

IMI Accommodation and Binocular Vision in Myopia Development and Progression

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The role of accommodation in myopia development and progression has been debated for decades. More recently, the understanding of the mechanisms involved in accommodation and the consequent alterations in ocular parameters has expanded. This International Myopia Institute white paper reviews the variations in ocular parameters that occur with accommodation and the mechanisms involved in accommodation and myopia development and progression. Convergence is synergistically linked with accommodation and the impact of this on myopia has also been critiqued. Specific topics reviewed included accommodation and myopia, role of spatial frequency, and contrast of the task of objects in the near environment, color cues to accommodation, lag of accommodation, accommodative-convergence ratio, and near phoria status. Aspects of retinal blur from the lag of accommodation, the impact of spatial frequency at near and a short working distance may all be implicated in myopia development and progression. The response of the ciliary body and its links with changes in the choroid remain to be explored. Further research is critical to understanding the factors underlying accommodative and binocular mechanisms for myopia development and its progression and to guide recommendations for targeted interventions to slow myopia progression.

Keywords: accommodation, binocular vision, myopia development, myopia progression, emmetropization

The association between sustained near work demanding high levels of ocular accommodation and the development of myopia has been well documented.¹ Epidemiologic studies have also shown a correlation between the amount of near work and the onset and progression of myopia.²⁻⁴ Consequently, increased accommodative effort required during near work has been proposed as a causative factor in the development of myopia. However, the relationship between accommodative demand and myopia is complex. Due to the synergistic response of the vergence system, the status of binocular vision at near work also varies with accommodation, yet the impact of heterophoria at near work on myopia onset and progression is not fully understood. This article provides a comprehensive review of the research evidence on the influence of accommodation and binocular vision in myopia development and progression; it also translates the current evidence and main findings to clinical practice.

VARIATIONS IN OCULAR STRUCTURE DURING ACCOMMODATION

Owing to the purported links between accommodative dysfunction and myopia, investigations of structural and functional differences in the accommodative apparatus and associated ocular elements are of particular interest. One of the broader academic and clinical motivations driving such endeavors is the opportunity to elucidate structural variations or trends that may be predictive of specific patterns of myopia progression, for example, in identifying those at particular risk of the onset of myopia, high myopia, or rapid progression of myopia.

To facilitate the understanding of how and why the structure of a myopic eye may affect accommodative behavior, the following section presents a brief review of the mechanism of human accommodation. Although the literature stands equivocal concerning the exact mechanism, it does



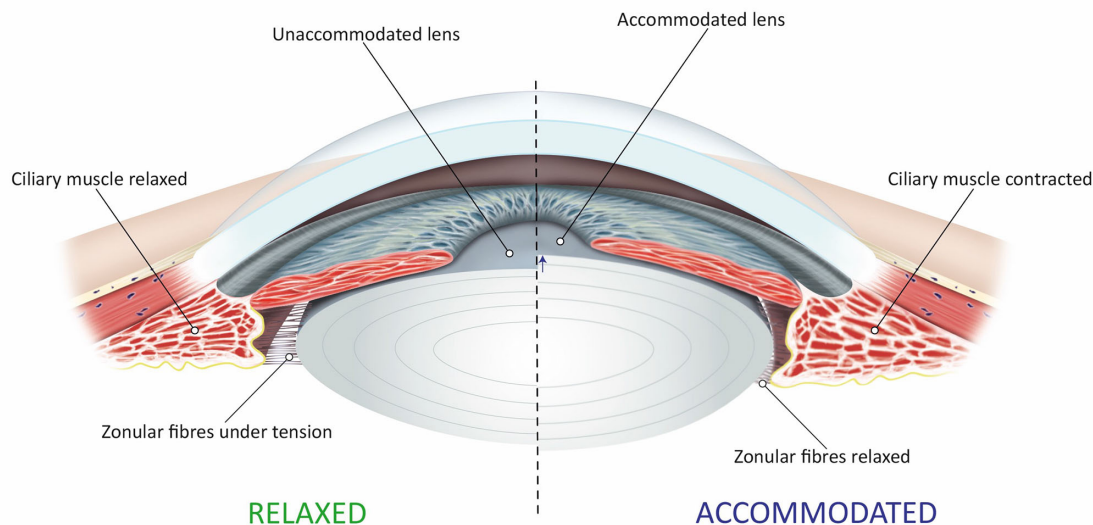


FIGURE 1. Differences in anterior eye structure in the relaxed (unaccommodated) and accommodated eye. Copyright © 2021 by IMI.

largely acquiesce to a Helmholtzian model of accommodation (1855). In this model, the ciliary muscle (a smooth muscle ring) is in a relaxed state while viewing an object at optical infinity. As the apex of the ciliary muscle has a relatively large diameter in this state of relaxation, the anterior zonular fibers from which the crystalline lens is suspended are maintained under tension due to strain from the posterior pars plana fibers. Consequently, the stretched anterior zonules exert strong radial forces on the capsule and flatten the crystalline lens. When the eye shifts focus to a near target, the ciliary muscle contracts, moving its mass anteriorly and centripetally and releasing tension on the zonules. Helmholtz proposed that this structural change occurs because the capsule and the lens matrix are inherently elastic; when freed from the zonular pull, the lens, with the aid of its capsule, can assume an axially thicker^{5–16} and rounder shape, with a reduced diameter.^{17–22} Refractive change during accommodation is primarily attributable to an increase in anterior surface curvature of the crystalline lens surface^{5,23,24} and a simultaneously smaller increase in posterior surface curvature.^{6,25,26} These dimensional changes result in a reduction in anterior chamber depth, yet overall an increase in anterior segment length (distance from the cornea to the posterior surface of the lens).^{10,12,27} Once accommodation ceases (Fig. 1), the ciliary muscle is thought to return to its relaxed position as a result of elastic recoil imparted by the choroid.²⁸

Despite the advent of high-resolution and dynamic ocular imaging systems allowing visualization of many previously unknown anatomic subtleties, the iris still prevents imaging of the key accommodative structures. These limitations also apply to studies attempting to determine whether accommodative mechanics differ as a function of ametropia. Consequently, at present, several models exist, with varying levels of evidence regarding accommodation induced structural changes that may be instrumental in myopia onset and progression.

It is well documented from biometric studies that increased vitreous chamber depth is the primary structural change in the majority of cases of myopia,²⁹ and that

myopic eyes are generally globally larger and longer than emmetropic eyes.^{30,31} The literature also reports other differences in ocular structure as a function of ametropia, including corneal curvature,^{32–35} anterior chamber depth,³⁶ crystalline lens thickness,^{37–39} choroidal thickness,⁴⁰ and scleral rigidity.^{41,42} The anatomic complexities of each of these structures in relation to accommodation and refractive error give rise to potential corollaries for accommodative performance and myopia progression.

The first consideration is the nature of global eye size in terms of the optics of the eye and the implications for accommodative performance. Davies and colleagues⁴³ explained using ray tracing that axially myopic and axially hyperopic eyes show different vergence contributions for light rays entering the anterior segment. They attributed this optical behavior to a consequence of “natural damping” associated with negative vergence and axial length changes. The spectacle corrected myope also has to accommodate and converge less for a near target than an emmetrope does due to the prismatic effect of the lenses.⁴⁴ Therefore, accommodative response for a similar demand will be slightly greater in a longer (myopic) eye compared to a shorter (hyperopic) eye due to differences in eye size.

CHANGES IN THE ANTERIOR SEGMENT IN RELATION TO ACCOMMODATION AND MYOPIA

Pupil Size

Given the evidence that axial growth is influenced by visual experience inclusive of retinal image quality and optical defocus^{45–48} and data suggesting that myopes display unusually high levels of aberration and/or larger accommodative lags relative to those who remain emmetropic,^{49–59} the role of the pupil in myopigenesis is unclear. As the pupil acts as an aperture stop, theoretically, inter- and intra-individual pupil size variations present a potential innate and dynamic physiological mechanism whereby optical image properties, including retinal image blur, higher-order aberrations, depth of focus, and accommodative lag, could differ between

myopes and nonmyopes or fluctuate in a myopigenic fashion over time contributing to progression in susceptible individuals.⁶⁰ Generally, larger pupil diameters lead to greater wave-front aberrational blur,⁶¹ whereas during accommodation, the blurring effect of a given dioptric lag would be proportionally greater due to the larger retinal blur circle diameter.⁶⁰

Nonetheless, most human studies have failed to find significant differences in unaccommodated pupil diameter between age-matched emmetropic and myopic groups.^{60,62–65} A few studies have reported a weakly associated increase in pupil diameter in myopes, but these studies have important design limitations, including differences in target distance⁶⁶ or age⁶⁷ between groups. Further, anecdotal evidence supporting a lack of correlation can be drawn from numerous studies that report isocoria in anisometropes, which is counter to expectation should more myopic eyes have systematically larger pupils.^{60,68} Differences in pupil size or response during steady-state accommodation or the notion of systematically higher levels of retinal image blur in myopes with larger pupils are also unsupported by *in vivo* data.^{60,65}

It would therefore seem plausible that pupillary characteristics in accommodated and unaccommodated eyes are independent of ametropia and the notion that pupil-related factors play a role in myopia genesis is currently unsubstantiated. It should, however, be noted that the aforementioned studies show considerable variations among individuals, generally examine adult populations, and do not differentiate between progressive and stable myopia. It has been suggested that different trends may be evident in more homogenized refractive error or age groups, particularly pediatric populations.⁶⁰

Ciliary Muscle

As ciliary muscle contraction is a prerequisite to accommodation,⁶⁹ interest in morphological differences in ciliary muscle anatomy has increased⁷⁰ in the context of how they may contribute to the association between nearwork and myopia. In the unaccommodated state, myopic children^{71–74} and adults^{75–79} have been shown to have thicker ciliary muscles in the posterior-most aspect, typically 2 to 3 mm behind the scleral spur,^{70,71,73–76,78} with thickness correlating positively with increasing axial length. Meanwhile, some studies have also reported a thinner anterior portion of the ciliary muscle in axially longer eyes.^{73,79,80} In hypermetropic children, the ciliary muscle shows its maximum thickness anteriorly, approximately 1 mm from the scleral spur.⁷³ Interocular differences have been reported in anisometropia, with significantly thicker muscles observed in eyes that have unilateral high myopia compared with the fellow eye.⁷⁶ Furthermore, region-specific differences in thickness have also been reported, with the longitudinal fiber portion being thicker and the apical fiber region being thinner in the more myopic eye.⁷⁹ Nonetheless, Sheppard and Davies⁸¹ found a positive correlation between axial length and ciliary muscle length, but not between axial length and ciliary muscle thickness when considered as distances from the scleral spur as a percentage of the total length of the ciliary muscle.

Studies examining general ciliary muscle morphology under various accommodative demands,^{77,81–85} have suggested a linear relationship between ciliary muscle thickness and accommodative response,^{74,82,86} showing that the muscle thickens anteriorly and thins posteriorly

with increasing accommodative effort.^{74,81,82} Sheppard and Davies⁸¹ and Lewis et al.⁷⁴ examined accommodation-induced morphological changes between refractive groups and found no dependence of the ciliary muscle accommodative response on axial length or ciliary muscle baseline thickness. Interestingly, Jeon et al.⁷⁷ reported reduced movement of the ciliary muscle during accommodation in individuals with increased axial length and ciliary muscle thickness. However, as accommodation responses were not assessed, it remains unclear whether there was a smaller relative change in crystalline lens thickness per unit of accommodative response for eyes with longer axial lengths,⁴³ or whether there were functional consequences (e.g. increased lag).

Although it is clear that differences in ciliary muscle anatomy between myopes and nonmyopes exist, if or how this would translate into a myopigenic effect remains undetermined. Only minor differences in accommodative behavior (optical coherence tomography [OCT] assessed microfluctuations of accommodation, velocity of accommodation and disaccommodation, and lag of accommodation) occur between emmetropes and myopes despite the morphological differences between them,⁸⁶ suggesting that ciliary muscle size may not be a contributing or critical factor in myopia development. Nonetheless, other models have been proposed.

One early suggestion is that the ciliary muscle tonus could in turn affect choroidal tension, resulting in axial length change (see later section regarding transient axial elongation).⁸⁷ Alternatively, a thicker ciliary muscle might prevent the equatorial stretch, which can occur with myopia and thus maintain emmetropia, thereby being a factor in myopigenesis.⁸⁸ However, a myopic shift in refraction has been found not to be associated with a change in ciliary muscle thickness over time in children.⁸⁹ A hypertrophic ciliary muscle could theoretically lead to myopia development, perhaps due to poor contractibility resulting in accommodative inaccuracies and chronic retinal hyperopic defocus under nearwork conditions. Seemingly, the evidence that children and adults with myopia have higher accommodative lags than emmetropes, and that higher lags of accommodation are associated with faster myopia progression support this.^{50,55,57,90} However, most studies concede that high accommodative lag is more likely to represent a consequence, rather than a stimulus for myopia,^{91–93} and the relatively thinner anterior muscle in myopes has been suggested to be indicative that the increase in myopic ciliary muscle length may occur as a result of the muscle mass relocating to a more posterior position due to axial elongation, rather than the ciliary muscle undergoing related growth-related hypertrophy.⁸¹

Crystalline Lens

Structural changes in the crystalline lens are central to myopia development. Crystalline lens power reduces markedly during infancy,⁹⁴ with substantial inhibition of lens thinning and flattening evident 1 year before or within a year of myopia onset in children.⁹⁵ This phenomenon is concomitant with a reduction in both the refractive index and the dioptric power of the crystalline lens.⁹⁵ These findings support the notion that early onset myopia results from a breakdown in the independent relationship between lens changes and axial elongation.⁹⁵ Interestingly, it has been shown that there is a tendency for the crystalline lens to be

thinner in myopic eyes than emmetropic eyes,^{37–39} despite the apparent breakdown in co-ordination between lens thinning and axial growth. However, due to difficulties obtaining *in vivo* data of the crystalline lens' parameters as it accommodates, little is known about whether there are relevant functional implications of crystalline lens size or anatomic features, such as refractive index and rigidity, and whether these parameters differ between refractive groups.

CHANGES IN THE POSTERIOR SEGMENT IN RELATION TO ACCOMMODATION AND MYOPIA

Ostensibly, performance variation in the accommodative apparatus represents the most obvious anatomic candidate capable of precipitating myopia; yet, structural changes within the posterior segment during accommodation are emerging as being more likely to promote a myopic shift in susceptible eyes.

Various experimental paradigms using partial coherence interferometry^{96–98} and optical low coherence reflectometry^{99–102} have shown that the eye experiences a transient period of axial elongation after brief periods of sustained accommodation, both on axis^{96–100,102} and in the periphery,¹⁰¹ with the magnitude of change increasing with larger accommodative demand.⁹⁹ The exact mechanics by which the accommodative process instigates this phenomenon remains unclear; however, it is a long-held belief that the accommodating ciliary muscle applies an internal mechanical force upon the globe.^{87,103} One such proposal is that posterior pole elongation occurs to maintain ocular volume despite the decreases in scleral and choroidal equatorial circumference, which arises owing to the increasing force exerted on the equatorial choroid by the contraction of the ciliary smooth muscle.^{96,97} Although data to explicitly evidence a mechanical force model are scarce, Croft and colleagues¹⁰⁴ have reported centripetal movement of both the equatorial choroid and retina in rhesus monkeys during Edinger-Westphal stimulated accommodation, seemingly fitting this hypothesis.

The discovery of accommodation driven fluctuations in ocular length has given rise to the hypothesis that eyes which experience a greater magnitude of transient axial elongation may be more susceptible to permanent myopic shift.⁹⁷ Indeed, this notion seemingly dovetails with the suspicion that ocular rigidity differences may make an axially myopic eye more pliant to transient elongation.⁹⁷ There is now considerable evidence that myopic eyes demonstrate reduced posterior choroidal,¹⁰⁵ scleral,^{106–109} and overall equatorial ocular wall^{41,110} thickness compared with emmetropic eyes. Nonetheless, it remains unclear whether an association exists between *in vivo* anterior ocular rigidity and myopia susceptibility or progression,^{41,42,111} particularly in light of the data derived from differential Schiøtz tonometry, which suggests emmetropic and myopic adults¹¹² and children⁴¹ have similar ocular rigidity and ocular wall stress.

To date, research comparing the magnitude of accommodation-induced transient axial elongation between emmetropic and myopic adults has produced contradictory findings, although it must be noted that studies have varied in design, type of accommodative stimulus, age range of participants, and refractive error. Mallen and colleagues⁹⁷ reported the largest disparity with a mean elongation of 0.037 mm in emmetropes versus 0.058 mm in myopes for

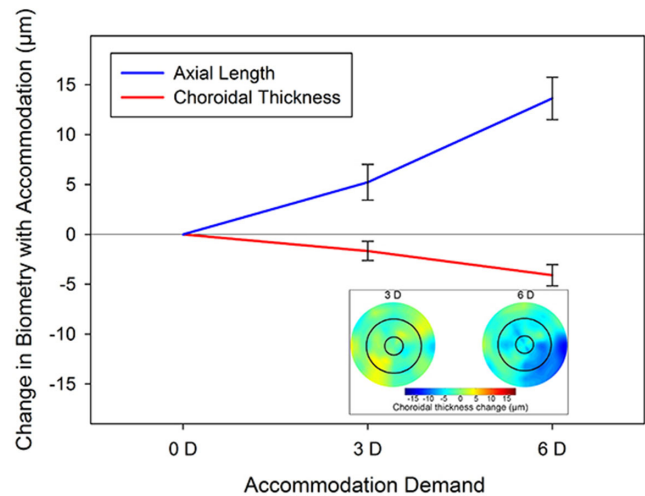


FIGURE 2. The changes in axial length (top, blue line) and choroidal thickness (bottom, red line) occurring during a short duration 3.0 D and 6.0 D accommodation task. Note the significant eye elongation and choroidal thinning that occurs at the higher accommodation demand. Inset illustrates the topographical choroidal thickness changes in the macular region occurring with 3.0 D and 6.0 D of accommodation (note that cool colors indicate a choroidal thinning with accommodation). From Woodman-Pieterse et al.¹¹⁵

a 6.0 D accommodative stimulus. Although it has since been suggested that these values present an overestimation due to artefactual instrument optical path length errors,¹¹³ corrected values of 0.026 and 0.047 mm, respectively, are still in excess of those found by other studies.¹⁰¹ Other researchers have reported either no significant group difference,^{99,100,102} increased elongation in emmetropes,⁹⁶ or only a very small, but significantly greater, transient axial elongation in myopes.⁹⁹

Nonetheless, data suggesting no differences in the physical extent of relative elongation with ametropia do not necessarily rule out a potential role for transient axial elongation in accommodation-related myopia genesis,⁹⁹ as this does not account for variations in duration or intensity of nearwork activities¹¹⁴ or other related features, which may even be responsible in isolation. All aforementioned studies are limited to providing a snapshot of biometric change during relatively short-duration accommodation tasks. The influence of longer periods of accommodation on transient axial elongation, and its ability and time period of recovery from these findings remain unknown.⁹⁹

Although the mechanical model for transient axial elongation involves the choroid in an intermediary force transmission role, recent data indicate that its contribution may be substantially greater.⁴⁰ Certainly, in spatial terms, choroidal thinning during accommodation accounts for a significant degree of total elongation.^{100,115,116} Woodman et al.¹⁰⁰ examined the subfoveal choroidal thickness change during a sustained 4.0 D accommodation task and reported a $-8 \mu\text{m}$ choroidal thinning and approximately $20 \mu\text{m}$ axial elongation in a cohort of myopic and emmetropic participants. Subsequent OCT studies with higher accommodative stimuli have produced consistent findings,^{115,116} and uncovered regional variations, with choroidal thinning being most prominent in temporal, inferior, and infero-temporal parafoveal zones (Fig. 2).¹¹⁵ Choroidal thinning under transient axial elongation is likely to represent an element of

feedback response of the choroid resulting from the accommodation, rather than purely a mechanical consequence of ciliary muscle contraction. The potential role of the choroid in the regulation of eye growth is currently under much scrutiny as changes in choroidal thickness are known to accompany eye growth, be more marked in highly myopic eyes and be bidirectional, with myopigenic factors leading to choroidal thinning and myopia-protective factors leading to causing choroidal expansion.⁴⁰ In the case of accommodation, choroidal thinning may be a compensatory mechanism to maintain a stable, optimally focused retinal image.^{40,117}

How differences in choroidal thickness during accommodation may contribute to myopia development in the longer term is undetermined, and more work is needed to elucidate variations in response and recovery in myopes and emmetropes. Similarly, how changes in choroidal dynamics and position interact with other optical features of the myopic or pre-myopic eye, such as increased negative spherical aberration or accommodative lag, cannot be discounted as contributing factors to the development of myopia.⁴⁰

Anterior Sclera

The semirigid scleral cup is the principal determinant of eye size and shape. During the development of myopia, the sclera undergoes a long-term, permanent remodeling process, whereby the structural and biomechanical properties of the sclera alter, making the globe more susceptible to expansion.^{106,118} Changes in eye shape occur globally in all three dimensions (horizontal, vertical, and axial), although the magnitude of changes may vary with dimensions. It has been shown in humans that, compared with the emmetropic eyes, the eyes with myopia are elongated in both equatorial and axial dimensions, although the globe is elongated more in the axial dimension, resulting in a more prolate shape of the eye.¹¹⁹ Significant negative correlations have also been reported between anterior scleral thickness near the scleral spur and increasing levels of myopia and axial length,¹²⁰ consistent with the negative correlation between posterior sclera thickness and axial length.¹²¹ The scleral changes in myopia may thus occur well beyond the posterior pole and extend to the equatorial region or beyond.

The time courses of the accommodative system and scleral modeling vary substantially: accommodation has a much more rapid time course compared with scleral biomechanical changes in myopia.¹²² The close juxtaposition of the accommodation apparatus, including the ciliary body, with the anterior sclera makes it plausible that accommodation could affect the anterior scleral properties. Recent studies have provided some evidence that the scleral shape undergoes short-term changes with accommodation. Woodman-Pieterse et al. measured changes in the anterior temporal sclera (1, 2, and 3 mm posterior to the scleral spur) in adult myopes and emmetropes using high-resolution anterior OCT, whereas the subjects fixated monocularly at near accommodative stimuli of 0.0, 3.0, and 6.0 D through a custom-mounted Badal optometer.¹²³ It was shown that the 6.0 D accommodative stimulus induced significant thinning of the anterior sclera, with more prominent changes in the myopic eyes at 3 mm posterior to the scleral spur for both accommodative stimuli. Niyazmand et al. reported changes in the shape of the anterior sclera in the horizontal meridian using eye surface profilometry in myopic and emmetropic young adults under conditions of 5.0 D

accommodative demand, 9 degrees simulated convergence demand, and their combination.¹²⁴ Although changes were primarily evident at the naso-scleral region, all three conditions produced a significant reduction in the sagittal height of the anterior sclera (i.e. a reduction in elevation of the anterior sclera), whereas accommodation also produced a significant flattening of the anterior eye surface, but only when coupled with simulated convergence. These findings suggest that the anterior sclera perhaps thins and moves forward in response to accommodation. However, the reported changes could be due to convergent eye movement associated with accommodation or medial rectus contraction rather than an optically driven scleral response.¹²⁵

MECHANISMS OF HOW ACCOMMODATION INTERRUPTS EMMETROPIZATION IN HUMANS

Whereas emmetropization is the long-term response of the eye in reducing or eliminating the defocus perceived at the fovea, accommodation is the immediate response of the eye to eliminate or reduce the hyperopic defocus presented during near work. The accuracy of accommodation has long been linked to the accuracy of refractive error development. Larger lags associated with high accommodative demand produce hyperopic defocus at the fovea providing a stimulus for the eye to grow longer and become myopic.^{52,126} Previous studies have shown that myopic children accommodate less than emmetropic children.^{50,57,91,127-130} The higher lags are shown to persist in some studies even when a near addition is given to the myopic children, as they use the add power and underaccommodate.¹³¹ Several mechanisms have been proposed for how accommodation could cause myopia development in humans.

Accommodative Lag and Foveal Vision

Axial form deprivation due to the diffuse blur from high levels of accommodative lag and hyperopic defocus in the central retina could lead to the development or progression of myopia, as evidenced in animal experiments.^{52,132,133} To date, longitudinal studies comparing the magnitude of initial accommodative lag with subsequent myopia progression have come to conflicting conclusions.^{59,134} Accommodative lags of over 1.0 D are common during near vision in both emmetropes and myopes. These errors in accommodation are summarized for children in [Table 1](#) and for young adults in [Table 2](#). A lag of accommodation does not necessarily mean that the visual quality is poor during near vision. The need for accommodation will depend on the range of clear focus which is influenced by monofocal and chromatic aberrations, pupil size,¹³⁵ and neural factors.¹³⁶ For a constant pupil diameter, differences in ocular aberrations between myopes and emmetropes are observed and are variable in both accommodative and nonaccommodative states.^{137,138} Attempts to slow myopia progression using interventions targeted at improving accommodative lag, such as progressive lens wear groups (PALs) have been largely unsuccessful, even when including children with high lags of accommodation and near esophoria.¹³⁹⁻¹⁴¹ Cheng et al.¹⁴¹ additionally used base in prism along with progressive addition lenses to offset the positive-lens-induced exophoria and found no difference in myopia control efficacy in children with high lags of accommodation, however, the small gain in efficacy may be related to

TABLE 1. Effect of Refractive Error and Measurement Methods on Accommodation Errors at Near Vision in Children

| Paper | Measurement Method | Accommodation Stimuli | Mode of Myopic Correction | Age, y | Refractive Groups | AE, D | Summary of Results |
|---|---|---------------------------------|---|--------------|---------------------|---------------------------------------|---|
| Rouse et al. (1984) ¹²⁸ | MEM dynamic retinoscopy | Monocular FV usual near demand | Habitual correction spectacle correction | 5–11 | Not specified | –0.30 | Relationship between age and lag |
| Gwiazda et al. (1993) ⁵⁰ | Canon R–1 Autorefractor | Monocular FV/NL demand | Soft contact lenses | 5–17 | EMMs MYPs EMMs MYPs | –0.30 FV –0.56 NL –1.61 NL | MYPs had greater lags than EMMs. Lags were greater for NL |
| Chen and O'Leary (2002) ²⁸⁷ | Canon R–1 Autorefractor | Monocular FV/NL demand | N/A | 3–14 | EMMs | –0.29 FV –0.69 NL | Lags greater for NL |
| McClelland et al. (2004) ¹²⁷ | Not Dynamic Retinoscopy | Monocular FV 4–10 D demand | Habitual correction | 4–15 | Not specified | –0.30 at 4 D –2.50 at 10 D | Lags increased as the demand increased |
| Mutti et al. (2006) ⁹¹ | Grand Seiko WR5001K or Canon R–1 Autorefractor | BLV/FV 2 D and 4 D demand | Habitual spectacle correction | 6–15 | EMMs EMMs MYPs MYPs | –1.00 FV BLV –1.12 FV –1.40 BLV | Increased lags found in MYPs after they became myopic but not in EMMs who became MYPs |
| Langaas et al. (2008) ¹⁴⁵ | Plus Optix Power Refractor 11 | Binocular FV 0.25–4 D demand | Spectacle correction | Ave 13 14 | EMMs EOMs | –0.10 –0.10 | Lags were greater at the 2 D than the 4 D viewing condition |
| Weizhong et al. (2008) ¹³⁴ | Shin-Nippon Autorefractor | Monocular FV 3 D demand | Spectacle correction | Ave 11 | EOMs | –0.76 | No relationship between accommodation lag and myopia progression over 1 y |
| COMET 2 (2011) ¹⁴⁰ | Grand Seiko WR5001K | Monocular FV 3 D demand | Spectacle correction | 8–12 | MYPs SVL MYPs PAL | –1.40 –1.47 | Both myopic groups of children exhibited larger accommodative lags. The treatment effect of the PALs was greater in children with lags greater than –1.5 D. |
| Berntsen et al. (2011) ¹³⁹ | Grand Seiko WR5001K or Canon R–1 Autorefractor | BLV/FV 4 D demand | Spectacle correction | 6–14 | MYPs SVL | –1.59 | Myopic children had high lags of accommodation, but the magnitude of the lag was not related to the annual myopia progression |
| Yeo et al. (2013) ²⁴⁸ | Shin-Nippon Autorefractor | Binocular FV 3 and 4 D demand | Spectacle correction | 7–12 | EMMs MYPs | –0.96 –1.01 | Chinese children had high lags of accommodation when reading either English or Chinese texts |
| Han et al. (2018) ²⁸⁸ | Fused cross cyl | Binocular, Phoropter 4 D demand | Spectacle correction | 9–14 | MYPs SVL | –1.0 | Orthokeratology and concentric progressive lenses reduced the lag of accommodation |
| Ma et al. (2019) ²⁸⁹ | Shin-Nippon Autorefractor | Monocular FV 3 D demand | Spectacle correction | 8–12 | MYPs SVL | –1.0 | Myopic children with high lags showed reduction in lag both with in office placebo therapy and accommodation vergence training |
| Chen et al. (2019) ¹³⁰ | Grand Seiko WR5001K | Monocular FV 4 D demand | Spectacle correction | 8–12 | EMMs MYPs SVL | –0.20 –0.65 | Myopic children had greater lags. Lags increased in mesopic lighting conditions |

AE, accommodative error at highest demand conditions; BLV, Badal lens viewing; EMMs, emmetropes; EOMs, early onset myopes; FV, free viewing; HS, Hartmann Shack; lag, accommodation lag; MYPs, myopes; N/A, not applicable; NL, negative lens series; PAL, progressive lens wear group; PL, positive lens series; SVL, single vision lens wear group; VA, visual acuity.

TABLE 2. Effect of Refractive Error and Measurement Methods on Accommodation Errors at Near Work in Young Adults

| Paper | Measurement Method | Accommodation Stimuli | Mode of Myopic Correction | Age, y | Refractive Groups | AE (D) | AEI | ASRC | Summary of Results | | |
|---|--|---|-----------------------------------|--------|-------------------|----------|-----|------|--|---------|---------------------|
| McBrien and Millodot, (1986) ⁴⁹ | Canon R-1 Autoref | Binocular free viewing (FV) 0–5 D demand | Soft contact lenses | 18–23 | EMMs | –0.54 | | | EOMs and LOMs had greater lags than EMMs | | |
| Bullimore et al. (1992) ²⁹⁰ | Canon R-1 Autoref | Monocular FV/NL/PL 1–5 D demand | Soft contact lenses | 19–23 | EMMs | –0.60 | | | LOMs had greater lags for passive tasks at high demands | | |
| | | | | | | | | | | FOMs | –0.69 |
| Abbott et al. (1998) ⁵⁷ | Canon R-1 Autoref | Monocular FV/NL/PL 0–4 D demand | Soft contact lenses | 18–31 | EMMs | 0.01 NL | | | Progressing MYPs had greater lags for NL conditions only | | |
| | | | | | | | | | | LOMs | –0.73 |
| Jiang and Morse (1999) ²⁹¹ | Canon R-1 Autoref | Monocular Badal lens viewing BLV up to 5 D demand | Soft contact lenses or spectacles | 20–30 | EMMs | | | 0.74 | All 3 refractive groups had similar lags | | |
| | | | | | | | | | | SMs PMS | 0.01 NL –0.52 NL |
| Rosenfield et al. (2002) ²⁹² | Canon R-1 Autoref | Binocular FV 0–5 D demand | Soft contact lenses | 21–27 | EMMs | –0.34 FV | | 0.99 | Greater lags found in stable MYPs than initial EMMs and MYPs that progressed over a 1 y period | | |
| | | | | | | | | | | SMS | 0.77 |
| | | | | | | | | | | PMS | 0.67 |
| Subbaram and Bullimore (2002) ⁶⁵ | Canon R-1 Autoref | Monocular BLV 0–4 D demand | Spectacles | 20–30 | EMMs | –0.29 | | 0.96 | Small lags found in both refractive groups | | |
| | | | | | | | | | | SMS | –0.34 FV |
| | | | | | | | | | | PMS | –0.20 FV |
| Seidel et al. (2003) ²⁹³ | Canon R-1 Autoref | Monocular BLV 0–4.5 D demand | Soft contact lenses | 17–26 | EMMs | –0.29 | | 0.81 | All 3 groups had similar lags but greater response variability in the myopic groups | | |
| | | | | | | | | | | PMS | |
| Hazel et al. (2003) ²⁹⁴ | Shin-Nippon Autoref SRW 5000 Wavefront Sensor (HS) | Monocular NL 0–4 D demand | Soft contact lenses | 18–27 | EMMs | –0.72 | | 0.80 | Lags greater when measured with the autorefractor when adjusted for similar pupil size | | |
| | | | | | | | | | | LOMs | 0.81 |
| | | | | | | | | | | EOMs | |

TABLE 2. Continued

| Paper | Measurement Method | Accommodation Stimuli | Mode of Myopic Correction | Age, y | Refractive Groups | AE (D) | AEI | ASRC | Summary of Results |
|--|------------------------------|--|---------------------------------|------------------|------------------------------|-------------------------------|--------------|------|---|
| Nakatsuka et al. (2003) ⁵⁴ | Open field autorefractor | Monocular FV 2-6,25 D demand | Habitual spectacle correction | 19-38 | MYPs EMMs MYPs EMMs | -1.01 -0.50 HS -0.43 HS | | 1.02 | Good accommodative accuracy in both refractive groups |
| Schmid et al. (2005) ²⁹⁵ | Shin-Nippon Autoref SRW 5000 | Monocular BLV 4 D demand | Soft contact lenses | 18-25 | EOMs EMMs | 0.29 | | 1.05 | EMMs and MYPs had similar lags, response more accurate for smaller targets at the same distance |
| Day et al. (2006) ²⁹⁶ | Shin-Nippon Autoref SRW 5000 | Monocular BLV 0-4 D demand | Soft contact lenses | Ave 22 | MYPs EMMs | 0.33 | 0.73 | | EMMs and LOMs had greater lags than the EOMs |
| Allen and O'Leary (2006) ⁵⁹ | Power refractor | Monocular and Binocular FV 3 D demand | Habitual correction | Ave 22 Ave 28 | EOMs LOMs | | 0.86 0.70 | | Increased binocular lags with increasing degree of myopia |
| Harb et al. (2006) ¹⁶² | Power refractor | FV 3.5 D demand | Soft contact lenses | 18-25 22-28 | EMMs EOMs LOMs EMMs | | 0.35 0.41 | | Myopes had greater variability in their accommodation response and had larger lags at greater reading distances |
| Sreenivasan et al. (2013) ²⁹⁷ | COAS Aberrrometer | Monocular plus 3 Binocular tasks 1-5 D demand | Spectacle correction equivalent | 18-25 | MYPs EMMs | -0.99 -0.70 | | | MYPs showed greater lags but had better near VA than EMMs |

AE, accommodative error at highest demand conditions; AEI, accommodation error index; ASRC, slope of the accommodation stimulus response curve; BLV, Badal Lens Viewing; EMMs, emmetropes; EOMs, early onset myopes; FV, free viewing; HS, Hartmann Shack; lag, accommodation lag; LOMs, late onset myopes; MYPs, myopes; NL, negative lens series; PAL, progressive lens wear group; PL, positive lens series; PMs, progressing myopes; SMs, stable myopes; SVL, single vision lens wear group; VA, visual acuity.

improved accommodation-convergence balance. The accommodative lag hypothesis in myopia thus remains contentious and warrants further investigation.

Accommodative Instability

Besides inaccuracies in accommodation, it seems that accommodative instability (as assessed by objective dynamic accommodation recordings to different dioptric targets) may be important in myopia development as both children^{142,143} and adults¹⁴⁴ with myopes showing less stable accommodation responses. Unstable accommodation responses would prevent the formation of a steady clear retinal image, with possible consequences for myopia development and progression.

Near Induced Transient Myopia

Another important characteristic of the accommodation response is that, after prolonged exposure to a near stimulus, there is normally a delay in accommodation relaxation when the person looks far away, termed “near work induced transient myopia.” Retinal defocus induced by near work induced transient myopia is larger and persists for longer in late-onset¹⁴⁵ and progressing^{146,147} adult myopes and children in whom it lasts longer,¹⁴⁸ indicating a possible contributing factor to permanent myopia.¹⁴⁹ Interestingly, near work induced transient myopia is also increased in the more myopic eye compared with the fellow less myopic eye of anisomyopes.¹⁵⁰

Near-Peripheral Vision and Accommodation

Relative peripheral refraction, measured as the difference between foveal and peripheral refractive error, is known to have a significant influence on myopia development and control.^{151,152} Myopes tend to have hyperopic relative peripheral refraction, whereas hyperopes have a myopic relative peripheral refraction.^{132,152} Changes in the shape of the eye with accommodation and accommodative lag could further influence the peripheral refractive error and also aberration changes with accommodation may effect off-axis refractive errors during accommodation. Myopes are likely to have larger ciliary muscle mass,^{78,153–155} therefore accommodation could lead to an expansion in the dimensions of the myopic eye due to the force created by the larger ciliary muscle. This would lead to changes in relative peripheral refraction in myopes. As previously discussed, evidence on clinically significant changes in axial length and central refractive error with near work is equivocal.^{156–158} Discrepancies in these studies can be attributed to the level of myopia in the participants and the techniques used, with significant differences in high myopes. Accommodation has been shown to induce the ocular shape to become more prolate.¹⁵⁹ The changes in relative peripheral refraction with accommodation are modest and are relatively similar in myopes and emmetropes.^{157,160,161} Yet, the larger accommodative lags present during near work (which might be higher in myopic children due to the close working distances adopted) would increase the peripheral hyperopic defocus further in myopic eyes.¹⁶²

Sensitivity to defocus in the peripheral retina is expected to be lower than the central retinal sensitivity. Cone and ganglion cell density and visual quality decreases with field angle, so peripheral visual resolution is low and has lower

sensitivity to defocus. The depth of focus at a peripheral field of up to 45 degrees remains around ± 1 D¹⁶³; therefore, any changes in the peripheral focus of over ± 1 D are likely to be perceived as defocused in the peripheral retina and could disrupt the emmetropization process. Postural control is a requisite in maintaining a stable body and to ensure safety and prevent injuries and the visual system contributes significantly to postural stability.^{164,165} Myopes show a higher postural instability to peripheral stimuli and distortions presented in the stimuli than emmetropes, further indicating that the peripheral vision in myopes is likely to be more sensitive than in emmetropes.¹⁶⁶ It has been shown that myopes display an asymmetry to defocus being less sensitive to negative defocus (hyperopic) than positive (myopic) defocus in both peripheral and central vision compared with a more symmetrical response in emmetropes.^{167–169} It has also been suggested that the eye derives the odd error cues for the direction of defocus using the oblique astigmatic foci (difference between radial and tangential foci) in the peripheral vision.¹³⁵

Stimuli falling on the peripheral retina can elicit an accommodative response.^{170–172} However, the accuracy of accommodative response progressively reduces with retinal eccentricity. Hartwig et al.¹⁷² found that relative to accommodative stimulus-response slope to central targets, the rate of reduction in slope with peripheral accommodative stimuli was lower in myopes when compared with emmetropes. This finding supports previous studies that indicate that the peripheral retina in myopes is more sensitive to hyperopic defocus than emmetropes up to field angles of at least 15 degrees. Although these studies show that the peripheral retina can alter the accommodation response of the eye, the exact nature of the response and how this might summate with the stimuli falling on different regions of the retina is still unclear.

Sensitivity to Blur: Detection and Discrimination Thresholds

Blur sensitivity is decreased in adults with myopia,^{173,174} and the detrimental effect of central attention in peripheral vision is also larger in myopia.¹⁷⁵ Schmidt et al.¹⁷⁶ measured children’s ability to detect blur and found no differences among refractive groups, but they did not evaluate blur discrimination. More recently, Labhishetty et al.¹⁷⁷ showed that even though children with progressive myopia show increased depth of focus, they do not show increased blur detection thresholds. The effect of blur adaptation^{178,179} on blur sensitivity is also larger in early onset myopes compared to emmetropes,¹⁸⁰ although this effect may only occur with isolated letters,¹⁸¹ perhaps due to lateral masking, and it is dependent on the lateral extent of the stimulus.¹⁸² These findings suggest that the reduced sensitivity to defocus in myopia may be compensated with higher level adaptation processes to preserve the subjective clarity even in the presence of decreased retinal image quality.¹⁷⁷ One limitation is the lack of consideration of whether myopes regularly wore their full correction, thus potentially impacting on adaption.

Current models of refractive error development agree on the importance of image quality across the retina to guide emmetropization, not only at the fovea.^{183–187} It appears that a balance across the retina is critical for normal emmetropization; peripheral blur, with or without clear central vision, may induce myopia.^{184–188} Retinal defo-

cus is known to decrease peripheral sensitivity, particularly to low light level stimuli.¹⁸⁹ The human decoding system for blur is tuned for low and mid-spatial frequencies and appears to be located in the retinal near periphery (up to 15 degrees).^{182,190,191} Accommodation can also be elicited by near peripheral defocus,^{192,193} and myopes may demonstrate less effective peripheral accommodation.¹⁹⁴

Greater losses of peripheral function have been noted in myopes than emmetropes,¹⁹⁵⁻¹⁹⁷ probably due to retinal expansion.¹⁹⁸ Myopes also show a greater degree of adaptation to peripheral blur,¹⁹⁹ and, unlike emmetropes, myopes do not show a constant pattern of peripheral defocus during accommodation.¹⁹² Differences in sensitivity to myopic and hyperopic defocus in the periphery are only seen in myopes, indicating different effects of radial and tangential blur during emmetropization.²⁰⁰

Spatial Frequency and Contrast Cues in Accommodation

Reading often requires viewing high-contrast text at close distances for prolonged periods. Spatial frequency and contrast of reading text are often limited in range when compared to natural scenes, which can lead to further spatial and contrast adaptation.¹²² Myopes show a reduced sensitivity to defocus blur when compared with non-myopes.^{168,169,201,202} The reduction in blur sensitivity diminishes the effect of accommodative lag on visual performance and increases blur and contrast adaptation in uncorrected myopes.²⁰³ Contrast adaptation leads to a decrease in contrast sensitivity at a specific spatial frequency after viewing high-contrast targets of a similar spatial frequency.²⁰⁴ The adaptation effect increases with time and a longer adaptation period requires a longer recovery period.^{205,206} A degraded retinal image as a consequence of contrast adaptation may lead to perceptual blur, which in turn could result in myopia development.²⁰⁷ During reading tasks, contrast adaptation is expected to reduce contrast sensitivity to spatial frequencies similar to the row or stroke frequency of the text.²⁰⁸ Studies on myopic children and adults have shown that myopes demonstrate a significantly higher level of contrast adaptation (nearly 2 times) in comparison to emmetropes.^{208,209} The contrast adaptation was shown at different spatial frequencies in these two studies owing to differences in targets used (paper versus cathode ray tube display) and age of the participants (children versus adults). Nonetheless, the higher contrast adaptation levels, as seen in myopes, are expected to degrade retinal image significantly more in myopes during prolonged near tasks, therefore, possibly contributing to myopia development/progression. However, it is unclear whether these differences in contrast adaptation are a precursor or consequence of myopia.

Contrast adaptation has been shown to occur when the eye is exposed to positive (myopic) defocus but not to negative (hyperopic) defocus, however, the reason for this is currently unknown.²¹⁰ In addition, McGonigle et al.²⁰⁸ found that myopes show higher levels of contrast adaptation after reading text on a cathode ray tube when compared to emmetropes, despite ensuring that there was no accommodative lag present in either group. The contrast adaptation differences between myopes and emmetropes are, therefore, unlikely to be caused due to larger lags seen in myopes when reading.^{91,211}

In regions where the prevalence of myopia is high, children and adults read both Chinese and English. Chinese characters have a relatively greater content of high spatial frequency components compared to Latin characters.²¹² Accommodation to low spatial frequencies (1 c/deg or less) tends to produce higher lags; the optimal accommodative response is produced for spatial frequencies at the peak of photopic contrast sensitivity (3–5 c/deg).²¹³⁻²¹⁵ No systematic differences have been found in accommodative responses of emmetropes and myopes to sinusoidal grating targets of different spatial frequencies,²¹⁶ nor to Chinese and Latin characters.^{217,218} Contrast adaptation too was similar for Chinese and Latin text, although it was found to be higher in myopes.²⁰⁹

INTERACTIONS OF MONOCHROMATIC ABERRATIONS AND ACCOMMODATION

Higher-order aberrations affect the visual quality of the eye and provide odd-error signals, which can help the eye detect the direction of defocus thereby contributing to the regulation of accommodation and refractive error development. Spherical aberration can provide odd-error cues to identify the sign of defocus in the central visual field, whereas coma and astigmatism can provide the cues for direction of defocus in the peripheral visual field.^{135,219,220} Higher-order aberrations alter in a similar way to spherical and cylindrical refractive errors during emmetropization.²²¹ The intersubject variability in higher-order aberrations is high and this may be why studies looking at differences in aberrations between myopes and emmetropes have reported inconclusive results, both in cross-sectional and longitudinal studies.^{137,138,222} The interaction between individual higher order aberrations, such as spherical aberration and defocus, is more likely to affect the visual quality and refractive development rather than the absolute magnitude of individual aberrations or the total root mean square error of higher-order aberrations. Higher order aberrations change with accommodation; spherical aberration has been consistently shown to have a negative shift with accommodation in young individuals with a greater change in myopes.^{138,223} Negative spherical aberration can improve image quality when it interacts with myopic defocus and can degrade image quality when combined with hyperopic defocus as produced by accommodative lag.²²⁰ It is therefore hypothesized that the higher accommodative lags during extended periods of near work in myopes, when combined with the negative spherical aberration produced during accommodation, would interact and degrade retinal image quality further in myopes more than that in emmetropes who experience lower lags during near work.

Color Based Cues

Longitudinal chromatic aberration can extend the best focus of the eye by approximately 2.0 D and, hence, can also provide the odd error cue for accommodation and emmetropization (Fig. 3). Accommodative response in humans also varies with wavelength, with the eye accommodating more for longer wavelength and showing an approximately 1.0 D difference in response across the visible spectrum.²²⁴ The difference in contrast produced due to longitudinal chromatic aberration between long and short-wavelength light can also help detect the direction

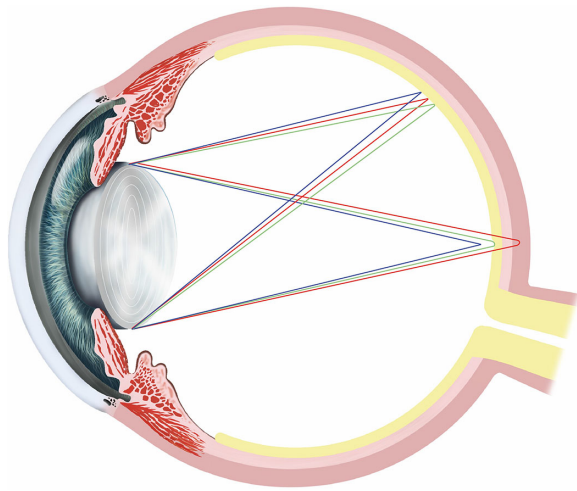


FIGURE 3. The visual stimulus from chromatic aberration in longitudinal (along the optic axis) and transverse (affecting the peripheral retinal image) planes. Copyright © 2021 by IMI.

of defocus.²²⁵ Although the eye can accommodate and emmetropize in the absence of chromatic cues, as shown by the monochromatic light studies in animals, the presence of chromatic signals seems to increase the response accuracy of both emmetropization and accommodation systems.²²⁶ It has been hypothesized that the myopic eye emmetropizes to reach optimal focus using either the red/green color sensitive mechanism or the luminance sensitive mechanism, relative to the optimal focus for the blue/yellow color, which is more myopically defocused.²²⁷ This hypothesis is supported by the fact that myopes show increased sensitivity to long wavelength cone contrast and reduced sensitivity to short wavelength cone contrast when compared to emmetropes.²²⁸ However, how this translates to a mechanism for myopia development is unclear.

NEAR WORK POSTURE

Near working distances tend to be between 10 and 40 cms in 6 to 11-year-old children and children with habitually short reading distances are likely to have higher magnitudes of myopia.^{4,229–231} The relatively short near working distances in addition to the asymmetric head posture, as adopted by most children, can lead to differences in accommodative demands between the two eyes. As the reading distance is reduced, the intraocular difference in accommodative demand increases with all spatially extended tasks.²³² As the working distance gets closer, the head tilt increases.^{129,233} With a head tilt, one eye would consistently encounter higher time-averaged accommodative demand than the other eye leading to aniso-accommodative demand. As accommodation is a binocular process, aniso-accommodation is likely to be rather small (0.25 D or less) between the two eyes.^{234,235} Therefore, substantial levels of blur can be perceived by the eye when the aniso-accommodative demand is coupled with high accommodative lags. Further, this nonuniform distribution of dioptric stimuli during near work could also exacerbate the effect of defocus in peripheral vision, particularly so when head tilts occur.

Working distance, head posture, and eye movements have been shown to be similar in adult myopes and emmetropes

over relatively short periods of reading tasks.^{236–238} However, myopic Chinese children have been shown to have significantly closer working distances during near tasks, which tend to be closest with video game tasks on hand held devices.²³³ Working distance also reduces with increased attention and concentration.²³¹ This could reduce the working distance with hand held devices when compared to previous studies conducted with paper based reading tasks. The closer working distances would lead to yet higher accommodative lags, further degrading vision particularly at higher spatial frequencies.

DIFFERENCES IN INDOOR AND OUTDOOR ENVIRONMENTS AS RELATED TO ACCOMMODATION

It is well established that spending more time outdoors prevents myopia development and progression.^{239–257} One significant difference of outdoor versus indoor environments is the level and uniformity of dioptric blur across the retina¹⁹⁰; objects are typically further away so there is less dioptric variation across the visual scenes in outdoor environments and pupil miosis is greater due to higher illumination levels leading to a greater depth of focus, therefore, less accommodative response is demanded.

Binocular Vision

Binocularity is important in the formation of the retinal image. Binocularity improves the accommodative response to defocus,²⁵⁸ and, in turn, blur due to defocus is a useful cue in binocularity.^{259,260} This effect may be different in myopes.²⁶¹ Although emmetropization signals are found locally at the retinal level, binocular vision may play a significant role in retinal image focus and therefore in emmetropization and potentially for myopia development. Blur sensitivity, for example, is reduced in myopes under monocular but not binocular conditions.¹⁷³ Myopes also show reduced stereopsis with flickering stimuli and greater binocular imbalance compared with emmetropes.²⁶² Night myopia, or tonic accommodation, is reduced under binocular conditions²⁶³ and the accommodative gain is different with a translucent occluder over the nonviewing eye than binocularly in emmetropes but not in myopes.²⁶⁴

One method to clinically measure disturbances of binocular vision is the magnitude of the accommodative-convergence to accommodation (AC/A) ratio. Higher AC/A ratios have been documented in myopic children compared to emmetropic children.²⁶⁵ Studies have found the AC/A ratio to be elevated prior to myopia onset¹²⁶ and as early as 4 years prior to myopia onset.²⁶⁶ The AC/A ratio has been found to reach its peak at myopia onset and remain both stable and raised through at least 5 years after myopia onset. The increased AC/A ratio in myopic children could result from a higher gain of the cross-link from accommodation to convergence, or it could represent an increased effort required per diopter of accommodative output, even if the accommodative convergence cross-link gain relationship may be relatively constant. Mutti and colleagues found a higher AC/A ratio correlated with a greater lag of accommodation, but was not associated with a faster rate of myopia progression.²⁶⁶ This effect may be related to the observed changes in the ciliary muscle between myopes and emmetropes.^{78,153} The effect of refractive error on phoria and AC/A is summarized in Table 3.

TABLE 3. Effect of Refractive Error on Phoria and AC/A in Children and Young Adults

| Paper | Measurement Method | Mode of Myopic Correction | Age, y | Refractive Groups | Near Phoria (Δ) | Response AC/A (Δ /D) | Summary of Results |
|--|---|---------------------------|--------|----------------------|--------------------------|------------------------------|---|
| Rosenfield and Gilmartin (1987) ²⁹⁸ | IR Autoref and Maddox rod | Trial frame and lenses | 18-27 | EMMs | | 3.0 | Higher AC/A ratios in LOMs than EOMs |
| Goss (1991) ²⁹⁹ | Canon R-1 Autoref von Graefe phoria | Trial frame and lenses | 6-15 | EOMs LOMs | -2 exo | 3.9 | Onset of myopia preceded by vergence changes |
| Jiang (1995) ³⁰⁰ | Canon R-1 Autoref Phoria method not mentioned | Trial frame and lenses | 18-27 | Became MYPs EMMs | +1 eso | 4.6 | Higher AC/A ratios in EMMs that became Myopes |
| Gwiazda et al. (1999) ³⁰¹ | Canon R-1 Autoref with attached motorized Risley prism and Maddox rod | Trial frame and lenses | 6-14 | Became MYPs EMMs | | 1.4 3.9 | Higher AC/A ratios in myopic children |
| Mutti et al. (2000) ³⁰⁵ | Simultaneous accommodation and vergence measures Canon R-1 Autoref Purkinje images I and IV | Habitual correction | 6-14 | MYPs EMMs | | 6.4 3.9 | Higher AC/A ratios in myopic children |
| Chen et al. (2003) ³⁰² | Shin-Nippon Autoref with Howell Dwyer Card | Trial frame and lenses | 8-12 | MYPs EMMs | -0.7 exo | 6.4 2 | AC/A ratios and phoria were similar in EMMs and MYPs |
| Gwiazda et al. (2005) ¹³⁶ | Canon R-1 Autoref with attached motorized Risley prism and Maddox rod | Trial frame and lenses | 6-18 | MYPs EMMs | -1.0 exo -2.9 exo | 3 7.5 | Elevated AC/A in EMMs who became myopic, 2 y prior to onset |
| Allen and O'Leary (2006) ⁵⁹ | PowerRefractor with a Bernel Muscle Imbalance Measure (MIM) test card and Maddox rod | Trial frame and lenses | 18-22 | Became MYPs EMMs | -0.4 exo | >9 3.5 | Elevated AC/A not related to myopia progression |
| Price et al. (2013) ²⁷⁴ | Shin-Nippon Autoref with Howell Dwyer Card | Trial frame and lenses | 14-21 | EOMs LOMs MYPs | | 4.2 3.6 4 | Elevated AC/A was related to myopia progression |
| Zadnik et al. (2015) ³⁰³ | Simultaneous accommodation and vergence Canon R-1 Autoref Purkinje images I and IV | Habitual correction | 7-13 | EMMs | | 4 | High AC/A myopia risk factor |
| Mutti et al. (2017) ³⁰⁶ | Simultaneous accommodation and vergence Canon R-1 Autoref Purkinje images I and IV | Habitual correction | 6-14 | Became MYPs EMMs | | 7 4 | AC/A increased up to 4 y prior to myopia onset |
| | | | | Became MYPs | | 7 | |

AC/A, accommodation convergence to accommodation response ratio; EMMs, emmetropes; EOMs, early onset myopes; LOMs, late onset myopes; MYPs, myopes.

Theoretically, a greater AC/A is also likely to shift the eyes toward esophoria at near work in these myopic children. Near positive (base in) fusional vergences are also higher in progressing myopes.²⁶⁷ Interestingly, myopic children exhibit less convergent shifts in vergence adaptation compared to emmetropes, which could be attributed to higher accommodative adaptation (as assessed by changes in tonic accommodation).²⁶⁸ When myopia is controlled with orthokeratology, the child's zone of clear single binocular vision becomes more divergent and the accommodation responses increase relative to that measured under correction with single vision spectacles.²⁶⁹

Accommodation With Optical Myopia Control Interventions

All contemporary optical interventions for myopia are based on a common premise that reducing off-axis hyperopic blur or inducing off-axis myopic blur should slow the progression of myopia.¹⁵² Their optical designs incorporate one or more paracentral or peripheral zones of plus power around a central clear zone so as to induce areas of peripheral or simultaneous myopic blur in the retina while providing clear on-axis focus and vision through the center. Such dual power designs have the potential to interfere with the accommodative and binocular system, because myopic children may underaccommodate by looking through relative plus zones, further weakening the potentially diminished accommodative function due to myopia.

Several studies have investigated the effect of soft bifocal or multifocal contact lenses on accommodative response in adults, but the results are mixed. Some studies have shown either similar response to single vision contact lens wear²⁷⁰ or a lead of accommodation,²⁷¹ others have shown increased accommodative lag,²⁷² reduced monocular accommodative facility,²⁷³ and exophoric shifts at near.²⁷² It has also been shown that spherical aberration modifying lenses do not affect accommodative facility and horizontal phoria,²⁷⁴ and adding negative aberration can improve the slope of the accommodation stimulus-response curve, reducing lag of accommodation.²⁷⁵ Orthokeratology lens wear has also been shown to increase exophoria in young adult myopes.²⁶⁹ However, unlike soft multifocal lenses, orthokeratology lenses have been found to lower accommodative lags at near, prompting some to suggest that these lenses may be a better strategy to slow reduce myopia progression in adults with binocular vision disorders.²⁷⁶

Studies in children show reduced accommodation response and an increase in exophoria while wearing center-distance soft bifocal²⁷⁷ or multifocal contact lenses²⁷⁸ compared with single vision contact lenses, suggesting that perhaps children resort to using the relative plus power in an attempt to relax accommodation. However, in other studies, no difference in binocular or accommodative function can be detected in children wearing dual-focus contact lenses or extended depth of focus lenses, compared with single vision contact lenses^{279–282} suggesting that they can accommodate normally using the distance portion of the lenses, but longer term monitoring is warranted.

TRANSLATION TO CLINICAL PRACTICE

Evidence from animal studies shows that exposure to hyperopic defocus results in a disruption to the normal

emmetropization process and leads to the development of myopia.¹³² Although the evidence in humans is less clear, chronic retinal defocus at near work, due to a lag in accommodative response, is more frequent and often greater in myopes. This blur at near work has been suggested to trigger a series of biochemical events, which could result in scleral remodeling and axial elongation in an attempt to improve image clarity.¹³² Thus, addressing retinal blur arising from accommodation has been explored in human longitudinal studies, but results from these studies are mixed.^{152,283,284}

A large-scale longitudinal cohort study has shown that an increased accommodative lag occurs in children after the onset of myopia.⁹¹ Therefore, an elevated accommodative lag is unlikely to be a useful predictive factor for the onset of myopia. Lag of accommodation has not been found to be associated with myopia progression.²⁸⁵ It is more probable that an increased hyperopic defocus from accommodative lag may be a consequence rather than a cause of myopia. Esophoria at near work has not been associated with myopia progression in studies using bifocal or progressive addition spectacle lenses (for review see Wildsoet et al.¹⁵²) and may result as compensation for deficient accommodation rather than a causative factor for myopia progression.²⁸⁶

CONCLUDING REMARKS

It is evident that, to date, the role of accommodation and binocular vision in the development and progression of myopia is not fully understood. Aspects of blur from the lag of accommodation, the impact of spatial frequency at near work, and a short working distance may all be implicated in myopia development and progression. The response of the ciliary body and its links with changes in the choroid are still being explored with respect to myopia development and progression. Researchers have not ruled out the role of the accommodative system in this field, but current methods of intervention based on this theory have not yielded significant results. Based on the evidence to date, eye care practitioners should consider assessing the accommodation and convergence system in young myopes and those at risk of myopia development to ensure they manage their patients by providing a clear retinal image. Current evidence does not point toward a role for accommodation and binocular vision in myopia development and progression.

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References

- Rosenfield M, Gilmartin B. *Myopia and Nearwork*. Woburn, MA: Butterworth-Heinemann; 1998.
- Mutti DO, Mitchell GL, Moeschberger ML, Jones LA, Zadnik K. Parental myopia, near work, school achievement, and children's refractive error. *Invest Ophthalmol Vis Sci*. 2002;43(12):3633–3640.
- Saw SM, Tong L, Chua WH, et al. Incidence and progression of myopia in Singaporean school children. *Invest Ophthalmol Vis Sci*. 2005;46(1):51–57.
- Ip JM, Saw SM, Rose KA, et al. Role of near work in myopia: findings in a sample of Australian school children. *Invest Ophthalmol Vis Sci*. 2008;49(7):2903–2910.
- Koretz JF, Cook CA, Kaufman PL. Accommodation and presbyopia in the human eye: changes in the anterior segment and crystalline lens with focus. *Invest Ophthalmol Vis Sci*. 1997;38(3):569–578.
- Kirschkamp T, Dunne M, Barry JC. Phakometric measurement of ocular surface radii of curvature, axial separations and alignment in relaxed and accommodated human eyes. *Ophthalmic Physiol Opt*. 2004;24(2):65–73.
- Richdale K, Bullimore MA, Zadnik K. Lens thickness with age and accommodation by optical coherence tomography. *Ophthalmic Physiol Opt*. 2008;28(5):441–447.
- Doyle L, Little JA, Saunders KJ. Repeatability of OCT lens thickness measures with age and accommodation. *Optom Vis Sci*. 2013;90(12):1396–1405.
- Shum PJT, Ko LS, Ng CL, Lin SL. A biometric study of ocular changes during accommodation. *Am J Ophthalmol*. 1993;115(1):76–81.
- Drexler W, Baumgartner A, Findl O, Hitzenberger CK, Fercher AF. Biometric investigation of changes in the anterior eye segment during accommodation. *Vision Res*. 1997;37(19):2789–2800.
- Dubbelman M, Van Der Heijde GL, Weeber HA. Change in shape of the aging human crystalline lens with accommodation. *Vision Res*. 2005;45(1):117–132.
- Ostrin L, Kasthurirangan S, Win-Hall D, Glasser A. Simultaneous measurements of refraction and A-scan biometry during accommodation in humans. *Optom Vis Sci*. 2006;83(9):657–665.
- Tsorbatzoglou A, Németh G, Széll N, Biró Z, Berta A. Anterior segment changes with age and during accommodation measured with partial coherence interferometry. *J Cataract Refract Surg*. 2007;33(9):1597–1601.
- Strenk SA, Strenk LM, Semmlow JL, DeMarco JK. Magnetic resonance imaging study of the effects of age and accommodation on the human lens cross-sectional area. *Invest Ophthalmol Vis Sci*. 2004;45(2):539–545.
- Strenk SA, Strenk LM, Koretz JF. The mechanism of presbyopia. *Prog Retin Eye Res*. 2005;24(3):379–393.
- Hermans E, Dubbelman M, van der Heijde R, Heethaar R. The shape of the human lens nucleus with accommodation. *J Vis*. 2007;7(10):16.
- Glasser A, Kaufman PL. The mechanism of accommodation in primates. *Ophthalmology*. 1999;106(5):863–872.
- Strenk SA, Semmlow JL, Strenk LM, Munoz P, Gronlund-Jacob J, DeMarco JK. Age-related changes in human ciliary muscle and lens: a magnetic resonance imaging study. *Invest Ophthalmol Vis Sci*. 1999;40(6):1162–1169.
- Richdale K, Bullimore MA, Sinnott LT, Zadnik K. The effect of age, accommodation, and refractive error on the adult human eye. *Optom Vis Sci*. 2016;93(1):3–11.
- Tse PU, Whitney D, Anstis S, Cavanagh P. Voluntary attention modulates motion-induced mislocalization. *J Vis*. 2011;11(3):1–6.
- Jones CE, Atchison DA, Pope JM. Changes in lens dimensions and refractive index with age and accommodation. *Optom Vis Sci*. 2007;84(10):990–995.
- Khan A, Pope JM, Verkicharla PK, Suheimat M, Atchison DA. Change in human lens dimensions, lens refractive index distribution and ciliary body ring diameter with accommodation. *Biomed Opt Express*. 2018;9(3):1272.
- Koretz JF, Cook CA, Kaufman PL. Aging of the human lens: changes in lens shape upon accommodation and with accommodative loss. *J Opt Soc Am A*. 2002;19(1):144.
- Rosales P, Dubbelman M, Marcos S, van der Heijde R. Crystalline lens radii of curvature from Purkinje and Scheimpflug imaging. *J Vis*. 2006;6(10):1057–1067.
- Garner LF, Yap MKH. Changes in ocular dimensions and refraction with accommodation. *Ophthalmic Physiol Opt*. 1997;17(1):12–17.
- Ciuffreda KJ. The Glenn A. Fry invited lecture. Accommodation to gratings and more naturalistic stimuli. *Optom Vis Sci*. 1991;68(4):243–260.
- Bolz M, Prinz A, Drexler W, Findl O. Linear relationship of refractive and biometric lenticular changes during accommodation in emmetropic and myopic eyes. *Br J Ophthalmol*. 2007;91(3):360–365.
- Gullstrand A. In: *Appendices II and IV. In Helmholtz's Handbuch Der Physiologischen Optik*; 1909:Vol 1, pp. 301–358, 382–414.
- Tian Y, Tarrant J, Wildsoet CF. Optical and biometric characteristics of anisomyopia in human adults. *Ophthalmic Physiol Opt*. 2011;31(5):540–549.
- Atchison DA, Jones CE, Schmid KL, et al. Eye shape in emmetropia and myopia. *Invest Ophthalmol Vis Sci*. 2004;45(10):3380–3386.
- Logan NS, Gilmartin B, Wildsoet CF, Dunne MCM. Posterior retinal contour in adult human anisomyopia. *Invest Ophthalmol Vis Sci*. 2004;45(7):2152–2162.
- Chang SW, Tsai IL, Hu FR, Lin LLK, Shih YF. The cornea in young myopic adults. *Br J Ophthalmol*. 2001;85(8):916–920.
- Grosvenor T, Goss DA. Role of the cornea in emmetropia and myopia. *Optom Vis Sci*. 1998;75(2):132–145.
- Garner LF, Stewart AW, Owens H, Kinnear RF, Frith MJ. The Nepal longitudinal study: biometric characteristics of developing eyes. *Optom Vis Sci*. 2006;83(5):274–280.
- Goss DA, Van Veen HG, Rainey BB, Feng B. Ocular components measured by keratometry, phakometry, and ultrasonography in emmetropic and myopic optometry students. *Optom Vis Sci*. 1997;74(7):489–495.
- Scott R, Grosvenor T. Structural model for emmetropic and myopic eyes. *Ophthalmic Physiol Opt*. 1993;13(1):41–47.
- McBrien NA, Adams DW. A longitudinal investigation of adult-onset and adult-progression of myopia in an occupational group: refractive and biometric findings. *Invest Ophthalmol Vis Sci*. 1997;38(2):321–333.
- McBrien NA, Millodot M. A biometric investigation of late onset myopic eyes. *Acta Ophthalmol*. 1987;65(4):461–468.
- Zadnik K, Mutti DO, Fusaro RE, Adams AJ. Longitudinal evidence of crystalline lens thinning in children. *Invest Ophthalmol Vis Sci*. 1995;36(8):1581–1587.
- Read SA, Fuss JA, Vincent SJ, Collins MJ, Alonso-Caneiro D. Choroidal changes in human myopia: insights from optical coherence tomography imaging. *Clin Exp Optom*. 2019;102(3):270–285.
- Schmid KL, Li RWH, Edwards MH, Lew JKF. The expandability of the eye in childhood myopia. *Curr Eye Res*. 2003;26(2):65–71.

42. Patel H, Gilmartin B, Cubbidge RP, Logan NS. In vivo measurement of regional variation in anterior scleral resistance to Schiøtz indentation. *Ophthalmic Physiol Opt.* 2011;31(5):437–443.
43. Davies LN, Dunne MCM, Gibson GA, Wolffsohn JS. Vergence analysis reveals the influence of axial distances on accommodation with age and axial ametropia. *Ophthalmic Physiol Opt.* 2010;30(4):371–378.
44. Hunt OA, Wolffsohn JS, García-Resúa C. Ocular motor triad with single vision contact lenses compared to spectacle lenses. *Contact Lens Anterior Eye.* 2006;29(5):239–245.
45. Diether S, Schaeffel F. Local changes in eye growth after imposed local defocus. *Invest Ophthalmol Vis Sci.* 1996;37(3):659–668.
46. Wildsoet CF. Active emmetropization — evidence for its existence and ramifications for clinical practice. *Ophthalmic Physiol Opt.* 1997;17(4):279–290.
47. Smith EL, Hung LF, Arumugam B. Visual regulation of refractive development: Insights from animal studies. *Eye.* 2014;28(2):180–188.
48. Troilo D, Smith EL, Nickla DL, et al. IMI – report on experimental models of emmetropization and myopia. *Invest Ophthalmol Vis Sci.* 2019;60(3):M31–M88.
49. McBrien NA, Millodot M. Amplitude of accommodation and refractive error. *Invest Ophthalmol Vis Sci.* 1986;27(7):1187–1190.
50. Gwiazda J, Thorn F, Bauer J, Held R. Myopic children show insufficient accommodative response to blur. *Invest Ophthalmol Vis Sci.* 1993;34(3):690–694.
51. Gwiazda JE, Hyman L, Norton TT, et al. Accommodation and related risk factors associated with myopia progression and their interaction with treatment in COMET children. *Invest Ophthalmol Vis Sci.* 2004;45(7):2143–2151.
52. Charman WN. Near vision, lags of accommodation and myopia. *Ophthalmic Physiol Opt.* 1999;19(2):126–133.
53. Seidemann A, Schaeffel F. An evaluation of the lag of accommodation using photorefractometry. *Vision Res.* 2003;43(4):419–430.
54. Nakatsuka C, Hasebe S, Nonaka F, Ohtsuki H. Accommodative lag under habitual seeing conditions: comparison between adult myopes and emmetropes. *Jpn J Ophthalmol.* 2003;47(3):291–298.
55. Gwiazda J, Bauer J, Thorn F, Held R. A dynamic relationship between myopia and blur-driven accommodation in school-aged children. *Vision Res.* 1995;35(9):1299–1304.
56. Drobe B, de Saint-André R. The pre-myopic syndrome. *Ophthalmic Physiol Opt.* 1995;15(5):375–378.
57. Abbott ML, Schmid KL, Strang NC. Differences in the accommodation stimulus response curves of adult myopes and emmetropes. *Ophthalmic Physiol Opt.* 1998;18(1):13–20.
58. He JC, Gwiazda J, Thorn F, Held R, Vera-Diaz FA. The association of wavefront aberration and accommodative lag in myopes. *Vision Res.* 2005;45(3):285–290.
59. Allen PM, O’Leary DJ. Accommodation functions: co-dependency and relationship to refractive error. *Vis Res.* 2006;46(4):491–505.
60. Charman WN, Radhakrishnan H. Accommodation, pupil diameter and myopia. *Ophthalmic Physiol Opt.* 2009;29(1):72–79.
61. Applegate RA, Donnelly WJ, III, Koenig DE. Three-dimensional relationship high-order root-mean-square between wavefront error, pupil diameter, and aging. *J Opt Soc Am A.* 2007;24(3):578–587.
62. Winn B, Whitaker D, Elliott DB, Phillips NJ. Factors affecting light-adapted pupil size in normal human subjects. *Invest Ophthalmol Vis Sci.* 1994;35(3):1132–1137.
63. Jones R. Do women and myopes have larger pupils? *Invest Ophthalmol Vis Sci.* 1990;31(7):1413–1415.
64. Brown SM, Bradley JC. Pupil size in refractive surgery candidates [1]. *J Refract Surg.* 2005;21(3):303.
65. Subbaram M V, Bullimore MA. Visual acuity and the accuracy of the accommodative response. *Ophthalmic Physiol Opt.* 2002;22(4):312–318.
66. Hirsch MJ, Weymouth FW. Pupil size in ametropia. *J Appl Physiol.* 1949;1(9):646–648.
67. Chaidaroon W, Juwattanasomran W. Colvard pupillometer measurement of scotopic pupil diameter in emmetropes and myopes. *Jpn J Ophthalmol.* 2002;46(6):640–644.
68. Bremner FD. *The Pupil: Anatomy, Physiology, and Clinical Applications*. By Loewenfeld Irene E. . 1999. Oxford, UK: Butterworth-Heinemann. 2278. ISBN 0-750-67143-2.
69. Ciuffreda KJ. Accommodation, the Pupil, and Presbyopia. In: Benjamin William J. *Borish’s Clinical Refraction Second Edition*. New York, NY: Elsevier; 2006:93–144.
70. Wagner S, Zrenner E, Strasser T. Ciliary muscle thickness profiles derived from optical coherence tomography images. *Biomed Opt Express.* 2018;9(10):5100.
71. Bailey MD, Sinnott LT, Mutti DO. Ciliary body thickness and refractive error in children. *Invest Ophthalmol Vis Sci.* 2008;49(10):4353–4360.
72. Schultz KE, Sinnott LT, Mutti DO, Bailey MD. Accommodative fluctuations, lens tension, and ciliary body thickness in children. *Optom Vis Sci.* 2009;86(6):677–684.
73. Pucker AD, Sinnott LT, Kao CY, Bailey MD. Region-specific relationships between refractive error and ciliary muscle thickness in children. *Invest Ophthalmol Vis Sci.* 2013;54(7):4710–4716.
74. Lewis HA, Kao CY, Sinnott LT, Bailey MD. Changes in ciliary muscle thickness during accommodation in children. *Optom Vis Sci.* 2012;89(5):727–737.
75. Oliveira C, Tello C, Liebmann JM, Ritch R. Ciliary body thickness increases with increasing axial myopia. *Am J Ophthalmol.* 2005;140(2):324–325.
76. Muftuoglu O, Hosal BM, Zilelioglu G. Ciliary body thickness in unilateral high axial myopia. *Eye.* 2009;23(5):1176–1181.
77. Jeon S, Lee WK, Lee K, Moon NJ. Diminished ciliary muscle movement on accommodation in myopia. *Exp Eye Res.* 2012;105:9–14.
78. Buckhurst H, Gilmartin B, Cubbidge RP, Nagra M, Logan NS. Ocular biometric correlates of ciliary muscle thickness in human myopia. *Ophthalmic Physiol Opt.* 2013;33(3):294–304.
79. Kuchem MK, Sinnott LT, Kao CY, Bailey MD. Ciliary muscle thickness in anisometropia. *Optom Vis Sci.* 2013;90(11):1312–1320.
80. Wagner S, Schaeffel F, Zrenner E, Straßer T. Prolonged nearwork affects the ciliary muscle morphology. *Exp Eye Res.* 2019;186:107741.
81. Sheppard AL, Davies LN. In vivo analysis of ciliary muscle morphologic changes with accommodation and axial ametropia. *Invest Ophthalmol Vis Sci.* 2010;51(12):6882–6889.
82. Richdale K, Sinnott LT, Bullimore MA, et al. Quantification of age-related and per diopter accommodative changes of the lens and ciliary muscle in the emmetropic human eye. *Invest Ophthalmol Vis Sci.* 2013;54(2):1095–1105.
83. Lossing LA, Sinnott LT, Kao CY, Richdale K, Bailey MD. Measuring changes in ciliary muscle thickness with accommodation in young adults. *Optom Vis Sci.* 2012;89(5):719–726.
84. Ruggeri M, de Freitas C, Williams S, et al. Quantification of the ciliary muscle and crystalline lens interaction during

- accommodation with synchronous OCT imaging. *Biomed Opt Express*. 2016;7(4):1351.
85. Zhou SB, Li H, Tan J, Hong HF. Anterior segment changes during accommodation in myopia with OCT. *Int Eye Sci*. 2013;13(6):1209–1211.
 86. Wagner S, Zrenner E, Strasser T. Emmetropes and myopes differ little in their accommodation dynamics but strongly in their ciliary muscle morphology. *Vision Res*. 2019;163:42–51.
 87. Van Alphen GWHM. Choroidal stress and emmetropization. *Vision Res*. 1986;26(5):723–734.
 88. Mutti DO. Hereditary and environmental contributions to emmetropization and myopia. *Optom Vis Sci*. 2010;87(4):255–259.
 89. Bailey MD. How should we measure the ciliary muscle? *Invest Ophthalmol Vis Sci*. 2011;52(3):1817–1818.
 90. Gwiazda J, Thorn F, Held R. Accommodation, accommodative convergence, and response AC/A ratios before and at the onset of myopia in children. *Optom Vis Sci*. 2005;82(4):273–278.
 91. Mutti DO, Mitchell GL, Hayes JR, et al. Accommodative lag before and after the onset of myopia. *Invest Ophthalmol Vis Sci*. 2006;47(3):837–846.
 92. Rosenfield M, Desai R, Portello JK. Do progressing myopes show reduced accommodative responses? *Optom Vis Sci*. 2002;79(4):268–273.
 93. Weizhong L, Zhikuan Y, Wen L, Xiang C, Jian G. A longitudinal study on the relationship between myopia development and near accommodation lag in myopic children. *Ophthalmic Physiol Opt*. 2008;28(1):57–61.
 94. Wood ICJ, Mutti DO, Zadnik K. Crystalline lens parameters in infancy. *Ophthalmic Physiol Opt*. 1996;16(4):310–317.
 95. Mutti DO, Mitchell GL, Sinnott LT, et al. Corneal and crystalline lens dimensions before and after myopia onset. *Optom Vis Sci*. 2012;89(3):251–262.
 96. Drexler W, Findl O, Schmetterer L, Hitzenberger CK, Fercher AF. Eye elongation during accommodation in humans: differences between emmetropes and myopes. *Invest Ophthalmol Vis Sci*. 1998;39(11):2140–2147.
 97. Mallen EAH, Kashyap P, Hampson KM. Transient axial length change during the accommodation response in young adults. *Invest Ophthalmol Vis Sci*. 2006;47(3):1251–1254.
 98. Woodman EC, Read SA, Collins MJ, et al. Axial elongation following prolonged near work in myopes and emmetropes. *Br J Ophthalmol*. 2011;95(5):652–656.
 99. Read SA, Collins MJ, Woodman EC, Cheong SH. Axial length changes during accommodation in myopes and emmetropes. *Optom Vis Sci*. 2010;87(9):656–662.
 100. Woodman EC, Read SA, Collins MJ. Axial length and choroidal thickness changes accompanying prolonged accommodation in myopes and emmetropes. *Vision Res*. 2012;72:34–41.
 101. Aldossari H, Suheimat M, Atchison DA, Schmid KL. Effect of accommodation on peripheral eye lengths of emmetropes and myopes. *Optom Vis Sci*. 2017;94(3):361–369.
 102. Loughton DS, Sheppard AL, Mallen EAH, Read SA, Davies LN. Does transient increase in axial length during accommodation attenuate with age? *Clin Exp Optom*. 2017;100(6):676–682.
 103. van Alphen GWHM, Graebel WP. Elasticity of tissues involved in accommodation. *Vision Res*. 1991;31(7-8):1417–1438.
 104. Croft MA, Nork MT, McDonald JP, Katz A, Lütjen-Drecoll E, Kaufman PL. Accommodative movements of the vitreous membrane, choroid, and sclera in young and presbyopic human and nonhuman primate eyes. *Invest Ophthalmol Vis Sci*. 2013;54(7):5049–5058.
 105. Ikuno Y, Tano Y. Retinal and choroidal biometry in highly myopic eyes with spectral-domain optical coherence tomography. *Invest Ophthalmol Vis Sci*. 2009;50(8):3876–3880.
 106. Summers Rada JA, Shelton S, Norton TT. The sclera and myopia. *Exp Eye Res*. 2006;82(2):185–200.
 107. Pekel G, Yałci R, Acer S, Ongun GT, Çetin EN, Simavli H. Comparison of corneal layers and anterior sclera in emmetropic and myopic eyes. *Cornea*. 2015;34(7):786–790.
 108. Ohno-Matsui K, Akiba M, Modegi T, et al. Association between shape of sclera and myopic retinochoroidal lesions in patients with pathologic myopia. *Invest Ophthalmol Vis Sci*. 2012;53(10):6046–6061.
 109. Friedman E. Scleral Rigidity, Venous Obstruction, and Age-Related Macular Degeneration: A Working Hypothesis. In: BenEzra D, Ryan SJ, Glaser BM, Murphy RP, eds. *Ocular Circulation and Neovascularization*. Netherlands, US: Springer; 1987:197–204.
 110. Guthoff R, Berger RW, Draeger J. Ultrasonographic measurement of the posterior coats of the eye and their relation to axial length. *Graefes Arch Clin Exp Ophthalmol*. 1987;225(5):374–376.
 111. Dastiridou AI, Ginis HS, de Brouwere D, Tsilimbaris MK, Pallikaris IG. Ocular rigidity, ocular pulse amplitude, and pulsatile ocular blood flow: the effect of intraocular pressure. *Invest Ophthalmol Vis Sci*. 2009;54(3):287–2092.
 112. Wong E, Yap MKH. Factors affecting ocular rigidity in the Chinese. *Clin Exp Optom*. 1991;74(5):156–159.
 113. Atchison DA, Smith G. Possible errors in determining axial length changes during accommodation with the IOLMaster. *Optom Vis Sci*. 2004;81(4):283–286.
 114. Read SA, Collins MJ, Becker H, et al. Changes in intraocular pressure and ocular pulse amplitude with accommodation. *Br J Ophthalmol*. 2010;94(3):332–335.
 115. Woodman-Pieterse EC, Read SA, Collins MJ, Alonso-Caneiro D. Regional changes in choroidal thickness associated with accommodation. *Invest Ophthalmol Vis Sci*. 2015;56(11):6414–6422.
 116. Huang F, Huang S, Xie R, et al. The effect of topical administration of cyclopentolate on ocular biometry: an analysis for mouse and human models. *Sci Rep*. 2017;7(1):9952.
 117. May CA. Non-vascular smooth muscle cells in the human choroid: distribution, development and further characterization. *J Anat*. 2005;207(4):381–390.
 118. Backhouse S, Gentle A. Scleral remodelling in myopia and its manipulation: a review of recent advances in scleral strengthening and myopia control. *Ann Eye Sci*. 2018;3(1):5.
 119. Atchison DA, Pritchard N, Schmid KL, Scott DH, Jones CE, Pope JM. Shape of the retinal surface in emmetropia and myopia. *Invest Ophthalmol Vis Sci*. 2005;46(8):2698–2707.
 120. Oliveira C, Tello C, Liebmann J, Ritch R. Central corneal thickness is not related to anterior scleral thickness or axial length. *J Glaucoma*. 2006;15(3):190–194.
 121. Norman RE, Flanagan JG, Rausch SM, et al. Dimensions of the human sclera: thickness measurement and regional changes with axial length. *Exp Eye Res*. 2010;90(2):277–284.
 122. Wallman J, Winawer J. Homeostasis of eye growth and the question of myopia. *Neuron*. 2004;43(4):447–468.
 123. Woodman-Pieterse EC, Read SA, Collins MJ, Alonso-Caneiro D. Anterior scleral thickness changes with accommodation in myopes and emmetropes. *Exp Eye Res*. 2018;177:96–103.
 124. Niyazmand H, Read SA, Atchison DA, Collins MJ. Effects of accommodation and simulated convergence on anterior scleral shape. *Ophthalmic Physiol Opt*. 2020;40(4):482–490.

125. Schachar RA, Kamangar F. Sclera does not change its shape during accommodation. *Ophthalmic Physiol Opt.* 2017;37(5):624–625.
126. Gwiazda J, Thorn F, Held R. Accommodation, accommodative convergence, and response AC/A ratios before and at the onset of myopia in children. *Optom Vis Sci.* 2005;82(4):273–278.
127. McClelland JF, Saunders KJ. Accommodative lag using dynamic retinoscopy: age norms for school-age children. *Optom Vis Sci.* 2004;81(12):929–933.
128. Rouse MW, Hutter RF, Shiftlett R. A normative study of the accommodative lag in elementary school children. *Am J Optom Physiol Opt.* 1984;61(11):693–697.
129. Li SM, Li SY, Kang MT, et al. Near work related parameters and myopia in Chinese children: the Anyang Childhood Eye Study. *PLoS One.* 2015;10(8):e0134514.
130. Chen AH, Ahmad A, Kearney S, Strang N. The influence of age, refractive error, visual demand and lighting conditions on accommodative ability in Malay children and adults. *Graefes Arch Clin Exp Ophthalmol.* 2019;257(9):1997–2004.
131. Altoaimi BH, Kollbaum P, Meyer D, Bradley A. Experimental investigation of accommodation in eyes fit with multifocal contact lenses using a clinical auto-refractor. *Ophthalmic Physiol Opt.* 2018;38(2):152–163.
132. Troilo D, Smith 3rd EL, Nickla DL, et al. IMI - report on experimental models of emmetropization and myopia. *Invest Ophthalmol Vis Sci.* 2019;60(3):M31–M88.
133. Flitcroft DI. A model of the contribution of oculomotor and optical factors to emmetropization and myopia. *Vis Res.* 1998;38(19):2869–2879.
134. Weizhong L, Zhikuan Y, Wen L, Xiang C, Jian G. A longitudinal study on the relationship between myopia development and near accommodation lag in myopic children. *Ophthalmic Physiol Opt.* 2008;28(1):57–61.
135. Charman WN. Keeping the world in focus: how might this be achieved? *Optom Vis Sci.* 2011;88(3):373–376.
136. Dhallu SK, Sheppard AL, Drew T, et al. Factors influencing pseudo-accommodation—the difference between subjectively reported range of clear focus and objectively measured accommodation range. *Vision.* 2019;3(3):34.
137. Charman WN. Aberrations and myopia. *Ophthalmic Physiol Opt.* 2005;25(4):285–301.
138. Hughes RP, Vincent SJ, Read SA, Collins MJ. Higher order aberrations, refractive error development and myopia control: a review. *Clin Exp Optom.* 2020;103(1):68–85.
139. Berntsen DA, Sinnott LT, Mutti DO, Zadnik K, CLEERE Study Group. Accommodative lag and juvenile-onset myopia progression in children wearing refractive correction. *Vision Res.* 2011;51(9):1039–1046.
140. Correction of Myopia Evaluation Trial 2 Study Group for the Pediatric Eye Disease Investigator Group. Progressive-addition lenses versus single-vision lenses for slowing progression of myopia in children with high accommodative lag and near esophoria. *Invest Ophthalmol Vis Sci.* 2011;52(5):2749–2757.
141. Cheng D, Woo GC, Drobe B, Schmid KL. Effect of bifocal and prismatic bifocal spectacles on myopia progression in children: three-year results of a randomized clinical trial. *JAMA Ophthalmol.* 2014;132(3):258–264.
142. Langaas T, Riddell PM. Accommodative instability: relationship to progression of early onset myopia. *Clin Exp Optom.* 2012;95(2):153–159.
143. Langaas T, Riddell PM, Svarverud E, Ystenaes AE, Langeeggen I, Bruenech JR. Variability of the accommodation response in early onset myopia. *Optom Vis Sci.* 2008;85(1):37–48.
144. Maiello G, Kerber KL, Thorn F, Bex PJ, Vera-Diaz FA. Vergence driven accommodation with simulated disparity in myopia and emmetropia. *Exp Eye Res.* 2018;166:96–105.
145. Ciuffreda KJ, Wallis DM. Myopes show increased susceptibility to nearwork aftereffects. *Invest Ophthalmol Vis Sci.* 1998;39(10):1797–1803.
146. Vera-Díaz FA, Strang NC, Winn B. Nearwork induced transient myopia during myopia progression. *Curr Eye Res.* 2002;24(4):289–295.
147. Ciuffreda KJ, Vasudevan B. Nearwork-induced transient myopia (NITM) and permanent myopia - is there a link? *Ophthalmic Physiol Opt.* 2008;28(2):103–114.
148. Wolffsohn JS, Gilmartin B, Li RW, et al. Nearwork-induced transient myopia in preadolescent Hong Kong Chinese. *Invest Ophthalmol Vis Sci.* 2003;44(5):2284–2289.
149. Ciuffreda KJ, Vasudevan B. Effect of nearwork-induced transient myopia on distance retinal defocus patterns. *Optometry.* 2010;81(3):153–156.
150. Lin Z, Vasudevan B, Liang YB, et al. Nearwork-induced transient myopia (NITM) in anisometropia. *Ophthalmic Physiol Opt.* 2013;33(3):311–317.
151. Charman WN, Radhakrishnan H. Peripheral refraction and the development of refractive error: a review. *Ophthalmic Physiol Opt.* 2010;30(4):321–338.
152. Wildsoet CF, Chia A, Cho P, et al. IMI – Interventions Myopia Institute: Interventions for controlling myopia onset and progression report. *Invest Ophthalmol Vis Sci.* 2019;60(3):M106–M131.
153. Bailey MD, Sinnott LT, Mutti DO. Ciliary body thickness and refractive error in children. *Invest Ophthalmol Vis Sci.* 2008;49(10):4353–4360.
154. Oliveira C, Tello C, Liebmann JM, Ritch R. Ciliary body thickness increases with increasing axial myopia. *Am J Ophthalmol.* 2005;140(2):324–325.
155. Sheppard AL, Davies LN. In vivo analysis of ciliary muscle morphologic changes with accommodation and axial anisometropia. *Invest Ophthalmol Vis Sci.* 2010;51(12):6882–6889. 7
156. Radhakrishnan H, Charman WN. Refractive changes associated with oblique viewing and reading in myopes and emmetropes. *J Vis.* 2007;7(8):1–15.
157. Whatham A, Zimmermann F, Martinez A, et al. Influence of accommodation on off-axis refractive errors in myopic eyes. *J Vis.* 2009;9(3):14.1–13.
158. Davies LN, Mullen EA. Influence of accommodation and refractive status on the peripheral refractive profile. *Br J Ophthalmol.* 2009;93(9):1186–1190.
159. Walker TW, Mutti DO. The effect of accommodation on ocular shape. *Optom Vis Sci.* 2002;79(7):424–430.
160. Calver R, Radhakrishnan H, Osuoben E, O'Leary D. Peripheral refraction for distance and near vision in emmetropes and myopes. *Ophthalmic Physiol Opt.* 2007;27(6):584–593.
161. Mathur A, Atchison DA, Charman WN. Effect of accommodation on peripheral ocular aberrations. *J Vis.* 2009;9(12):20 1-11.
162. Harb E, Thorn F, Troilo D. Characteristics of accommodative behavior during sustained reading in emmetropes and myopes. *Vis Res.* 2006;46(16):2581–2592.
163. Wang YZ, Thibos LN, Bradley A. Effects of refractive error on detection acuity and resolution acuity in peripheral vision. *Invest Ophthalmol Vis Sci.* 1997;38(10):2134–2143.
164. Verbecque E, Vereeck L, Hallemans A. Postural sway in children: a literature review. *Gait Posture.* 2016;49:402–410.
165. Najafpour Z, Godarzi Z, Arab M, Yaseri M. Risk factors for falls in hospital in-patients: a prospective nested case control study. *Int J Heal Policy Manag.* 2019;8(5):300–306.

166. Sayah DN, Asaad K, Hanssens JM, Giraudet G, Faubert J. Myopes show greater visually induced postural responses than emmetropes. *Invest Ophthalmol Vis Sci.* 2016;57(2):551–556.
167. Rosen R, Lundstrom L, Unsbo P. Sign-dependent sensitivity to peripheral defocus for myopes due to aberrations. *Invest Ophthalmol Vis Sci.* 2012;53(11):7176–7182.
168. Radhakrishnan H, Pardhan S, Calver RI, O'Leary DJ. Effect of positive and negative defocus on contrast sensitivity in myopes and non-myopes. *Vis Res.* 2004;44(16):1869–1878.
169. Radhakrishnan H, Pardhan S, Calver RI, O'Leary DJ. Unequal reduction in visual acuity with positive and negative defocusing lenses in myopes. *Optom Vis Sci.* 2004;81(1):14–17.
170. Bullimore MA, Gilmartin B. Retinal eccentricity and the accommodative response. *Am J Optom Physiol Opt.* 1987;64(8):644–645.
171. Gu YC, Legge GE. Accommodation to stimuli in peripheral vision. *J Opt Soc Am A.* 1987;4(8):1681–1687.
172. Hartwig A, Charman WN, Radhakrishnan H. Accommodative response to peripheral stimuli in myopes and emmetropes. *Ophthalmic Physiol Opt.* 2011;31(1):91–99.
173. Maiello G, Walker L, Bex PJ, Vera-Diaz FA. Blur perception throughout the visual field in myopia and emmetropia. *J Vis.* 2017;17(5):3.
174. Rosenfield M, Abraham-Cohen JA. Blur sensitivity in myopes. *Optom Vis Sci.* 1999;76(5):303–307.
175. Kerber K, Thorn F, Bex PJ, Vera-Diaz FA. Peripheral awareness and the effect of central attentional load in myopia. *Optom Vis Sci* 2014;91:E-abstract 145175.
176. Schmid KL, Robert Iskander D, Li RWH, Edwards MH, Lew JFK. Blur detection thresholds in childhood myopia: single and dual target presentation. *Vision Res.* 2002;42(2):239–247.
177. Labhishetty V, Chakraborty A, Bobier WR. Is blur sensitivity altered in children with progressive myopia? *Vision Res.* 2019;154:142–153.
178. Rosenfield M, Hong SE, George S. Blur adaptation in myopes. *Optom Vis Sci.* 2004;81(9):657–662.
179. McGonigle C, van der Linde I, Pardhan S, Engel SA, Mallen EAH, Allen PM. Myopes experience greater contrast adaptation during reading. *Vision Res.* 2016;121:1–9.
180. Cufflin MP, Mankowska A, Mallen EAH. Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Invest Ophthalmol Vis Sci.* 2007;48(6):2932–2939.
181. Wang B, Ciuffreda KJ, Vasudevan B. Effect of blur adaptation on blur sensitivity in myopes. *Vision Res.* 2006;46(21):3634–3641.
182. Venkataraman AP, Winter S, Unsbo P, Lundstrom L. Blur adaptation: contrast sensitivity changes and stimulus extent. *Vision Res.* 2015;110:100–106.
183. Schaeffel F. Myopia: what is old and what is new? *Optom Vis Sci.* 2016;93(9):1022–1030.
184. Wallman J, Gottlieb MD, Rajaram V, Fugate-Wentzke LA. Local retinal regions control local eye growth and myopia. *Science.* 1987;237(4810):73–77.
185. Smith EL, Ramamirtham R, Qiao-Grider Y, et al. Effects of foveal ablation on emmetropization and form-deprivation myopia. *Invest Ophthalmol Vis Sci.* 2007;48(9):3914–3922.
186. Huang J, Hung LF, Smith EL. Effects of foveal ablation on the pattern of peripheral refractive errors in normal and form-deprived infant rhesus monkeys (*Macaca mulatta*). *Invest Ophthalmol Vis Sci.* 2011;52(9):6428–6434.
187. Smith EL, Hung LF, Huang J, Arumugam B. Effects of local myopic defocus on refractive development in monkeys. *Optom Vis Sci.* 2013;90(11):1176–1186.
188. Smith EL, Hung LF. The role of optical defocus in regulating refractive development in infant monkeys. *Vision Res.* 1999;39(8):1415–1435.
189. Hirasawa K, Shoji N. Effect of optical defocus on the kinetic perimetry in young myopic participants. *Curr Eye Res.* 2015;40(8):847–852.
190. Flitcroft DI. The complex interactions of retinal, optical and environmental factors in myopia aetiology. *Prog Retin Eye Res.* 2012;31(6):622–660.
191. Chin MP, Chu PHW, Cheong AMY, Chan HHL. Human electroretinal responses to grating patterns and defocus changes by global flash multifocal electroretinogram. *PLoS One.* 2015;10(4):1–21.
192. Lundström L, Mira-Agudelo A, Artal P. Peripheral optical errors and their change with accommodation differ between emmetropic and myopic eyes. *J Vis.* 2009;9(6):17.1–11.
193. Mathur A, Atchison DA, Charman WN. Effect of accommodation on peripheral ocular aberrations. *J Vis.* 2009;9(2009):1–11.
194. Hartwig A, Charman WN, Radhakrishnan H. Accommodative response to peripheral stimuli in myopes and emmetropes. *Ophthalmic Physiol Opt.* 2011;31(1):91–99.
195. Vera-Diaz FA, McGraw P V, Strang NC, Whitaker D. A psychophysical investigation of ocular expansion in human eyes. *Invest Ophthalmol Vis Sci.* 2005;46(2):758–763.
196. Ehsaei A, Chisholm CM, Pacey IE, Mallen EAH. Visual performance fall-off with eccentricity in myopes versus emmetropes. *J Optom.* 2013;6(1):36–44.
197. Chui TYP, Yap MKH, Chan HHL, Thibos LN. Retinal stretching limits peripheral visual acuity in myopia. *Vision Res.* 2005;45(5):593–605.
198. Atchison DA, Schmid KL, Pritchard N. Neural and optical limits to visual performance in myopia. *Vision Res.* 2006;46(21):3707–3722.
199. Ghosh A, Zheleznyak L, Barbot A, Jung HW, Yoon G. Neural adaptation to peripheral blur in myopes and emmetropes. *Vision Res.* 2017;132:69–77.
200. Rosén R, Lundström L, Unsbo P. Sign-dependent sensitivity to peripheral defocus for myopes due to aberrations. *Invest Ophthalmol Vis Sci.* 2012;53(11):7176–7182.
201. Abraham-Cohen JA. Blur sensitivity in myopes. *Optom Vis Sci.* 1999;76(5):303–307.
202. Vasudevan B, Ciuffreda KJ, Wang B. Objective blur thresholds in free space for different refractive groups. *Curr Eye Res.* 2006;31(2):111–118.
203. Rosenfield M, Hong SE, George S. Blur adaptation in myopes. *Optom Vis Sci.* 2004;81(9):657–662.
204. Blakemore C, Campbell FW. On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *J Physiol.* 1969;203(1):237–260.
205. Georgeson MA, Georgeson JM. Facilitation and masking of briefly presented gratings: time-course and contrast dependence. *Vision Res.* 1987;27(3):369–379.
206. Magnussen S, Greenlee MW. Marathon adaptation to spatial contrast: saturation in sight. *Vision Res.* 1985;25(10):1409–1411.
207. Schaeffel F. Myopia: the importance of seeing fine detail. *Curr Biol.* 2006;16(7):R257–R259.
208. McGonigle C, van der Linde I, Pardhan S, Engel SA, Mallen EAH, Allen PM. Myopes experience greater contrast adaptation during reading. *Vision Res.* 2016;121:1–9.
209. Yeo ACH, Atchison DA, Schmid KL. Effect of text type on near work-induced contrast adaptation in myopic and emmetropic young adults. *Invest Ophthalmol Vis Sci.* 2013;54(2):1478–1483.

210. Ohlendorf A, Schaefel F. Contrast adaptation induced by defocus - a possible error signal for emmetropization? *Vision Res.* 2009;49(2):249–256.
211. Collins MJ, Buehren T, Iskander DR. Retinal image quality, reading and myopia. *Vision Res.* 2006;46(1-2):196–215.
212. Majaj NJ, Pelli DG, Kurshan P, Palomares M. The role of spatial frequency channels in letter identification. *Vision Res.* 2002;42(9):1165–1184.
213. Bour LJ. The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. *Vision Res.* 1981;21(8):1287–1296.
214. Charman WN, Tucker J. Dependence of accommodation response on the spatial frequency spectrum of the observed object. *Vision Res.* 1977;17(1):129–139.
215. Owens DA. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vision Res.* 1980;20(2):159–167.
216. Taylor J, Charman WN, O'Donnell C, Radhakrishnan H. Effect of target spatial frequency on accommodative response in myopes and emmetropes. *J Vision.* 2009;9(1):16 1-14.
217. Radhakrishnan H, Hartwig A, Charman WN, Llorente L. Accommodation response to Chinese and Latin characters in Chinese-illiterate young adults. *Clin Exp Optom.* 2015;98(6):527–534.
218. Yeo ACH, Atchison DA, Schmid KL. Children's accommodation during reading of Chinese and English texts. *Optom Vis Sci.* 2013;90(2):156–163.
219. Wilson BJ, Decker KE, Roorda A. Monochromatic aberrations provide an odd-error cue to focus direction. *J Opt Soc Am A Opt Image Sci Vis.* 2002;19(5):833–839.
220. Thibos LN, Bradley A, Liu T, Lopez-Gil N. Spherical aberration and the sign of defocus. *Optom Vis Sci.* 2013;90(11):1284–1291.
221. Brunette I, Bueno JM, Parent M, Hamam H, Simonet P. Monochromatic aberrations as a function of age, from childhood to advanced age. *Invest Ophthalmol Vis Sci.* 2003;44(12):5438–5446.
222. Mathur A, Atchison DA, Charman WN. Myopia and peripheral ocular aberrations. *J Vision.* 2009;9(10):15.
223. Radhakrishnan H, Charman WN. Age-related changes in ocular aberrations with accommodation. *J Vision.* 2007;7(7):11 1-21.
224. Seidemann A, Schaefel F. Effects of longitudinal chromatic aberration on accommodation and emmetropization. *Vision Res.* 2002;42(21):2409–2417.
225. Atrousseau F, Thibos L, Shevell SK. Chromatic and wavefront aberrations: L-, M- and S-cone stimulation with typical and extreme retinal image quality. *Vision Res.* 2011;51(21-22):2282–2294.
226. Rucker F. Monochromatic and white light and the regulation of eye growth. *Exp Eye Res.* 2019;184:172–182.
227. Rucker FJ. The role of luminance and chromatic cues in emmetropisation. *Ophthalmic Physiol Opt.* 2013;33(3):196–214.
228. Rucker FJ, Kruger PB. Cone contributions to signals for accommodation and the relationship to refractive error. *Vision Res.* 2006;46(19):3079–3089.
229. Rosenfield M, Wong NN, Solan HA. Nearwork distances in children. *Ophthalmic Physiol Opt.* 2001;21(1):75–76.
230. Quek TPL, Chua CG, Chong CS, et al. Prevalence of refractive errors in teenage high school students in Singapore. *Ophthalmic Physiol Opt.* 2004;24(1):47–55.
231. Wang Y, Bao J, Ou L, Thorn F, Lu F. Reading behavior of emmetropic schoolchildren in China. *Vision Res.* 2013;86:43–51.
232. Charman WN. Aniso-accommodation as a possible factor in myopia development. *Ophthalmic Physiol Opt.* 2004;24(5):471–479.
233. Bao J, Drobe B, Wang Y, Chen K, Seow EJ, Lu F. Influence of near tasks on posture in myopic Chinese schoolchildren. *Optom Vis Sci.* 2015;92(8):908–915.
234. Flitcroft DI, Judge SJ, Morley JW. Binocular interactions in accommodation control: effects of anisometric stimuli. *J Neurosci.* 1992;12(1):188–203.
235. Koh LH, Charman WN. Accommodative responses to anisoaccommodative targets. *Ophthalmic Physiol Opt.* 1998;18(3):254–262.
236. Hartwig A, Gowen E, Charman WN, Radhakrishnan H. Binocular saccades in myopes and emmetropes. *Optom Vis Sci.* 2013;90(9):980–987.
237. Hartwig A, Gowen E, Charman WN, Radhakrishnan H. Analysis of head position used by myopes and emmetropes when performing a near-vision reading task. *Vision Res.* 2011;51(14):1712–1717.
238. Hartwig A, Gowen E, Charman WN, Radhakrishnan H. Working distance and eye and head movements during near work in myopes and non-myopes. *Clin Exp Optom.* 2011;94(6):536–544.
239. Rose KA, French AN, Morgan IG. Environmental factors and myopia: Paradoxes and prospects for prevention. *Asia-Pacific J Ophthalmol.* 2016;5(6):403–410.
240. Guo Y, Liu LJ, Xu L, et al. Myopic shift and outdoor activity among primary school children: one-year follow-up study in Beijing. *PLoS One.* 2013;8(9):e75260.
241. Pärssinen O, Lyyra A. Myopia and myopic progression among school children: a three-year follow-up study. *Invest Ophthalmol Vis Sci.* 1993;34(9):2794–2802.
242. Jones LA, Sinnott LT, Mutti DO, Mitchell GL, Moeschberger ML, Zadnik K. Parental history of myopia, sports and outdoor activities, and future myopia. *Invest Ophthalmol Vis Sci.* 2007;48(8):3524–3532.
243. Rose KA, Morgan IG, Ip J, et al. Outdoor activity reduces the prevalence of myopia in children. *Ophthalmology.* 2008;115(8):1279–1285.
244. Dirani M, Tong L, Gazzard G, et al. Outdoor activity and myopia in Singapore teenage children. *Br J Ophthalmol.* 2009;93(8):997–1000.
245. Wu P-C, Tsai C-L, Hu C-H, Yang Y-H. Effects of outdoors activities on myopia among rural school children in Taiwan. *Ophthalmic Epidemiol.* 2010;17(5):338–342.
246. Guggenheim JA, Northstone K, McMahon G, et al. Time outdoors and physical activity as predictors of incident myopia in childhood: a prospective cohort study. *Investig Ophthalmol Vis Sci.* 2012;53(6):2856–2865.
247. Wu PC, Tsai CL, Wu HL, Yang YH, Kuo HK. Outdoor activity during class recess reduces myopia onset and progression in school children. *Ophthalmology.* 2013;120(5):1080–1085.
248. Lin Z, Vasudevan B, Jhanji V, et al. Near work, outdoor activity, and their association with refractive error. *Optom Vis Sci.* 2014;91(4):376–382.
249. Jin JX, Hua WJ, Jiang X, et al. Effect of outdoor activity on myopia onset and progression in school-aged children in northeast china: The Sujiatun Eye Care Study. *BMC Ophthalmol.* 2015;15:73.
250. Wu LJ, Wang YX, You QS, et al. Risk factors of myopic shift among primary school children in Beijing, China: a prospective study. *Int J Med Sci.* 2015;12(8):633–638.
251. He M, Xiang F, Zeng Y, et al. Effect of time spent outdoors at school on the development of myopia among children in China a randomized clinical trial. *JAMA Ophthalmology.* 2015;314(11):1142–1148.

252. Shah RL, Huang Y, Guggenheim JA, Williams C. Time outdoors at specific ages during early childhood and the risk of incident myopia. *Invest Ophthalmol Vis Sci*. 2017;58(2):1158–1166.
253. Guo Y, Liu LJ, Tang P, et al. Outdoor activity and myopia progression in 4-year follow-up of Chinese primary school children: The Beijing Children Eye Study. *PLoS One*. 2017;12(4):1–14.
254. Saxena R, Vashist P, Tandon R, et al. Incidence and progression of myopia and associated factors in urban school children in Delhi: The North India Myopia Study (NIM Study). Pan C-W, ed. *PLoS One*. 2017;12(12):e0189774.
255. Sánchez-Tocino H, Villanueva Gómez A, Gordon Bolaños C, et al. The effect of light and outdoor activity in natural lighting on the progression of myopia in children. *J Fr Ophtalmol*. 2019;42(1):2–10.
256. Guo Y, Liu L, Lv Y, et al. Outdoor jogging and myopia progression in school children from rural Beijing: the Beijing Children Eye Study. *Transl Vis Sci Technol*. 2019;8(3):2.
257. Huang PC, Hsiao YC, Tsai CY, et al. Protective behaviours of near work and time outdoors in myopia prevalence and progression in myopic children: a 2-year prospective population study. *Br J Ophthalmol*. 2020;104(7):956–961.
258. Hoffman DM, Banks MS. Focus information is used to interpret binocular images. *J Vision*. 2010;10(5):13.
259. Mather G. The use of image blur as a depth cue. *Perception*. 1997;26(9):1147–1158.
260. Mather G, Smith DRR. Blur discrimination and its relation to blur-mediated depth perception. *Perception*. 2002;31(10):1211–1219.
261. Seidel D, Gray LS, Heron G. The effect of monocular and binocular viewing on the accommodation response to real targets in emmetropia and myopia. *Optom Vis Sci*. 2005;82(4):279–285.
262. Vera-Diaz FA, Bex PJ, Ferreira A, Kosovicheva A. Binocular temporal visual processing in myopia. *J Vision*. 2018;18(11):1–12.
263. Chirre E, Prieto PM, Schwarz C, Artal P. Night myopia is reduced in binocular vision. *J Vision*. 2016;16(8):1–10.
264. Huang CT, Satou T, Niida T. Effect of pupil size and binocular viewing on accommodative gain in emmetropia and myopia. *J Binocul Vis Ocul Motil*. 2020;70(3):103–108.
265. Mutti DO, Jones LA, Moeschberger ML, Zadnik K. AC/A ratio, age, and refractive error in children. *Invest Ophthalmol Vis Sci*. 2000;41(9):2469–2478.
266. Mutti DO, Mitchell GL, Jones-Jordan LA, et al. The response AC/A ratio before and after the onset of myopia. *Invest Ophthalmol Vis Sci*. 2017;58(3):1594–1602.
267. Jorge J, de Almeida JB, Parafita MA, Jorge Jorge JB de A. Binocular vision changes in university students: a 3-year longitudinal study. *Optom Vis Sci*. 2008;85(10):E999–E1006.
268. Sreenivasan V, Irving EL, Bobier WR. Effect of heterophoria type and myopia on accommodative and vergence responses during sustained near activity in children. *Vision Res*. 2012;57:9–17.
269. Gifford KL, Gifford P, Hendicott PL, Schmid KL. Zone of clear single binocular vision in myopic orthokeratology. *Eye Contact Lens*. 2020;46(2):82–90.
270. Madrid-Costa D, Ruiz-Alcocer J, Radhakrishnan H, Ferrer-Blasco T, Montés-Micó R. Changes in accommodative responses with multifocal contact lenses: a pilot study. *Optom Vis Sci*. 2011;88(11):1309–1316.
271. Tarrant J, Severson H, Wildsoet CF. Accommodation in emmetropic and myopic young adults wearing bifocal soft contact lenses. *Ophthalmic Physiol Opt*. 2008;28(1):62–72.
272. Kang P, Wildsoet CF. Acute and short-term changes in visual function with multifocal soft contact lens wear in young adults. *Cont Lens Anterior Eye*. 2016;39(2):133–140.
273. Ozkan J, Fedtke C, Chung J, Thomas V, Bakaraju RC. Short-term adaptation of accommodative responses in myopes fitted with multifocal contact lenses. *Eye Contact Lens*. 2018;44:S30–S37.
274. Price H, Allen PM, Radhakrishnan H, et al. The Cambridge Anti-myopia Study: variables associated with myopia progression. *Optom Vis Sci*. 2013;90(11):1274–1283.
275. Theagarayan B, Radhakrishnan H, Allen PM, Calver RI, Rae SM, O’Leary DJ. The effect of altering spherical aberration on the static accommodative response. *Ophthalmic Physiol Opt*. 2009;29(1):65–71.
276. Gifford K, Gifford P, Hendicott PL, Schmid KL. Near binocular visual function in young adult orthokeratology versus soft contact lens wearers. *Cont Lens Anterior Eye*. 2017;40(3):184–189.
277. Aller TA, Liu M, Wildsoet CF. Myopia control with bifocal contact lenses: a randomized clinical trial. *Optom Vis Sci*. 2016;93(4):344–352.
278. Gong CR, Troilo D, Richdale K. Accommodation and phoria in children wearing multifocal contact lenses. *Optom Vis Sci*. 2017;94(3):353–360.
279. Anstice NS, Phillips JR. Effect of dual-focus soft contact lens wear on axial myopia progression in children. *Ophthalmology*. 2011;118(6):1152–1161.
280. Chamberlain P, Peixoto-De-Matos SC, Logan NS, Ngo C, Jones D, Young G. A 3-year randomized clinical trial of MiSight lenses for myopia control. *Optom Vis Sci*. 2019;96(8):556–567.
281. Ruiz-Pomeda A, Pérez-Sánchez B, Cañadas P, Prieto-Garrido FL, Gutiérrez-Ortega R, Villa-Collar C. Binocular and accommodative function in the controlled randomized clinical trial MiSight Assessment Study Spain (MASS). *Graefes Arch Clin Exp Ophthalmol*. 2019;257(1):207–215.
282. Tilia D, Sha J, Thomas V, Bakaraju RC. Vision performance and accommodative/binocular function in children wearing prototype extended depth-of-focus contact lenses. *Eye Contact Lens*. 2019;45(4):260–270.
283. Walline JJ, Lindsley KB, Vedula SS, et al. Interventions to slow progression of myopia in children. *Cochrane Database Syst Rev*. 2020;12:CD004916.
284. Gwiazda J, Hyman L, Hussein M, et al. A randomized clinical trial of progressive addition lenses versus single vision lenses on the progression of myopia in children. *Invest Ophthalmol Vis Sci*. 2003;44(4):1492–1500.
285. Chen Y, Drobe B, Zhang C, et al. Accommodation is unrelated to myopia progression in Chinese myopic children. *Sci Rep*. 2020;10(1):12056.
286. Labhishetty V, Bobier WR. Are high lags of accommodation in myopic children due to motor deficits? *Vision Res*. 2017;130:9–21.
287. Chen AH, O’Leary DJ. Are there age differences in the accommodative response curve between 3 and 14 years of age? *Ophthalmic Physiol Opt*. 2002;22(2):119–125.
288. Han X, Xu D, Ge W, Wang Z, Li X, Liu W. A comparison of the effects of orthokeratology lens, Medcall lens, and ordinary frame glasses on the accommodative response in myopic children. *Eye Contact Lens*. 2018;44(4):268–271.
289. Ma MM, Shi J, Li N, Scheiman M, Chen X. Effect of vision therapy on accommodative lag in myopic children: a randomized clinical trial. *Optom Vis Sci*. 2019;96(1):17–26.
290. Bullimore MA, Gilmartin B, Royston JM. Steady-state accommodation and ocular biometry in late-onset myopia. *Doc Ophthalmol*. 1992;80(2):143–155.

291. Jiang BC, Morse SE. Oculomotor functions and late-onset myopia. *Ophthalmic Physiol Opt.* 1999;19(2):165–172.
292. Rosenfield M, Desai R, Portello JK. Do progressing myopes show reduced accommodative responses? *Optom Vis Sci.* 2002;79(4):268–273.
293. Seidel D, Gray LS, Heron G. Retinotopic accommodation responses in myopia. *Invest Ophthalmol Vis Sci.* 2003;44(3):1035–1041.
294. Hazel CA, Cox MJ, Strang NC. Wavefront aberration and its relationship to the accommodative stimulus-response function in myopic subjects. *Optom Vis Sci.* 2003;80(2):151–158.
295. Schmid KL, Hilmer KS, Lawrence RA, Loh SY, Morrish LJ, Brown B. The effect of common reductions in letter size and contrast on accommodation responses in young adult myopes and emmetropes. *Optom Vis Sci.* 2005;82(7):602–611.
296. Day M, Strang NC, Seidel D, Gray LS, Mallen EA. Refractive group differences in accommodation microfluctuations with changing accommodation stimulus. *Ophthalmic Physiol Opt.* 2006;26(1):88–96.
297. Sreenivasan V, Aslakson E, Kornaus A, Thibos LN. Retinal image quality during accommodation in adult myopic eyes. *Optom Vis Sci.* 2013;90(11):1292–1303.
298. Rosenfield M, Gilmartin B. Effect of a near-vision task on the response AC/A of a myopic population. *Ophthalmic Physiol Opt.* 1987;7(3):225–233.
299. Goss DA. Clinical accommodation and heterophoria findings preceding juvenile onset of myopia. *Optom Vis Sci.* 1991;68(2):110–116.
300. Jiang BC. Parameters of accommodative and vergence systems and the development of late-onset myopia. *Invest Ophthalmol Vis Sci.* 1995;36(8):1737–1742.
301. Gwiazda J, Grice K, Thorn F. Response AC/A ratios are elevated in myopic children. *Ophthalmic Physiol Opt.* 1999;19(2):173–179.
302. Chen JC, Schmid KL, Brown B, Edwards MH, Yu BS, Lew JK. AC/A ratios in myopic and emmetropic Hong Kong children and the effect of timolol. *Clin Exp Optom.* 2003;86(5):323–330.
303. Zadnik K, Sinnott LT, Cotter SA, et al. Prediction of juvenile-onset myopia. *JAMA Ophthalmol.* 2015;133(6):683–689.