The stability of steady state accommodation in human infants

T. Rowan Candy Indiana University School of Optometry, Bloomington, IN, USA

Shrikant R. Bharadwaj Indiana University School of Optometry, Bloomington, IN, USA

Retinal image quality in infants is largely determined by the accuracy and the stability of their accommodative responses. Although the accuracy of infants' accommodation has been investigated previously, little is known about the stability of their responses. We performed two experiments that characterized the stability of infants' steady state accommodation. Analyses were performed in the time domain (root mean square [RMS] deviation) and in the frequency domain (spectral analysis). In Experiment 1, accommodation responses were recorded for a period of 3 s from the left eye of four groups of infants (8–10, 11–13, 14–19, and 20–30 weeks of age) and eight prepresbyopic adults while they focused on a small toy placed at a dioptric viewing distance of 1.0 D (at 1 m). In Experiment 2, accommodation responses were recorded for a period of 14 s from the left eye of a group of 8- to 12-week-old infants and six prepresbyopic adults while they focused on a cartoon image placed at three different dioptric viewing distances (1.25, 2.0, and 3.0 D). The data, collected using a photorefractor sampling at 25 Hz, showed two important characteristics. First, the RMS deviations and the power were quantitatively similar across different infant age groups, and they were significantly larger in infants than in adults. Second, the overall and relative power also increased with the dioptric viewing distance both in infants and adults. At all three dioptric viewing distances, the measures of power were larger in infants than in adults. These data demonstrate that infants' accommodative responses contain instabilities that are qualitatively very similar to those observed in adults. However, the larger RMS deviations suggest that infants are likely to experience larger fluctuations in retinal image quality than adults.

Keywords: accommodation, human infant, microfluctuations, power spectrum, viewing distance, visual development

Citation: Candy, T. R., & Bharadwaj, S. R. (2007). The stability of steady state accommodation in human infants. *Journal of Vision, 7*(11):4, 1–16, http://journalofvision.org/7/11/4/, doi:10.1167/7.11.4.

Introduction

Ocular accommodation exhibits small oscillations of approximately 0.1–0.3 D in adults during steady state viewing (Charman & Heron, 1988). These small changes in refractive power, termed "accommodative microfluctuations," arise primarily from changes in the crystalline lens, with a small addition arising from changes in the axial length of the eye (van der Heijde, Beers, & Dubbelman, 1996). Following the initial work of Alpern (1958), Campbell, Robson, and Westheimer (1959), and Campbell, Westheimer, and Robson (1958), a number of studies have characterized features of these microfluctuations, as listed below and reviewed by Charman and Heron (1988).

i. The microfluctuations are composed of two prominent frequency bands, one called the low-frequency component (LFC; at <0.5 Hz) and the other called the high-frequency component (HFC; at 1.3–2.2 Hz; Charman & Heron, 1988). The power of the LFC (at 0.5 Hz) is typically approximately twice the value for the HFC (Gray, Winn, & Gilmartin, 1993a; Winn, Pugh, Gilmartin, & Owens, 1990b).
ii. The mean power spectral density (Denieul, 1982; Miege & Denieul, 1988) and the amplitudes of the LFC (Heron & Schor, 1995) and HFC (Heron & Schor, 1995; Kotulak & Schor, 1986b) tend to increase with the accommodative demand up to 4 D. Further increments in accommodative demands tend to decrease the mean power spectral density (Miege & Denieul, 1988).
iii. The frequencies and amplitudes of the fluctuations are highly correlated in the two eyes (Campbell, 1960).
iv. The root mean squared (RMS) fluctuation increases with decreases in contrast (Bour, 1981) and luminance (Gray, Winn, & Gilmartin, 1993b) of the accommodative target.
v. The LFC is described as "intrinsic" to the accommodative control system (Charman & Heron, 1988). Increasing the depth of focus (DOF) using pinholes of progressively smaller sizes systematically increases the magnitude of the LFC (Gray et al., 1993a). In contrast, the magnitude of the HFC either decreases (when retinal illuminance was held constant; Campbell et al., 1959) or remains constant (when retinal illuminance was

doi: 10.1167/7.11.4 Received October 6, 2006; published August 17, 2007 ISSN 1534-7362 © ARVO

permitted to vary with pupil size; Gray et al., 1993a), suggesting that the HFC might not be systematically related to ocular DOF.

vi. The HFC is highly correlated with the systemic arterial pulse (Collins, Davis, & Wood, 1995; van der Heijde et al., 1996; Winn & Gilmartin, 1992; Winn, Pugh, Gilmartin, & Owens, 1990a). It also shows larger intersubject and interexperiment variability in amplitude and frequency than the LFC (Charman & Heron, 1988).

Functional roles have been proposed for these microfluctuations in adults irrespective of whether they are intrinsic to the accommodation system or are produced by an extrinsic perturbation (e.g., arterial pulse). The resulting temporal variation in retinal defocus has been proposed as a cue to help discern the magnitude and the sign of the mean level of defocus (Alpern, 1958; Campbell et al., 1959; Kotulak & Schor, 1986a; Walsh & Charman, 1988). This cue could be used to drive accommodative responses. The fluctuations have also been proposed to enhance the average accommodative response (Hung, Semmlow, & Ciuffreda, 1982).

Very little is known about the characteristics of microfluctuations in human infants' accommodation. Studies of steady state accommodative behavior in infants have concentrated on the mean accuracy of the accommodative response, with little emphasis on its stability (Aslin, 1993). These previous studies used retinoscopy (Banks, 1980; Brookman, 1983; Haynes, White, & Held, 1965), photorefraction (Braddick, Atkinson, French, & Howland, 1979; Hainline, Riddell, Grose-Fifer, & Abramov, 1992; Howland, Dobson, & Sayles, 1987; Howland & Sayles, 1983), or autorefraction (Aslin, Shea, & Metz, 1990) to collect data. Accommodation was measured either in a single sample fashion that precluded any investigation of accommodative stability or without sufficient temporal resolution to systematically examine stability (e.g., photorefraction at 2 Hz; Howland et al., 1987).

Unstable accommodation could degrade infants' habitual retinal image quality when viewing stationary targets and could influence both neural and optical development. The variability in retinal image quality could result in a varying percept for the developing infant and could influence synaptic refinement in neural circuits that underlie spatial vision (Mitchell & Timney, 1984). It could also, as introduced above, provide defocus cues for both accommodation (Campbell et al., 1959; Kotulak & Schor, 1986a) and emmetropization (Wallman & Winawer, 2004; Wildsoet, 1997).

There are reasons to suspect that the characteristics of infants' microfluctuations differ from those of adults. First, theoretical calculations of the visual system's DOF (based on eye size, pupil size, and visual acuity) by Green, Powers, and Banks (1980) predict the neonatal DOF (1–3 months: ±1.0–0.3 D) to be much larger than that of adults (±0.05 D). Because the magnitude of the LFC increases with increasing DOF in adults (Gray et al., 1993a), it logically follows that a larger DOF in infants may be associated with a larger LFC. Second, Heron and Schor (1995) and Mordi and Ciuffreda (2004) found the amplitude of microfluctuations to reduce with aging, which they attributed to an increase in viscosity and a decrease in compliance of the structures in the accommodative plant (Fisher, 1971; Schor, Bharadwaj, & Burns, 2007; van Alphen & Graebel, 1991; Weeber et al., 2005). Consistent with this idea, van Alphen and Graebel (1991), using a limited sample size, observed that the compliance of the structures in the accommodative plant decreased from infancy to adulthood.

Two experiments were performed in the current study to determine the characteristics of habitual fluctuations in accommodation in human infants. The goal was to determine the magnitude, the temporal frequency distribution, and the viewing distance dependence of microfluctuations in infants and to compare them to those of adults. Experiment 1 determined the characteristics of microfluctuations as a function of age (8–30 weeks). In Experiment 2, the viewing distance-dependent characteristics were determined in a group of 8- to 12-week-old infants and adults. Parts of this research were presented at the Association for Research in Vision and Ophthalmology (ARVO) annual meeting (Candy, Tondel, & Wang, 2004).

Methods

Subjects

A total of 63 infants born within 2 weeks of their due date, with no medical or ocular complications, were recruited from local birth records. Forty-five infants participated in Experiment 1 and 18 infants participated in Experiment 2. The age range of the infants was from 8 to 30 weeks, which was selected to incorporate the early improvement in accommodative gain (e.g., Banks, 1980) and acuity (e.g., Teller & Movshon, 1986) plus a time during which emmetropization is likely to be occurring (e.g., Mayer, Hansen, Moore, Kim, & Fulton, 2001). Prepresbyopic adults (eight adults for Experiment 1 and six adults for Experiment 2) with no reported accommodative abnormalities or symptoms were recruited from the local academic department. All of the adult subjects were emmetropic and wore no refractive correction during the experiments. The parents and adult subjects provided informed consent after the study had been approved by the local Indiana University IRB.

Procedure

Each subject's steady state accommodative response was recorded from the two eyes simultaneously using a video-based eccentric photorefractor (PowerRefractor, Multichannel Systems; Choi et al., 2000; Schaeffel, Wilhelm, & Zrenner, 1993). A steady state response was defined as "the maintenance of a refractive state by the subject to keep a stationary target of interest in focus" (Bour, 1981). The photorefraction technique has been previously described in detail (Roorda, Campbell, & Bobier, 1997; Schaeffel et al., 1993), and so only a brief description is provided here. When using the PowerRefractor, the subject is aligned at 1 m from a set of LED light sources immediately adjacent to a camera aperture. Light from the LEDs passes into the eye and is reflected back from the retina through the pupil. The dioptric focus of the eye in one meridian is derived from the slope of a linear regression fit to the distribution of reflected light across the pupil. In addition to measuring the eye's dioptric focus, the PowerRefractor measures gaze position based on the relative displacement of the first Purkinje image from the center of the entrance pupil. As will be discussed below, gaze position information was used to monitor the alignment of the eye. The accommodation and gaze position responses were sampled by the PowerRefractor at 25 Hz (temporal resolution: 40 ms). Power spectra (PS) in the adult steady state accommodation literature show that most of the power is distributed below 5.0 Hz (Charman & Heron, 1988; Winn et al., 1990b), and therefore the characteristics of the adult fluctuations should be well represented by the 25-Hz sampling frequency.

The accommodative stimuli were presented in a dimly lit room using different equipment in Experiments 1 and 2. In Experiment 1, a high-contrast internally illuminated toy was held adjacent to the camera aperture at its 1.0-m distance, 3° above the camera axis (Figure 1, panel a). The toy subtended 1.1° × 1.4° at 1.0 m and contained broadband spatial frequency content. The subject's attention was attracted to the toy while data were collected with the photorefractor. The first 2.56 s of stable data from the left eye was included in the analysis yielding a total of 64 (2^6) data points per subject. In Experiment 2, subjects viewed a high-contrast cartoon image (with an angular subtense of 2.3° × 2.3° at a viewing distance of 50 cm). The cartoon also contained broadband spatial frequency content. This image was displayed on an LCD monitor and was aligned with the subject using reflection from a beam splitter while the photorefractor camera collected images through the beam splitter on the same axis (Figure 1, panel b). The LCD monitor and the beam splitter were mounted on a motorized track with an operating range of 20–80 cm from the subject in real space. Steady state accommodative responses were measured at three different dioptric viewing distances (1.25, 2.0, and 3.0 D corresponding to 80, 50, and 33 cm viewing distances). Because the accommodative stimuli were presented at different physical distances in front of the subject, all the cues to accommodation (defocus, proximity, and disparity-driven vergence) were present and they were consistent with each other. The target was presented at each dioptric viewing distance for a period of 14 s in a pseudorandomized order across subjects. The first 10.24 s of stable recording from the right eye of each subject was included in the analysis (yielding 256 [2^8] data points for each viewing distance). Infants' head movements were minimized by gently resting their chin in an experimenter's hand in both experiments. Adult subjects were instructed to hold their heads as stable as possible during the measurements and they were given no specific instructions regarding the accommodative task.

Data analysis

The data from Experiments 1 and 2 were analyzed using Matlab®, Microsoft Excel®, and SPSS®. The steady state accommodation data (2^6 data points per recording in Experiment 1 and 2^8 data points per recording in Experiment 2) were included in the analyses only if they met the following criteria.

a. The data were collected from a gaze eccentricity of less than 15° from the pupillary axis. The concern

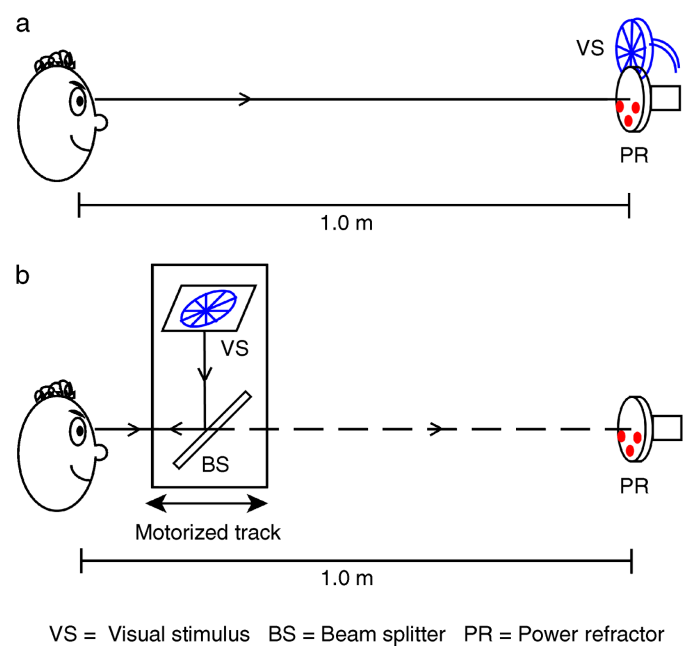

Figure 1. Schematic illustration of the equipment used in Experiments 1 (panel a) and 2 (panel b) to measure the stability of accommodative responses. In Experiment 1, a high-contrast internally illuminated toy (VS) was held 3° above the PowerRefractor camera (PR) at a viewing distance of 1.0 m. In Experiment 2, subjects viewed a cartoon character displayed on a horizontal LCD screen (VS) through a beam splitter (BS) while the PowerRefractor camera (PR) measured accommodation responses from a viewing distance of 1.0 m. The LCD screen and the beam splitter were mounted on a motorized track and could be placed anywhere between 20 and 80 cm in front of the subject's eyes.

was that the effects of intermittent peripheral fixations could not be distinguished from accommodative fluctuations because the optical quality of the eye changes with gaze eccentricity (Jennings & Charman, 1981; Navarro, Artal, & Williams, 1993). The threshold criterion was based on adult data as there are currently no comparable data from infants. As noted earlier, the PowerRefractor tracks the first Purkinje image, and so simultaneous gaze position estimates could be used to apply the criterion to the accommodation data. The infants and adults typically maintained stable gaze on the target, and so very little data were excluded because of this criterion.

b. The data fell within the linear operating range of the instrument, between +4 and −6 D, and the pupil diameter was greater than 3 mm and less than 8 mm (required for the instrument to collect data; Choi et al., 2000).

c. There were no sections of missing data that were longer than eight consecutive points (320 ms). These could be the result of blinks or periods of fussiness or inattention. Sections of missing data of less than eight points were interpolated using a cubic spline algorithm (Collins et al., 1995).

d. In the Experiment 2, responses were only included when the mean accommodation response changed with the change in viewing distance, and the measured steady state mean error of accommodation ("lag" or "lead") was within ±1 D of the appropriate viewing distance. These criteria are reasonable because both adults (Bharadwaj & Schor, 2005; Hung & Ciuffreda, 1988; Kasthurirangan, Vilupuru, & Glasser, 2003) and infants (Tondel & Candy, 2007) have the ability to track step or ramp changes in defocus. With regard to the total accommodative demand, infants are typically hyperopic (Mayer et al., 2001), and we assumed that the subjects participating in this study had refractive errors that were representative of the general population (no specific attempt was made to estimate the distance refractive error of the infants who took part in our study). We wanted to determine habitual image quality for these viewing distances, and so we only included accommodative responses that were clearly related to these distances.

If the subject generated any recordings that met these criteria, the first one for each experimental condition was included in the analyses (Figure 2). These "scorable" recordings were subjected to two kinds of analyses. The first was based in the time domain and involved computing the RMS accommodative fluctuation in diopters (Gray et al., 1993a, 1993b). The second was conducted in the temporal frequency domain by computing the PS of the accommodative responses (Campbell et al., 1959, 1958; Charman & Heron, 1988; Pugh, Eadie, Winn, & Heron, 1987). The individual subjects' PS were averaged within each age group (eight subjects each in Experiment 1) and within each viewing distance (six subjects each in Experiment 2) to obtain the mean PS. The summed power (in D^2) between the fundamental frequency and 12.5 Hz (overall power) and the summed power in each of three frequency bins (fundamental frequency to 1 Hz, 1.1–2 Hz, and 2.1–3 Hz; relative power) were calculated.

With regard to the calibration of the PowerRefractor, Blade and Candy (2006) observed that the instrument, on average, slightly overestimated changes in defocus in infants and slightly underestimated changes in adults. The mean calibration slopes and the standard deviations in infants and adults were 1.06 ± 0.16 and 0.90 ± 0.18, respectively. There was no effect of infant age (range: 7–19 weeks) on the slope of the calibration function, but the infants' slopes were statistically significantly different from those of adults (t test, $p < .05$). This difference in calibration slopes was accounted for in this study by scaling the data segments in infants and adults by the age appropriate value. Blade and Candy also compared the

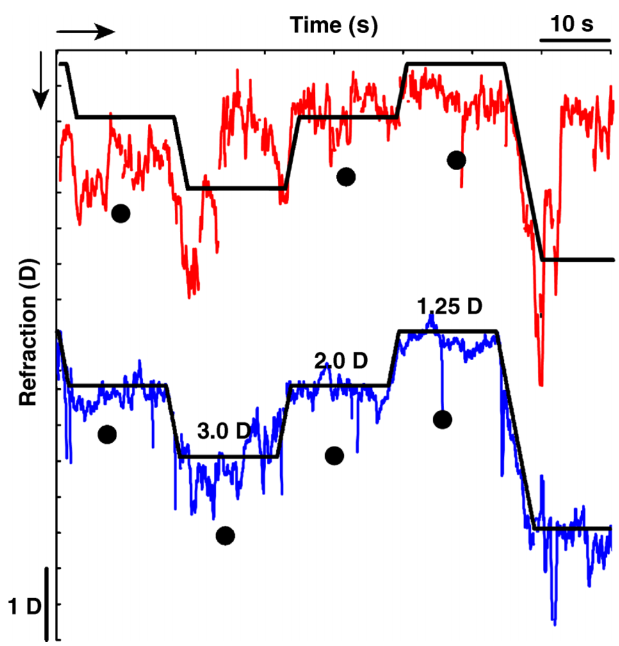

Figure 2. Examples of steady state accommodative responses recorded from a 12-week-old infant (top red) and an adult (bottom blue) at 25 Hz. The dioptric position of the stimulus is also indicated (black). Fourteen seconds of steady state accommodative responses at each of three different viewing distances (1.25, 2.0, and 3.0 D) is displayed. The infant and adult data have been vertically offset from each other for clarity but are accurately plotted relative to the stimulus functions. The rightward and downward pointing arrows represent the directions of increase in time and accommodation, respectively. The black dots indicate the accommodative responses that fulfilled the criteria described in the text and that were eligible for further analysis. For example, the 3.0-D infant data were not considered for analysis because more than eight consecutive data points were missing from the recording.

offset between the PowerRefractor reading and a simultaneous retinoscopy (equivalent to the intercept of a calibration slope). This suggested that the PowerRefractor reads an extra half diopter of hyperopia in both adults and infants, implying that the ±1 D criterion used for the vertical meridian data in Experiment 2 may reflect slightly shifted values.

Results

Of the 63 infants who took part in this study, data from 32 of 45 were included in the analysis of Experiment 1, and data from 9 of 18 were included in the analysis of Experiment 2. The data from the other infants were excluded due to fussiness, blinking, and/or inattention, which resulted in their data not meeting the inclusion criteria above. The 32 infants in Experiment 1 were equally divided into four age groups of eight infants each and were compared with the adults to examine the effect of age (8–10, 11–13, 14–19, and 20–30 weeks). In Experiment 2, the data were analyzed as a function of viewing distance and age (8- to 12-week-olds were compared with adults, with six subjects of each age at each distance). The relatively low success rate in Experiment 2 reflects the demands placed on the infant. They had to maintain focus on the LCD screen (within ±1 D) for at least 10 s continuously. Comparison data were successfully collected from all of the adults (eight in Experiment 1 and six in Experiment 2).

The mean accommodative positions obtained from infants and adults in the two experiments are shown in Table 1. Infants showed a larger apparent "lag" of accommodation and larger intersubject variability than adults in both experiments. This could arise from poorer accommodative accuracy (Banks, 1980; Haynes et al., 1965) or the higher prevalence of astigmatism in infants (Howland, Atkinson, Braddick, & French, 1978; Mohindra, Held, Gwiazda, & Brill, 1978). A one-factor univariate ANOVA indicated that the mean accommodative positions did not significantly vary across different age groups, $F(4, 35) = 1.74$, $p > .16$. In Experiment 2, the mean accommodative position systematically increased with the dioptric viewing distance in both infants and adults. The main effect of dioptric viewing distance was significant, $F(2, 30) = 115.5$, $p < .001$, whereas the main effect of age was not significant, $F(1, 30) = 3.2$, $p = .08$, in a two-factor ANOVA (age and viewing distance). The interaction between age and viewing distance was marginally significant, $F(2, 30) = 3.82$, $p = .03$, probably reflecting the tendency of the youngest infants to have a low accommodative gain.

Figure 2 shows representative raw data from the left eyes of an infant and an adult. Visual inspection suggests that there are fluctuations in accommodation in both sets of data, consistent with the literature on adults. The characteristics of the microfluctuations were quantified in the time domain by computing the RMS deviation of the responses (Figure 3). For Experiment 1, a one-factor univariate ANOVA indicated that RMS deviation varied with age, $F(4, 35) = 6.94$, $p < .001$. Post hoc testing indicated that the RMS did not significantly vary across the different infant age groups (Bonferroni corrected $p > .5$ in all cases; Table 2), but that the RMS deviation was larger in each group of infants than in the adults (Bonferroni corrected $p < .04$ in all cases; Table 2). In Experiment 2, the main effect of dioptric viewing distance was not significant, $F(2, 30) = 1.22$, $p = .31$, in a two-factor ANOVA (age and viewing distance), and the interaction between age and viewing distance was not significant, $F(2, 30) = 0.15$, $p = .86$, indicating that the pattern of RMS deviations with viewing distance was similar in infants and adults. However, consistent with Experiment 1, the main effect of age was significant, $F(1, 30) = 12.17$, $p = .002$, indicating that the mean RMS deviation in the 8- to 12-week-old infants was larger than the mean RMS deviation in the adults (Figure 3 and Table 3). Figure 4 shows RMS deviation plotted as a

	Age	Viewing distance (D)	Mean response (D)
Experiment 1	8–10 weeks	1.0	0.57 ± 0.99
	11–13 weeks	1.0	0.36 ± 0.83
	14–19 weeks	1.0	0.36 ± 1.35
	20–30 weeks	1.0	0.67 ± 0.88
	Adults	1.0	1.39 ± 0.65
Experiment 2	Infant	1.25	0.94 ± 0.49
		2.0	2.06 ± 0.38
		3.0	2.66 ± 0.40
	Adult	1.25	1.15 ± 0.44
		2.0	1.88 ± 0.19
		3.0	3.08 ± 0.23

Table 1. Mean (±1 SD) accommodative position of infants and adults for the different age groups in Experiment 1 and for the three dioptric viewing distances in Experiment 2.

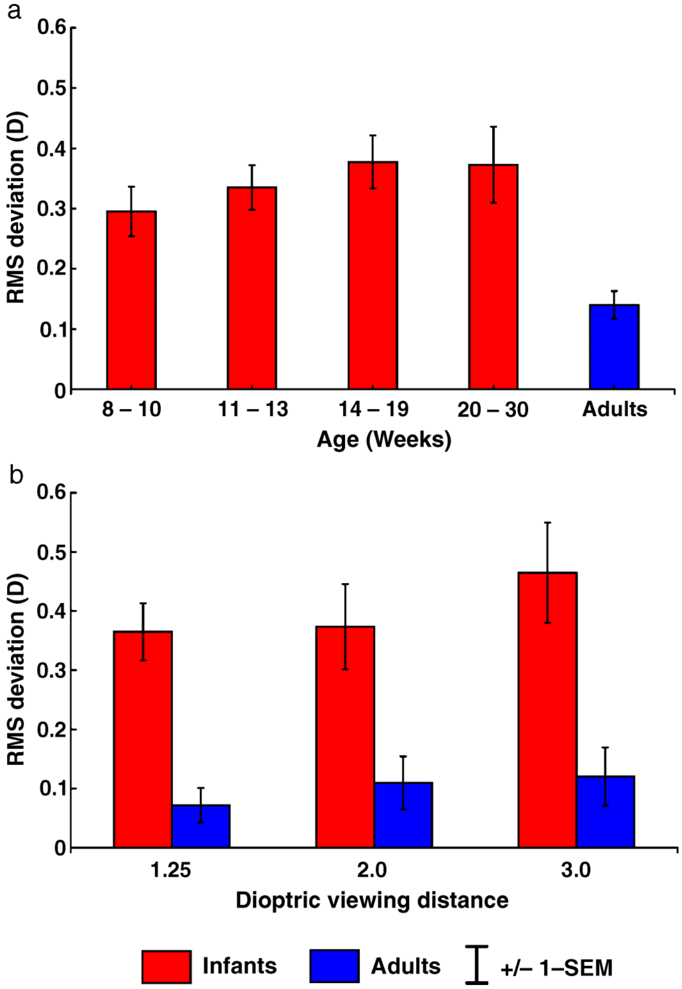

Figure 3. The root mean square (RMS) deviation of the data collected from infants and adults in Experiment 1 (panel a) and Experiment 2 (panel b). The infants in Experiment 2 were all between 8 and 12 weeks of age. In both experiments, the RMS deviation in infants was significantly higher than the RMS deviation in adults. The error bars indicate ±1 *SEM*.

function of the mean accommodative position from each infant and adult subject. At each dioptric viewing distance, the infants showed a larger intersubject variability than the adults. In both infants and adults, the RMS deviations were only moderately correlated with the mean accommodative position (infants: $r = .36$, $df = 32$, $p = .02$; adults: $r = .32$, $df = 24$, $p = .10$).

The PS are shown in Figures 5 and 7. The individual and mean spectra derived from each group of subjects in Experiment 1 are shown in Figure 5, panels a–f. All of the spectra show a characteristic increase in power at low temporal frequencies. A mean overall power (from the fundamental frequency of 0.39–12.5 Hz) and mean powers for the three frequency bands (0.39–1.0, 1.1–2.0, and 2.1–3.0 Hz) were calculated for each mean spectrum. A one-factor univariate ANOVA indicated that the mean overall power varied in a marginally significant fashion with age, $F(4, 35) = 2.45$, $p = .064$. Post hoc testing indicated that there was no significant difference across infant age groups (Bonferroni corrected $p > .5$; Figure 6 and Table 2), but that the mean overall power for the 11- to 13-week-old group was marginally significantly larger than the adult value (Bonferroni corrected $p = .074$).

Considering the relative power distribution, the first frequency bin (0.39–1.0 Hz) contributed the most to the mean overall power in all of the infant groups (Figure 6). In adults, the power in the first and second bins contributed more equally. The main effect of frequency bin was significant in a two-factor univariate ANOVA (age and frequency bin), $F(2, 105) = 8.21$, $p < .001$, and post hoc testing revealed that the power in the first bin was significantly larger than the contributions of the other two bins (Bonferroni corrected $p < .05$ for the first bin compared with either of the other two, and $p = .384$ for the second bin compared with the third). The main effect of age was once again significant, $F(4, 105) = 3.37$, $p = .012$, and the interaction between age and frequency bin was not, $F(8, 105) = 0.88$, $p = .54$.

The mean PS from Experiment 2 are shown in Figure 7. The longer recording protocol used in Experiment 2 resulted in a lower fundamental frequency of 0.098 Hz. These spectra demonstrate an increase in power at low temporal frequencies, as noted in Experiment 1. At all three dioptric viewing distances, the power in the first frequency bin (0.09–1.0 Hz) contributed the most to the overall power in both infants and adults (Table 3). The three-factor ANOVA (age, viewing distance, and frequency bin) indicated significant main effects of all three factors: age, $F(1, 90) = 11.47$, $p = .001$; viewing distance, $F(2, 90) = 3.81$, $p = .026$; and frequency bin, $F(2, 90) =$

Age (weeks)	RMS (D)	OP (D^2)	RP I (D^2)	RP II (D^2)	RP III (D^2)	MDD (D)
8–10 (*n* = 8)	0.31 ± 0.04	0.20 ± 0.06	0.08 ± 0.03	0.06 ± 0.02	0.02 ± 0.004	0.61
11–13 (*n* = 8)	0.36 ± 0.04	0.38 ± 0.14	0.15 ± 0.07	0.06 ± 0.03	0.03 ± 0.011	0.71
14–19 (*n* = 8)	0.40 ± 0.04	0.27 ± 0.07	0.08 ± 0.02	0.06 ± 0.03	0.02 ± 0.007	0.78
20–30 (*n* = 8)	0.40 ± 0.06	0.33 ± 0.10	0.11 ± 0.04	0.07 ± 0.04	0.02 ± 0.004	0.78
Adult (*n* = 8)	0.12 ± 0.02	0.03 ± 0.01	0.01 ± 0.002	0.01 ± 0.005	0.002 ± 0.001	0.24

Table 2. Mean (±1 *SEM*) root mean square (RMS) deviation, overall power (OP), power between 0.39 and 1.0 Hz (RP I), power between 1.1 and 2.0 Hz (RP II), and power between 2.1 and 3.0 Hz (RP III) in the four groups of infants and the adults in Experiment 1. The minimum discriminable defocus (MDD), computed using a d' value of 1.96, for the four groups of infants and adults is shown in the last column.

Stimulus position (D)		RMS (D)	OP (D^2)	RP I (D^2)	RP II (D^2)	RP III (D^2)	MDD (D)
Infants (n = 6)	1.25	0.37 ± 0.05	0.16 ± 0.05	0.14 ± 0.05	0.007 ± 0.001	0.004 ± 0.0003	0.73
	2.0	0.37 ± 0.07	0.23 ± 0.06	0.19 ± 0.05	0.02 ± 0.005	0.007 ± 0.001	0.73
	3.0	0.46 ± 0.08	0.33 ± 0.07	0.28 ± 0.06	0.01 ± 0.005	0.005 ± 0.002	0.90
Adults (n = 6)	1.25	0.08 ± 0.03	0.08 ± 0.02	0.06 ± 0.02	0.008 ± 0.003	0.003 ± 0.001	0.16
	2.0	0.26 ± 0.05	0.09 ± 0.03	0.07 ± 0.03	0.008 ± 0.002	0.003 ± 0.001	0.51
	3.0	0.28 ± 0.05	0.17 ± 0.04	0.13 ± 0.04	0.02 ± 0.004	0.007 ± 0.002	0.55

Table 3. Mean (±1 *SEM*) root mean square (RMS) deviation, overall power (OP), power between 0.098 and 1.0 Hz (RP I), power between 1.1 and 2.0 Hz (RP II), and power between 2.1 and 3.0 Hz (RP III) from infants and adults for the three viewing distances in Experiment 2. The minimum discriminable defocus (MDD), computed using a d' value of 1.96, is provided for each age and viewing distance in the last column.

58.17, p < .001. The Age × Frequency interaction was significant, $F(2, 90) = 10.62$, p < .001, which is consistent with the infant frequency function being steeper than that of the adults. The Frequency × Viewing distance interaction was also significant, $F(4, 90) = 3.02$, $p = .02$, but the Age × Viewing distance, $F(2, 90) = 0.30$, $p > .5$, and the Age × Frequency × Viewing distance, $F(4, 90) = 0.30$, $p > .5$, interactions were not.

Do infants use an active searching strategy to improve their retinal image quality?

It has been suggested that the LFC of microfluctuations is "intrinsic" to the accommodative control system and that it might play a "role in searching to maintain the necessary contrast gradient to sustain an accommodative response" (Winn, Charman, Pugh, Heron, & Eadie, 1989). If so, the microfluctuations might be an active searching strategy used to optimize optical quality. For example, increased numbers of responses at the extremes of the DOF range might indicate an explicit strategy of alternating between under- and overaccommodating to determine if one direction leads to an improvement in image focus. We asked whether infants and adults showed any evidence of this type of searching strategy. A simple sinusoidal modulation of accommodation, for example, would result in a greater number of data points at the extremes of the dioptric range of the microfluctuations (as illustrated in Figure 8, panel a). To address this question, we constructed a frequency histogram of the accommodation data obtained from Experiment 1 for each infant and adult. These frequency distributions were then averaged within each age group (after normalizing each subject's distribution to its standard deviation to compare the shape of the distribution across subjects). The mean distributions were then tested for normality. The frequency histograms from Experiment 1 are shown in Figure 8 (panels b–f). The infant and adult data are all consistent with a normally distributed process over the 2.56-s period. Goodness-of-fit tests, comparing the mean data to predicted normal functions (shown in black in Figure 8), generated chi-squared values of 2.25 for the 8- to 10-week-olds (p > .75), 0.81 for the 11- to 13-week-olds (p > .975), 0.83 for the 14- to 19-week-olds (p > .95), 1.81 for the 20- to 30-week-olds (p > .75), and 0.69 for the adults (p > .975; Bendat & Piersol, 2000). These data therefore provide no evidence that the distributions represent anything other than a normal distribution, or that infants are using an active searching strategy to guide their accommodation response, at least within this time frame.

With the knowledge that the microfluctuation histograms are approximately normally distributed, we calculated the amount of mean defocus that would need to be added to a retinal image for the new mean value to be discriminable from the previous one with a d' of 1.96

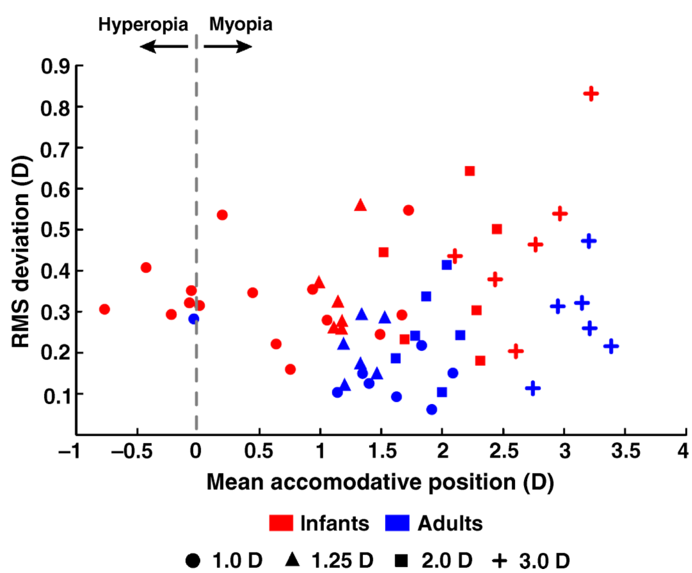

Figure 4. Root mean square (RMS) deviation of each infant (red symbols) and adult (blue symbols) plotted as a function of their mean accommodative position. Data from the 1.0-D viewing distance were obtained from Experiment 1, and the data from the 1.25-, 2.0-, and 3.0-D viewing distances were obtained from Experiment 2. For the 1.0-D viewing distance, data from only 8- to 10- and 11- to 13-week-old infants (16 data points) and adults (8 data points) have been included. For the other three viewing distances, data points from all infants and adults (6 data points at each viewing distance) have been included. The mean accommodative positions obtained in infants and adults for the two experiments are shown in Table 1.

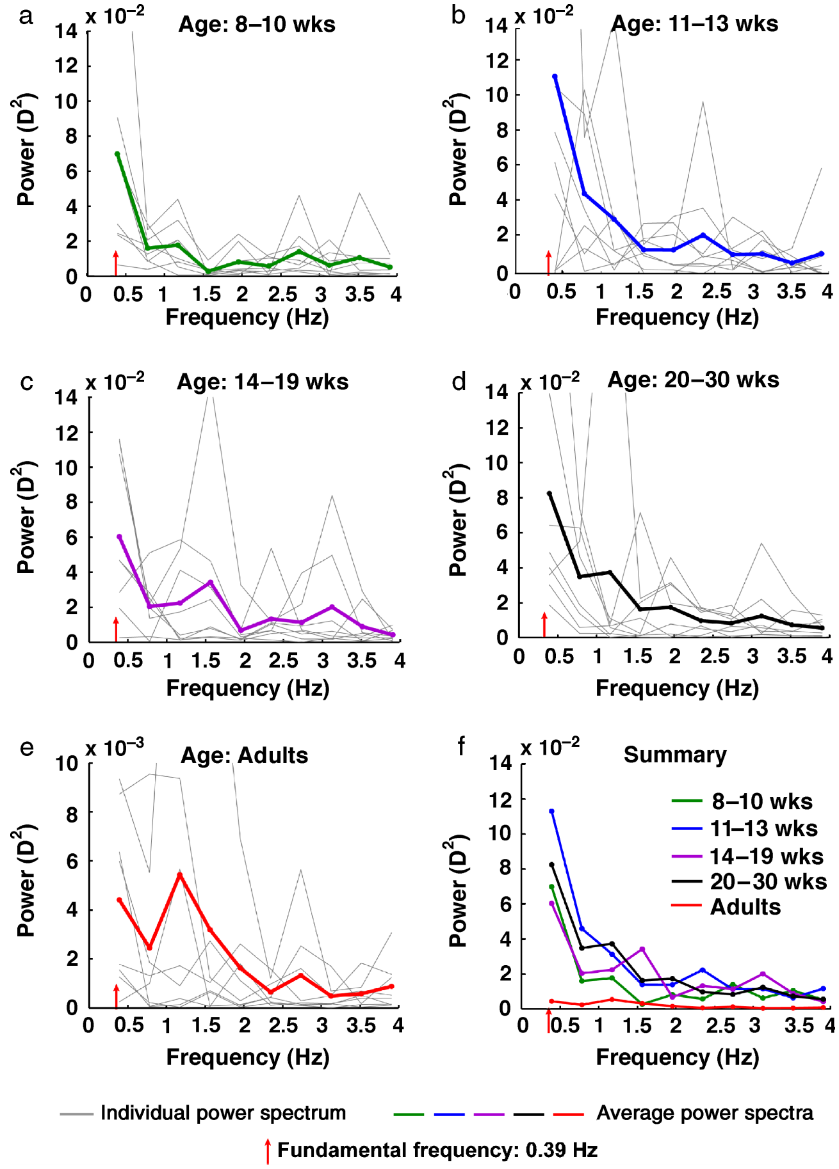

Figure 5. Power spectra (PS) obtained from infants (a–d) and adults (e) in Experiment 1. The gray functions represent spectra from individual subjects, and the thicker colored functions represent the mean PS for the relevant age group. The individual points from the discrete Fourier transforms are connected for visual effect. Panel f presents the mean PS obtained from each age group. The vertical arrow in each panel indicates the position of the fundamental frequency (0.39 Hz) on the abscissa. Note that the ordinate scale in panel e is magnified to show the PS in adults.

(Macmillan & Creelman, 1991). These calculated values are provided in Tables 2 and 3 in the final columns. It is likely that the histograms include measurement error from the photorefraction technique, and therefore these values can be considered a conservative estimate.

Measurement variability introduced by the PowerRefractor

The variability in refractive power of the eye measured by the PowerRefractor could have a number of sources, both biological and due to measurement error. For instance, the PowerRefractor measures the eye's refraction by computing the slope of a linear regression fit to the distribution of reflected light across the pupil (Schaeffel et al., 1993). Any error in estimating this slope would affect the apparent refractive power of the eye. Although the PowerRefractor has been previously employed to measure microfluctuations in human adults (Harb, Thorn, & Troilo, 2006), the instrument's measurement variability has not been documented. We collected data from a model eye to estimate the effect of instrument variability on our data. The model eye was set to three different myopic refractive states (−1.25, −2.0, and −3.0 D) and six 14-s recordings were made for each of them. The first 10.24 s of each

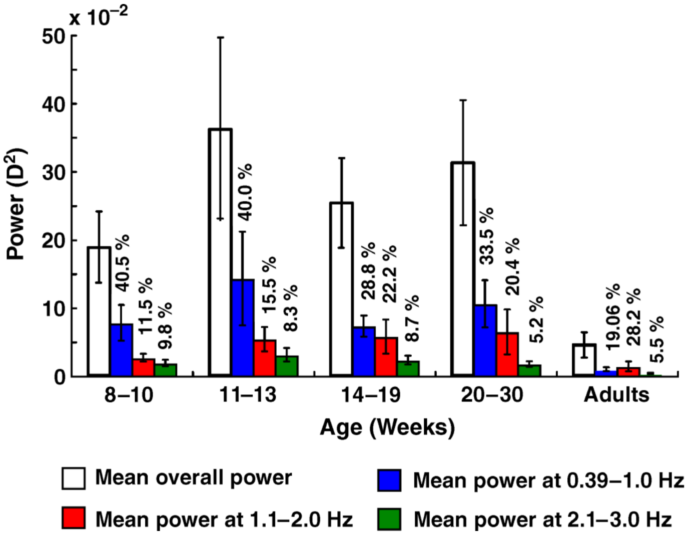

Figure 6. Overall (open bars) and relative (colored bars) power plotted as a function of age in Experiment 1. The error bars indicate ±1 *SEM* of the mean. The percentage contributions of the three frequency bands to the overall power are noted above the corresponding bar in each graph.

recording (2^8 data points) was included in the analysis to mimic Experiment 2. PS were computed for each recording and were averaged to obtain a mean PS for each refractive state. These mean spectra are plotted with the adult data from Experiment 2 in Figure 9. Three features can be noted. First, the model eye power is highest for the −1.25 D refractive state and lowest for the −3.0 D refractive state, indicating that the measurement variability decreased with increase in refractive state. The adult and infant data from Experiment 2, if anything, showed the opposite effect. Second, the mean power obtained from the model eye was much lower than that recorded from adults in Experiment 2 (compare thin with thick functions). Third, unlike the spectra obtained from adults, no systematic increase in power at frequencies less than 0.5 Hz was noted for the model eye. Taken together, these data suggest that although the PowerRefractor introduces variability, its influence on the characteristics of the microfluctuations seems to be negligible.

Discussion

Summary of results and comparison with previous studies

The results of this study can be summarized into two principal findings:

1. The RMS deviations and the overall and relative power in the fluctuations were quantitatively similar across different infant age groups (8–30 weeks) but they were significantly larger in infants than in adults (Figures 3 and 6).
2. The overall and relative power marginally increased with dioptric viewing distance (1.25, 2.0, and 3.0 D) in 8- to 12-week-old infants and in adults (however, the RMS data showed no significant effect of viewing distance). At all three dioptric viewing distances, all measures were larger in the infants than adults (Figures 3 and 7).

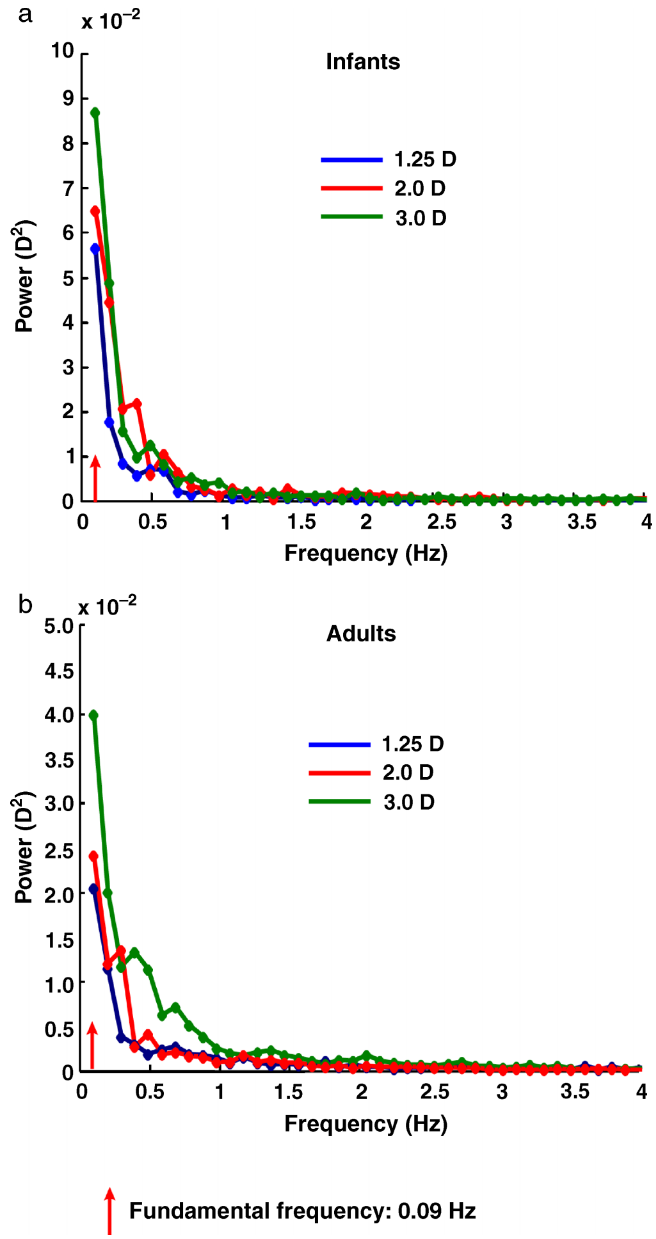

Figure 7. Power spectra (PS) obtained from infants (panel a) and adults (panel b) in Experiment 2. The three functions represent mean spectra obtained across different individuals. The vertical arrow in each panel indicates the position of the fundamental frequency (0.09 Hz) on the abscissa. The ordinate scale in panel b is magnified to show the adult PS.

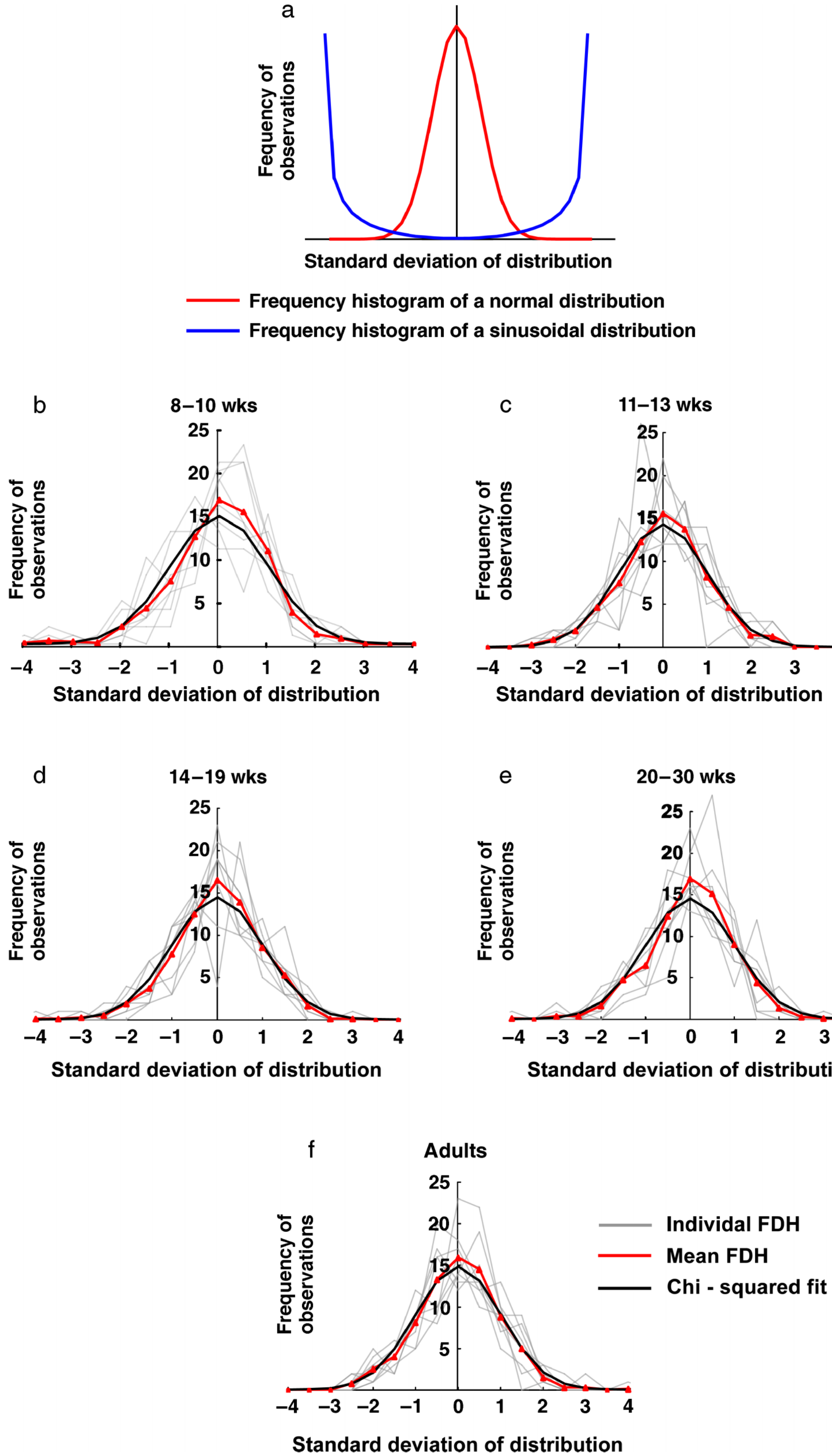

Figure 8. Frequency distributions of steady state accommodative responses in infants and adults. Panel a illustrates predictions for fluctuations that are normally (red) and sinusoidally (blue) distributed around the mean level. This illustration was calculated with the same root mean square (RMS) for each distribution. Panels b to f show distributions from individuals (gray) and the mean for each age group (red). The individual functions were each scaled by their standard deviation to permit comparison of their shapes. Panels b to f also present a normal distribution fit to the data for comparison.

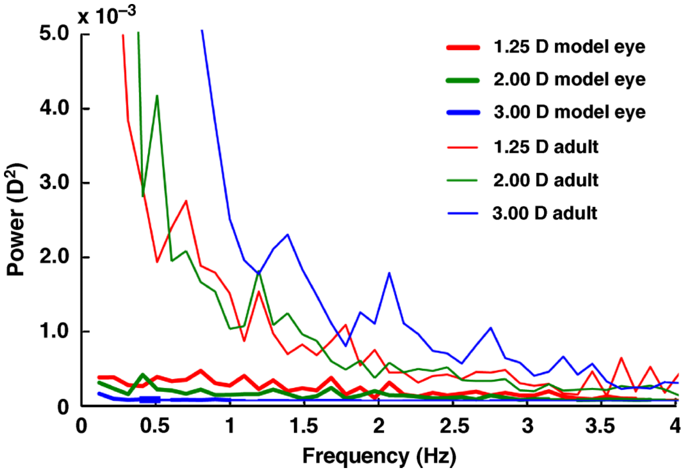

Figure 9. Comparison of spectra recorded from a model eye (thicker functions) with those from human adults (thinner traces) at three refractive states. Each function represents the mean of six individual spectra.

The only previously published quantitative data regarding the variability in infants' accommodative responses are shown in Figure 5 of Howland et al. (1987). Sampling accommodation at 2 Hz, their data (from two infants aged 4.5 and 9 months) vary over a range of approximately 1 D for a static target. Atkinson and Braddick (1978) and Braddick et al. (1979) also discussed "inconsistent" infants of less than 3 months who would focus at a target's distance on some trials but not on others. Atkinson and Braddick and Braddick et al. recorded single photorefraction photographs and therefore probably refer to a time scale greater than the 3 s considered here. These reports are in reasonable agreement with the current data, although the observation made by Atkinson and Braddick and Braddick et al. may also reflect infants' changing motivation or attention across a longer time frame.

The RMS fluctuations recorded from our adult subjects also compare well with the results of previous experiments (Bour, 1981; Gray, Gilmartin, & Winn, 2000; Gray et al., 1993a; Harb et al., 2006; Kotulak & Schor, 1986b). For instance, Gray et al. (1993a) observed RMS deviations of steady state accommodation of less than 0.25 D for pupil diameters ranging from 4 to 6 mm. For comparable pupil diameters (5–7 mm), we observed a mean RMS deviation of 0.12 ± 0.02 D in our adult subjects (Figure 3 and Table 2). Similarly, Kotulak and Schor (1986b) and Harb et al. (2006) observed standard deviations of steady state accommodation to increase from approximately 0.15 to 0.3 D for dioptric viewing distances ranging from 1.25 to 3.5 D. We observed the RMS deviations of steady state accommodation to increase from 0.08 to 0.28 D across our distances in adults (Figure 3 and Table 3). Qualitative and quantitative similarities in results were obtained despite the use of different experimental conditions and techniques to record accommodation.

Although the overall shape of the infant and adult PS recorded in our experiments was similar to earlier reports, we failed to observe the presence of a significant HFC (1.0–2.5 Hz) in the mean spectra of either group. This HFC has not been consistently observed in previous studies (Campbell et al., 1959; Charman & Heron, 1988; Harb et al., 2006). Although Harb et al. (2006) describe the power at 1.0–2.3 Hz, the qualitative shape of the PS obtained from our adult subjects was very similar to theirs (Figure 3 of Harb et al., 2006). As both studies used the PowerRefractor, there is a possibility that the absence of a significant HFC is related to the methodology. The absolute values of the power at frequencies other than the HFC are consistent with other studies (Gray et al., 1993a; Winn et al., 1990b) and therefore it is unlikely that extraneous noise is masking the HFC in our data. Differences in the characteristics of the HFC when measured using ultrasonography and optical techniques have also been discussed by van der Heijde et al. (1996). We did observe possible high-frequency fluctuations in some individuals, but not in others (Figure 6). These possible HFCs were not consistent enough to appear in the mean. Whatever the reason for the absence of the HFC in adults, the fact that it is also absent in infants suggests that it has relatively little direct influence on retinal image quality during early development. Further data collection would be required to determine whether infants have a small component related to their arterial pulse, which is typically almost a factor of two faster than found in adults (Behrman, Kliegman, & Jenson, 2004).

The results of Experiment 2 compare well with earlier reports of an increase in RMS deviations and mean power spectral density with dioptric viewing distance in adults (Heron & Schor, 1995; Kotulak & Schor, 1986b; Miege & Denieul, 1988), although our RMS data did not reach statistical significance. The increase may result from a decrease in tension on the crystalline lens with increased slackening of the lens zonules (Kotulak & Schor, 1986b; Miege & Denieul, 1988). The reduced tension on the lens would permit it to oscillate more in response to any perturbation in force. We found no evidence that the infants' pattern of fluctuations with viewing distance was any different from that of adults.

Why are the accommodative microfluctuations larger in infants than in adults?

We have considered four possible explanations:

i. Body movement: The head and body movements of uninstructed infants could move the focal plane of the eye with respect to the PowerRefractor camera. This movement could be recorded as hyperopic and myopic shifts when in reality there was no change in the subject's accommodation. Head and body movements were minimized in our experiment, however, by gently resting the infants' chins in an experimenter's hand. Residual movements were likely to be very small, infrequent, and aperiodic.

ii. Depth of focus: Gray et al. (1993a) noted an increase in the RMS deviation and the LFC in adults with an increase in their DOF (achieved by reducing pupil diameter). This raises the possibility that the larger RMS deviation (Figure 3) and larger LFC (Figure 5) noted in infants could also be a result of their larger predicted DOF; in other words, their insensitivity to blur. Based on their visual acuity and pupil diameter, Green et al. (1980) predicted the perceptual DOF of neonates to be larger than that of adults. The average pupil diameters of the infants who took part in our experiment were 4.9, 5.2, and 5.1 mm for the 3.0-, 2.0-, and 1.25-D viewing distances, respectively. The visual acuity of 8- to 30-week-old infants measured using the forced-choice preferential looking technique ranges from 1.5 to 5.0 cpd (Teller, McDonald, Preston, Sebris, & Dobson, 1986; Teller & Movshon, 1986). Incorporating these measures into the equation developed by Green et al. yields predicted depths of foci of ±0.92, ±0.46, ±0.34, and ±0.28 D for a dioptric viewing distance of 1.25 D for the 8- to 10-, 11- to 13-, 14- to 19-, and 20- to 30-week-old infants, respectively. The corresponding adult value is ±0.05 D for a pupil diameter of 5.0 mm and a visual acuity of 30 cpd (Campbell & Green, 1965). The infants' RMS deviations (0.31, 0.36, 0.40, and 0.40 D; Figure 3, panel a) were only smaller than the predicted DOF in the two younger infant groups. Also, if the larger RMS deviations and LFC in infants were driven by their larger DOF, we would predict a decrease in these parameters with age, consistent with their decreasing DOF. However, there was no significant difference in the microfluctuations with infant age in Experiment 1.

iii. Refractive error: The mean amount of hyperopia in young infants (approximately 2.0 D; Mayer et al., 2001) imposes a higher accommodative demand in infants than in adults. It is therefore possible that the larger infant fluctuations are the result of their hyperopia. A simple comparison of the infant RMS for the 1.25-D viewing distance and the adult RMS for the 3.0-D viewing distance in Figure 3 shows that the adult value is still only approximately one third of the infant RMS with this potentially matched mean demand. The prevalence of astigmatism greater than 1 D is higher in infants than in adults (Howland et al., 1978; Mohindra et al., 1978). It has been proposed that the accommodative system of astigmatic individuals might fluctuate between their two principal focal lines in an attempt to "search" for the plane of best focus (Arnulf, Santamaria, & Bescos, 1981; Charman & Heron, 1988; Santamaria, Plaza, & Bescos, 1984). Hence, it is possible that the larger fluctuations of infants are an attempt to find the plane of best focus. However, Dobson, Howland, Moss, and Banks (1983) observed that, unlike astigmatic adults (Freeman, 1975), 3-month-old astigmatic infants did not modulate their accommodative response to focus on the orientation of a grating target.

The cycloplegic refractions of our subjects would be required to make any definitive interpretation.

iv. The mechanical properties of the lens: Accommodative responses in humans are elicited by a change in curvature of the crystalline lens in response to a contraction of the ciliary muscle (Glasser & Kaufman, 2003). The efficiency with which the ciliary muscle changes the lens curvature critically depends on the compliance of the lens, which decreases with aging (Glasser & Kaufman, 2003). This decrease has been implicated in the reduction of microfluctuation amplitude noted with aging (Heron & Schor, 1995; Mordi & Ciuffreda, 2004). The infant lens is likely to be more compliant than that of an adult. van Alphen and Graebel (1991) estimated the infant modulus of elasticity (modulus of elasticity = 1/compliance) to be approximately half that of the adult (infant lens: 3.7×10^3 N/m^2; 20–30 years old lens: 6.7×10^3 N/m^2; 40–50 years old lens: 11.7×10^3 N/m^2). Accordingly, the infant lens is likely to fluctuate more in response to small changes in the ciliary muscle, assuming the characteristics of the zonules are largely adultlike.

Implications for measurement of refractive error

The refractive error of young children is typically measured in a clinical setting using either retinoscopy or autorefraction. The results of this study suggest that it is inadvisable to use only a single estimate of refractive error if it was collected on a time scale of much less than 1 s. For a 1-s measurement window, the estimate would only involve integration over fluctuation frequencies greater than 1 Hz, allowing the LFC fluctuations to influence the measurement. The RMS deviations recorded here suggest that a single image sample, which could be more than 2 standard deviations from the mean, may result in an error of up to approximately 0.75 D in an infant. It is therefore advisable to complete a number of sweeps with a retinoscope when assessing the average reflex motion for each lens power and to average a number of autorefractor readings to obtain a stable mean estimate.

Implications for emmetropization

Human infants are typically hyperopic at birth (Mayer et al., 2001) and tend to emmetropize during the first postnatal years (Ehrlich, Atkinson, Braddick, Bobier, & Durden, 1995; Mayer et al., 2001). It has been proposed that a signal for emmetropization might be derived from temporal integration of retinal defocus (Flitcroft, 1998; Winawer & Wallman, 2002; Zhu, Winawer, & Wallman, 2003). The fluctuations in retinal image defocus reported here suggest that defocus may need to be integrated over an extended period to increase the reliability of the signal. Winawer and Wallman (2002) observed that chicks fail to emmetropize when they are exposed to positive or negative lenses for extremely brief periods (2 s every 2 min for 3 days). Perhaps fluctuations in defocus in chick eyes are large enough to make some defocus signals for emmetropization unreliable over such short periods.

Although fluctuations introduce noise into a retinal defocus signal, they also provide information about the sign of the mean defocus (hyperopic or myopic) that is not available from a single retinal defocus sample (Charman & Heron, 1988; Kotulak & Schor, 1986a). Modulations used as signals to drive the direction of emmetropization or accommodation could only be used on a time scale reciprocally related to the temporal frequency of the fluctuation however. Infants of 8 weeks of age are capable of generating accommodative responses with latencies of less than a second, and therefore the direction of defocus would have to be detected on this time scale (Tondel & Candy, 2007).

Alternatively, an eye's refractive error could be more reliably indicated by an accommodative effort signal than by a short sample of retinal defocus. For instance, a typical two-diopter human infant hyperope will have an increased accommodative effort irrespective of whether they happen to momentarily overaccommodate or underaccommodate to a target. The retinal image, however, will contain a myopic error when they happen to overaccommodate and a hyperopic error when they happen to underaccommodate. In particular, humans' overaccommodation (Banks, 1980; Hainline et al., 1992; Turner, Horwood, Houston, & Riddell, 2002) for distant targets in the first months after birth would be incorrectly signaled as myopia based on retinal image defocus and would be correctly signaled as hyperopia based on accommodative effort. Although animal models suggest that eyes can compensate in the correct direction for induced defocus after ciliary and optic nerve section (preventing accommodation; Raviola & Wiesel, 1990; Troilo & Wallman, 1991; Wildsoet & Pettigrew, 1988; Wildsoet & Wallman, 1995), the endpoint of the compensation tends to be inaccurate (Schmid & Wildsoet, 1996; Troilo & Wallman, 1991; Wildsoet & Wallman, 1995).

Implications for cortical development

Substantial evidence from a number of species now suggests that cortical circuitry becomes tuned and matures postnatally based on neural activity arriving from the thalamus (Hebb, 1949; Stent, 1973). A question yet to be answered is whether normal experience-dependent synaptic refinement requires neural activity representing information at a spatial scale finer than the cortex can currently process. In other words, whether the cortex is iteratively tuning itself to input of a finer spatial scale than it can resolve. Accommodation is a mechanism by which the infant visual system controls its own postnatal visual experience—the accuracy of accommodation will determine the spatial scale of the information available for encoding in the retina. The hypothesis of Green et al. (1980) that infants only accommodate to the DOF derived from their acuity implies that the retinal image may only be focused to the current resolution of the cortex. Providing the cortex with information at finer spatial scales would require that the accommodative DOF be smaller than a cortically based DOF, or that a mechanism such as these fluctuations in accommodation generate at least transiently focused retinal images.

Acknowledgments

We would like to thank Bill Monette for developing the experimental equipment, Diane Goss for recruiting the infant subjects, the infants and parents for their participation, and Jingyun Wang and Grazyna Tondel for help with the data collection.

This research was supported by National Institutes of Health Grant EY-014460 (TRC).

Commercial relationships: none.
Corresponding author: T. Rowan Candy.
Email: rcandy@indiana.edu.
Address: Indiana University School of Optometry, 800 E. Atwater Ave, Bloomington, IN 47405.

References

Alpern, M. (1958). Variability of accommodation during steady fixation at various levels of illuminance. *Journal of the Optical Society of America, 48,* 193–197. [PubMed]

Arnulf, A., Santamaria, J., & Bescos, J. (1981). A cinematographic methods for the dynamic study of the image formation by the human eye. Microfluctuations of the accommodation. *Journal of Optics, 12,* 123–128.

Aslin, R. N. (1993). Infant accommodation and convergence. In K. Simons (Ed.), *Early visual development—*

Normal and abnormal (pp. 30–37). New York: Oxford University Press.

Aslin, R. N., Shea, S. L., & Metz, H. S. (1990). Use of the Canon R-1 autorefractor to measure refractive errors an accommodative responses in infants. *Clinical Vision Science, 5,* 61–70.

Atkinson, J., & Braddick, O. (1978). Visual development in the human infant. *Archives Italiennes de Biologie, 116,* 352–357. [PubMed]

Banks, M. S. (1980). Infant refraction and accommodation. *International Ophthalmology Clinic, 20,* 205–232. [PubMed]

Behrman, R. E., Kliegman, R. M., & Jenson, H. B. (2004). *Nelson textbook of pediatrics* (17 ed.). Philadelphia: Saunders.

Bendat, J. S., & Piersol, A. G. (2000). Statistical principles. In J. S. Bendat & A. G. Piersol (Eds.), *Random data—Analysis and measurement procedures* (3rd ed., pp. 86–117). New York: Wiley, Inc.

Bharadwaj, S. R., & Schor, C. M. (2005). Acceleration characteristics of human ocular accommodation. *Vision Research, 45,* 17–28. [PubMed] [Article]

Blade, P. J., & Candy, T. R. (2006). Validation of the PowerRefractor for measuring human infant refraction. *Optometry and Vision Science, 83,* 346–353. [PubMed]

Bour, L. J. (1981). The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. *Vision Research, 21,* 1287–1296. [PubMed]

Braddick, O., Atkinson, J., French, J., & Howland, H. C. (1979). A photorefractive study of infant accommodation. *Vision Research, 19,* 1319–1330. [PubMed]

Brookman, K. E. (1983). Ocular accommodation in human infants. *American Journal of Optometry and Physiological Optics, 60,* 91–99. [PubMed]

Campbell, F. W. (1960). Correlation of accommodation between the two eyes. *Journal of the Optical Society of America, 50,* 738. [PubMed]

Campbell, F. W., & Green, D. G. (1965). Optical and retinal factors affecting visual resolution. *The Journal of Physiology, 181,* 576–593. [PubMed] [Article]

Campbell, F. W., Robson, J. G., & Westheimer, G. (1959). Fluctuations of accommodation under steady viewing conditions. *The Journal of Physiology, 145,* 579–594. [PubMed] [Article]

Campbell, F. W., Westheimer, G., & Robson, J. G. (1958). Significance of fluctuations of accommodation. *Journal of the Optical Society of America, 48,* 669. [PubMed]

Candy, T. R., Tondel, G. M., & Wang, J. (2004). *Infant's accommodative responses to static targets*. Paper presented at the Association for Research in Vision and Ophthalmology, Fort Lauderdale.

Charman, W. N., & Heron, G. (1988). Fluctuations in accommodation: A review. *Ophthalmic & Physiological Optics, 8,* 153–164. [PubMed]

Choi, M., Weiss, S., Schaeffel, F., Seidemann, A., Howland, H. C., Wilhelm, B., et al. (2000). Laboratory, clinical, and kindergarten test of a new eccentric infrared photorefractor (PowerRefractor). *Optometry and Vision Science, 77,* 537–548. [PubMed]

Collins, M., Davis, B., & Wood, J. (1995). Microfluctuations of steady-state accommodation and the cardiopulmonary system. *Vision Research, 35,* 2491–2502. [PubMed]

Denieul, P. (1982). Effects of stimulus vergence on mean accommodation response, microfluctuations of accommodation and optical quality of the human eye. *Vision Research, 22,* 561–569. [PubMed]

Dobson, V., Howland, H. C., Moss, C., & Banks, M. S. (1983). Photorefraction of normal and astigmatic infants during viewing of patterned stimuli. *Vision Research, 23,* 1043–1052. [PubMed]

Ehrlich, D. L., Atkinson, J., Braddick, O., Bobier, W., & Durden, K. (1995). Reduction of infant myopia: A longitudinal cycloplegic study. *Vision Research, 35,* 1313–1324. [PubMed]

Fisher, R. F. (1971). Elastic properties of the human lens. *Experimental Eye Research, 11,* 143. [PubMed]

Flitcroft, D. I. (1998). A model of the contribution of oculomotor and optical factors to emmetropization and myopia. *Vision Research, 38,* 2869–2879. [PubMed]

Freeman, R. D. (1975). Asymmetries in human accommodation and visual experience. *Vision Research, 15,* 483–492. [PubMed]

Glasser, A., & Kaufman, P. L. (2003). Accommodation and presbyopia. In P. L. Kaufman & A. Alm (Eds.), *Adler's physiology of the eye* (10 ed., pp. 197–237). St. Louis: Mosby.

Gray, L. S., Gilmartin, B., & Winn, B. (2000). Accommodation microfluctuations and pupil size during sustained viewing of visual display terminals. *Ophthalmic & Physiological Optics, 20,* 5–10. [PubMed]

Gray, L. S., Winn, B., & Gilmartin, B. (1993a). Accommodative microfluctuations and pupil diameter. *Vision Research, 33,* 2083–2090. [PubMed]

Gray, L. S., Winn, B., & Gilmartin, B. (1993b). Effect of target luminance on microfluctuations of accommodation. *Ophthalmic & Physiological Optics, 13,* 258–265. [PubMed]

Green, D. G., Powers, M. K., & Banks, M. S. (1980). Depth of focus, eye size and visual acuity. *Vision Research, 20,* 827–835. [PubMed]

Hainline, L., Riddell, P., Grose-Fifer, J., & Abramov, I. (1992). Development of accommodation and convergence in infancy. *Behavioural Brain Research, 49,* 33–50. [PubMed]

Harb, E., Thorn, F., & Troilo, D. (2006). Characteristics of accommodative behavior during sustained reading in emmetropes and myopes. *Vision Research, 46,* 2581–2592. [PubMed] [Article]

Haynes, H., White, B. L., & Held, R. (1965). Visual accommodation in human infants. *Science, 148,* 528–530. [PubMed]

Hebb, D. O. (1949). *Organization of behavior*. New York: Wiley.

Heron, G., & Schor, C. (1995). The fluctuations of accommodation and ageing. *Ophthalmic & Physiological Optics, 15,* 445–449. [PubMed]

Howland, H. C., Atkinson, J., Braddick, O., & French, J. (1978). Infant astigmatism measured by photorefraction. *Science, 202,* 331–333. [PubMed]

Howland, H. C., Dobson, V., & Sayles, N. (1987). Accommodation in infants as measured by photorefraction. *Vision Research, 27,* 2141–2152. [PubMed]

Howland, H. C., & Sayles, N. (1983). Photorefractive studies of normal and handicapped infants and children. *Behavioural Brain Research, 10,* 81–85. [PubMed]

Hung, G. K., & Ciuffreda, K. J. (1988). Dual-mode behaviour in the human accommodation system. *Ophthalmic & Physiological Optics, 8,* 327–332. [PubMed]

Hung, G. K., Semmlow, J. L., & Ciuffreda, K. J. (1982). Accommodative oscillation can enhance average accommodative response: A simulation study. *IEEE Transactions on Systems, Man, and Cybernetics, 12,* 594–598.

Jennings, J. A., & Charman, W. N. (1981). Off-axis image quality in the human eye. *Vision Research, 21,* 445–455. [PubMed]

Kasthurirangan, S., Vilupuru, A. S., & Glasser, A. (2003). Amplitude dependent accommodative dynamics in humans. *Vision Research, 43,* 2945–2956. [PubMed]

Kotulak, J. C., & Schor, C. M. (1986a). A computational model of the error detector of human visual accommodation. *Biological Cybernetics, 54,* 189–194. [PubMed]

Kotulak, J. C., & Schor, C. M. (1986b). Temporal variations in accommodation during steady-state conditions. *Journal of the Optical Society of America A, Optics and image science, 3,* 223–227. [PubMed]

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. New York: Cambridge University Press.

Mayer, D. L., Hansen, R. M., Moore, B. D., Kim, S., & Fulton, A. B. (2001). Cycloplegic refractions in healthy children aged 1 through 48 months. *Archives of Ophthalmology, 119,* 1625–1628. [PubMed]

Miege, C., & Denieul, P. (1988). Mean response and oscillations of accommodation for various stimulus vergences in relation to accommodation feedback control. *Ophthalmic & Physiological Optics, 8,* 165–171. [PubMed]

Mitchell, D. E., & Timney, B. (1984). Postnatal development of function in the mammalian visual system. In *Handbook of physiology—The nervous system III* (vol. 3, pp. 507–555). Washington, DC: American Physiological Society.

Mohindra, I., Held, R., Gwiazda, J., & Brill, J. (1978). Astigmatism in infants. *Science, 202,* 329–331. [PubMed]

Mordi, J. A., & Ciuffreda, K. J. (2004). Dynamic aspects of accommodation: Age and presbyopia. *Vision Research, 44,* 591–601. [PubMed]

Navarro, R., Artal, P., & Williams, D. R. (1993). Modulation transfer of the human eye as a function of retinal eccentricity. *Journal of the Optical Society of America A, Optics and image science, 10,* 201–212. [PubMed]

Pugh, J. R., Eadie, A. S., Winn, B., & Heron, G. (1987). Power spectrum analysis in the study of ocular mechanisms. *Ophthalmic & Physiological Optics, 7,* 321–324. [PubMed]

Raviola, E., & Wiesel, T. N. (1990). Neural control of eye growth and experimental myopia in primates. *Ciba Foundation Symposium, 155,* 22–44. [PubMed]

Roorda, A., Campbell, M. C., & Bobier, W. R. (1997). Slope-based eccentric photorefraction: Theoretical analysis of different light source configurations and effects of ocular aberrations. *Journal of the Optical Society of America A, Optics, image science, and vision, 14,* 2547–2556. [PubMed]

Santamaria, J., Plaza, A., & Bescos, J. (1984). Dynamic recording of the binocular point spread function o the eye optical system. *Optica Applicata, 14,* 341–347.

Schaeffel, F., Wilhelm, H., & Zrenner, E. (1993). Inter-individual variability in the dynamics of natural accommodation in humans: Relation to age and refractive errors. *The Journal of Physiology, 461,* 301–320. [PubMed] [Article]

Schmid, K. L., & Wildsoet, C. F. (1996). Effects on the compensatory responses to positive and negative lenses of intermittent lens wear and ciliary nerve section in chicks. *Vision Research, 36,* 1023–1036. [PubMed]

Schor, C. M., Bharadwaj, S. R., & Burns, C. D. (2007). Dynamic performance of accommodating intraocular lenses in a negative feedback control system: A simulation-based study. *Computers in Biology and Medicine, 37,* 1020–1035. [PubMed]

Stent, G. S. (1973). A physiological mechanism for Hebb's postulate of learning. *Proceedings of the National Academy of Sciences of the United States of America, 70,* 997–1001. [PubMed] [Article]

Teller, D. Y., McDonald, M. A., Preston, K., Sebris, S. L., & Dobson, V. (1986). Assessment of visual acuity in infants and children: The acuity card procedure. *Developmental Medicine and Child Neurology, 28,* 779–789. [PubMed]

Teller, D. Y., & Movshon, J. A. (1986). Visual development. *Vision Research, 26,* 1483–1506. [PubMed]

Tondel, G. M., & Candy, T. R. (2007). Human infants' accommodation responses to dynamic stimuli. *Investigative Ophthalmology & Visual Science, 48,* 949–956. [PubMed]

Troilo, D., & Wallman, J. (1991). The regulation of eye growth and refractive state: An experimental study of emmetropization. *Vision Research, 31,* 1237–1250. [PubMed]

Turner, J. E., Horwood, A. M., Houston, S. M., & Riddell, P. M. (2002). Development of the response AC/A ratio over the first year of life. *Vision Research, 42,* 2521–2532. [PubMed]

van Alphen, G. W., & Graebel, W. P. (1991). Elasticity of tissues involved in accommodation. *Vision Research, 31,* 1417–1438. [PubMed]

van der Heijde, G. L., Beers, A. P., & Dubbelman, M. (1996). Microfluctuations of steady-state accommodation measured with ultrasonography. *Ophthalmic & Physiological Optics, 16,* 216–221. [PubMed]

Wallman, J., & Winawer, J. (2004). Homeostasis of eye growth and the question of myopia. *Neuron, 43,* 447–468. [PubMed] [Article]

Walsh, G., & Charman, W. N. (1988). Visual sensitivity to temporal change in focus and its relevance to the accommodation response. *Vision Research, 28,* 1207–1221. [PubMed]

Weeber, H. A., Eckert, G., Soergel, F., Meyer, C. H., Pechhold, W., & van der Heijde, R. G. (2005). Dynamic mechanical properties of human lenses. *Experimental Eye Research, 80,* 425–434. [PubMed]

Wildsoet, C. F. (1997). Active emmetropization—Evidence for its existence and ramifications for clinical practice. *Ophthalmic & Physiological Optics, 17,* 279–290. [PubMed]

Wildsoet, C. F., & Pettigrew, J. (1988). Experimental myopia and anomalous eye growth patterns unaffected by optic nerve sectioning in chickens: Evidence for local control of eye growth. *Clinical Vision Science, 3,* 99–107.

Wildsoet, C. F., & Wallman, J. (1995). Choroidal and scleral mechanisms of compensation for spectacle lenses in chicks. *Vision Research, 35,* 1175–1194. [PubMed]

Winawer, J., & Wallman, J. (2002). Temporal constraints on lens compensation in chicks. *Vision Research, 42,* 2651–2668. [PubMed]

Winn, B., Charman, W. N., Pugh, J. R., Heron, G., & Eadie, A. S. (1989). Perceptual detectability of ocular accommodation microfluctuations. *Journal of the Optical Society of America A, Optics and image science, 6,* 459–462. [PubMed]

Winn, B., & Gilmartin, B. (1992). Current perspective on microfluctuations of accommodation. *Ophthalmic & Physiological Optics, 12,* 252–256. [PubMed]

Winn, B., Pugh, J. R., Gilmartin, B., & Owens, H. (1990a). Arterial pulse modulates steady-state ocular accommodation. *Current Eye Research, 9,* 971–975. [PubMed]

Winn, B., Pugh, J. R., Gilmartin, B., & Owens, H. (1990b). The frequency characteristics of accommodative microfluctuations for central and peripheral zones of the human crystalline lens. *Vision Research, 30,* 1093–1099. [PubMed]

Zhu, X., Winawer, J. A., & Wallman, J. (2003). Potency of myopic defocus in spectacle lens compensation. *Investigative Ophthalmology & Visual Science, 44,* 2818–2827. [PubMed] [Article]