Journal of Modern Optics
2011, 1–7, iFirst

Taylor & Francis
Taylor & Francis Group

Clinical importance of spherical and chromatic aberration on the accommodative response in contact lens wear

M. Wahlberg[a]*, A. Lindskoog Pettersson[a], R. Rosén[b], M. Nilsson[a], P. Unsbo[b] and R. Brautaset[a]

[a]*Unit of Optometry, Department of Clinical Neuroscience, Karolinska Institutet, Box 8056, S-104 35, Stockholm, Sweden;* [b]*Biomedical and X-ray Physics, Department of Applied Physics, Royal Institute of Technology, Roslagstullsbacken 21, 10691 Stockholm, Sweden*

(*Received 30 November 2010; final version received 16 February 2011*)

The aim of this study was to evaluate the accommodation response under both mono- and polychromatic light while varying the amount of spherical aberration. It is thought that chromatic and spherical aberrations are directional cues for the accommodative system and could affect response time, velocity or lag. Spherical aberration is often eliminated in modern contact lenses in order to enhance image quality in the unaccommodated eye. This study was divided into two parts. The first part was done to evaluate the amount of spherical and other Zernike aberrations in the unaccommodated eye when uncorrected and with two types of correction (trial lens and spherical-aberration controlled contact lens) and the second part evaluated the dynamic accommodation responses obtained when wearing each of the corrections under polychromatic and monochromatic conditions. Measurements of accommodation showed no significant differences in time, velocity and lag of accommodation after decreasing the spherical aberration with a contact lens, neither in monochromatic nor polychromatic light. It is unlikely that small to normal changes of spherical aberration in white light or monochromatic mid-spectral light affect directional cues for the accommodative system, not in white light or mid-spectral monochromatic light, since the accommodative response did not show any change.

Keywords: spherical aberration; accommodation; response; lag; contact lenses

1. Introduction

Accommodation is the adjustment of the refractive power of the eye. Within the accommodative system, different components contribute to the final accommodative response. These components are normally described as reflex accommodation, tonic accommodation, proximal accommodation, convergence accommodation and adaptation of accommodation [1–3]. However, when fixation is changed from one distance to another, reflex accommodation is the largest and most important component of accommodation in clearing the image, i.e. reflex accommodation is blur-driven and acts in response to blur [3,4]. The amount of blur is therefore a cue to reflex accommodation in order to determine the amount of change in accommodation that is needed. However, cues are also needed for direction, i.e. in order to know if accommodation has to be increased or reduced. The main directional cues for the accommodative system are thought to be chromatic aberration (CA) and spherical aberration (SA) [5–8], but even proximity has been suggested, and under binocular conditions directional information is obtained through the convergence accommodative cross-link [9,10]. If all directional cues are removed, the accommodative system would respond directionally with a chance of 50% incorrect, respectively 50% correct, response [9]. Previous studies of Troelstra et al. [11] have showed that it is possible for the accommodative system to operate correctly on an error signal with the cues present (spherical and chromatic aberration, astigmatism and normal fluctuation of the lens) even if the direction or amount of the stimuli is unknown. Van der Wildt et al. [12] have shown that the anticipation of the stimuli could act as a cue and guide the system to the right direction of accommodation.

SA refers to the lack of coincidence of focus between the peripheral rays and the central rays. SA will change almost linearly with the level of accommodation, changing from a positive value (i.e. the peripheral rays come to a focus in front of the central rays) in the unaccommodated eye to becoming negative (i.e. the central rays come to a focus in front of the peripheral rays) in the accommodated eye [6,8,13]. Previous studies have come to different conclusions regarding the effect of changing SA on the accommodative response. Gambra et al. [14] and Theagarayan et al. [15] have shown that by

*Corresponding author. Email: marika.wahlberg@ste.ki.se

ISSN 0950–0340 print/ISSN 1362–3044 online

DOI: 10.1080/09500340.2011.565374
http://www.informaworld.com

increasing the amount of negative SA to a level higher than normally found in the human eye, the lag of accommodation reduces and therefore the accommodative response improves. However, this effect was not found by He et al. [8].

Currently, with refractive surgery and modern contact lenses, SA is often eliminated in order to enhance image quality in the unaccommodated eye. This is done without knowing the effect that it might have on the accuracy of accommodation. In a natural visual environment, accommodation is able to change relatively fast. The total time of accommodation can be specified as reaction time and response time. Previous studies have showed that the reaction has the constant values of 0.29 ± 0.07 s [16,17], while response time depends on the amount of accommodation that is needed and has been found to be between 0.74 ± 0.30 s [17] and 0.87 ± 0.12 s [16] when the stimulus is 2.0 D. Studies have revealed that the response time is the same binocularly and monocularly [16]. Furthermore, the velocity by which accommodation can be changed has been found to be $\sim$2.2 D/s (1.4–3.1 D) [17].

Theoretically, the total longitudinal CA for all visible wavelengths will be more than 2 D [18], however, for wavelengths between 486–656 nm it will be about 1 D, and even less at low luminance levels [19]. In polychromatic light and under photoptic conditions the eye is most sensitive to light of 555 nm [20]. Using monochromatic light will eliminate directional information to the accommodative system from the CA and could affect the accuracy of accommodation [10,21,22], e.g. response time, velocity and lag.

The aim of the present study was to evaluate different aspects of the accommodation response under both mono- and polychromatic light while varying the amount of spherical aberration, since the precise role of SA and CA as directional cues in the control of accommodation is still unknown.

2. Materials and methods

This study was divided in two parts. Part one was done in order to evaluate the amount of SA in terms of the fourth-order Zernike coefficient, in the uncorrected eye, with trial lenses and with spherical-aberration-controlled contact lenses. Part two was done to evaluate the accommodative response under both mono- and polychromatic light while varying the amount of spherical aberration.

Twenty subjects aged between 21 and 30 years (mean age 25.0 ± 2.37 SD) were recruited among students at the School of Optometry, Karolinska Institutet, Stockholm, Sweden.

In order to be included in the study the following criteria had to be met: (a) refractive error between -10 D $\pm$ 6 D (in order to be in range of the power of the contact lenses) and astigmatism less than 0.75 D (in order to achieve a high level of visual acuity when corrected with non-toric contact lenses); (b) younger than 35 years of age (in order to ensure a reasonable amplitude of accommodation); (c) no ocular pathology or systemic disorder; (d) not taking any drugs with a known effect on accommodation or any other aspects of vision; (e) distance visual acuity of 1.0 or better monoculary; and (f) no corneal abnormalities based on keratometry readings and slit lamp inspection. Ethical approval was given by the local ethical committee and the study adhered to the declaration of Helsinki. The patient received written information and informed consent was obtained from all the participants.

The subjects had their dominant eye refracted under binocular conditions, i.e. non-dominant eye being fogged, in order to relax accommodation. The spherical refraction, i.e. spherical equivalent, was determined as the most positive spherical power that gave the highest visual acuity. In the text below, this refraction is called Trial Frame Correction (TFC) since the refraction was performed in a trial frame. The subjects were fitted with a PureVison contact lens, which is a single-vision contact lens intended to correct spherical aberration by $-0.15\,\mu$m in all powers over a 6.0 mm pupil [23] (Bausch & Lomb Incorporated Rochester, NY, US). The power of the lenses fitted was drawn on the basis of the TFC, i.e. no astigmatism was corrected. The lenses were inspected for acceptable movement, centration and corneal coverage. After twenty minutes of adaptation (Bausch & Lomb guidelines) to the lenses, a spherical over-refraction was performed. If necessary, the lens power was adjusted to achieve best visual acuity. In the text below, this refraction is referred to as spherical-aberration-controlled contact lens refraction (SACL).

2.1. Part one

When included, the subjects had their aberrations measured in the dominant eye with a Zywave aberrometer (Bausch & Lomb, Surgical, Salt Lake City, Utah, US), which is based on the Hartman–Shack wavefront technique [24]. Wavefront aberrations were measured in the uncorrected eye (UC), as well as with TFC and with SACL correction. The aberrations were measured in the relaxed eye, i.e. target set at infinity. Within a Zywave measurement, five consecutive wavefront measurements were made, three of which were used to calculate the mean aberrations [25,26]. These wavefront measurements were made three times, in which a total of nine used wavefront readings were obtained. The average wavefront aberration was then calculated. Aberration measurements were performed in a dark room and the subjects were covered with a dark cloth to get maximum pupil size without the use of dilatation. Based on the wavefront data for the maximum pupil size obtained with the Zywave, analytical scaling of the data was done using the method described by Lundström and Unsbo [27] to calculate the aberrations for pupil sizes 4.0, 5.0 and 6.0 mm.

2.2. *Part two*

The PowerRefractor (MultiChannel Systems, Reutlingen, Germany – now manufactured by PlusOptix, Nürnberg, Germany) was used to measure ocular accommodation. The PowerRefractor allows continuous measurement (25 Hz) of refraction/accommodation, eye position and pupil size, and has been described in detail elsewhere [28].

The PowerRefractor measurements were made in all subjects after aberrometry, both wearing either the TFC or SACL correction. During measurements, fixation was maintained on a printed text (equivalent to 0.6 Snellen visual acuity) located at 1.14 m from the eye, at the same distance the PowerRefractor was placed. The 2× extension lens was used and refraction/accommodation was obtained in only one eye. The measurement was completed in both polychromatic and monochromatic light (589 nm). Monochromatic light was used to eliminate CA as a directional clue to accommodation [21,22].

The PowerRefractor was placed in front of the subject and a head and chin rest was used to maintain a constant distance. The TFC lenses were placed in a trial frame with the non-dominant eye occluded. The subjects were instructed to look at the printed text and to keep it clear at all times. For the accommodation measurement two examiners were required, one who operated the PowerRefractor and one who inserted the accommodative stimulus. The accommodative stimulus was a –2.0 D lens, which also was placed in the trial frame. The subjects fixated the target for four seconds to obtain a steady-state level of accommodation [29]. The accommodative stimulus was then inserted in front of the eye for four seconds, after four seconds the lens was removed and the subjects were asked to keep looking at the target for another four seconds. This sequence was repeated three times with a total time of 28 seconds, only data from the increase in accommodation – i.e. only when the –2.0 D was introduced and not when it was removed – were calculated. The accommodation measurement sequence was done under both polychromatic and monochromatic light

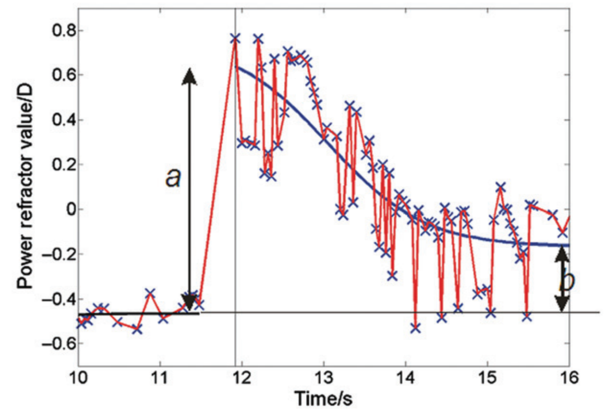

Figure 1. An example of the accommodative curve for one subject. At $t = 11.5$ seconds the –2 D lens is placed in front of the eye. The eye then accommodates, with the final state reached at $t = 15$ seconds. (The colour version of this figure is included in the online version of the journal.)

condition. The fixation target was illuminated and the average surface illuminance was 43 lx and 60 lx with the poly- and monochromatic sources, respectively. The entire sequence was repeated with SACL correction.

2.3. *Calculations*

An example of the data for one subject can be seen in Figure 1. At $t = 11.5$ seconds the –2 D lens was placed in front of the measured eye, and therefore the refractive state plotted by the PowerRefractor immediately changes, before any accommodation occurs. Surprisingly, the instantaneous shift a in the graph was not the full 2 D, but rather averaged around 1.5 D, which might indicate a limitation of the PowerRefractor when performing over-refraction.

Therefore, the accommodative data were scaled up so that the shift a for each individual became 2.0 D, with the same factor applied to the lag of accommodation b. In the example shown, the scaling factor is 2/(0.64–(–0.465)) = 1.81, a bit larger than the average of 1.3. The shape of the accommodative response curve was then modelled to be a sigmoid function $Acc = K_0 + \frac{K_1 - K_0}{1+e^{(t_0-t)/s}}$ where K_0 is the initial accommodative state (about 0.64 D in the example figure before scaling, 1.16 D after scaling), K_1 the final state (–0.16 D before scaling, –0.29 D after scaling), t the time, t_0 the time when half of the accommodation has occurred (13.5 seconds in the example) and s the time constant of the curve [30]. The parameters K_0, K_1, t_0 and s were fit to the data for each individual stimulation of accommodation with the method of least squares. The total accommodation of the eye was taken as $K_1 - K_0$ and the lag $2 - (K_1 - K_0)$, with total accommodation 1.45 D and lag 0.55 D in the example.

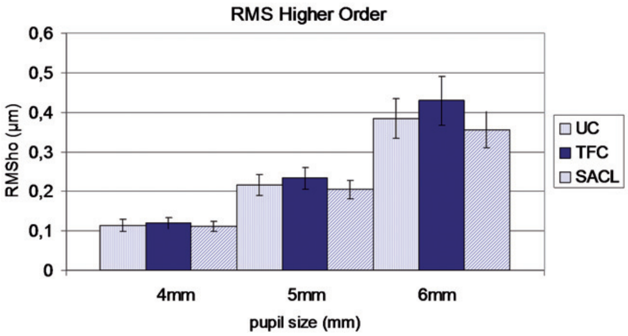

Figure 2. Root Mean Square (RMS) (µm ± 95% confidence intervals) uncorrected (UC); with trial frame correction (TFC) and with spherical-aberration controlled contact lens correction (SACL) over a 4, 5 and 6 mm pupil. (The colour version of this figure is included in the online version of the journal.)

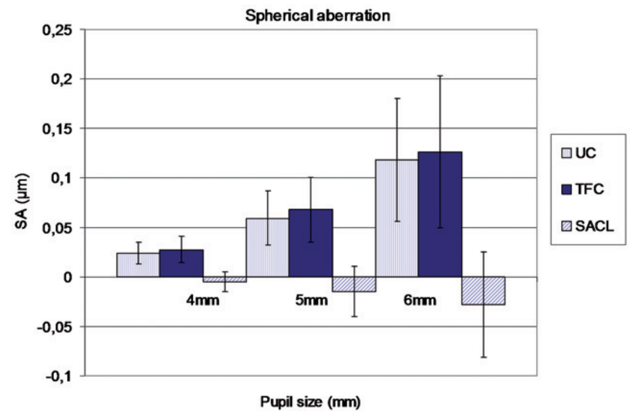

Figure 3. Mean spherical aberration (SA) (µm ± 95% confidence intervals) uncorrected (UC); with trial frame correction (TFC) and with spherical-aberration controlled contact lens correction (SACL) over a 4, 5 and 6 mm pupil. (The colour version of this figure is included in the online version of the journal.)

In the fitted sigmoid function, it is the time constant s that determines the response time. Estimation of the response time was done in accordance with the method chosen by Fernández and Artal [30]: the starting point was chosen as the time when 2% of accommodation was reached and the end point when 98% of the response was reached, corresponding to a total of 7.8 s. The peak velocity of accommodation was calculated with the derivative at $t = t_0$ as $(K_1 - K_0)/2s$, i.e. a small value of the time constant s will mean a tight curve and a high velocity, whereas a large value will mean a low velocity.

3. Results

3.1. Statistics

For statistical analysis of the aberration and accommodation data, a one way analysis of variance (ANOVA) with Tukey–Kramer multiple comparisons post hoc test (InStat GraphPad) was used with a significant level of 0.05.

3.2. Part one: aberrations

The mean refraction was –0.92 D (±1.96 SD). The average amount of RMS of higher-order aberrations (RMSho) in the UC, with TFC and with SACL correction for 4.0, 5.0 and 6.0 mm pupils can be seen in Figure 2.

Statistical analysis showed no difference in the amount of RMSho comparing UC, TFC or SACL corrections ($p > 0.05$) for all three pupil sizes. Figure 2 shows that the aberration controlled contact lens did not significantly change the total average amount of higher-order aberrations.

The average amount of SA in the UC, with TFC and with SACL correction for 4.0, 5.0 and 6.0 mm pupils can be seen in Figure 3.

Statistical analysis showed no difference in the amount of SA comparing UC and TFC corrections ($p > 0.05$) for all three pupil sizes. However, SA with SACL correction was found to have a statistically significant negative shift ($p < 0.001$) as compared with both UC and TFC correction over all three pupil sizes. Figure 3 shows that the aberration-controlled contact lens decreased the spherical aberration to negative values.

3.3. Part two: accommodation

Values for the accommodation measurement results: lag of accommodation, response time and velocity can be seen in Table 1. The analysis of the time for the subjects to accommodate from 2% to 98%, i.e. accommodation response time, showed no significant difference ($p > 0.05$) between TFC and SACL corrections, not in chromatic or monochromatic light. Furthermore, no statistically significant difference could be found for the peak velocity and the size of the accommodative lag between TFC and SACL corrections under the two light conditions.

The mean pupil size as obtained with the PowerRefractor under the two lighting condition can be seen in Table 2. The slightly smaller pupil size in monochromatic light was not statistically different from the pupil size in polychromatic light.

Table 1. Mean (±SD) values of accommodation.

	Lag of accommodation	Response time	Velocity
	Diopters	Seconds	Diopters/seconds
TFC–polychromatic	0.47 ± 0.44	1.52 ± 0.86	2.48 ± 1.22
TFC–monochromatic	0.30 ± 0.34	1.33 ± 0.56	2.22 ± 1.14
SACL–polychromatic	0.90 ± 0.81	1.23 ± 0.77	1.94 ± 1.19
SACL–monochromatic	0.34 ± 0.56	1.27 ± 0.47	2.27 ± 1.07

Lag of accommodation: the difference between maximal accommodation and the strength of the accommodation stimulus. Response time: between 2% and 98% of accommodation response. Velocity: the peak velocity was calculated from the fitted sigmoid curve. Trial frame correction (TFC), spherical aberration controlled contact lens (SACL).

Table 2. Average pupil size before accommodation under different light conditions.

	Pupil size	
	Polychromatic light	Monochromatic light
TFC	5.62 ± 0.65	5.00 ± 0.84
SACL	5.43 ± 0.60	4.91 ± 0.78

Using the data for individual subjects, linear regression fits were made for SA/velocity and total RMS/velocity under both polychromatic and monochromatic conditions. The aberration values used were those for the uncorrected eye over a 5 mm pupil. For SA/velocity, the R2 values were 0.02 and 0.06 in white and monochromatic light, respectively, the corresponding R2 values for RMS/velocity being 0.005 and 0.08.

4. Discussion

The aim of the present study was to evaluate different aspects of the accommodation response under both mono- and polychromatic light while varying the amount of spherical aberration.

In the first part, the average spherical aberration found at distance in the uncorrected eye was positive, at 0.060 μm over a 5 mm pupil, and the average RMSho was 0.217 μm under the same condition. The result for spherical aberration is similar to results found in previous studies [6,31–33]. At all pupil diameters, SA with SACL was shifted to a more negative value than was found with the UC eye or the TFC. These results are in line with Lindskoog et al. [31], who found that the aberration-controlled contact lens reduced the spherical aberration or tended to overcorrect. The results are also close to what the manufacturer claims [23] (Bausch & Lomb) over a 6 mm pupil.

With the PowerRefractor, measurements of pupil size were obtained while measuring the accommodative response. Pupil size was found to be slightly smaller in monochromatic light; however, the difference was not statistically different. The smaller pupil size in monochromatic light is most likely an effect of the luminance level being higher with the monochromatic source as compared with the polychromatic light source. This small difference in pupil size is unlikely to have made any influence on the accommodative measurements under the different lighting conditions.

The PowerRefractor measured the immediate change in refraction to be lower than the actual 2.0 D by which the stimulus was changed with the inserted negative lens. The response measured with the PowerRefractor was therefore recalculated. However, all conclusions were identical when the data were not scaled, i.e. no dependence on spherical aberrations or on whether mono- or polychromatic light was used. The incorrect step in refraction measured with the PowerRefractor was surprising, and was not due to accommodation. Subsequent tests with dilated eyes (using Tropicamid) and lenses of different powers showed the same phenomenon. Our conclusion is that caution should be advised when performing over-refraction with this instrument. The same method was used under all four conditions to find the difference in accommodation response even if the method used had some weakness. However, in this study, the aim was to compare accommodation in four different conditions, not to find an absolute value. Furthermore, the response time, velocity and lag of accommodation that we found are well in line with previous findings, indicating that the potential limitations with the method should be very small and insignificant [16,17,34].

The accommodation measurements were done under two different levels of spherical aberration and with a pupil size of about 5 mm. Measurements of accommodation showed no significant differences in time, velocity and lag of accommodation after decreasing the spherical aberration with the PureVision contact lens in both monochromatic and polychromatic light. The change in SA does not change the accommodative response and this is similar to what was found by Atchison et al. [35] and He et al. [36], and indicates that spherical aberration is not a strong, directional cue to accommodation, at least when accommodation is changed in large steps. However, this is not in line with the recent results of Theagarayan et al. [15] who found that the accommodative lag was affected when altering spherical aberration. On the other hand, the negative changes in SA induced by Theagarayan et al. [15] were much larger than those induced in the present study and had a magnitude much greater than that normally found in the human eye. Since SA is the optical effect of peripheral rays not coming to focus in the same point as central rays, it is difficult to see how this can directionally guide accommodation for a target that is 2.0 D out of focus, since the SA refraction pattern is small and far out of focus. This might be why we and others have found no effect on accommodation when changing the amount of normal values of SA. Therefore, it might be that, in most eyes where the amount of SA is small, SA is rather a cue for maintaining a steady state level of accommodation rather than a directional cue for large changes in accommodation [37]. Fernandez and Artal [30] found that correcting aberrations increased the response time and decreased the peak velocity but the precision of the accommodation was not affected. In the present study the amount of SA was about one fourth of the total RMSho in the uncorrected eye and about one tenth or less with SACL (Figures 2 and 3). The contact lens almost corrects the SA but has little impact on the total RMSho, which indicates that it is possible to change SA with a SACL but still the accommodation will be largely unaffected.

When comparing the accommodative response time, velocity and lag of accommodation under monochromatic and chromatic conditions, no differences could be found in this study. These results are in line with Troelstra et al. [11] who found that spherical and chromatic aberrations were not important to determine the initial direction of accommodation. In contrast, Aggarwala and colleagues [21,22] found that accommodation under monochromatic conditions was not as accurate as accommodation under chromatic conditions which indicates the importance of CA as a cue for accommodation. The difference in our findings could be due to the use of step rather than oscillatory stimuli, as used by Aggarwala et al. [21], since the stationary target stimulates voluntary accommodation. Also, the use of only a mid-spectral monochromatic light source, compared with Aggarwala et al. [21] who used 10 different wavelengths, could affect the results of accommodation in relationship to CA.

When stimulating accommodation, Fernandez et al. [30] used a 2.0 D lens with 1.5 D stimuli in direction from far to near, respectively, which are known by the subjects, and which are similar to the stimuli used in the present study. This means that the stimulus change was predictable in both magnitude and direction. It is possible then that subjects could learn what sort of change of accommodation that they had to make and that this could help to maintain the same dynamic response profile. To avoid learning effects, several different lenses with different negative powers could have been used, so that subjects could not anticipate whether a positive or negative response was required.

However, a pilot study with five subjects was done prior to the main experiment with accommodation stimuli of 1 D steps and random direction. We were not able to find any learning trend in the pilot study, which is why the stimuli of 2 D, in only one direction, for accommodation, were chosen. These results are similar to the findings of Troelstra et al. [11] who found that the average error is about 50% and that there is no indication of trends or learning. However, the predictable accommodation could be a weakness of the present study and could possibly explain the difference in result as compared with Aggarwala et al. [21,22].

In combination, our results indicate that both SA and CA most likely do not contribute as the only directional cues for accommodation when accommodation is changed in larger steps, since eliminating each one at a time or both does not alter the accommodative response. It is therefore likely that the accommodative system uses other cues for directional control. Under monocular conditions, proximal information, i.e. monocular cues to distance such as parallax motion, perspective, overlap, etc., are the most likely cues for directional control. Under binocular condition, these monocular cues are combined with input from the vergence system, i.e. convergence accommodation cross-links information, to yield the directional cues to accommodation.

5. Conclusions

It is unlikely that small to normal changes of the amount of spherical aberration affect directional cues for the accommodative system, not in white light or mid-spectral monochromatic light, since the accommodative response was not affected by the induced change. Non-custom-made contact lenses with aberration control will therefore not change the accommodative response. The accommodative system is likely also to rely on proximal and vergence cues for directional control.

References

[1] Heath, G.G. *Am. J. Optom. Arch. Am. Acad. Optom.* **1956,** *33,* 569–578.

[2] Miles, F.A. *Rev. Oculomot. Res.* **1985,** *1,* 81–94.

[3] Ciuffreda, K.J. *Optometry* **2002,** *73,* 177–198.

[4] Hung, G.; Ciuffreda, K.J.; Rosenfield, M. *Ophthalmic Physiol. Opt.* **1996,** *16,* 31–41.

[5] Applegate, R.A. *Optom. Vis. Sci.* **2004,** *81,* 167–177.

[6] Cheng, H.; Barnett, J.K.; Vilupuru, A.S.; Marsack, J.D.; Kasthurirangan, S.; Applegate, R.A.; Roorda, A. *J. Vis.* **2004,** *16,* 272–280.

[7] Chin, S.; Hampson, K.; Mallen, E. *Clin. Exp. Optometry* **2009,** *92,* 227–237.

[8] He, J.C.; Burns, S.A.; Marcos, S. *Vision Res.* **2000,** *40,* 41–48.

[9] Ciuffreda, K.J. *Vision and Visual Dysfunction, Vol. 1. Visual Optics and Instrumentation*: Chairman, N., Ed.; Macmillan Press: UK, 1991; Chapter 11.

[10] Fincham, E.F. *Br. J. Ophthalmol.* **1951,** *35,* 381–393.

[11] Troelstra, A.; Zuber, B.L.; Miller, D.; Stark, L. *Vision Res.* **1964,** *4,* 585–594.

[12] Van der Wildt, G.J.; Bouman, M.A.; Van De Kraats, J. *Opt. Acta* **1974,** *21,* 843–860.

[13] Plainis, S.; Ginis, H.S.; Pallikaris, A. *J. Vis.* **2005,** *23,* 466–477.

[14] Gambra, E.; Sawides, L.; Dorronsoro, C.; Marcos, S. *J. Vis.* **2009,** *9,* 1–15.

[15] Theagarayan, B.; Radhakrishnan, H.; Allen, P.M.; Calver, R.I.; Rae, S.M.; O'Leary, D.J. *Ophthal. Physiol. Opt.* **2009,** *29,* 65–71.

[16] Heron, G.; Winn, B. *Ophthal. Physiol. Opt.* **1989,** *9,* 176–183.

[17] Tucker, J.; Charman, W.N. *Am. J. Optom. Physiol. Opt.* **1979,** *56,* 490–503.

[18] von Helmholtz, H. *A Treatise on Physiological Optics, Vol. 3*; Optical Society of America: Southall, New York, 1924; reprinted Dover Publication: New York, 1962.

[19] Bradley, A. *Optom. Vis. Sci.* **1992,** *69,* 512–521.

[20] Benjamin, W.J. *Borish's Clinical Refraction*; Saunders: Chicago, 1998; pp 77–120.

[21] Aggarwala, K.R.; ; Nowbotsing, S.; Kruger, P.B. *Invest. Ophthalmol. Vis. Sci.* **1995,** *36,* 2695–2705.

[22] Aggarwala, K.; Kruger, E.; Mathewa, S.; Kruger, P. *J. Opt. Soc. Am.* **1995,** *12,* 450–455.

[23] Bausch & Lomb. Product Information BL 73457 SE.

[24] Liang, J.; Williams, D.R. *J. Opt. Soc. Am. A Opt. Image Sci. Vis.* **1997,** *14,* 2873–2883.

[25] Efron, S.; Efron, N.; Morgan, P.B. *Cont. Lens Anterior Eye.* **2008,** *31,* 81–88.

[26] Mirshahi, A.; Bühren, J.; Gerhardt, D.; Kohnen, T. *J. Cataract Refract. Surg.* **2003,** *29,* 2295–2301.

[27] Lundström, L.; Unsbo, P. *J. Opt. Soc. Am. A Opt. Image Sci. Vis.* **2007,** *24,* 569–577.

[28] Choi, M.; Weiss, S.; Schaeffel, F.; Seidermann, A.; Howland, H.C.; Wilhelm, B.; Wilhelm, H. *Optom. Vis. Sci.* **2000,** *77,* 537–548.

[29] Vasudevan, B.; Ciuffreda, K.J.; Wang, B. *Graefes. Arch. Clin. Exp. Ophthalmol.* **2006,** *244,* 930–937.

[30] Fernández, E.; Artal, P. *Opt. Soc. Am.* **2005,** *22,* 1732–1738.

[31] Lindskoog Pettersson, A.; Jarkö, C.; Alvin, A.; Unsbo, P.; Brautaset, R. *Cont. Lens Anterior Eye* **2008,** *31,* 189–193.

[32] Wang, Y.; Zhao, K.; Jin, Y.; Niu, Y.; Zuo, T. *J. Refract. Surg.* **2003,** *19,* 270–274.

[33] Thibos, L.; Hong, X.; Bradley, A.; Cheng, X. *J. Opt. Soc. Am. A* **2001,** *19,* 2329–2348.

[34] Whatham, A.; Zimmermann, F.; Martinez, A.; Delgado, S.; de la Jara, P.L.; Sankaridurg, P.; Ho, A. *J. Vis.* **2009,** *9,* 1–13.

[35] Atchison, D.A.; Collins, M.J.; Wildsoet, C.F.; Christensen, J.; Waterworth, M.D. *Vis. Res.* **1995,** *35,* 313–323.

[36] He, J.C.; Gwiazda, J.; Thorn, F.; Held, R.; Vera-Diaz, F.A. *Vis. Res.* **2005,** *45,* 285–290.

[37] Li, J.; Xiong, Y.; Wang, N.; Li, S.; Dai, Y.; Xue, L.; Zhao, H.; Jiang, W.; Zhang, Y. *J. Cataract Refract. Surg.* **2009,** *35,* 1389–1395.