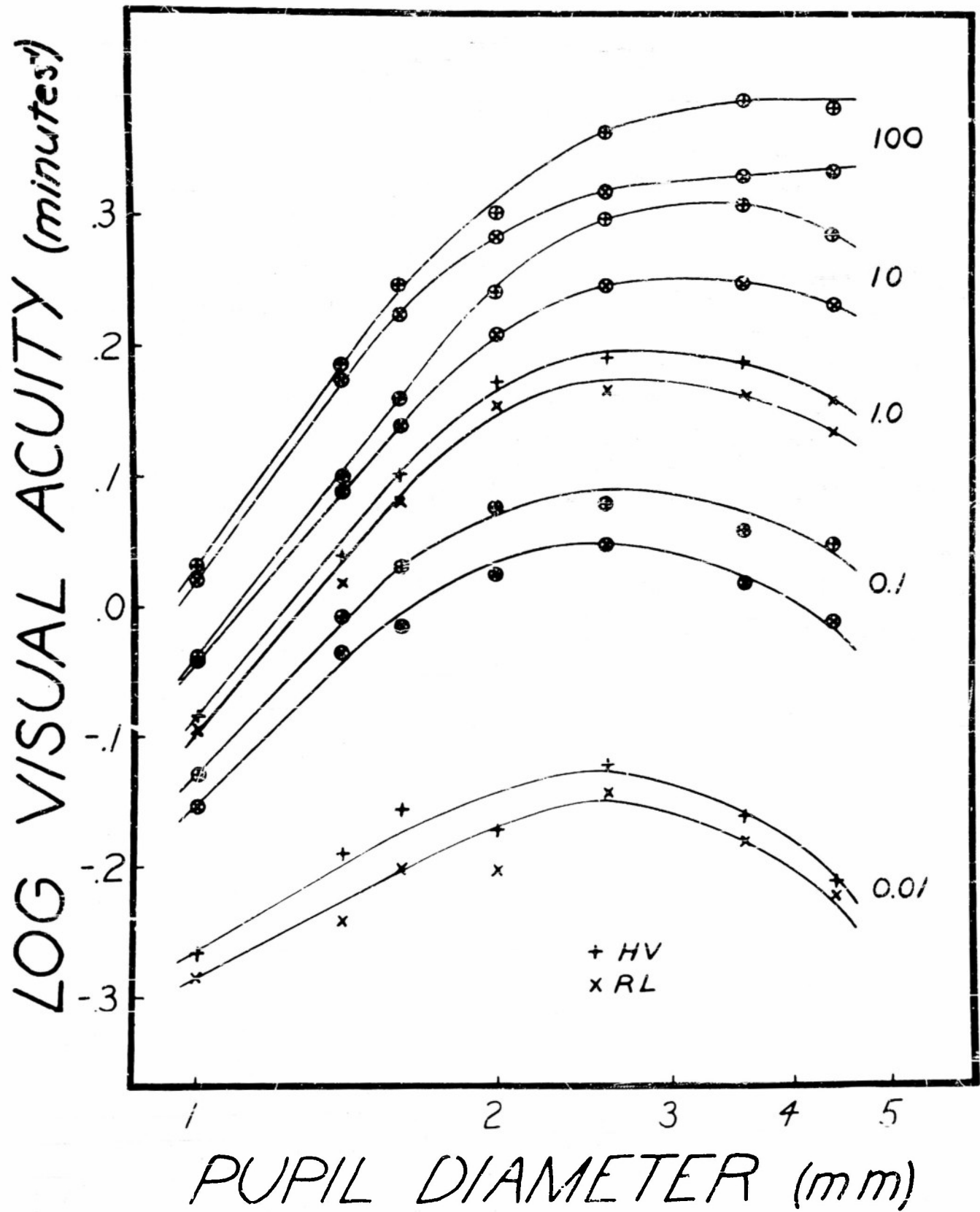
Orientation of grating test object		Threshold angle of resolution (seconds of arc)
Degrees from vertical		:
		:
Counterclockwise		:
		:
90 (H)		30.1
		:
67.5		31.8
		:
45 (L)		35.4
		:
22.5		34.4
		:
Vertical - 0 (V)		32.4
		:
		:
Clockwise		:
		:
22.5		33.3
		:
45.0 (R)		34.2
		:
67.5		32.8
		:
90 (H)		30.1
		:
		:
		:

FIGURE LEGENDS

Fig. 1 Log visual acuity as a function of log pupil diameter for a grating test object oriented horizontally and vertically (+) and oriented 45° to the right and left of vertical (x). The luminance of the acuity test field was previously adjusted to match a reference field of constant luminance viewed by the other eye through a 2-mm pupil. The luminance values of the reference field, in millilamberts, are indicated at the right of the curves. Circled points represent averaged data for both subjects; uncircled points are for subject L. The curves for the highest luminance level have been shifted upwards 0.6 log units on the ordinate axis.

Fig. 2. Log visual acuity as a function of log pupil diameter for grating test objects with opaque bars $1/2$, $1/4$, and $1/8$ the distance between the centers of adjacent ^{open} bars. The luminance of the acuity test field was previously matched with a 100 millilambert reference field viewed by the other eye through a 2-mm pupil.

Fig. 3. Log visual acuity as a function of the orientation of the grating test object. The test field luminance was 100 millilamberts and was viewed through a 4.75 mm artificial pupil.



LOG VISUAL ACUITY (min⁻¹)

