Accommodation and Binocular Vision in Myopia Development and Progression

Nicola S Logan (1)
Hema Radhakrishnan (2)
Fiona Cruickshank (2)
Peter M Allen (3)
Praveen K Bandela (4,5)
Leon N Davies (1)
Satoshi Hasebe (6)
Safal Khanal (7)
Katrina Schmid (8)
Fuensanta Vera-Diaz (9)
James S Wolffsohn (1)

(1) School of Optometry, Aston University, Birmingham, UK.
(2) Division of Pharmacy & Optometry, School of Health Sciences, Faculty of Biology, Medicine and Health, The University of Manchester, Manchester, UK
(3) Vision and Hearing Sciences Research Centre, School of Psychology and Sports Sciences, Anglia Ruskin University, Cambridge, UK
(4) Brien Holden Vision Institute, Sydney, New South Wales, Australia
(5) School of Optometry and Vision Science, University of New South Wales, Sydney, New South Wales, Australia
(6) Department of Ophthalmology, Kawasaki Medical School, Japan
(7) School of Optometry, University of Alabama at Birmingham, Birmingham, Alabama, United States
(8) School of Optometry and Vision Science, Queensland University of Technology, Brisbane, Australia
(9) New England College of Optometry, Boston, United States

ABSTRACT

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 near environment, colour 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.

The association between sustained nearwork 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 nearwork and the onset and progression of myopia.[2–4] Consequently, increased accommodative effort required during nearwork 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 also varies with accommodation, yet the impact of heterophoria at near 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 endeavours 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 behaviour, the following section presents a brief review of the mechanism of human accommodation. Although the literature stands equivocal concerning the exact mechanism it does 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 fibres from which the crystalline lens is suspended are maintained under tension due to strain from the posterior pars plana fibres. 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 simultaneous smaller increase in posterior surface curvature.[6,25,26] These dimensional changes result in a reduction in anterior chamber depth, yet overall increase in anterior segment length (distance from the cornea to the posterior surface of the lens).[12,14,27] Once accommodation ceases, 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 visualisation of many previously unknown anatomical 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 anatomical 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 colleagues[43] 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 behaviour 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 non-myopes 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] whilst 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 distance[66] or age[67] between groups. Further, anecdotal evidence supporting a lack of correlation can be drawn from numerous studies that report isocoria in ansiometropes, 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 homogenised refractive error or age groups, particularly paediatric populations.[60]

Ciliary Muscle

As ciliary muscle contraction is a prerequisite to accommodation,[69] interest in morphological differences in ciliary muscle anatomy has increased[70] in the context of how they may contribute to the association between near-work 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 2-3 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 1mm from the scleral spur.[73] Inter-ocular 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 fibre portion being thicker and the apical fibre region being thinner in the more myopic eye.[79] Nonetheless, Sheppard and Davies[81] 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 Davies[81] 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).

While it is clear that differences in ciliary muscle anatomy between myopes and non-myopes exist, if or how this would translate into a myopigenic effect remains undetermined. Only minor differences in accommodative behaviour (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 near-work conditions. Seemingly, the evidence that myopic children and adults have higher accommodative lags than emmetropes, and that higher lags of accommodation are associated with faster myopia progression support this.[50,56,58,90] 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 one 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 anatomical features such as refractive index and rigidity and whether these parameters differ between refractive groups.

Figure 1 here

CHANGES IN THE POSTERIOR SEGMENT IN RELATION TO ACCOMMODATION AND MYOPIA

Ostensibly, performance variation in the accommodative apparatus represents the most obvious anatomical 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] Though data to explicitly evidence a mechanical force model are scarce, Croft and colleagues[104] 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 Schiotz tonometry which suggests emmetropic and myopic adults[112] and children[41] 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 colleagues[97] reported the largest disparity with a mean elongation of 0.037 mm in emmetropes versus 0.058 mm in myopes for a 6.0 D accommodative stimulus. Though 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 significant 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 near work activities[114] 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].

While 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 sub-foveal choroidal thickness change during a sustained 4.0 D accommodation task and reported a -8 μm choroidal thinning and ~20 μm 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.[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 bi-directional, 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 focussed retinal image.[40,117]

Figure 2 HERE

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 semi-rigid 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 to the emmetropic eyes, 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 modelling 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 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 while 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 nasoscleral 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), while 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 INTERRUPT EMMETROPIZATION IN HUMANS

Whilst 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.[53,126] Previous studies have shown that myopic children accommodate less than emmetropic children.[50,58,91,127–130] 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.[53,132,133] To date, longitudinal studies comparing the magnitude of initial accommodative lag with subsequent myopia progression have come to conflicting conclusions.[51,134] Accommodative lags of over 1.0 D are common during near vision in both emmetropes and myopes. These errors in accommodation are summarised 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 dependent 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 non-accommodative states.[137,138] Attempts to slow myopia progression using interventions targeted at improving accommodative lag, such as 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 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 adults[144] 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 ‘nearwork induced transient myopia’. Retinal defocus induced by nearwork induced transient myopia is larger and persists for longer in late-onset[145] and progressing[146,147] adult myopes and children in whom it lasts longer[148], indicating a possible contributing factor to permanent myopia.[149] Interestingly, nearwork 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 while 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 ±1D;[163] therefore, any changes in the peripheral focus of over ±1D are likely to be perceived as defocussed 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 which 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 defocus 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 15º).[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 2x) in comparison to emmetropes.[208,209] The contrast adaption was shown at different spatial frequencies in these two studies owing to differences in targets used (paper vs. cathode ray tube display) and age of the participants (children vs. 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 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 inter-subject 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 aberration 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 hypothesised 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.

Colour based cues

Figure 3 HERE

Longitudinal chromatic aberration can extend the best focus of the eye by ~2.0 D and hence, can also provide the odd error cue for accommodation and emmetropization. Accommodative response in humans also varies with wavelength, with the eye accommodating more for longer-wavelength and showing an ~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 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 hypothesised that the myopic eye emmetropizes to reach optimal focus using either the red/green colour sensitive mechanism or the luminance sensitive mechanism, relative to the optimal focus for the blue/yellow colour 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 - 40cms in 6 – 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 (0.25D or less) between the two eyes.[234,235] Therefore substantial levels of blur can be perceived by the eye when the anisoaccommodative demand is coupled with high accommodative lags. Further, this non-uniform 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 retina;[258] 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,[259] and in turn blur due to defocus is a useful cue in binocularity.[260,261] This effect may be different in myopes.[262] 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.[263] Night myopia, or tonic accommodation, is reduced under binocular conditions[264] and the accommodative gain is different with a translucent occluder over the non-viewing eye than binocularly in emmetropes but not in myopes.[265]

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.[266] Studies have found the AC/A ratio to be elevated prior to myopia onset[126] and as early as 4 years prior to myopia onset.[267] 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 dioptre 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.[267] 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 summarised in Table 3.

Theoretically a greater AC/A is also likely to shift the eyes towards esophoria at near in these myopic children. Near positive (base in) fusional vergences are also higher in progressing myopes.[268] 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).[269] 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.[270]

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 centre. 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 wear[271] or a lead of accommodation,[272] others have shown increased accommodative lag,[273] reduced monocular accommodative facility,[274] and exophoric shifts at near.[273] It has also been shown that spherical aberration modifying lenses do not affect accommodative facility and horizontal phoria,[275] and adding negative aberration can improve the slope of the accommodation stimulus-response curve, reducing lag of accommodation.[276] Orthokeratology lens wear has also been shown to increase exophoria in young adult myopes.[270] 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.[277]

Studies in children show reduced accommodation response and an increase in exophoria while wearing centre-distance soft bifocal[278] or multifocal contact lens[279] 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[280–283] 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] While the evidence in humans is less clear, chronic retinal defocus at near, due to a lag in accommodative response, is more frequent and often greater in myopes. This blur at near has been suggested to trigger a series of biochemical events which could result in scleral remodelling 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.[152,284,285]

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.[286] 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 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.[287]

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 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 towards a role for accommodation and binocular vision in myopia development and progression.

Tables

Table 1: Effect of refractive error and measurement methods on accommodation errors at near in children.

Paper	Measurement Method	Accommodation Stimuli	Mode of Myopic Correction	Age (yr)	Refractive Groups	AE (D)	Summary of Results
Rouse *et al.* (1984)[128]	MEM Dynamic Retinoscopy	Monocular FV Usual near demand	Habitual spectacle correction	5-11	Not specified	-0.30	Relationship between age and lag
Gwiazda *et al.* (1993)[50]	Canon R-1 Autoref	Monocular FV/ NL/ PL 0-4 D demand	Soft contact lenses	5-17	EMMs MYPs EMMs MYPs	-0.30 FV -0.66 FV -0.56 NL -1.61 NL	MYPs had greater lags than EMMs. Lags were greater for NL
Chen and O'Leary, (2002)[288]	Canon R-1 Autoref	Monocular FV/NL 0-4 D demand	N/A	3-14	EMMs	-0.29 FV -0.69 NL	Lags greater for NL
McClelland et al., (2004)[127]	Nott 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 Autoref	BLV/ FV 2 D and 4D demand	Habitual spectacle correction	6-15	EMMs EMMs MYPs MYPs	-1.00 FV -0.91 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)[143]	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 Autoref	Monocular FV 3 D demand	Spectacle correction	Ave 11	EOMs	-0.76	No relationship between accommodation lag and myopia progression over one year
COMET 2 (2011)[140]	Grand Seiko WR5001K	Monocular FV	Spectacle correction	8-12	MYPs SVL MYPs PAL	-1.40 -1.47	Both myopic groups of children exhibited larger accommodative

		3 D demand					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 Autoref	BLV/ FV 4D 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)[218]	Shin-Nippon Autoref	Binocular FV 3 & 4D 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)[289]	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)[290]	Shin-Nippon Autoref	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

Abbreviations: EMMs = emmetropes, EOMs = early onset myopes, MYPs = myopes, NL= negative lens series, PL = positive lens series, HS = Hartmann Shack, BLV = Badal Lens Viewing, FV = Free Viewing, lag = accommodation lag, VA = visual acuity, AE = accommodative error at highest demand conditions, SVL = single vision lens wear group, PAL = progressive lens wear group.

Table 2: Effect of refractive error and measurement methods on accommodation errors at near in young adults

Paper	Measurement Method	Accommodation Stimuli	Mode of Myopic Correction	Age (yr)	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 EOMs LOMs	-0.54 -0.69 -0.83			EOMs and LOMs had greater lags than EMMs
Bullimore *et al*. (1992)[291]	Canon R-1 Autoref	Monocular FV/ NL/ PL 1-5 D demand	Soft contact lenses	19-23	EMMs LOMs	-0.60 -0.73			LOMs had greater lags for passive tasks at high demands
Abbott *et al*. (1998)[58]	Canon R-1 Autoref	Monocular FV/ NL/ PL 0-4 D demand	Soft contact lenses	18-31	EMMs SMs PMs	0.01 NL 0.01 NL -0.52 NL			Progressing MYPs had greater lags for NL conditions only
Jiang and Morse, (1999)[292]	Canon R-1 Autoref	Monocular Badal lens viewing (BLV) Up to 5D demand	Soft contact lenses or spectacles	20-30	EMMs SMs PMs			0.74 0.77 0.67	All 3 refractive groups had similar lags
Rosenfield *et al*. (2002)[293]	Canon R-1 Autoref	Binocular FV 0-5 D demand	Soft contact lenses	21-27	EMMs SMs PMs	-0.34 FV -0.34 FV -0.20 FV		0.99 0.96	Greater lags found in stable MYPs than initial EMMs and MYPs that progressed over a 1 year period
Subbaram and Bullimore, (2002)[65]	Canon R-1 Autoref	Monocular BLV 0-4 D demand	Spectacles	20-30	EMMs PMs	-0.29 -0.29			Small lags found in both refractive groups
Seidel *et al*. (2003)[294]	Canon R-1 Autoref	Monocular BLV 0-4.5 D demand	Soft contact lenses	17-26	EMMs LOMs EOMs			0.81 0.81 0.80	All 3 groups had similar lags but greater response variability in the myopic groups
Hazel *et al.* (2003)[295]	Shin-Nippon Autoref SRW 5000	Monocular NL 0-4 D demand	Soft contact lenses	18-27	EMMs MYPs EMMs	-0.72 -1.01 -0.50 HS			Lags greater when measured with the autorefractor when

	Wavefront Sensor (HS)				MYPs	-0.43 HS			adjusted for similar pupil size
Nakatsuka *et al.* (2003)[55]	Open field autorefractor	Monocular FV 2-6.25 D demand	Habitual spectacle correction	19-38	EMMs EOMs			1.02 1.05	Good accommodative accuracy in both refractive groups
Schmid *et al*. (2005)[296]	Shin-Nippon Autoref SRW 5000	Monocular BLV 4 D demand	Soft contact lenses	18-25	EMMs MYPs	0.29 0.33			EMMs and MYPs had similar lags, response more accurate for smaller targets at the same distance
Day *et al*. (2006)[297]	Shin-Nippon Autoref SRW 5000	Monocular BLV 0-4 D demand	Soft contact lenses	Aves 22 22 28	EMMs EOMs LOMs		0.73 0.86 0.70		EMMs and LOMs had greater lags than the EOMs
Allen and O'Leary (2006)[51]	Power Refractor	Monocular and Binocular FV 3 D demand	Habitual correction	18-25	EMMs EOMs LOMs		0.35 0.41		Increased binocular lags with increasing degree of myopia
Harb *et al.* (2006)[162]	Power Refractor	FV 3.5 D demand	Soft contact lenses	22-28	EMMs MYPs	-0.99 -0.99			Myopes had greater variability in their accommodation response and had larger lags at greater reading distances
Sreenivasan *et al.* (2013)[298]	COAS Aberrometer	Monocular plus 3 Binocular tasks 1-5 D demand	Spectacle correction equivalent	18-25	EMMs MYPs	-0.70 -1.20			MYPs showed greater lags but had better near VA than EMMs

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

Table 3 Effect of refractive error on phoria and AC/A in children and young adults

Paper	Measurement Method	Mode of Myopic Correction	Age (yr)	Refractive Groups	Near Phoria (Δ)	Response AC/A (Δ/ D)	Summary of Results
Rosenfield, Gilmartin (1987)[299]	IR Autoref and Maddox rod	Trial frame and lenses	18-27	EMMs EOMs LOMs		3.0 3.9 4.6	Higher AC/A ratios in LOMs than EOMs than EMMs
Goss (1991)[300]	Canon R-1 Autoref von Graefe phoria	Trial frame and lenses	6-15	EMMs Became MYPs	-2 exo +1 eso		Onset of myopia preceded by vergence changes
Jiang (1995)[301]	Canon R-1 Autoref Phoria method not mentioned	Trial frame and lenses	18-27	EMMs Became MYPs		0.9 1.4	Higher AC/A ratios in EMMs that became Myopes
Gwiazda et al., (1999)[302]	Canon R-1 Autoref with attached motorized Risley prism and Maddox rod	Trial frame and lenses	6-14	EMMs MYPs		3.9 6.4	Higher AC/A ratios in myopic children
Mutti et al., (2000)[266]	Simultaneous accommodation and vergence measures Canon R-1 Autoref Purkinje images I and IV	Habitual correction	6-14	EMMs MYPs		3.9 6.4	Higher AC/A ratios in myopic children
Chen et al., (2003)[303]	Shin-Nippon Autoref with Howell Dwyer Card	Trial frame and lenses	8-12	EMMs MYPs	-0.7 exo -1.0 exo	2 3	AC/A ratios and phoria were similar in EMMs and MYPs
Gwiazda et al., (2005)[126]	Canon R-1 Autoref with attached motorized Risley prism and Maddox rod	Trial frame and lenses	6-18	EMMs Became MYPs	-2.9 exo -0.4 exo	7.5 >9	Elevated AC/A in EMMs who became myopic, two years prior to onset
Allen, O'Leary (2006)[51]	PowerRefractor with a Bernell Muscle Imbalance Measure	Trial frame and lenses	18-22	EMMs EOMs LOMs		3.5 4.2 3.6	Elevated AC/A not related to myopia progression

	(MIM) test card and Maddox rod						
Price et al., (2013)[275]	Shin-Nippon Autoref with Howell Dwyer Card	Trial frame and lenses	14-21	MYPs		4	Elevated AC/A was related to myopia progression
Zadnik et al., (2015)[304]	Simultaneous accommodation and vergence Canon R-1 Autoref Purkinje images I and IV	Habitual correction	7-13	EMMs Became MYPs		4 7	High AC/A myopia risk factor
Mutti et al., (2017)[267]	Simultaneous accommodation and vergence Canon R-1 Autoref Purkinje images I and IV	Habitual correction	6-14	EMMs Became MYPs		4 7	AC/A increased up to 4 years prior to myopia onset

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

Figure Legends

Figure 1

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

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 colours indicate a choroidal thinning with accommodation). From Woodman-Pieterse et al.[115]

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.

References

1. Rosenfield M. and Gilmartin B. *Myopia and Nearwork*. Butterworth-Heinemann; 1998.

2. 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.

3. 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. doi:10.1167/iovs.04-0565

4. Ip JM, Saw SM, Rose KA, et al. Role of near work in myopia: Findings in a sample of Australian school children. *Investig Ophthalmol Vis Sci*. 2008;49(7):2903-2910. doi:10.1167/iovs.07-0804

5. Koretz JF, Cook CA, Kaufman PL. Accommodation and presbyopia in the human eye: Changes in the anterior segment and crystalline lens with focus. *Investig Ophthalmol Vis Sci*. 1997;38(3):569-578.

6. 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. doi:10.1046/j.1475-1313.2003.00168.x

7. Strenk SA, Strenk LM, Koretz JF. The mechanism of presbyopia. *Prog Retin Eye Res*. 2005;24(3):379-393. doi:10.1016/j.preteyeres.2004.11.001

8. Hermans E, Dubbelman M, van der Heijde R, Heethaar R. The shape of the human lens nucleus with accommodation. *J Vis*. 2007;7(10). doi:10.1167/7.10.16

9. Richdale K, Bullimore MA, Zadnik K. Lens thickness with age and accommodation by optical coherence tomography. *Ophthalmic Physiol Opt*. 2008;28(5):441-447. doi:10.1111/j.1475-1313.2008.00594.x

10. Doyle L, Little JA, Saunders KJ. Repeatability of OCT lens thickness measures with age and accommodation. *Optom Vis Sci*. 2013;90(12):1396-1405. doi:10.1097/OPX.0000000000000080

11. Shum PJT, Ko LS, Ng CL, Lin SL. A biometric study of ocular changes during accommodation. *Am J Ophthalmol*. 1993;115(1):76-81. doi:10.1016/S0002-9394(14)73528-7

12. 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. doi:10.1016/S0042-6989(97)00066-7

13. 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. doi:10.1016/j.visres.2004.07.032

14. 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. doi:10.1097/01.opx.0000232810.61191.02

15. 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. doi:10.1016/j.jcrs.2007.05.021

16. 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. *Investig Ophthalmol Vis Sci*. 2004;45(2):539-545. doi:10.1167/iovs.03-0092

17. Glasser A, Kaufman PL. The mechanism of accommodation in primates. *Ophthalmology*. 1999;106(5):863-872. doi:10.1016/S0161-6420(99)00502-3

18. 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. *Investig Ophthalmol Vis Sci*. 1999;40(6):1162-1169.

19. 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. doi:10.1097/OPX.0000000000000757

20. Tse PU, Whitney D, Anstis S, Cavanagh P. Voluntary attention modulates motion-induced mislocalization. *J Vis*. 2011;11(3):1-6. doi:10.1167/11.3.1

21. 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. doi:10.1097/OPX.0b013e318157c6b5

22. 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. doi:10.1364/boe.9.001272

23. 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. doi:10.1364/josaa.19.000144

24. 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. doi:10.1167/6.10.5

25. Garner LF, Yap MKH. Changes in ocular dimensions and refraction with accommodation. *Ophthalmic Physiol Opt*. 1997;17(1):12-17. doi:10.1016/S0275-5408(96)00050-6

26. Ciuffreda KJ. The Glenn A. Fry invited lecture. Accommodation to gratings and more naturalistic stimuli. *Optom Vis Sci*. 1991;68(4):243-260. doi:10.1097/00006324-199104000-00001

27. 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. doi:10.1136/bjo.2006.099879

28. Gullstrand A. No Title. In: *Appendices II and IV. In Helmholtz's Handbuch Der Physiologischen Optik*. ; 1909:Vol 1, pp 301-358, 382-414.

29. Tian Y, Tarrant J, Wildsoet CF. Optical and biometric characteristics of anisomyopia in human adults. *Ophthalmic Physiol Opt*. 2011;31(5):540-549. doi:10.1111/j.1475-1313.2011.00858.x

30. Atchison DA, Jones CE, Schmid KL, et al. Eye shape in emmetropia and myopia. *Investig Ophthalmol Vis Sci*. 2004;45(10):3380-3386. doi:10.1167/iovs.04-0292

31. Logan NS, Gilmartin B, Wildsoet CF, Dunne MCM. Posterior retinal contour in adult human

anisomyopia. *Investig Ophthalmol Vis Sci*. 2004;45(7):2152-2162. doi:10.1167/iovs.03-0875

32. Chang SW, Tsai IL, Hu FR, Lin LLK, Shih YF. The cornea in young myopic adults. *Br J Ophthalmol*. 2001;85(8):916-920. doi:10.1136/bjo.85.8.916

33. Grosvenor T, Goss DA. Role of the cornea in emmetropia and myopia. *Optom Vis Sci*. 1998;75(2):132-145. doi:10.1097/00006324-199802000-00017

34. 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. doi:10.1097/01.opx.0000215251.27409.16

35. 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. doi:10.1097/00006324-199707000-00015

36. Scott R, Grosvenor T. Structural model for emmetropic and myopic eyes. *Ophthalmic Physiol Opt*. 1993;13(1):41-47. doi:10.1111/j.1475-1313.1993.tb00424.x

37. McBrien NA, Adams DW. A longitudinal investigation of adult-onset and adult-progression of myopia in an occupational group: Refractive and Biometric Findings. *Investig Ophthalmol Vis Sci*. 1997;38(2):321-333.

38. McBrien NA, Millodot M. A biometric investigation of late onset myopic eyes. *Acta Ophthalmol*. 1987;65(4):461-468. doi:10.1111/j.1755-3768.1987.tb07024.x

39. Zadnik K, Mutti DO, Fusaro RE, Adams AJ. Longitudinal evidence of crystalline lens thinning in children. *Investig Ophthalmol Vis Sci*. 1995;36(8):1581-1587.

40. 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. doi:10.1111/cxo.12862

41. Schmid KL, Li RWH, Edwards MH, Lew JKF. The expandability of the eye in childhood myopia. *Curr Eye Res*. 2003;26(2):65-71. doi:10.1076/ceyr.26.2.65.14513

42. Patel H, Gilmartin B, Cubbidge RP, Logan NS. In vivo measurement of regional variation in anterior scleral resistance to Schiotz indentation. *Ophthalmic Physiol Opt*. 2011;31(5):437-443. doi:10.1111/j.1475-1313.2011.00840.x

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. doi:10.1111/j.1475-1313.2010.00749.x

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. doi:https://doi.org/10.1016/j.clae.2006.08.004

45. Diether S, Schaeffel F. Local changes in eye growth after imposed local defocus. *Investig 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. doi:10.1111/j.1475-1313.1997.tb00059.x

47. Smith EL, Hung LF, Arumugam B. Visual regulation of refractive development: Insights from

animal studies. *Eye*. 2014;28(2):180-188. doi:10.1038/eye.2013.277

48. Troilo D, Smith EL, Nickla DL, et al. IMI – Report on experimental models of emmetropization and myopia. *Investig Ophthalmol Vis Sci*. 2019;60(3):M31-M88. doi:10.1167/iovs.18-25967

49. McBrien NA, Millodot M. Amplitude of accommodation and refractive error. *Investig 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. *Investig Ophthalmol Vis Sci*. 1993;34(3):690-694.

51. Allen PM, O'Leary DJ. Accommodation functions: co-dependency and relationship to refractive error. *Vis Res*. 2006;46(4):491-505. doi:10.1016/j.visres.2005.05.007

52. 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. doi:10.1167/iovs.03-1306

53. Charman WN. Near vision, lags of accommodation and myopia. *Ophthalmic Physiol Opt*. 1999;19(2):126-133. doi:10.1046/j.1475-1313.1999.00414.x

54. Seidemann A, Schaeffel F. An evaluation of the lag of accommodation using photorefraction. *Vision Res*. 2003;43(4):419-430. doi:10.1016/S0042-6989(02)00571-0

55. 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. doi:10.1016/S0021-5155(03)00013-3

56. 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. doi:10.1016/0042-6989(94)00238-H

57. Drobe B, de Saint-André R. The pre-myopic syndrome. *Ophthalmic Physiol Opt*. 1995;15(5):375-378. doi:10.1016/0275-5408(95)00075-O

58. 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. doi:10.1016/S0275-5408(97)00072-0

59. 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. doi:10.1016/j.visres.2004.08.027

60. Charman WN, Radhakrishnan H. Accommodation, pupil diameter and myopia. *Ophthalmic Physiol Opt*. 2009;29(1):72-79. doi:10.1111/j.1475-1313.2008.00611.x

61. Applegate RA, Donnelly III WJ, Marsack JD, 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. *Investig Ophthalmol Vis Sci*. 1994;35(3):1132-1137.

63. Jones R. Do women and myopes have larger pupils? *Investig 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. doi:10.3928/1081-597x-20050501-19

65. Subbaram M V., Bullimore MA. Visual acuity and the accuracy of the accommodative response. *Ophthalmic Physiol Opt*. 2002;22(4):312-318. doi:10.1046/j.1475-1313.2002.00037.x

66. Hirsch MJ, Weymouth FW. Pupil size in ametropia. *J Appl Physiol*. 1949;1(9):646-648. doi:10.1152/jappl.1949.1.9.646

67. Chaidaroon W, Juwattanasomran W. Colvard pupillometer measurement of scotopic pupil diameter in emmetropes and myopes. *Jpn J Ophthalmol*. 2002;46(6):640-644. doi:10.1016/S0021-5155(02)00556-7

68. Bremner FD. The Pupil: Anatomy, Physiology, and Clinical Applications: By Irene E. Loewenfeld. 1999. Oxford: Butterworth-Heinemann. Pp. 2278. ISBN 0-750-67143-2. *Brain*. 2001;124(9):1881-1883. doi:10.1093/brain/124.9.1881

69. Ciuffreda KJ. Accommodation, the Pupil, and Presbyopia. In: *Borish's Clinical Refraction*. ; 2006:93-144. doi:10.1016/B978-0-7506-7524-6.50009-0

70. Wagner S, Zrenner E, Strasser T. Ciliary muscle thickness profiles derived from optical coherence tomography images. *Biomed Opt Express*. 2018;9(10):5100. doi:10.1364/boe.9.005100

71. Bailey MD, Sinnott LT, Mutti DO. Ciliary body thickness and refractive error in children. *Investig Ophthalmol Vis Sci*. 2008;49(10):4353-4360. doi:10.1167/iovs.08-2008

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. doi:10.1097/OPX.0b013e3181a7b3ce

73. Pucker AD, Sinnott LT, Kao CY, Bailey MD. Region-specific relationships between refractive error and ciliary muscle thickness in children. *Investig Ophthalmol Vis Sci*. 2013;54(7):4710-4716. doi:10.1167/iovs.13-11658

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. doi:10.1097/OPX.0b013e318253de7e

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. doi:10.1016/j.ajo.2005.01.047

76. Muftuoglu O, Hosal BM, Zilelioglu G. Ciliary body thickness in unilateral high axial myopia. *Eye*. 2009;23(5):1176-1181. doi:10.1038/eye.2008.178

77. Jeon S, Lee WK, Lee K, Moon NJ. Diminished ciliary muscle movement on accommodation in myopia. *Exp Eye Res*. 2012;105:9-14. doi:10.1016/j.exer.2012.08.014

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). doi:10.1111/opo.12039

79. Kuchem MK, Sinnott LT, Kao CY, Bailey MD. Ciliary muscle thickness in anisometropia. *Optom Vis Sci*. 2013;90(11):1312-1320. doi:10.1097/OPX.0000000000000070

80. Wagner S, Schaeffel F, Zrenner E, Straßer T. Prolonged nearwork affects the ciliary muscle morphology. *Exp Eye Res*. 2019;186(107741). doi:10.1016/j.exer.2019.107741

81. Sheppard AL, Davies LN. In vivo analysis of ciliary muscle morphologic changes with accommodation and axial ametropia. *Investig Ophthalmol Vis Sci*. 2010;51(12):6882-6889. doi:10.1167/iovs.10-5787

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. *Investig Ophthalmol Vis Sci*. 2013;54(2):1095-1105. doi:10.1167/iovs.12-10619

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. doi:10.1097/OPX.0b013e318252cadc

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. doi:10.1364/boe.7.001351

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. doi:10.3980/j.issn.1672-5123.2013.06.42

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. doi:10.1016/j.visres.2019.08.002

87. Van Alphen GWHM. Choroidal stress and emmetropization. *Vision Res*. 1986;26(5):723-734. doi:10.1016/0042-6989(86)90086-6

88. Mutti DO. Hereditary and environmental contributions to emmetropization and myopia. *Optom Vis Sci*. Published online 2010. doi:10.1097/OPX.0b013e3181c95a24

89. Bailey MD. How should we measure the ciliary muscle? *Investig Ophthalmol Vis Sci*. 2011;52(3):1817-1818. doi:10.1167/iovs.11-7313

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. doi:10.1097/01.OPX.0000159363.07082.7D

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. doi:10.1167/iovs.05-0888

92. Rosenfield M, Desai R, Portello JK. Do progressing myopes show reduced accommodative responses? *Optom Vis Sci*. 2002;79(4):268-273. doi:10.1097/00006324-200204000-00014

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. doi:10.1111/j.1475-1313.2007.00536.x

94. Wood ICJ, Mutti DO, Zadnik K. Crystalline lens parameters in infancy. *Ophthalmic Physiol Opt*. 1996;16(4):310-317. doi:10.1016/0275-5408(95)00131-X

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. doi:10.1097/OPX.0b013e3182418213

96. Drexler W, Findl O, Schmetterer L, Hitzenberger CK, Fercher AF. Eye elongation during

accommodation in humans: Differences between emmetropes and myopes. *Investig 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. *Investig Ophthalmol Vis Sci*. 2006;47(3):1251-1254. doi:10.1167/iovs.05-1086

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. doi:10.1136/bjo.2010.180323

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. doi:10.1097/OPX.0b013e3181e87dd3

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. doi:10.1016/j.visres.2012.09.009

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. doi:10.1097/OPX.0000000000001037

102. Laughton 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. doi:10.1111/cxo.12533

103. van Alphen GWHM, Graebel WP. Elasticity of tissues involved in accommodation. *Vision Res*. 1991;31(7-8):1417-1438. doi:10.1016/0042-6989(91)90061-9

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. *Investig Ophthalmol Vis Sci*. 2013;54(7):5049-5058. doi:10.1167/iovs.12-10847

105. Ikuno Y, Tano Y. Retinal and choroidal biometry in highly myopic eyes with spectral-domain optical coherence tomography. *Investig Ophthalmol Vis Sci*. 2009;50(8):3876-3880. doi:10.1167/iovs.08-3325

106. Summers Rada JA, Shelton S, Norton TT. The sclera and myopia. *Exp Eye Res*. 2006;82(2):185-200. doi:10.1016/j.exer.2005.08.009

107. Pekel G, Yaɫci 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. doi:10.1097/ICO.0000000000000422

108. Ohno-Matsui K, Akiba M, Modegi T, et al. Association between shape of sclera and myopic retinochoroidal lesions in patients with pathologic myopia. *Investig Ophthalmol Vis Sci*. 2012;53(10):6046-6061. doi:10.1167/iovs.12-10161

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*. Springer Netherlands; 1987:197-204. doi:10.1007/978-94-009-3337-8_31

110. Guthoff R, Berger RW, Draeger J. Ultrasonographic measurement of the posterior coats of the eye and their relation to axial length. *Graefe's Arch Clin Exp Ophthalmol*. 1987;225(5):374-376. doi:10.1007/BF02153409

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. *Investig Ophthalmol Vis Sci*. Published online 2009. doi:10.1167/iovs.09-3760

112. Wong E, Yap MKH. Factors affecting ocular rigidity in the Chinese. *Clin Exp Optom*. 1991;74(5):156-159. doi:10.1111/j.1444-0938.1991.tb04633.x

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. doi:10.1097/00006324-200404000-00015

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. doi:10.1136/bjo.2009.166355

115. Woodman-Pieterse EC, Read SA, Collins MJ, Alonso-Caneiro D. Regional changes in choroidal thickness associated with accommodation. *Investig Ophthalmol Vis Sci*. 2015;56(11):6414-6422. doi:10.1167/iovs.15-17102

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). doi:10.1038/s41598-017-09924-5

117. May CA. Non-vascular smooth muscle cells in the human choroid: distribution, development and further characterization. *J Anat*. 2005;207(4):381-390. doi:10.1111/j.1469-7580.2005.00460.x

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. doi:10.1167/iovs.04-1506

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. doi:10.1097/01.ijg.0000212220.42675.c5

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. doi:10.1016/j.exer.2009.11.001

122. Wallman J, Winawer J. Homeostasis of eye growth and the question of myopia. *Neuron*. 2004;43(4):447-468. doi:10.1016/j.neuron.2004.08.008

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. doi:10.1016/j.exer.2018.07.023

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.

doi:10.1111/opo.12697

125. Schachar RA, Kamangar F. Sclera does not change its shape during accommodation. *Ophthalmic Physiol Opt*. 2017;37(5):624-625. doi:10.1111/opo.12395

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. doi:10.1097/01.OPX.0000159363.07082.7D

127. McClelland JF, Saunders KJ. Accommodative lag using dynamic retinoscopy: Age norms for school-age children. *Optom Vis Sci*. 2004;81(12):929-933. doi:10.1097/01.OPX.0000147681.94971.28

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. doi:10.1097/00006324-198411000-00008

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. doi:10.1371/journal.pone.0134514

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. doi:10.1007/s00417-019-04405-z

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. doi:10.1111/opo.12438

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. doi:10.1167/iovs.18-25967

133. Flitcroft DI. A model of the contribution of oculomotor and optical factors to emmetropization and myopia. *Vis Res*. 1998;38(19):2869-2879. doi:10.1016/s0042-6989(98)00087-x

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. doi:10.1111/j.1475-1313.2007.00536.x

135. Charman WN. Keeping the world in focus: how might this be achieved? *Optom Vis Sci*. 2011;88(3):373-376. doi:10.1097/OPX.0b013e31820b052b

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. doi:10.1111/j.1475-1313.2005.00297.x

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. doi:10.1111/cxo.12960

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. doi:10.1016/j.visres.2011.02.016

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. doi:10.1167/iovs.10-6631

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. doi:10.1001/jamaophthalmol.2013.7623

142. Langaas T, Riddell PM. Accommodative instability: relationship to progression of early onset myopia. *Clin Exp Optom*. 2012;95(2):153-159. doi:10.1111/j.1444-0938.2011.00699.x

143. Langaas T, Riddell PM, Svarverud E, Ystenaes AE, Langeggen I, Bruenech JR. Variability of the accommodation response in early onset myopia. *Optom Vis Sci*. 2008;85(1):37-48. doi:10.1097/OPX.0b013e31815ed6e9

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. doi:10.1016/j.exer.2017.10.004

145. Ciuffreda KJ, Wallis DM. Myopes show increased susceptibility to nearwork aftereffects. *Investig 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. doi:10.1076/ceyr.24.4.289.8418

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. doi:10.1111/j.1475-1313.2008.00550.x

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. doi:10.1167/iovs.02-0373

149. Ciuffreda KJ, Vasudevan B. Effect of nearwork-induced transient myopia on distance retinal defocus patterns. *Optometry*. 2010;81(3):153-156. doi:10.1016/j.optm.2009.03.022

150. Lin Z, Vasudevan B, Liang YB, et al. Nearwork-induced transient myopia (NITM) in anisometropia. *Ophthalmic Physiol Opt*. 2013;33(3):311-317. doi:10.1111/opo.12049

151. Charman WN, Radhakrishnan H. Peripheral refraction and the development of refractive error: a review. *Ophthalmic Physiol Opt*. 2010;30(4):321-338. doi:10.1111/j.1475-1313.2010.00746.x

152. Wildsoet CF, Chia A, Cho P, et al. IMI – Interventions myopia institute: Interventions for controlling myopia onset and progression report. *Investig Ophthalmol Vis Sci*. 2019;60(3):M106-M131. doi:10.1167/iovs.18-25958

153. Bailey MD, Sinnott LT, Mutti DO. Ciliary body thickness and refractive error in children. *Invest Ophthalmol Vis Sci*. 2008;49(10):4353-4360. doi:10.1167/iovs.08-2008

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. doi:10.1016/j.ajo.2005.01.047

155. Sheppard AL, Davies LN. In vivo analysis of ciliary muscle morphologic changes with accommodation and axial ametropia. *Investig Ophthalmol Vis Sci*. 2010;51(12):6882-6889. doi:10.1167/iovs.10-5787

156. Radhakrishnan H, Charman WN. Refractive changes associated with oblique viewing and reading in myopes and emmetropes. *J Vis*. 2007;7(8):1-15. doi:10.1167/7.8.5

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. doi:10.1167/9.3.14

158. Davies LN, Mallen EA. Influence of accommodation and refractive status on the peripheral refractive profile. *Br J Ophthalmol*. 2009;93(9):1186-1190. doi:10.1136/bjo.2009.159053

159. Walker TW, Mutti DO. The effect of accommodation on ocular shape. *Optom Vis Sci*. 2002;79(7):424-430. doi:10.1097/00006324-200207000-00010

160. Calver R, Radhakrishnan H, Osuobeni E, O'Leary D. Peripheral refraction for distance and near vision in emmetropes and myopes. *Ophthalmic Physiol Opt*. 2007;27(6):584-593. doi:10.1111/j.1475-1313.2007.00518.x

161. Mathur A, Atchison DA, Charman WN. Effect of accommodation on peripheral ocular aberrations. *J Vis*. 2009;9(12):20 1-11. doi:10.1167/9.12.20

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. doi:10.1016/j.visres.2006.02.006

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. doi:10.1016/j.gaitpost.2016.08.003

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. doi:10.15171/ijhpm.2019.11

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. doi:10.1167/iovs.15-17478

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. doi:10.1167/iovs.11-9034

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. doi:10.1016/j.visres.2004.03.007

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. doi:10.1097/00006324-200401000-00005

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. doi:10.1364/josaa.4.001681

172. Hartwig A, Charman WN, Radhakrishnan H. Accommodative response to peripheral stimuli in myopes and emmetropes. *Ophthalmic Physiol Opt*. 2011;31(1):91-99. doi:10.1111/j.1475-1313.2010.00796.x

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. doi:10.1167/17.5.3

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. In: ; 2014:Abstract 175.

176. Schmid KL, Robert Iskander D, Li RWH, Edwards MH, Lew JKF. Blur detection thresholds in childhood myopia: single and dual target presentation. *Vision Res*. 2002;42(2):239-247. doi:10.1016/S0042-6989(01)00277-2

177. Labhishetty V, Chakraborty A, Bobier WR. Is blur sensitivity altered in children with progressive myopia? *Vision Res*. 2019;154:142-153. doi:10.1016/j.visres.2018.11.002

178. Rosenfield M, Hong SE, George S. Blur adaptation in myopes. *Optom Vis Sci*. 2004;81(9):657-662. doi:10.1097/01.opx.0000144743.34976.da

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. doi:10.1016/j.visres.2016.01.001

180. Cufflin MP, Mankowska A, Mallen EAH. Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Investig Ophthalmlogy Vis Sci*. 2007;48(6):2932-2939. doi:10.1167/iovs.06-0836

181. Wang B, Ciuffreda KJ, Vasudevan B. Effect of blur adaptation on blur sensitivity in myopes. *Vision Res*. 2006;46(21):3634-3641. doi:10.1016/j.visres.2006.03.015

182. Venkataraman AP, Winter S, Unsbo P, Lundstrom L. Blur adaptation: contrast sensitivity changes and stimulus extent. *Vision Res*. 2015;110:100-106. doi:10.1016/j.visres.2015.03.009

183. Schaeffel F. Myopia: What is Old and What is New ? *Optom Vis Sci*. 2016;93(9):0-8.

184. Wallman J, Gottlieb MD, Rajaram V, Fugate-Wentzek LA. Local retinal regions control local eye growth and myopia. *Science (80-)*. 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. *Investig Ophthalmol Vis Sci*. 2007;48(9):3914-3922. doi:10.1167/iovs.06-1264

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). *Investig Ophthalmol Vis Sci*. 2011;52(9):6428-6434. doi:10.1167/iovs.10-6757

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. doi:10.1097/OPX.0000000000000038

188. Smith EL 3rd, Hung LFLF. The role of optical defocus in regulating refractive development in infant monkeys. *Vision Res*. 1999;39(8):1415-1435. doi:10.1016/S0042-6989(98)00229-6

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. doi:10.3109/02713683.2014.961614

190. Flitcroft DI. The complex interactions of retinal, optical and environmental factors in myopia aetiology. *Prog Retin Eye Res*. Published online 2012.

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. doi:10.1371/journal.pone.0123480

192. Lundström L, Mira-Agudelo A, Artal P, Lundstrom 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. doi:10.1167/9.6.17

193. Mathur A, Atchison D a, Charman WN. Effect of accommodation on peripheral ocular aberrations. *J Vis*. 2009;9(2009):1-11. doi:10.1167/9.12.20.Introduction

194. Hartwig A, Charman WN, Radhakrishnan H. Accommodative response to peripheral stimuli in myopes and emmetropes. *Ophthalmic Physiol Opt*. 2011;31(1):91-99. doi:10.1111/j.1475-1313.2010.00796.x

195. Vera-Diaz FA, McGraw P V., Strang NC, Whitaker D. A psychophysical investigation of ocular expansion in human eyes. *Investig Ophthalmol Vis Sci*. 2005;46(2):758-763. doi:10.1167/iovs.04-0127

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. doi:10.1016/j.optom.2012.07.001

197. Chui TYP, Yap MKH, Chan HHL, Thibos LN. Retinal stretching limits peripheral visual acuity in myopia. *Vision Res*. 2005;45(5):593-605. doi:10.1016/j.visres.2004.09.016

198. Atchison DA, Schmid KL, Pritchard N. Neural and optical limits to visual performance in myopia. *Vision Res*. 2006;46(21):3707-3722. doi:10.1016/j.visres.2006.05.005

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. doi:10.1016/j.visres.2016.09.017

200. Rosén R, Lundström L, Unsbo P. Sign-dependent sensitivity to peripheral defocus for myopes due to aberrations. *Investig Ophthalmol Vis Sci*. 2012;53(11):7176-7182. doi:10.1167/iovs.11-9034

201. Abraham-Cohen JA. Blur sensitivity in myopes. *Optom Vis Sci*. 1999;76(5):303-307. doi:10.1097/00006324-199905000-00018

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. doi:10.1080/02713680500514669

203. Rosenfield M, Hong SE, George S. Blur adaptation in myopes. *Optom Vis Sci*. 2004;81(9):657-662. doi:10.1097/01.opx.0000144743.34976.da

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. doi:10.1113/jphysiol.1969.sp008862

205. Georgeson MA, Georgeson JM. Facilitation and masking of briefly presented gratings: time-course and contrast dependence. *Vis Res*. 1987;27(3):369-379. doi:10.1016/0042-6989(87)90086-1

206. Magnussen S, Greenlee MW. Marathon adaptation to spatial contrast: saturation in sight. *Vis Res*. 1985;25(10):1409-1411. doi:10.1016/0042-6989(85)90218-4

207. Schaeffel F. Myopia: the importance of seeing fine detail. *Curr Biol*. 2006;16(7):R257-9. doi:10.1016/j.cub.2006.03.006

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. doi:10.1016/j.visres.2016.01.001

209. Yeo ACH, Atchison DA, Schmid KL. Effect of text type on near work-induced contrast adaptation in myopic and emmetropic young adults. *Investig Ophthalmol Vis Sci*. 2013;54(2):1478-1483. doi:10.1167/iovs.12-11496

210. Ohlendorf A, Schaeffel F. Contrast adaptation induced by defocus - a possible error signal for emmetropization? *Vis Res*. 2009;49(2):249-256. doi:10.1016/j.visres.2008.10.016

211. Collins MJ, Buehren T, Iskander DR. Retinal image quality, reading and myopia. *Vis Res*. 2006;46(1-2):196-215. doi:10.1016/j.visres.2005.03.012

212. Majaj NJ, Pelli DG, Kurshan P, Palomares M. The role of spatial frequency channels in letter identification. *Vis Res*. 2002;42(9):1165-1184. doi:10.1016/s0042-6989(02)00045-7

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. *Vis Res*. 1981;21(8):1287-1296. doi:10.1016/0042-6989(81)90233-9

214. Charman WN, Tucker J. Dependence of accommodation response on the spatial frequency spectrum of the observed object. *Vis Res*. 1977;17(1):129-139. doi:10.1016/0042-6989(77)90211-5

215. Owens DA. A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. *Vis Res*. 1980;20(2):159-167. doi:10.1016/0042-6989(80)90158-3

216. Taylor J, Charman WN, O'Donnell C, Radhakrishnan H. Effect of target spatial frequency on accommodative response in myopes and emmetropes. *J Vis*. 2009;9(1):16 1-14. doi:10.1167/9.1.16

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. doi:10.1111/cxo.12296

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. doi:10.1097/OPX.0b013e31827ce23a

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.

doi:10.1364/josaa.19.000833

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. doi:10.1097/OPX.0000000000000040

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. doi:10.1167/iovs.02-1042

222. Mathur A, Atchison DA, Charman WN. Myopia and peripheral ocular aberrations. *J Vis*. 2009;9(10):15. doi:10.1167/9.10.15

223. Radhakrishnan H, Charman WN. Age-related changes in ocular aberrations with accommodation. *J Vis*. 2007;7(7):11 1-21. doi:10.1167/7.7.11

224. Seidemann A, Schaeffel F. Effects of longitudinal chromatic aberration on accommodation and emmetropization. *Vis Res*. 2002;42(21):2409-2417. doi:10.1016/s0042-6989(02)00262-6

225. Autrusseau F, Thibos L, Shevell SK. Chromatic and wavefront aberrations: L-, M- and S-cone stimulation with typical and extreme retinal image quality. *Vis Res*. 2011;51(21-22):2282-2294. doi:10.1016/j.visres.2011.08.020

226. Rucker F. Monochromatic and white light and the regulation of eye growth. *Exp Eye Res*. 2019;184:172-182. doi:10.1016/j.exer.2019.04.020

227. Rucker FJ. The role of luminance and chromatic cues in emmetropisation. *Ophthalmic Physiol Opt*. 2013;33(3):196-214. doi:10.1111/opo.12050

228. Rucker FJ, Kruger PB. Cone contributions to signals for accommodation and the relationship to refractive error. *Vis Res*. 2006;46(19):3079-3089. doi:10.1016/j.visres.2006.04.009

229. Rosenfield M, Wong NN, Solan HA. Nearwork distances in children. *Ophthalmic Physiol Opt*. 2001;21(1):75-76. doi:10.1046/j.1475-1313.2001.00566.x

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. doi:10.1046/j.1475-1313.2003.00166.x

231. Wang Y, Bao J, Ou L, Thorn F, Lu F. Reading behavior of emmetropic schoolchildren in China. *Vis Res*. 2013;86:43-51. doi:10.1016/j.visres.2013.03.007

232. Charman WN. Aniso-accommodation as a possible factor in myopia development. *Ophthalmic Physiol Opt*. 2004;24(5):471-479. doi:10.1111/j.1475-1313.2004.00205.x

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. doi:10.1097/OPX.0000000000000658

234. Flitcroft DI, Judge SJ, Morley JW. Binocular interactions in accommodation control: effects of anisometropic 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. doi:10.1097/OPX.0000000000000015

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. *Vis Res*. 2011;51(14):1712-1717. doi:10.1016/j.visres.2011.05.014

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. doi:10.1111/j.1444-0938.2011.00623.x

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. doi:10.1097/APO.0000000000000233

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). doi:10.1371/journal.pone.0075260

241. 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). doi:10.1186/s12886-015-0052-9

242. 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. doi:10.7150/ijms.12133

243. 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 Opthalmology*. 2015;314(11):1142-1148. doi:10.1001/jama.2015.10803

244. Shah RL, Huang Y, Guggenheim JA, Williams C. Time outdoors at specific ages during early childhood and the risk of incident myopia. *Investig Ophthalmol Vis Sci*. 2017;58(2):1158-1166. doi:10.1167/iovs.16-20894

245. 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. doi:10.1371/journal.pone.0175921

246. 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. doi:10.1371/journal.pone.0189774

247. 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. doi:10.1016/j.jfo.2018.05.008

248. 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. doi:10.1167/tvst.8.3.2

249. 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. doi:10.1136/bjophthalmol-2019-314101

250. Pärssinen O, Lyyra A. Myopia and Myopic Progression Among School Children: A Three-Year Follow-Up Study. *Investig Ophthalmol Vis Sci*. 1993;34(9):2794-2802.

251. Jones LA, Sinnott LT, Mutti DO, Mitchell GL, Moeschberger ML, Zadnik K. Parental history of

myopia, sports and outdoor activities, and future myopia. *Investig Ophthalmlogy Vis Sci*. 2007;48(8):3524-3532. doi:10.1167/iovs.06-1118

252. Rose KA, Morgan IG, Ip J, et al. Outdoor activity reduces the prevalence of myopia in children. *Ophthalmology*. 2008;115(8):1279-1285. doi:10.1016/j.ophtha.2007.12.019

253. Dirani M, Tong L, Gazzard G, et al. Outdoor activity and myopia in Singapore teenage children. *Br J Ophthalmol*. 2009;93(8):997-1000. doi:10.1136/bjo.2008.150979

254. 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.

255. 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 Ophthalmlogy Vis Sci*. 2012;53(6):2856-2865. doi:10.1167/iovs.11-9091

256. 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. doi:10.1016/j.ophtha.2012.11.009

257. 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. doi:10.1097/OPX.0000000000000219

258. Flitcroft DI. The complex interactions of retinal, optical and environmental factors in myopia aetiology. *Prog Retin Eye Res*. Published online 2012. doi:10.1016/j.preteyeres.2012.06.004

259. Hoffman DM, Banks MS. Focus information is used to interpret binocular images. *J Vis*. 2010;10(5):13-13. doi:10.1167/10.5.13

260. Mather G. The use of image blur as a depth cue. *Perception*. 1997;26(9):1147-1158. doi:10.1068/p261147

261. Mather G, Smith DRR. Blur discrimination and its relation to blur-mediated depth perception. *Perception*. 2002;31(10):1211-1219. doi:10.1068/p3254

262. 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.

263. Vera-Diaz FA, Bex PJ, Ferreira A, Kosovicheva A. Binocular temporal visual processing in myopia. *J Vis*. 2018;18(11):1-12. doi:10.1167/18.11.17

264. Chirre E, Prieto PM, Schwarz C, Artal P. Night myopia is reduced in binocular vision. *J Vis*. 2016;16(8):1-10. doi:10.1167/16.8.16

265. 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*. Published online July 2020:1-6. doi:10.1080/2576117X.2020.1780878

266. 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.

267. 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. doi:10.1167/iovs.16-19093

268. 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. doi:10.1097/OPX.0b013e3181890d35

269. 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. doi:10.1016/j.visres.2012.01.011

270. 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. doi:10.1097/ICL.0000000000000614

271. 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. doi:10.1097/OPX.0b013e31822be35a

272. 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. doi:10.1111/j.1475-1313.2007.00529.x

273. 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. doi:10.1016/j.clae.2015.09.004

274. 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. doi:10.1097/icl.0000000000000299

275. 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. doi:10.1097/opx.0000000000000067

276. 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. doi:10.1111/j.1475-1313.2008.00610.x

277. 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. doi:10.1016/j.clae.2017.01.003

278. Aller TA, Liu M, Wildsoet CF. Myopia Control with Bifocal Contact Lenses: A Randomized Clinical Trial. *Optom Vis Sci*. 2016;93(4):344-352. doi:10.1097/opx.0000000000000808

279. Gong CR, Troilo D, Richdale K. Accommodation and Phoria in Children Wearing Multifocal Contact Lenses. *Optom Vis Sci*. 2017;94(3):353-360. doi:10.1097/opx.0000000000001044

280. Anstice NS, Phillips JR. Effect of dual-focus soft contact lens wear on axial myopia progression in children. *Ophthalmology*. 2011;118(6):1152-1161. doi:10.1016/j.ophtha.2010.10.035

281. 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. doi:10.1097/OPX.0000000000001410

282. 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. doi:10.1007/s00417-018-4115-5

283. 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. doi:10.1097/icl.0000000000000570

284. Walline JJ, Lindsley KB, Vedula SS, et al. Interventions to slow progression of myopia in children. *Cochrane Database Syst Rev*. 2020;(1). doi:10.1002/14651858.CD004916.pub4

285. 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. doi:10.1167/iovs.02-0816

286. Chen Y, Drobe B, Zhang C, et al. Accommodation is unrelated to myopia progression in Chinese myopic children. *Sci Rep*. 2020;10(1):12056. doi:10.1038/s41598-020-68859-6

287. Labhishetty V, Bobier WR. Are high lags of accommodation in myopic children due to motor deficits? *Vis Res*. 2017;130:9-21. doi:10.1016/j.visres.2016.11.001

288. 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. doi:10.1046/j.1475-1313.2002.00015.x

289. 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. doi:10.1097/icl.0000000000000390

290. 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. doi:10.1097/opx.0000000000001316

291. Bullimore MA, Gilmartin B, Royston JM. Steady-state accommodation and ocular biometry in late-onset myopia. *Doc Ophthalmol*. 1992;80(2):143-155. doi:10.1007/bf00161240

292. Jiang BC, Morse SE. Oculomotor functions and late-onset myopia. *Ophthalmic Physiol Opt*. 1999;19(2):165-172. doi:10.1046/j.1475-1313.1999.00431.x

293. Rosenfield M, Desai R, Portello JK. Do progressing myopes show reduced accommodative responses? *Optom Vis Sci*. 2002;79(4):268-273. doi:10.1097/00006324-200204000-00014

294. Seidel D, Gray LS, Heron G. Retinotopic accommodation responses in myopia. *Invest Ophthalmol Vis Sci*. 2003;44(3):1035-1041. doi:10.1167/iovs.02-0264

295. 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. doi:10.1097/00006324-200302000-00011

296. 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. doi:10.1097/01.opx.0000171337.02376.60

297. 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. doi:10.1111/j.1475-1313.2005.00347.x

298. 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. doi:10.1097/opx.0000000000000068

299. 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.

300. Goss DA. Clinical accommodation and heterophoria findings preceding juvenile onset of myopia. *Optom Vis Sci*. 1991;68(2):110-116. doi:10.1097/00006324-199102000-00005

301. Jiang BC. Parameters of accommodative and vergence systems and the development of late-onset myopia. *Invest Ophthalmol Vis Sci*. 1995;36(8):1737-1742.

302. Gwiazda J, Grice K, Thorn F. Response AC/A ratios are elevated in myopic children. *Ophthalmic Physiol Opt*. 1999;19(2):173-179. doi:10.1046/j.1475-1313.1999.00437.x

303. 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. doi:10.1111/j.1444-0938.2003.tb03128.x

304. Zadnik K, Sinnott LT, Cotter SA, et al. Prediction of Juvenile-Onset Myopia. *JAMA Ophthalmol*. 2015;133(6):683-689. doi:10.1001/jamaophthalmol.2015.0471