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Vision Research 44 (2004) 1115–1125

Vision Research

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Depth-of-focus of the human eye in the near retinal periphery

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Received 22 July 2003; received in revised form 23 December 2003

Abstract

Although the depth-of-focus in the foveal region has been well investigated, knowledge regarding the effect of retinal eccentricity on blur detection and sensitivity is limited. In the present study, the depth-of-focus at the fovea and in the near retinal periphery (0°–8°) was assessed psychophysically in 7 human subjects using a 5 mm artificial pupil with accommodation paralyzed. The group mean total depth-of-focus progressively increased linearly from 0.89 D at the fovea to 3.51 D at a retinal eccentricity of 8° at the rate of 0.29 D/degree, with response variability (S.E.M.) remaining relatively constant (±0.17 D). We speculate that the reduced detection and sensitivity to blur in the near periphery may be attributed to retinal topography, sharpness overconstancy, optical aberrations, and visual attention in peripheral vision.

Keywords: Defocus; Accommodation; Blur; Peripheral vision; Retinal eccentricity

1. Introduction

Accommodation refers to the process whereby changes in the dioptric power of the crystalline lens occur, so that an in-focus retinal image of an object is obtained and maintained (Ciuffreda, 1991). Blur is the stimulus that drives the accommodative response, which in turn reduces the defocus of the retinal image and leads to visual resolution of fine target details (Ciuffreda, 1991, 1998). An important component of the accommodative process is the depth-of-focus. This refers to the range of retinal defocus that can be tolerated without the perception of blur, with accommodation maintained constant.

Many studies have investigated the depth-of-focus of the human eye at the fovea under a range of photopic conditions, with values ranging from ±0.02 to ±1.75 D (see Ciuffreda, 1991, 1998 for a review; Oshima, 1958; Von Bahr, 1952). Several factors can influence the depth-of-focus. Some factors are related to target attributes, such as luminance (Campbell, 1957; Oshima, 1958), contrast (Atchison, Charman, & Woods, 1997; Campbell, 1957; Oshima, 1958), color (Campbell, 1957; Marcos, Moreno, & Navarro, 1999), size (Atchison et al., 1997; Jacobs, Smith, & Chan, 1989; Ogle & Schwartz, 1959; Tucker & Charman, 1975), and spatial frequency (Legge, Mullen, Woo, & Campbell, 1987). Other factors are related to eye/brain attributes, such as visual acuity (Green, Powers, & Banks, 1980; Legge et al., 1987), pupil size (Atchison et al., 1997; Campbell, 1957; Charman & Whitefoot, 1977; Legge et al., 1987; Marcos et al., 1999; Ogle & Schwartz, 1959; Oshima, 1958; Tucker & Charman, 1975), age (Green et al., 1980; Mordi & Ciuffreda, 1998, 2004), ocular length (Green et al., 1980), aberration (Marcos et al., 1999; Oshima, 1958), refractive error (Jiang & Morse, 1999; Rosenfield & Abraham-Cohen, 1999), visual cortical integrity (Ludlam, Wittenberg, Giglio, & Rosenberg, 1968; Ronchi & Fontana, 1975; Tucker & Charman, 1986; Tucker & Rabie, 1980), and retinal/brain disease (Ciuffreda, Hokoda, Hung, & Semmlow, 1984; Ong, Ciuffreda, & Tannen, 1993).

Another important factor is retinal eccentricity, which was the focus for and primary question of the present experiment. Although many investigations have been conducted on the depth-of-focus at the fovea, the effect of retinal eccentricity has rarely been investigated. Only one study has been conducted. Ronchi and Molesini (1975) measured the depth-of-focus at retinal eccentricities from 7° to 60°. Subjects fixated upon a

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doi:10.1016/j.visres.2004.01.001

Table 1
Methodological differences between Ronchi and Molesini's study (1975) and the present study

Parameter	Study	
	Ronchi and Molesini (1975)	Present study
Number of subjects	2	7
Test target	Monochromatic flashed spot of light (4 min of arc)	Edge of variable iris diaphragm; white light
Eccentricities	7°, 15°, 20°, 30°, 40°, 50° and 60°, part in each eye	0°, 0.5°, 1°, 2°, 3°, 4°, 5°, 6°, 7° and 8°, all in the right eye
Criterion	Loss of visibility of the test target	Discrimination of just detectable blur of the test target
Cycloplegia	No	Yes

small central dim reference light, without cycloplegia. The test target consisted of a small spot of light (4 arcmin), which was flashed on a black background at different eccentricities. The test target was defocused by introducing ophthalmic lenses of different powers between the target and eye. Pupil size was not specified. The depth-of-focus criterion used was the range of defocus within which the luminance of the flashing target remained 0.1 log units above the minimum value for detectability. The result demonstrated that the depth-of-focus increased as a function of retinal eccentricity, with values ranging from 5 to 12 D for blue light ($\lambda = 427$ nm) and from 2 to 7 D for red light ($\lambda = 632$ nm), for 7°–60 ° of retinal eccentricity, respectively. However, the sample size was small ($n = 2$); furthermore, the stimulus appeared to produce slightly elevated depth-of-focus values, presumably due to the absence of distinct contours within the test stimulus itself.

In the present study, the depth-of-focus (with cycloplegia) was measured psychophysically in the near retinal periphery using high contrast circular apertures as the stimuli. The primary experimental differences between Ronchi and Molesini's study (1975) and the present one are summarized in Table 1.

2. Methods

2.1. Subjects

The study was performed on 7 visually-normal adult subjects (6 males and 1 female), all of whom were students and faculty at the SUNY State College of Optometry. Subjects' ages ranged from 23 to 55 years, with a mean of 34 years. Subjects' experience in general psychophysical experiments ranged from modest to high. All had a corrected Snellen visual acuity of at least 20/20 in the tested right eye. The group mean ($n = 7$) spherical and cylindrical refractive correction of the tested right eye was -1.68 ± 1.46 D and -0.36 ± 0.56 D, respectively, which was either worn or compensated for by the optical system during all testing. The spherical refractive component ranged from -3.50 to $+0.50$ D ($n = 7$), while the cylindrical refractive component ranged from -0.50 to -1.50 D ($n = 3$). None of the subjects reported or had evidence of ocular, systemic, or neurologic disease; two subjects without any accommodative dysfunction participated in a comparison study without cycloplegia. Each subject was prescreened by a licensed optometrist and found to be free of any potential adverse side effects from the administration of 1% cyclopentolate HCL for both cycloplegia and pupillary dilatation during the testing. According to the guidelines of the World Medical Association Declaration of Helsinki (British Medical Journal 1991; 302: 1194), the experiment was undertaken with the full understanding and written informed consent of each subject.

2.2. Apparatus

The apparatus consisted of a two-channel Badal optical system, which was combined optically with a half-silvered mirror (HSM, transmittance: reflectance = 60:40) (Fig. 1A). One Badal system (CH1) was positioned in front of and aligned along the line-of-sight of the subject's right eye, while the other (CH2) was perpendicular to it. In addition, there was an artificial pupil (AP) of 5 mm diameter positioned in front of the tested eye and common to both channels, which was used for all test conditions. This relatively large pupil size was used to minimize the depth-of-focus to preclude it from extending beyond the 5 D proximal and 5 D distal range of the Badal optical system. There was also a carefully aligned headrest/chinrest assembly to maintain head stability; with any head movement, a small portion of the test field would disappear due to vignetting, and hence this loss of information functioned as a cue for the subject to realign the head. When the head was properly aligned, the entire circular test field was present.

The test target channel (CH1) consisted of a Badal camera lens (L1), an iris diaphragm (ID), slide holder (SH), and light box (LB1). L1 was a high-resolution macro camera lens (Steinheil Munchen, Macro-Quiner, 1:2.8, $f = 100$ mm, power = +10.0 D), with its secondary focal point coinciding with the entrance pupil of the right eye. Behind L1 there was a variable iris diaphragm (ID) (Edmund Industrial Optics, E42-121), which was dioptrically positioned at the far point of the subject's right eye. The iris diaphragm (ID) had a maximum

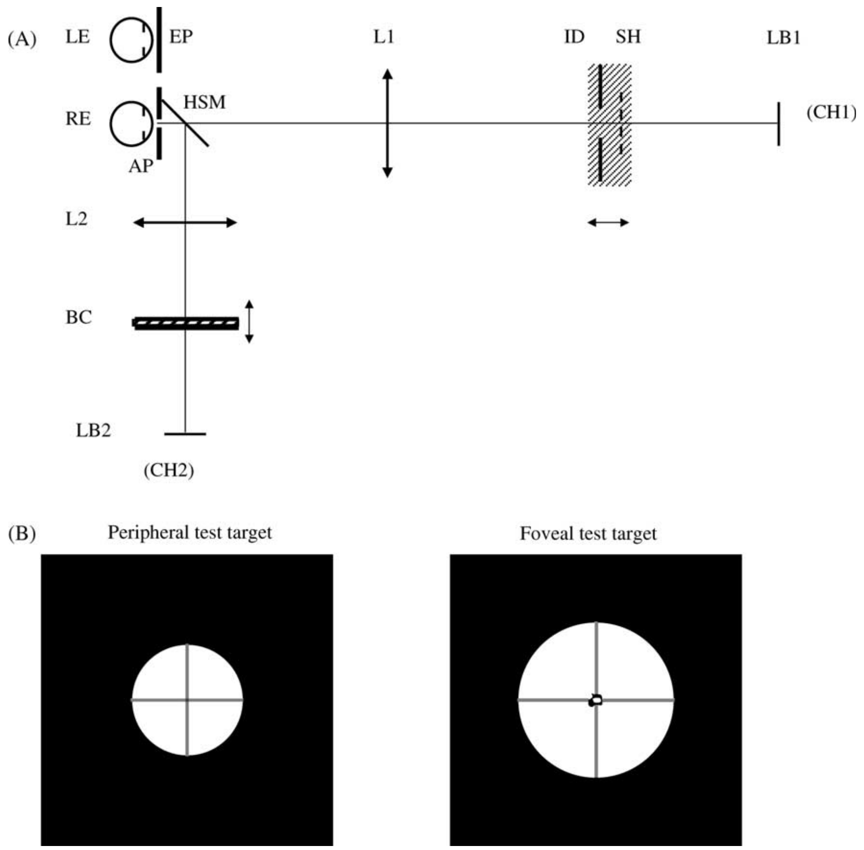

Fig. 1. (A) Top view schematic representation of the apparatus to measure depth-of-focus. Symbols: (CH1) test target channel, (CH2) fixation target channel, (RE) right eye, (LE) left eye, (EP) eye patch, (AP) artificial pupil, (HSM) half-silvered mirror, (L1) Badal camera lens system, (L2) Badal ophthalmic lens system, (ID) iris diaphragm, (SH) slide holder, (BC) black cross, (LB1) light box 1, and (LB2) light box 2. (B) Peripheral and foveal test targets. Subjects maintained their fixation on the intersection of the low contrast, dim central black cross, while they attended to the circular edge of the aperture for the peripheral test target and the edges of the small irregularly-shaped annular-like high contrast black form for the foveal test target.

aperture size of 30 mm and a minimum aperture size of 1.2 mm; it served as the eccentric test target. A slide holder (SH) was attached to the back of the iris diaphragm. The test target for measurements of the foveal depth-of-focus was an irregularly-shaped, annular-like high contrast (73%) black form mounted on the slide holder behind the iris diaphragm. The distance from the slide holder to the iris diaphragm was 2 cm, which made the difference in dioptric vergence between the iris diaphragm and the slide holder 2 D to minimize any potential accommodative blur drive produced by the aperture itself. When measuring the depth-of-focus with the foveal test target, the aperture size was set at 6°, with the foveal test target placed at the center of the aperture and superimposed on a low contrast black cross (BC). The iris diaphragm (ID) and slide holder (SH) were mounted on a micrometer stage (Edmund Industrial Optics, E03-601), which featured a fine stainless screw movement of 1 mm pitch with a range of 124 mm, so that the test target could be manually displaced smoothly, slowly, and in very small increments. A light box (LB1) containing an incandescent light source was positioned at the distal end of CH1. It served as the background illumination for the iris diaphragm; its contrast was 73% with a background luminance of 690 cd/m^2 (Minolta Camera Co., Ltd, Minolta Luminance Meter LS-100).

The fixation target channel (CH2) consisted of a Badal ophthalmic lens (L2), a low contrast and dim black cross (BC), and a light box (LB2) containing an incandescent light source. L2 was an ophthalmic lens of +20.00 D with its secondary focal point coinciding with the entrance pupil of the subject's right eye. Behind the Badal lens (L2), there was a fixation target consisting of a transparent film of a low contrast black cross (BC), which was dioptrically positioned at the far point of the subject's right eye. It served as a dim focus and fixation target. The cross was placed on the front surface of LB2, and it was sandwiched between a piece of transparent glass and ground glass diffuser. The lines of the black cross target subtended 10 arcmin at the subject's eye and filled the variable test field. Contrast of the cross was 8% with a background luminance of 690 cd/m^2 (Minolta Camera Co., Ltd., Minolta Luminance Meter LS-100).

All optical elements were mounted on the micrometer stages with an *X–Y–Z* axis configuration for fine alignment. The centers of the artificial pupil, iris diaphragm, camera lens, ophthalmic lens, and intersection point of the black cross were coincident.

2.3. Procedures

Prior to commencement of the testing, all subjects received several minutes of training in the recognition of very slight "just detectable blur". While gazing monocularly into the distance (6 m) at a Snellen chart with their refractive correction in place, +0.25 D and +0.50 D lenses were added in the spectacle plane to demonstrate the small blur changes. In addition, they received several minutes of training in the assessment of blur in the near retinal periphery for each target eccentricity within the test apparatus.

Then, the right eye (RE) of the subject was cyclopleged and dilated with two drops of cyclopentolate HCL (1% Akpentolate™, 2 mL, Akorn, Inc.), with instillation of each drop separated by 5 min per the manufacturer's instruction using a multi-dose vehicle. It took approximately 30 min to attain maximum pharmacological effect (Rosenfield & Linfield, 1986), at which time testing was initiated. In addition, the cycloplegic effect was checked subjectively by interposing a −0.25 D (or −0.50 D) lens over the habitual prescription (monocularly). Then, the subject was asked if the threshold distance Snellen letter appeared to be very slightly blurred. If so, accommodative responsivity was demonstrated to be negligible. Duration of its maximum effect was longer than the total test time (Mordi, Tucker, & Charman, 1986; Rosenfield & Linfield, 1986).

Once full cycloplegia and pupillary dilation were achieved, the subject was asked to look into the double Badal system through the artificial pupil with the right eye; the left eye (LE) was fully occluded with a black eye patch (EP). The overall stimulus for the peripheral test consisted of the variable, high contrast circular test aperture (camera iris diaphragm), with a centered low contrast and dim black fixation/focus cross (Fig. 1B). Test target radii were 0.5°, 1°, 2°, 3°, 4°, 5°, 6°, 7° and 8°. The foveal test stimulus consisted of the irregularly-shaped annular-like high contrast black form (approximate visual angle radius of 7.5 arcmin) with the centered low contrast and dim black fixation/focus cross (Fig. 1B). Order of presentation was counterbalanced across subjects.

Four measurements were taken at each retinal eccentricity. First, the test target was placed at the far point of the subject's eye. Then, the test target was carefully and slowly moved, either further from or closer to the subject's eye at a speed of approximately 0.1 D/s (Mordi & Ciuffreda, 1998). The subject fixated upon the intersection of the dim black cross which was centered in the optical system, while attending either to the clarity of the aperture edge for the eccentric test stimulus or the central irregular form for the foveal test stimulus. The subject was instructed to indicate when just detectable blur of the test target was perceived. Then, the investigator defocused the target an additional 1.5 D, and the target was similarly moved back towards the subject's far point. Now, the subject was instructed to indicate when the test target just regained clarity. The midpoint between the position of just detectable blur and the position of just detectable clarity was taken as one end of the depth-of-focus. The optical distance between the proximal and distal ends obtained in this manner was recorded as the total depth-of-focus (i.e., proximal plus distal distances combined). The initial direction of movement from the far point was randomized for the different test targets. The entire experiment consisted of 40 measurements (10 field angles and four measurements each), and lasted approximately 2 h for each subject.

There were two additional experiments performed. First, this entire protocol was conducted twice on one experienced subject (S_5) to assess repeatability of the measurements at five test sessions over a period of four months. Second, to determine possible contamination by any residual and small accommodative fluctuations or other possible variations in accommodation, the entire protocol was repeated in two subjects (S_2 and S_5), but now without cycloplegia.

3. Results

3.1. Main experiment

The group mean and S.E.M. results are presented in Fig. 2. The total depth-of-focus increased from

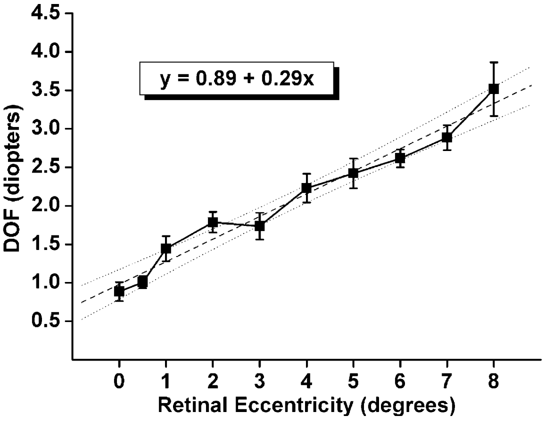

Fig. 2. Group mean depth-of-focus (±1 S.E.M.) as a function of retinal eccentricity. Linear regression: (dashed line) $y = 0.89 + 0.29x$, $r = +0.98$, $r^2 = 0.96$, $p < 0.0001$ ($N = 7$); (dotted lines) 95% confidence band.

Table 2
Post-hoc analysis (planned comparison test) probability matrix for the group mean depth-of-focus as a function of retinal eccentricity

	0	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
0	–	0.591	0.163	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
0.5	0.591	–	0.058	**0.001**	**0.002**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
1.0	0.163	0.058	–	0.133	0.198	**0.001**	**0.000**	**0.000**	**0.000**	**0.000**
2.0	**0.000**	**0.001**	0.133	–	0.825	0.054	**0.007**	**0.001**	**0.000**	**0.000**
3.0	**0.000**	**0.002**	0.198	0.825	–	**0.033**	**0.004**	**0.000**	**0.000**	**0.000**
4.0	**0.000**	**0.000**	**0.001**	0.054	**0.033**	–	0.394	0.091	**0.005**	**0.000**
5.0	**0.000**	**0.000**	**0.000**	**0.007**	**0.004**	0.394	–	0.391	**0.044**	**0.000**
6.0	**0.000**	**0.000**	**0.000**	**0.001**	**0.000**	0.091	0.391	–	0.235	**0.000**
7.0	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.005**	**0.044**	0.235	–	**0.007**
8.0	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.007**	–

Coding: gray = test retinal eccentricity (degrees), bold = statistically significant comparisons ($p \leqslant 0.05$), non-bold = statistically non-significant comparisons ($p > 0.05$), and dashes = self-comparisons.

0.89 ± 0.12 D at the fovea to 3.51 ± 0.35 D at 8° of retinal eccentricity. A one-way within-subjects (repeated measurements) ANOVA yielded a significant main effect of retinal eccentricity ($F_{9,70} = 27.791$, $p < 0.0001$). Based on the linear regression equation ($y = 0.89 + 0.29x$, $r = +0.98$, $p < 0.0001$), the depth-of-focus increased at the rate of 0.29 D/degree of retinal eccentricity. Response variability remained relatively constant (approximately ±0.17 D; S.E.M.) across the near retinal periphery, except at 8° where it increased to ±0.35 D. Post-hoc analysis (Planned Comparison Test) details are presented in Table 2, which shows that the depth-of-focus at each retinal eccentricity was only similar with those of neighboring eccentricities.

The individual subject results are presented in Fig. 3. A similar trend of a progressively increasing total depth-of-focus with greater retinal eccentricity was found in all subjects. The minimum range of depth-of-focus was from 0.55 to 2.65 D for S_1, and the maximum range was from 1 to 5.1 D for S_3.

3.2. Repeatability experiment

The results for the five individual test sessions for S_5 are plotted in Fig. 4A, while the mean values are plotted in Fig. 4B. Trends for the five individual test sessions were similar. The average range of values across eccentricities was 0.58 D; there was a minimum range of

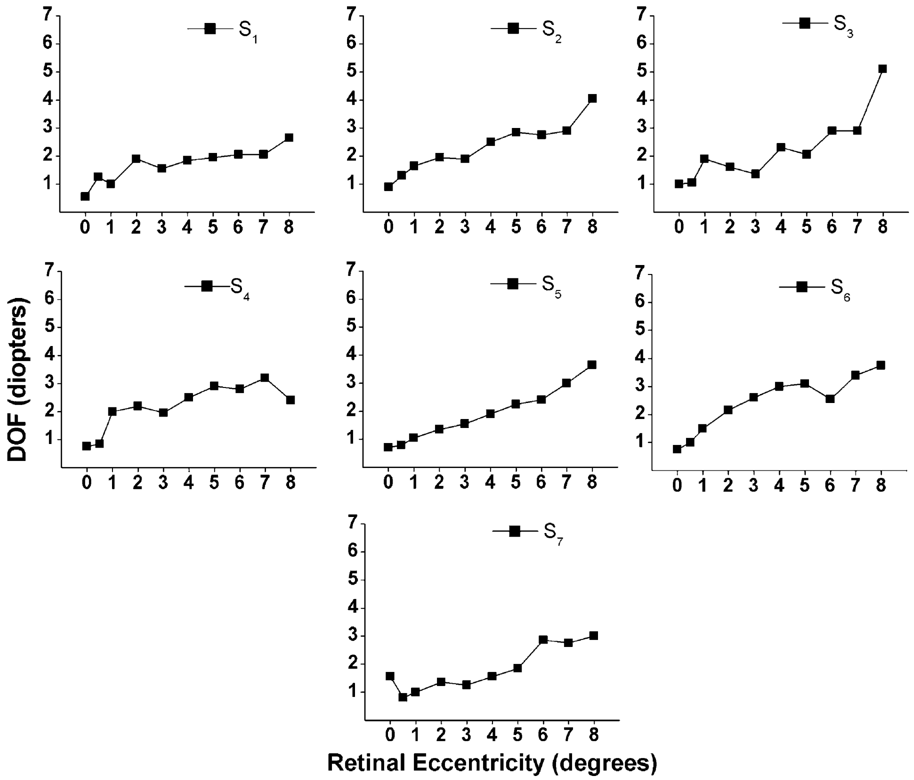

Fig. 3. Depth-of-focus as a function of retinal eccentricity for the seven individual subjects.

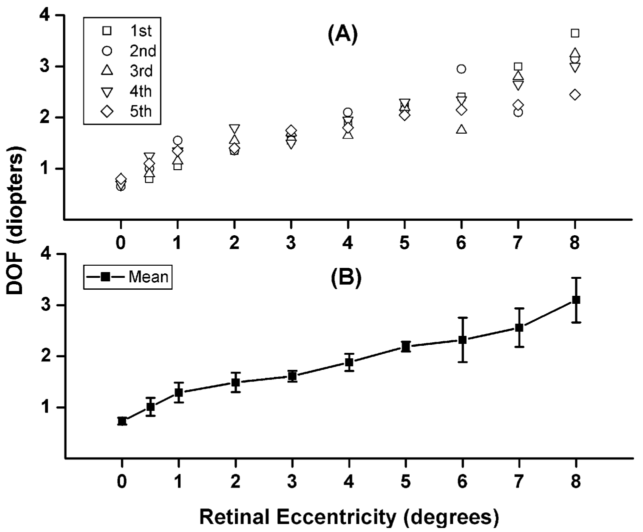

Fig. 4. (A) Depth-of-focus for the five individual test sessions as a function of retinal eccentricity for S_5. The different symbols represent the results from the five individual test sessions. (B) Depth-of-focus as a function of retinal eccentricity for the mean of the five test sessions (±1 S.D.).

0.15 D at the fovea, a range of 0.40 D in the middle region from 0.5 to 5.0°, and a maximum range of 1.1 D at the larger eccentricities of 6.0–8.0°.

3.3. Comparison experiment (with and without cycloplegia)

The depth-of-focus results with and without cycloplegia are presented in Fig. 5 for the two subjects tested (S_2 and S_5). Results were similar both within and between subjects (S_2: from 0.9 to 4.05 D vs. from 0.9 to 4.2 D, and S_5: from 0.7 to 3.65 D vs. from 0.65 D to 3.15 D; with and without cycloplegia, respectively). Although inter-session deviations as large as 1.0 D were found, especially at the larger retinal eccentricities, the overall trends were reasonably similar.

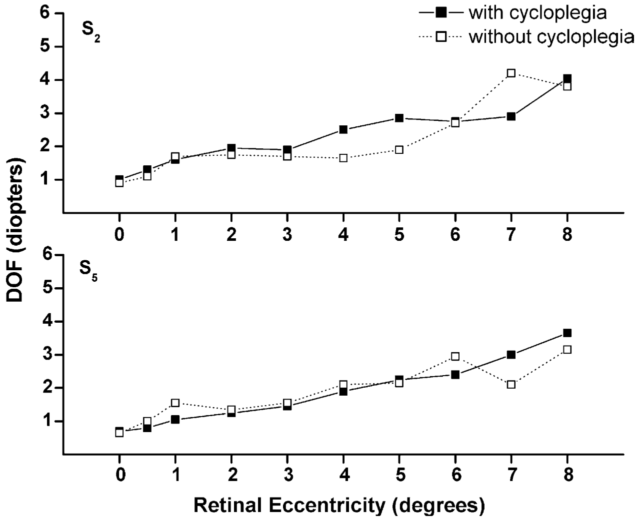

Fig. 5. Comparison of DOF with and without cycloplegia in the two subjects [S_2 (top) and S_5 (bottom)]. Symbols: (■) results with cycloplegia and (□) results without cycloplegia.

4. Discussion

4.1. Comparison with Ronchi and Molesini's study (1975) and other literature findings

Numerous investigations have been conducted to assess the depth-of-focus at the fovea, but only one has studied the depth-of-focus in detail in the far retinal periphery (Ronchi & Molesini, 1975). And, until now, no investigation has been conducted in the near retinal periphery, which may be of particular importance for both blur detection/sensitivity and accommodative responsivity. The findings of the present study fulfill this gap.

There are several substantial experimental differences between Ronchi and Molesini's study (1975) and the present study (Table 1). First, in the present study, the depth-of-focus was measured from the fovea to a retinal eccentricity of 8°. This region is regarded as the near retinal periphery (Candy, Crowell, & Banks, 1998), and it is likely to be important for blur detection/sensitivity and accommodation (e.g., accuracy) (Ciuffreda, 1991, 1998), as well as other vision functions. Second, in Ronchi and Molesini's (1975) study, the stimulus was comprised of a small, monochromatic flashed spot of light. It was presented to the two subjects at different retinal locations along the horizontal meridian. The temporal retina of the right eye was tested at eccentricities of 7°, 15°, and 20°, whereas the nasal retina of the left eye was tested at eccentricities of 30°, 40°, 50°, and 60°. Therefore, with their method, there existed the potential problem of retinal fragmentation and subtle eye differences (e.g., dominance) regarding stimulus presentation and effectiveness. In contrast, in the present study, the depth-of-focus in the near retinal periphery of the same eye for each of the seven subjects was averaged across all meridians at a given eccentricity due to the circular form of the test stimulus. Third, Ronchi and Molesini (1975) used the initial loss of visibility as their criterion by gradually decreasing the luminance of the test flash spotlight. The criterion used in the present study was the discrimination of just detectable blur, which has been used in the measurement of the depth-of-focus in most earlier studies. And, lastly, subjects in the present experiment had their accommodation pharmacologically paralyzed with 1% cyclopentolate HCL to prevent the potential adverse influence from any residual accommodative microfluctuations. However, the present comparison experiment showed no consistently large differences with and without cycloplegia, except at 4°

and beyond where slight increased variability was noted without cycloplegia.

Despite the aforementioned differences, similarities were also present, and hence the two studies could be regarded as complementary in nature, and furthermore provide a reasonable representation of the depth-of-focus over a very large retinal extent. Combining the results of the current study and the data from Ronchi and Molesini's (1975) experiment shows a reasonable continuum (Fig. 6). While piecewise linear regression can be used to describe either the present data or that of Ronchi and Molesini (1975), the best fit curve for the combined data is a first-order rising exponential with decaying slope.

One other related study deserves brief mention (Wang, Thibos, & Bradley, 1997). The effects of refractive error on detection acuity and resolution acuity in the periphery were investigated. No change was found for spatial resolution in far retinal periphery (20°–40°), even when peripheral refractive errors were varied over a large range. The results suggested that the depth-of-focus within this eccentric retinal range was approximately 6 D, in agreement with Ronchi and Molesini's findings (1975) of 5–7 D.

4.2. Foveal comparison of the depth-of-focus with earlier studies

It is also important to compare the present foveal findings with earlier studies. Values for the total depth-of-focus have run the gamut ranging from very small (0.04 D; Oshima, 1958) to very large (3.5 D; Von Bahr, 1952) depending upon target attributes, subject experience, instruction set, etc. [see Ciuffreda (1998), for a detailed review], with typical/most cited values being approximately 0.60–0.80 D (e.g., Campbell, 1957). Our finding (mean = 0.89 D; individual subject range = 0.55–1.55 D) is in the high normal range. However, two excellent studies had comparable data using similar pupil sizes (4.7 and 5.0 mm, respectively): Ogle and Schwartz (1959) found that the value of the total depth-of-focus ranged from 0.63 to 0.94 D, whereas Tucker and Charman's (1975) was approximately from 0.7 to 1.3 D.

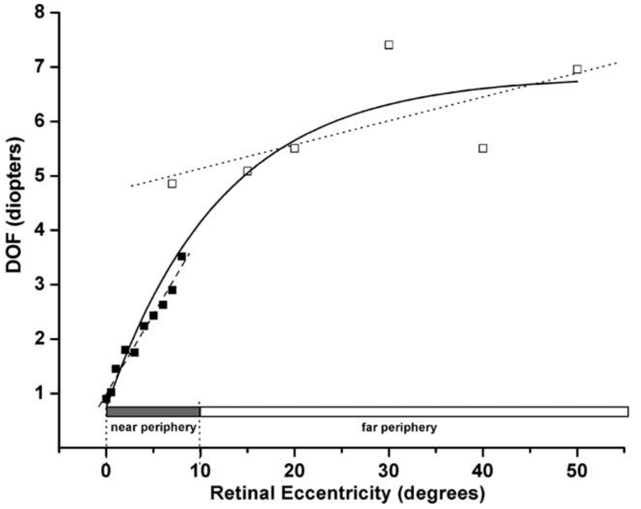

Fig. 6. Depth-of-focus as a function of retinal eccentricity in both near and far retinal periphery. Symbols: (■) present study; (□) Ronchi and Molesini's study. Near retinal periphery linear regression ($y = 0.89 + 0.29x$, $r = 0.98$, $r^2 = 0.96$, ■, dashed line), far retinal periphery linear regression ($y = 4.69 + 0.044x$, $r = 0.68$, $r^2 = 0.46$, □, dotted line), and overall near and far retinal periphery regression ($y = 6.83 - 6.08e^{-x/12.2}$, $r = 0.96$, $r^2 = 0.92$, ■ and □, solid line).

4.3. Possible mechanisms involved in blur detection

We propose four possible mechanisms that may influence the depth-of-focus and related blur perception in the near retinal periphery.

4.3.1. Neurophysiological

At the retinal level, cones and ganglion cells make a primary contribution to the spatial distribution of the depth-of-focus and related blur detection. Studies in human retinal topography (Curcio & Allen, 1990; Curcio, Sloan, Kalina, & Hendrickson, 1990; Østerberg, 1935; Popovic & Sjostrand, 2001; Sjostrand, Olsson, Popovic, & Conradi, 1999) have found that the densities of retinal cones and retinal ganglion cells (RGCs) declined with eccentricity, which resulted in an accompanying increase of the separation between cones and RGCs. In Fig. 7, the depth-of-focus is plotted together with the density of cones and RGCs as a function of retinal eccentricity. Based on the regression curve shown in Fig. 7, the density of cones and RGCs is plotted as a function of the corresponding depth-of-focus values for the respective retinal position across the retina. Figs. 7 and 8 show that the depth-of-focus gradient is less precipitous than that of either cone or ganglion cell density. This finding suggests that while the neurophysiology at the retinal level may play an important role in the determination of the depth-of-focus in the near retinal periphery, it cannot account fully for the blur sensitivity/detection change across the entire retinal extent, especially at the larger eccentricities.

Cortical neurophysiology may also be involved. Animal experiments (Ohzawa, Sclar, & Freeman, 1982) and human studies (Barlow, Kaushal, Hawken, & Parker, 1987; Boynton, Demb, Glover, & Heeger, 1999) have found neurons in the early visual cortex area (V1, V2d, V3d and V3A) involved in contrast gain control. Typically, the response–contrast relation of these cells had a linear suprathreshold portion when the baseline was low, with a saturation effect at higher contrast baselines. However, knowledge in this area is limited, and the effect of retinal eccentricity on the cortical neuronal response remains to be investigated.

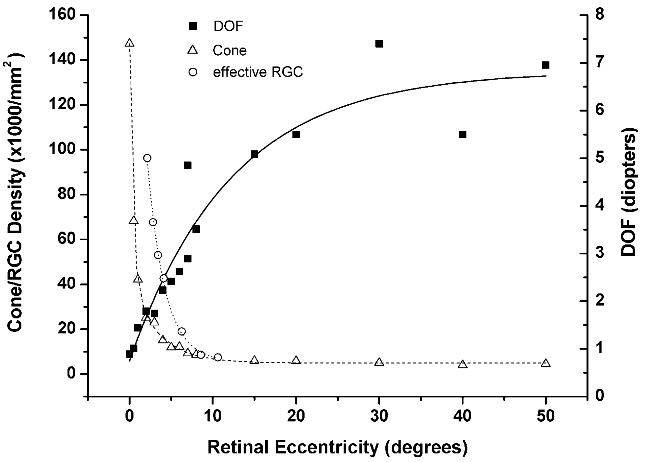

Fig. 7. Depth-of-focus, cone density, and effective RGC density as a function of retinal eccentricity. Symbols: (■) depth-of-focus, (△) cone density, (○) effective RGC density. Regression curve: depth-of-focus ($y = 6.83 - 6.08e^{-x/12.2}$, $r = 0.96$, $r^2 = 0.92$, ■, solid line), cone density ($y = 38.6e^{-x/4.0} + 156.4e^{-x/0.5} + 4.9e^{x/1.5}$, $r = 0.99$, $r^2 = 0.99$, △, dashed line), effective RGC density ($y = 5.7 + 247.9e^{-x/2.1}$, $r = 0.99$, $r^2 = 0.99$, ○, dotted line).

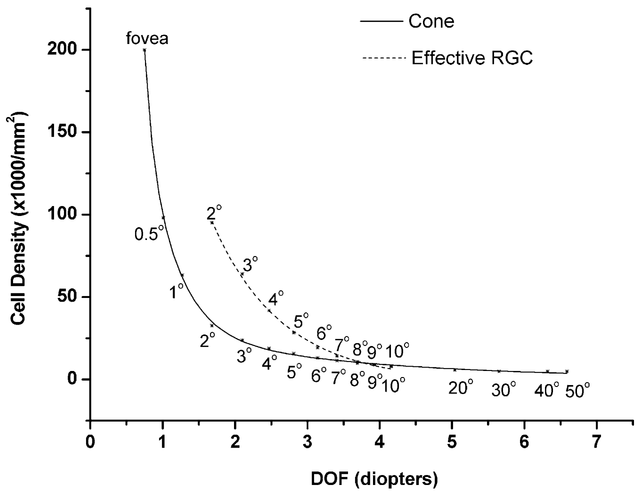

Fig. 8. Cone density and RGC density as a function of depth-of-focus for the respective retinal positions across the retina based on the regression equations in Fig. 7. Regression curve: cone density vs. DOF ($y = 156631e^{-x/0.09} + 767.9e^{-x/0.42} + 37.4e^{x/2.9}$, $r = 0.99$, $r^2 = 0.99$, solid line, retinal eccentricity: 0°–40°), effective RGC density vs. DOF ($y = -1.1 + 550.5e^{-x/0.97}$, $r = 0.99$, $r^2 = 0.99$, dashed line, eccentricity: 2°–10°).

4.3.2. Sharpness overconstancy

A perceptual phenomenon which may also be very important is sharpness overconstancy. It was shown by Galvin, O'Shea, Squire, and Govan (1997) that an edge, which was blurry when an observer looked at it directly (i.e., foveally), appeared sharp when the observer looked away from it (i.e., non-foveally). Galvin et al. (1997) called this phenomenon "sharpness overconstancy" in peripheral vision. After scaling the field sizes of peripheral stimuli by the cortical magnification factor, sharpness overconstancy was found to be independent of retinal eccentricity. Galvin et al. (1997) speculated that an assumption made by the human brain was that edges in the visual world were occlusion borders, and therefore, sharp. Based on this higher-level explanation, when a blurred edge is presented in the retinal periphery, the resulting percept seems to be a compromise between the incoming information and the percept of a sharp edge. Thus, when the incoming information about an edge in the periphery is degraded for whatever reason, a neural template of an edge derived from previous visual experience of its sharp appearance is applied. An important implication of peripheral sharpness overconstancy to the present investigation is that more retinal defocus may be necessary to create the perception of blur in the retinal periphery.

4.3.3. Visual optics

Visual optics must also be taken into consideration as a third possible contributory factor. The optical quality of the human eye is worse in the periphery as compared with central vision. Both monochromatic and chromatic aberrations have been shown to increase with retinal eccentricity (Artal, Marcos, Iglesias, & Green, 1996). These factors also provide important directional cues to control accommodation (Campbell & Westheimer, 1959).

There have been several primary investigations in this area. Three experiments were related to astigmatism in the retinal periphery. The findings of Ferree and Rand (1933), and Michel and Lamont (1974), suggested that astigmatism increased in the far retinal periphery, while remaining relatively constant in the near retinal periphery up to 10°. More recently, the study of Gustafsson, Terenius, Buchheister, and Unsbo (2001) showed a similar result. They found a large increase in astigmatism in the far retinal periphery; mean astigmatism increased by more than 7 D at an eccentricity of 60°. However, very little change was evident in the near retinal periphery up to an eccentricity of 10°. Investigations of monochromatic aberration and chromatic aberration as related to retinal eccentricity suggested the same. For example, in a study of Navarro, Artal, and Williams (1993), the overall monochromatic aberration, as defined by root-mean-square (rms) values of the wave-front error, increased slowly from the fovea in approximately a linear fashion. At an eccentricity of 40°, it was twice as large as that found at the fovea. At a retinal eccentricity of 10°, however, it was increased by only 25% as compared with its foveal value. Ogboso and Bedell (1987) found that lateral chromatic aberration increased from less than 1 min arc at the fovea to about 30 min arc nasally and 13 min arc temporally, at an eccentricity of 60°; however, within the central 10°, it remained relatively small (~2 min arc) and nearly constant. In addition, these studies suggested that in the near retinal eccentricity, the intersubject difference was significantly smaller as compared with the differences between eccentricities. Therefore, the effects of peripheral refractive variance between subjects were not included in our analysis. All of these peripheral optical changes produce retinal-image degradation, and may be of importance in blur detection in the far retinal periphery, but relatively small or even negligible with respect to the foveal and near retinal periphery.

4.3.4. Visual attention

Lastly, the spatial distribution of visual attention and the shift in visual attention across the retina should be considered. Shulman, Sheehy, and Wilson (1986) studied the gradient of spatial attention across the retina up to an eccentricity of 24.5°. Subjects were asked to look monocularly at a fixation point, and then a cue was presented at a certain eccentricity. They were instructed to attend, without moving their eyes, to the cued location. Once the cue was extinguished, a target light appeared, and the subject depressed a key as soon as it was detected. It was found that when the test target location was the same as the cue location, there was a trend for longer reaction times, thus suggesting compromised visual attention as retinal eccentricity increased. Saarinen (1993) compared subject's visual attention shift at the fovea and in the near retinal periphery. Two numerals were flashed sequentially. The first was presented at the fovea, and the second could appear either at the fovea or at an eccentricity of 7°. After each numeral pair disappeared, subjects were asked to report the first and the second numeral. The performance of the subjects was impaired when the second numeral appeared in the periphery, which suggested that it was difficult for attentional shift to occur from the fovea to an extrafoveal location without a correlated gaze shift. More recently, neuroimaging analysis (fMRI) of human brain activity has identified dynamic attentional sites. Brefczynski and DeYoe (1999) showed that human cortical topography of the attention-driven activity was in precise register with the topography of the visually-directed attentional locus. Subjects were instructed to maintain their gaze, while performing a task requiring shifts of visual attention from one specific location to the another within a dense array of targets and distractors. As visual attention shifted from central vision to the far retinal periphery (28°), the locus of cortical enhancement exhibited correlated attentional shift anteriorly and progressively away from the occipital pole. This process involved both striate (V1) and extrastriate cortex. All of the above studies suggested that visual attention became compromised with increased eccentricity, which could contribute to the relative insensitivity of blur perception and the resultant progressive increased depth-of-focus in the retinal periphery.

4.4. Comparison of the depth-of-focus with other selected visual functions in the near retinal periphery

For a better understanding of the change of depth-of-focus with retinal eccentricity, and possible similar relations of other vision functions with eccentricity, visual

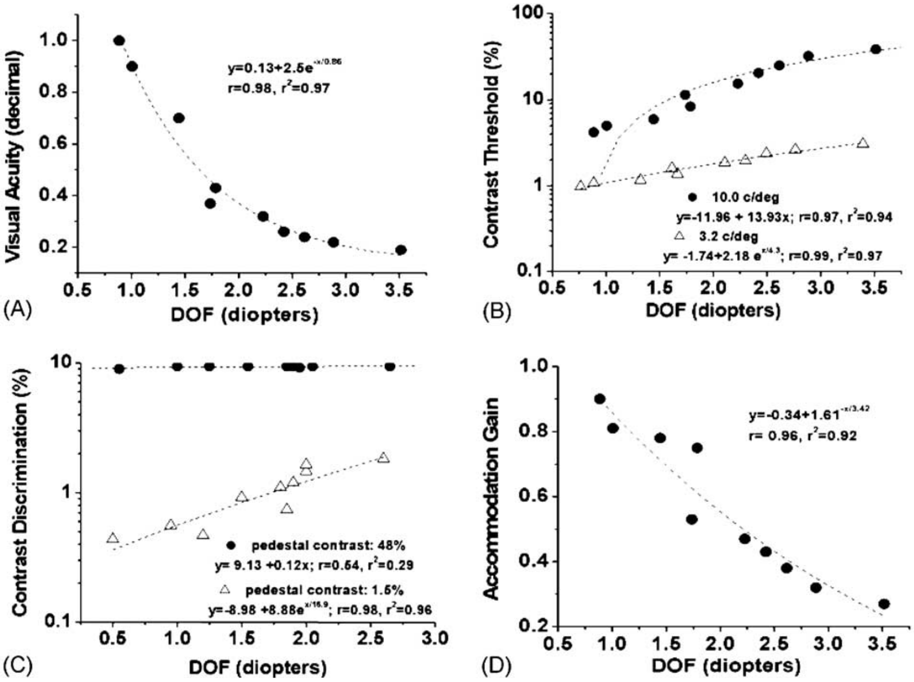

Fig. 9. Relation of the depth-of-focus to other selected vision functions across the human retina at eccentricities from 0° to 8°. (A) visual acuity; (B) contrast threshold; (C) contrast discrimination and (D) accommodation.

acuity (Ludvigh, 1941), contrast threshold (Pointer & Hess, 1989), contrast discrimination (Legge & Kersten, 1987), and accommodative gain (Bullimore & Gilmartin, 1987) were plotted as a function of the depth-of-focus value for corresponding retinal eccentricities in the near retinal periphery (Fig. 9). Fig. 9A, B, and D showed that depth-of-focus, visual acuity, contrast sensitivity, and accommodative gain each became worse with increasing eccentricity in the near retinal periphery. In Fig. 9C, contrast discrimination at low suprathreshold baseline levels increased with retinal eccentricity, while contrast discrimination at high baseline levels (as in present experiment) remained relatively constant.

4.5. Basic and clinic implications

Knowledge of the depth-of-focus in the near retinal periphery has important basic implications. As indicated by the depth-of-focus values in the present experiment, both blur detection and blur sensitivity remained reasonably good in the near retinal periphery. Thus, the near retinal periphery, and possibly also the far retinal periphery, may contribute by different extents to the overall detection and perception of blur. A weighted neural pooling process across the entire retina may be involved to produce the aggregate blur response and correlated accommodative response (Ciuffreda, 1991, 1998).

There are also important clinical implications. First, in patients with central retinal diseases (e.g., macular degeneration) in which the fovea and contiguous regions are adversely affected, the perception of blur will be impaired, as only the less sensitive near and possibly far retinal periphery can contribute to the process (Legge et al., 1987). Training of eccentric viewing in such patients might be performed to stabilize their gaze as close as possible to the nearest edge of the scotoma, where residual blur perception and accommodative responsivity are maximal (Hall & Ciuffreda, 2001). In addition, blur sensitivity in the periphery should be taken into consideration in the design of ophthalmic lenses and refractive surgery. Because blur sensitivity declines with retinal eccentricity, maximizing optical quality in the periphery may not be as critical as at the fovea. Knowledge of the depth-of-focus across the retina, especially in the near retinal periphery, will serve as a reference for lens optical design configurations in peripheral vision (Han, Ciuffreda, Selenow, & Ali, 2003; Han et al., 2003; Selenow, Bauer, Ali, Spencer, & Ciuffreda, 2002). And, lastly, the present findings may have implications with respect to myopia. It is believed that retinal defocus is an important environmentally-based myopigenic factor (Hung & Ciuffreda, 2002; Ong & Ciuffreda, 1997). Since the depth-of-focus increases with retinal eccentricity, retinal defocus and related blur tolerance may act to modulate eye growth differentially over the retinal extent.

Acknowledgements

We thank Drs. Jerome Feldman, Barry Lee, Milton Katz, Jordan Pola, Mark Rosenfield, William Swanson, and Harry Wyatt, as well as the anonymous reviewers, who provided us with many invaluable comments and suggestions. We would also like to acknowledge the assistance of Drs. Kathy Aquilante, Neera Kapoor, and Mark Rosenfield, who performed the clinical vision screening and cycloplegia administration on the subjects.

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