Modulation Transfer Functions in Children: Pupil Size Dependence and Meridional Anisotropy

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Purpose. This study quantified preschool children's optical quality in terms of their aberrations and modulation transfer function (MTF), and examined the dependence of MTF on pupil size and grating orientation.

Methods. Aberrometry was used to measure Zernike coefficients in 34 Chinese preschool children (18 males, 16 females; aged 4.95–6.89 years; mean, 5.91 ± 0.56). For each subject, after mathematical correction for refractive error, these wavefront errors were used to calculate MTF ($\lambda = 550$ nm) for pupil sizes from 1 to 5 mm and for gratings at orientations in 15° intervals.

Results. Aberrations were correlated between right and left eyes, for wavefront RMS and some Zernike coefficients. Average aberrometry results showed that third-order terms predominated, in addition to some positive spherical aberration with an average higher order root mean square (RMS) of 0.20 μm over a 5-mm pupil. Average MTFs were optimal for 3-mm pupil sizes at lower spatial frequencies (<69 cyc/deg) and slightly better than those found by similar techniques in young adults. Heights of MTFs were significantly related to higher order RMS (Spearman $\rho = -0.926$). MTFs showed a small meridional anisotropy for 3-mm pupils, with average MTF for vertical gratings (horizontal modulation) being slightly, but significantly better than for horizontal gratings (vertical modulation). There was no evidence of an oblique effect in the optics of these children.

Conclusions. In these children, ocular optical quality is pupil dependent, shows slight meridional anisotropy and is slightly better than that for young adults. (*Invest Ophthalmol Vis Sci.* 2003;44:3248–3256) DOI:10.1167/iovs.02-1064

It is known that children, even as late as preadolescence, have poorer spatial vision than adults, showing higher resolution and vernier thresholds and impaired contrast sensitivity.[1–6] It is also known that some visual functions such as resolution appear to develop earlier than other visual functions such as Vernier acuity.[3,5,6]

Previously, investigators have modeled this age-dependent improvement in spatial vision based on a variety of assumptions. Wilson[7] developed a model based on developmental changes in spatial tuning and sensitivity of spatial filters in the visual system. Banks and Bennett[8] produced a different model in which the developmental changes in spatial vision were interpreted primarily in terms of decreased photon capture in the immature photoreceptor matrix of children. Because there is no report in the literature on optical transfer functions of young children, neither model directly incorporated changes in optical quality, although in the former's case[7] the hypothesized age changes in spatial filters might be understood in terms of a change in both neural and optical factors. In the case of Banks and Bennett[8] the quality of the retinal image was assumed to be impaired only by photon noise. Otherwise, optical quality for adults and children was assumed to be identical, despite the fact that such differences would affect both vernier and resolution acuity.[9] Thus, measurements of optical quality in children may provide useful information for researchers in visual development.

The optical quality of children's eyes may be an important factor in limiting spatial aliasing by the human foveal cone matrix. In children's eyes, axial lengths tend to be shorter than in adult eyes[10] and foveal cones tend to be separated by larger distances.[11] These factors should lead to sparser sampling of space by children's foveal cones. For example, based on data from these studies, one would expect a foveal cone Nyquist frequency of 43 cyc/deg at the age of 45 months[12] compared with an adult foveal cone Nyquist frequency of 56 cyc/deg in adults.[13] If supra-Nyquist spatial frequencies are imaged on the retina, the subjects perceive spatial patterns that are coarser and distorted in appearance, orientation, and motion, compared with the stimulus—that is, they perceive aliases. An optical system with no aberrations (i.e., limited only by diffraction) passes frequencies higher than 43 cyc/deg if the pupil diameter is larger than 1.36 mm ($\lambda = 550$ nm). However, the presence of aberrations further degrades image quality and may curtail the possibility of aliasing with normal optics. This is the case in most adult observers (who usually need special interferometric systems for foveal perception of aliases), but if children have similar, or better optical quality than adults, then more supra-Nyquist information may be available to them.

It is also possible that optical quality may not be meridionally isotropic. In a previous study[14] of children with an average age of 9 years, Chinese subjects (but not Malay subjects), showed a small average amount of vertical coma that might be expected to cause blur in the vertical meridian (i.e., degrade the modulation transfer function [MTF] for horizontal gratings). Meridional anisotropies have also been noted in visual function, with one study of children showing that average resolution of oblique meridians was poorer by 35% than for horizontal and vertical gratings.[15] This oblique effect may also be race-dependent (e.g., present in white adults, but absent in Chinese adults).[16]

There is an increasing body of literature on the optical quality of children's eyes; however, most of this is currently in the form of aberration measurement on children aged 9 years or more,[14,17] and there is no information on optical quality of younger children. Moreover, there is currently no information on the MTF of young children, an index that describes the reduction in contrast of sine wave stimuli by the optical media. We redressed this lack of information by measuring aberrations in a group of normal preschool children and, from these measurements, calculating MTFs for different pupil sizes, allowing

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TABLE 1. Table of Correlations and Principle Axis Coefficients

	r	P	Sign for r in Mirror Symmetry	Slope	Y Intercept (μm)	Lower 95% Confidence Limit for Slope	Upper 95% Confidence Limit for Slope
C_2^{-2}	−0.452	0.008	−	−1.155	−0.029	−2.756	−0.535
C_2^0	0.965	<0.001	+	0.987	−0.008	0.893	1.091
C_2^2	0.828	<0.001	+	1.039	−0.004	0.809	1.337
C_3^{-3}	0.699	<0.001	+	0.951	0.014	0.644	1.393
C_3^{-1}	0.496	0.003	+	1.043	0.021	0.522	2.132
C_3^1	−0.136	0.454	−	—	—	—	—
C_3^3	−0.470	0.005	−	−0.648	0.009	−1.247	−0.261
C_4^{-4}	0.203	0.259	−	—	—	—	—
C_4^{-2}	0.050	0.784	−	—	—	—	—
C_4^0	0.810	<0.001	+	0.976	−0.003	0.745	1.277
C_4^2	0.213	0.235	+	—	—	—	—
C_4^4	−0.081	0.658	+	—	—	—	—
C_5^{-5}	0.190	0.293	+	—	—	—	—
C_5^{-3}	0.130	0.472	+	—	—	—	—
C_5^{-1}	0.187	0.301	+	—	—	—	—
C_5^1	−0.131	0.469	−	—	—	—	—
C_5^3	−0.190	0.293	−	—	—	—	—
C_5^5	−0.105	0.564	−	—	—	—	—
Log_{10} higher order RMS	0.472	0.005	+	1.258	0.17	0.626	2.904

Data are right-eye Zernike coefficients (y axis) plotted against left-eye (x axis) in 33 subjects for whom there were data for both eyes.

for the determination of which pupil size is optimal in children. In addition, by calculating the MTF for gratings of different orientations we could determine whether there was any average meridional optical anisotropy in this age group.

METHODS

Subjects were 34 (18 boys, 16 girls) Chinese children taking part in a vision screening at a Singaporean preschool. Average subject age was 5.91 ± 0.56 years (range, 4.95–to 6.89 years). This research adhered to the provisions of the Declaration of Helsinki. Written informed consent was provided by parents and procedures were approved by the Tan Tock Seng Hospital Ethics Committee. All procedures were performed with the subjects' assent. Before aberrometry measurement, subjects underwent induction of cycloplegia with 3 drops of 1% tropicamide—each drop instilled at 5-minute intervals, because tropicamide has been found to be a suitable cycloplegic agent in this age group.[18] Aberrometry measurements were attempted on the right and left eyes of subjects, approximately 30 minutes after the installation of the last drop (Zywave aberrometer; Bausch & Lomb, Rochester, NY). This is a Hartmann-Shack–based instrument[19] that samples the pupil at 0.6-mm intervals. Measurements in this age group were typically quick, at approximately 1 minute per eye, with image acquisition taking approximately 0.1 second. Aberration measurements could not be obtained from the left eye of one subject (a girl aged 5.6 years), because she had poor tear quality, and results for this (left) eye were excluded from analysis, but aberration measurements were obtained from the right eyes of all subjects.

For each subject, custom software (Zywave ver. 3.21; Bausch & Lomb) was used to fit the first 21 Zernike polynomials (i.e., up to and including the fifth order) of the wavefront aberration for a 5-mm diameter pupil centered on the subject's dilated pupil. Further Zernike coefficients were calculated for 1-, 2-, 3-, and 4-mm pupil diameters. These calculations were made directly from the Zernike coefficients for 5-mm pupils, using equations that can be transformed into those described in Table 1 of Schwiegerling.[20] This method of recalculating aberrations is based on an assumption that aberrations do not change sharply in different sections of the pupil (i.e., on the assumption that aberrations higher than the maximum order measured are not present to any significant extent). Optical transfer functions (OTFs) were calculated from the wavefront aberration for each subject for each pupil size using the sheared pupil method,[21] ignoring prism components and after mathematically removing sphere and cylinder by setting the C_2^{-2}, C_2^2, and C_2^0 Zernike coefficients to zero. In some respects this choice of defocus level is arbitrary, because the "best" image defocus varies with the image metric being optimized—for example, it depends on spatial frequency or on what aspect of a point-spread function is being optimized. There is no established criterion, however, for determining optimal defocus level, and our approach (setting C_2^{-2}, C_2^2, and C_2^0 to zero) is numerically convenient, is the defocus plane that minimizes wavefront RMS, and produces a defocus level that is close to optimal. Wavelength for OTF calculations was assumed to be 550 nm. OTFs were calculated at 0.1-log-unit intervals for spatial frequencies from 2.512 cyc/deg, up to the diffraction limit for the pupil size. Grating modulation orientations for OTF calculations ranged from 0° (horizontal grating modulation, i.e., a vertical grating) to 165° in 15° intervals. MTFs were calculated as the moduli of OTFs for each subject. For comparison we used the same techniques to calculate the MTFs for 31 normal young adults (15 women, 16 men) whose aberrometry results have been reported elsewhere.[22] The average age for these young adults was 19.7 ± 1.7 years. Aberrometry results were collected under cyclopentolate cycloplegia, using the same equipment as was used in young subjects.

RESULTS

Previously, researchers[23] have observed that aberrations are correlated between right and left eyes of subjects. This was also the case for our subjects, with the following higher order aberration coefficients showing significant interocular correlations: C_3^{-3} and C_3^3 (third order trefoil terms), C_3^{-1} (vertical coma term), and C_4^0 (spherical aberration). The lower order aberrations, C_2^0 (defocus), C_2^2 and C_2^{-2} (astigmatism terms), were also correlated between the eyes. Correlation coefficients are tabulated in Table 1, along with regression slopes and intercepts obtained by principal axis analysis. For those Zernike coefficients that showed significant correlation, principal axis slopes were not significantly different from 1 with the exception of C_2^{-2} and C_3^3, which have principal axis slopes not significantly different from −1. These results would be expected if right and left eyes showed mirror symmetry in their aberrations. Table 1 shows a list of those aberration coefficients expected to give negative correlations in mirror symmetry.

Individual optical quality is sometimes summarized using a higher order RMS (the root mean squared deviation of the wavefront after removing the contribution from second-order coefficients). Higher order RMS averaged across subjects was 0.202 ± 0.070 μm (SD) in the left eye and (for the same 33 subjects) 0.198 ± 0.077 μm in the right eye—a difference that was not statistically significant on matched-pairs *t*-tests (t_{32} = −0.291, P = 0.77). The logarithms of RMS were significantly correlated between right and left eyes (r = 0.472, $P < 0.005$) and principal axis analysis is contained in Table 1. In individual subjects, the absolute difference in RMS between left and right eyes averaged 0.06 μm (minimum, 0.0002 μm; maximum difference, 0.21 ± 0.05 μm; median = 0.054 μm, 75th percentile = 0.073 μm, 90th percentile = 0.107 μm; 95th percentile = 0.188 μm). By matched-pairs *t*-tests, there was no difference between the Zernike coefficients for the right and the left eyes (mirror reversed) except for a small but significant difference in C_5^1 which averaged 0.01 ± 0.009 μm in right eyes and 0.002 ± 0.014 μm in left eyes (t_{32} = 4.49, $P < 0.001$). Visual acuity with current correction averaged 0.14 ± 0.10 logarithm of the minimum angle of resolution (logMAR) in right eyes and 0.14 ± 0.09 in left eyes, interocular differences being 0.1 logMAR or less in all but one subject, in whom the interocular difference in VA was 0.2 logMAR. Given that aberrations for right and left eyes are related, subsequent analyses are reported for right eyes only.

Our results show that for higher order aberrations in the right eye, third-order terms and spherical aberration predominated, although there was considerable intersubject variation. The right eye intersubject averages for Zernike coefficients (5-mm pupils) are shown in Figure 1a along with intersubject standard deviations. The Zernike coefficient convention is that adopted by the Optical Society of America (OSA) Visual Science and its Applications (VSIA) task force.[24] The average of these higher order aberrations were significantly different from zero on multivariate analysis (Hotelling's trace = 3.948, $F_{15,19}$ = 5.001, P = 0.001). Higher order Zernike coefficients (right eye) with a population average different from zero were C_3^{-3} (t_{33} = 2.93, P = 0.006), C_3^{-1} (t_{33} = 2.9, P = 0.007), C_4^{-4} (t_{33} = 2.08, P = 0.045), C_4^0 (t_{33} = 5.37, $P < 0.001$), C_5^1 (t_{33} = 4.24, $P < 0.0002$), and C_5^5 (t_{33} = 3.14, P = 0.004). From the error bars in Figure 1a, it may be inferred that, although the population average for some Zernike coefficients lies close to zero, individual subjects may have greater magnitudes of aberration than is suggested by the population average. Figure 1b, a plot of the averages of absolute values for the Zernike coefficients highlights the fact that individual subjects differ from zero in terms of aberration magnitude. A commonly used index for summarizing an individual subject's aberration levels is RMS, the root mean squared deviation of the wavefront. For 5-mm pupils, individual subjects' higher order RMS averaged 0.20 ± 0.08 μm. Of these, the RMS for third-order aberrations was largest (average, 0.17 ± 0.07 μm), with the fourth-order aberrations having a lesser contribution (average RMS, 0.09 ± 0.05 μm), and the contribution from fifth order even less (average RMS, 0.04 ± 0.02 μm). The average RMS for coma (C_3^{-1} and C_3^1 combined) was 0.11 ± 0.08 μm and for spherical aberration was 0.06 ± 0.04 μm.

From autorefractor readings on the right eye, these subjects had spherical equivalent refractive errors that ranged from −4.38 to +1.63 D (mean, +0.08 ± 1.24 D [SD]). Based on vector analysis of the astigmatism,[25] subjects showed, on average, with-the-rule astigmatism, with J_0 ranging from −0.21 D to +1.12D (mean, +0.21 ± 0.35 D) and a variable oblique component with J_{45} ranging from −0.47D to +0.47D (mean, 0.02 ± 0.18). Average second order Zernike coefficients for the right eye were C_2^{-2}, −0.056 ± 0.182 μm; C_2^0, −0.364 ± 1.096 μm; and C_2^2, −0.204 ± 0.526 μm. The population average for the astigmatism term C_2^2 was significantly different from zero (t_{33} = −2.26, P = 0.031).

The MTFs show that, after correction of sphere and cylinder, average optical quality in these children is dependent on pupil size. This is illustrated in Figure 2, which shows MTFs averaged across right eyes of subjects and grating orientations for different pupil sizes. For 1- and 2-mm pupil diameters, MTFs were almost identical with those predicted from diffraction limits. The average MTF in 3-mm pupils was higher than those for 1- and 2-mm pupils across all spatial frequencies, was higher than 4 mm at spatial frequencies below 69 cyc/deg, and was higher than 5 mm at spatial frequencies below 80 cyc/deg. Thus, over a large range of spatial frequencies, the highest average MTF occurred in 3-mm pupils. For comparison, Figure 2 also contains MTFs calculated from the previously reported aberrometry results of 31 visually normal Chinese young adults.[22] As indicated by the error bars in Figure 2, there was considerable intersubject variability in MTF especially for larger pupil sizes, where aberrations cause performance to differ from the diffraction-limited case. This is illustrated in Figure 3, which shows MTF curves from individual children for 5-mm diameter pupils.

Higher order RMS and MTFs were both used to summarize image quality, although the exact relationship between the two metrics depends, for each subject, on relationships between Zernike coefficients. The average heights of MTFs (5-mm pupils) shown in Figure 3 were strongly related to the individual subject's higher order RMS (5-mm pupils), as illustrated in Figure 4, with average MT declining as RMS increased. Average MT was always 0.424 in the diffraction-limited case, when RMS = 0. The relationship between the two variables is reasonably well described by a single-parameter curve with the equation: averageMT = $(0.424^{-1} + a\text{RMS})^{-1}$, where a has the value of 26.70 μm^{-1} giving an r^2 of 0.852. The Spearman ρ for the relationship was −0.926, which was statistically different from zero ($P < 0.001$).

When the MTF was assessed for different orientations, it was found that on average MT was slightly poorer for modulation in the vertical meridian (i.e., horizontal gratings) than for other orientations, although there was intersubject variation and some variation with spatial frequency and pupil size. This is illustrated in Figure 5, in which contours of MT (averaged across subjects) are plotted at different orientations and spatial frequencies, for pupil sizes of 3, 4, and 5 mm. (MTFs for pupil sizes of 1 and 2 mm were not plotted in this way, because their close match for the diffraction limited function precludes orientation differences.) This figure illustrates a three-dimensional surface, on which cross sections through the x,y origin represent MTF for different orientations. Individual contour rings represent constant MT values with the origin representing an MT of 1, the centermost ring being an MT of 0.9, with MT decreasing by increments of 0.1 for each successive ring from the center. On such a diagram, poor performance at a specific orientation is denoted by the rings being smaller in that meridian (i.e., out-of-round). At different pupil sizes, the contours tend to be narrower in the vertical meridian, especially at higher MTs and lower spatial frequencies. This indicates that for vertically modulated gratings (i.e., gratings with horizontal stripes) the MTF tends to be lower than for horizontally modulated gratings.

This average orientation bias is small when compared with intersubject variation. This is illustrated in Figure 6a, which shows average MT plotted for different quadrants of orientation. The data in Figure 6a were obtained by splitting modulation orientation into four quadrants: 0° (MTF at 165°, 0°, and 15°); 45° (MTF at 30°, 45°, and 0°); 90° (MTF at 75°, 90°, and 105°); 135° (MTF at 120°, 135°, and 150°). MTF was then averaged along all spatial frequencies for sections of each

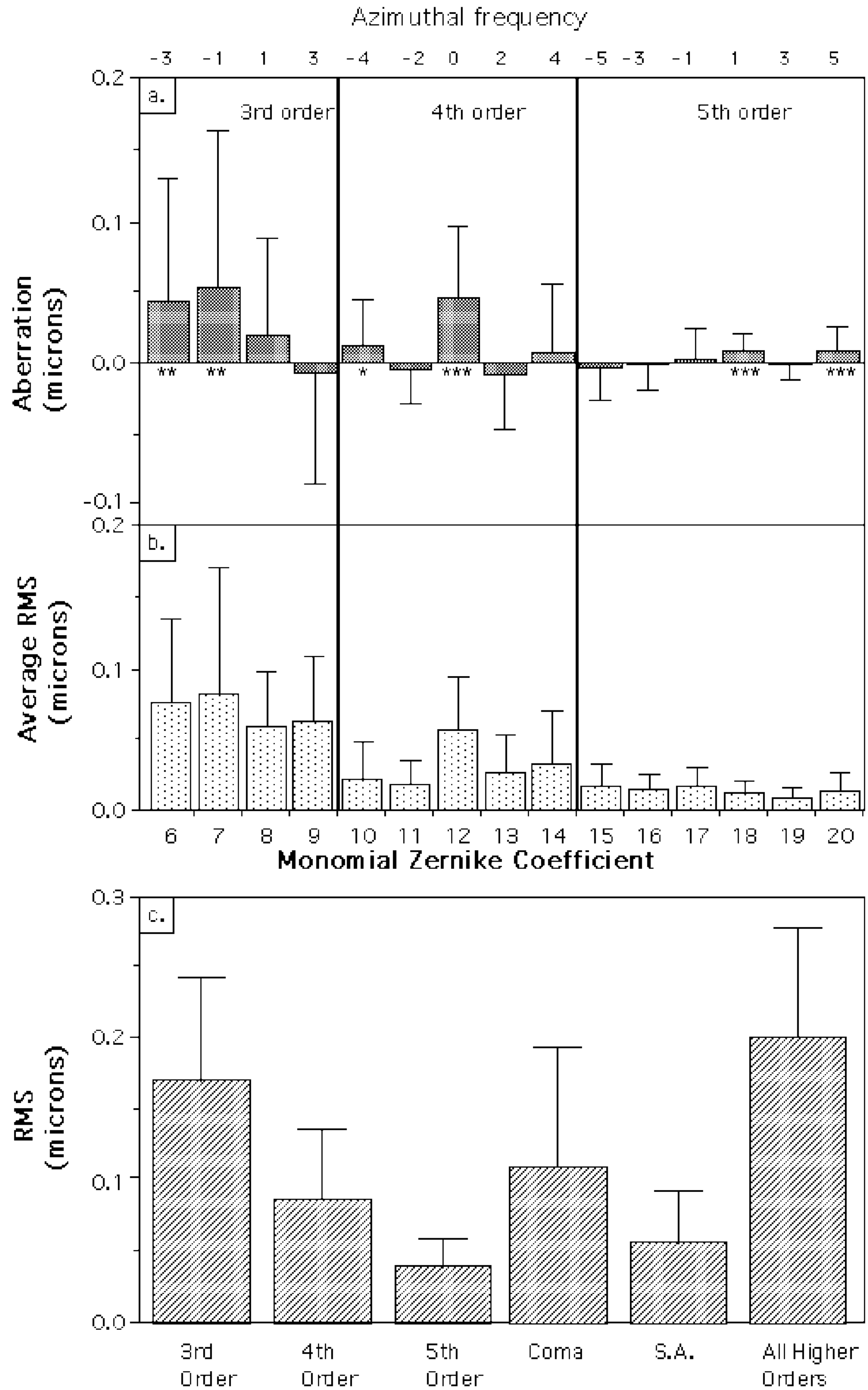

FIGURE 1. (**a**) Average higher order Zernike coefficients (5-mm pupils) for the right eyes of children in the present study. Numbering and sign convention is that of the OSA VSIA task force.[24] On the lower *x*-axis the monomial system for Zernike polynomial numbering is used. In the double-indexing system, the subscript is indicated in each frame (i.e., third order, fourth order, fifth order) and the superscript is indicated on the upper *x*-axis. Error bars are intersubject standard deviations. (**b**) Average of the absolute values of higher order Zernike coefficients for right eyes (5-mm pupils). (**c**) Average right eye RMS values for each order of Zernike coefficients, for coma, spherical aberration, and all higher order aberrations combined (5-mm pupils).

quadrant. Intersubject standard deviations are plotted in Figure 6a for comparison. When analyzed in this way the only statistically significant differences between quadrants were in 3-mm pupils ($F_{3,33} = 4.473$, $P = 0.01$), in which MT for the 90° quadrant (vertically modulated gratings), is lower than for the 0° quadrant ($t_{33} = 2.94$, $P = 0.00599$, $P_{FW} = 0.036$) and the 45° quadrant ($t_{33} = 3.211$, $P = 0.00294$, $P_{FW} = 0.0176$) on a Bonferroni matched-pairs t-test. MT did not differ significantly between quadrants at pupil sizes of 4 mm ($F_{3,33} = 2.179$, $P = 0.109$) and 5 mm ($F_{3,33} = 0.480$, $P = 0.699$).

To assess the role that coma might have in this meridional variation of image quality for each subject we calculated the magnitude of coma in the vertical meridian (i.e., the absolute value of C_3^{-1}), the magnitude of coma in the horizontal meridian (i.e., the absolute value of C_3^1), and the absolute values of coma (in terms of RMS) along the 45° and 135° meridians (by

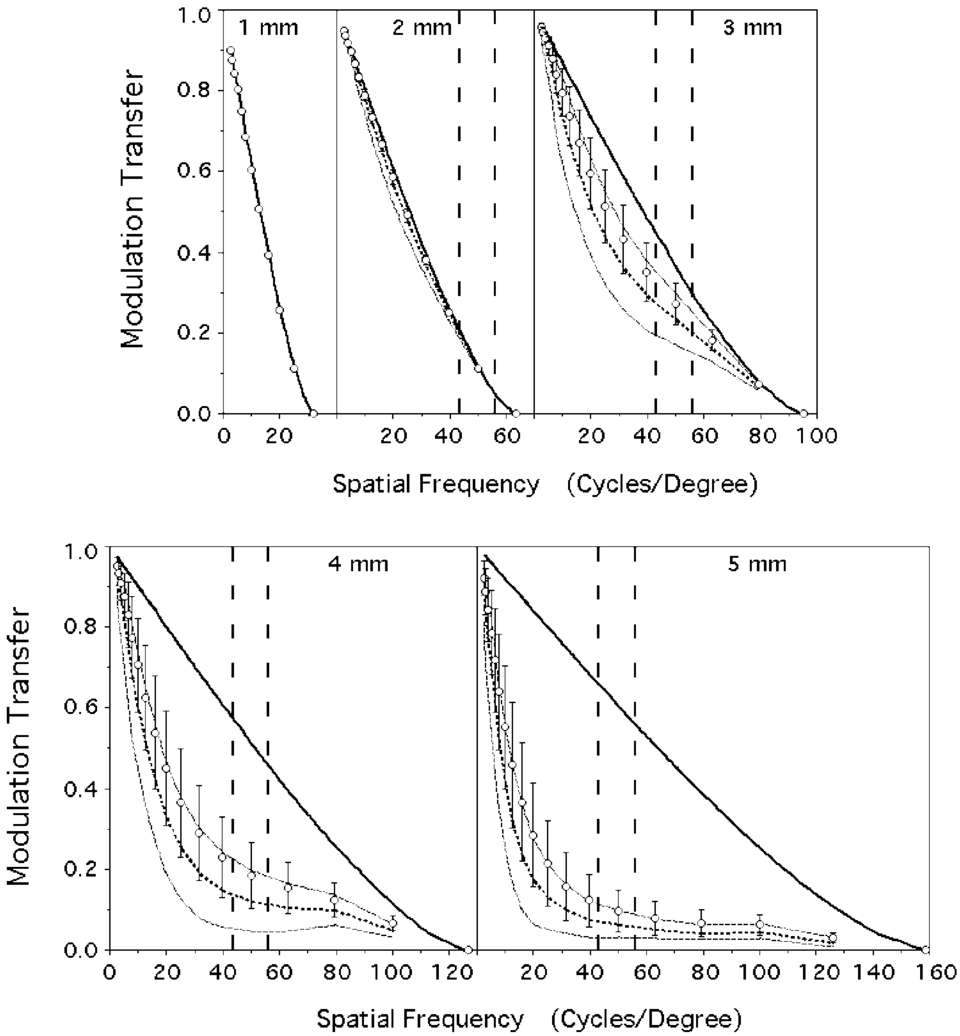

Figure 2. Intersubject average MTFs for right eyes with different pupil sizes denoted in each frame, averaged across all orientations and based on Hartmann-Shack aberrometry (λ = 550 nm). *Solid bold curves*: diffraction limits for that pupil size; (○) data from the children in this study, along with error bars denoting intersubject standard deviations; *bold dashed curves*: average MTF (right eyes) calculated using the same methods and equipment from aberrometry results of 31 young adults.[22] This curve is bounded by *fine dashed curves* denoting ±1 intersubject SD. *Vertical dashed lines:* calculated Nyquist frequencies for 45-month-old subjects (43 cyc/deg) and adults (56 cyc/deg) based on previous research.[12,13]

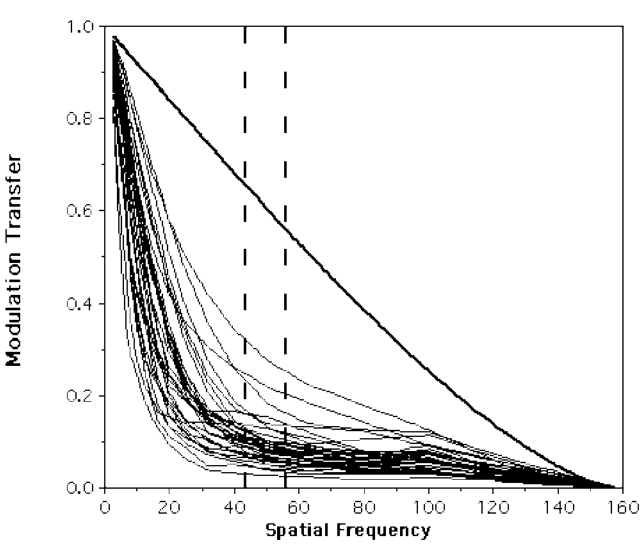

Figure 3. MTFs for right eyes of individual children for 5-mm pupil size (λ = 550 nm), along with diffraction limit (*solid bold curve*) and Nyquist frequencies at 45 months and adulthood (*vertical dashed lines*).

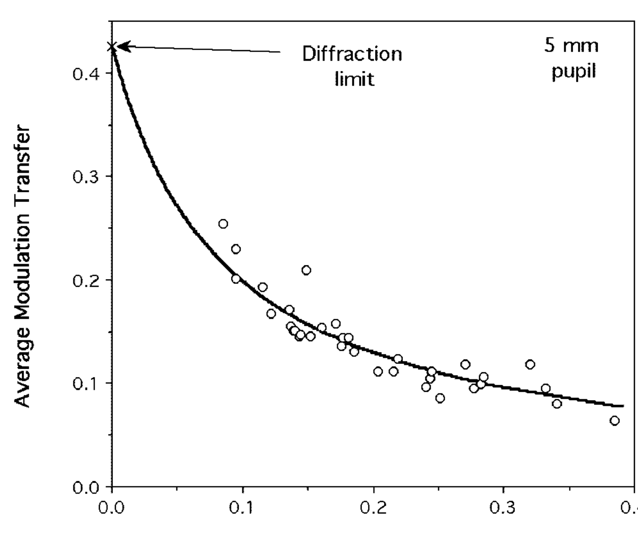

Figure 4. The relationship between RMS and the average height of MTFs shown in Figure 3 (5-mm pupils, right eyes). *Solid line*: least-squares regression fit of the equation averageMT = $(0424^{-1} + \alpha\text{RMS})^{-1}$ where α is the decay coefficient, 26.70 in this case; r^2 for the fit was 0.852.

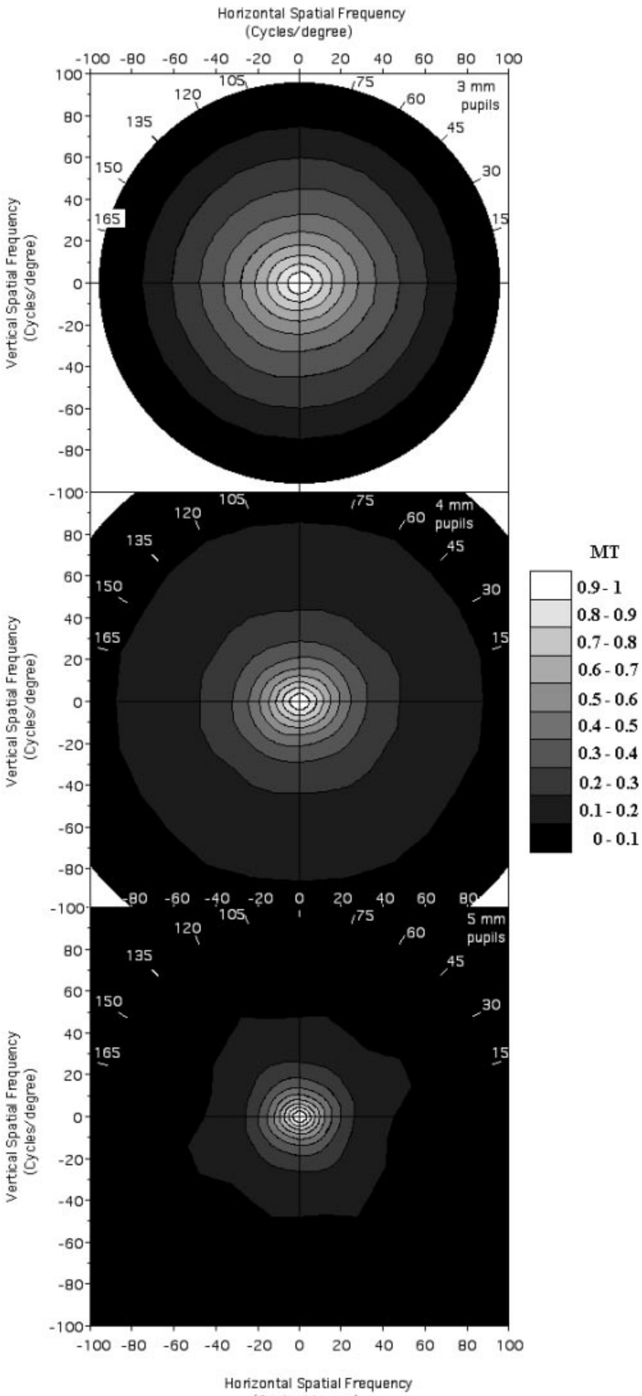

FIGURE 5. Contour plot showing the children's average MTFs for gratings of different orientation and different pupil sizes. Modulation orientation (90° to grating orientation) is shown radially on each frame. MT at the origin is 100%.

calculating the absolute values for new C_3^1 and C_3^{-1} determined with reference axes skewed through 45°). The sample averages for coma magnitude in each orientation and different pupil sizes are plotted in Figure 6b. Although average coma magnitude was greatest in the vertical meridian, there was no significant effect of orientation on coma magnitude in 3-mm pupils ($F_{3,33} = 2.469$, $P = 0.079$), in 4-mm pupils ($F_{3,33} = 1.769$, $P = 0.172$), and in 5-mm pupils ($F_{3,33} = 1.384$, $P = 0.265$). Thus, average meridional variations in MT were not well reflected in average meridional variations in coma, despite the fact that, across individual subjects, meridional anisotropy of MT correlated with meridional anisotropy of coma magnitude. For example, the difference in average MT between the 90° and 0° quadrants correlated significantly with differences in coma magnitude between the 90° and 0° meridians (in 3-mm pupils $r = -0.786$, $P < 0.001$; in 4-mm pupils $r = -0.571$ $P < 0.001$; and in 5-mm pupils $r = -0.465$ $P < 0.01$). Likewise, the difference in average MT between the 45° and 135° quadrants correlated significantly with differences in coma magnitude between the 45° and 135° meridians (in 3-mm pupils $r = -0.760$, $P < 0.001$; in 4-mm pupils $r = -0.686$ $P < 0.001$; and in 5-mm pupils $r = -0.614$ $P < 0.001$).

DISCUSSION

Our results are the first reported measurements of aberrometry in such an age group. Carkeet et al.,[14] reported similar measurements using similar methods on older Chinese children (mean age, 9.0 ± 0.82 years) and showed similar average higher order RMS of 0.19 ± 0.06 μm over a 5-mm pupil, compared with the present study's 0.20 ± 0.08 μm. The overall average wavefronts are similar between the present study and that of Carkeet et al., except that the average wavefront in the present study shows a slight amount of third-order trefoil C_3^{-3} not apparent in the averages shown by Carkeet et al.

Interocular Relationships between Higher Order Aberrations

We found that some higher order aberrations (C_3^{-3}, C_3^3, C_3^{-1}, and C_4^0) correlated significantly between the left and right eyes of our children. These coefficients contributed, on average, 85% of the RMS for the higher order wavefront in our subjects. Porter et al.[23] reported significant correlations for the same coefficients in a larger group of 109 adult subjects (pupil diameter = 5.7 mm) and also reported significant correlations in other higher order coefficients (C_3^1, C_4^2, C_5^{-5}, C_5^{-3}, and C_5^{-1}). We also report a significant correlation between the higher order RMS values for left and right eyes and that RMS values tended to be similar between the eyes of our subjects (an absolute interocular difference of <0.11 μm in 90% of our subjects). None of these subjects could be classified as clinically amblyopic, based on VA with their current corrections, although it is conceivable that large interocular differences in higher order aberrations RMS might lead to amblyogenesis. It may be that such aberration-driven amblyopia is rare. Recent research[26] has indicated that relatively large amounts of spherical aberration (0.51–0.61 μm RMS over a 4-mm pupil) are necessary to elevate visual acuity by 0.2 log units. These aberrations are somewhat larger than the interocular differences in aberrations found in our subjects, so that aberration-driven amblyopia may have been unlikely to occur in our small sample.

The present study is the first to report measurements of spatial MTFs in children. Our results showed a dependence of MTF on pupil size, with the best performance occurring at 3-mm diameter for spatial frequencies up to and slightly exceeding adult Nyquist frequencies. This dependence has been modeled by other investigators[27] as performance for small pupils that is limited by diffraction effects, with the effects of monochromatic aberrations degrading the MTF for larger pupil sizes. In adults, previous researchers have reported a similar dependence of optical quality on pupil size. Campbell and Gubisch[28] used a double-pass optical system to measure the line spread function of eyes of three subjects and inferred MTFs from these data. Optimum pupil diameter in their sub-

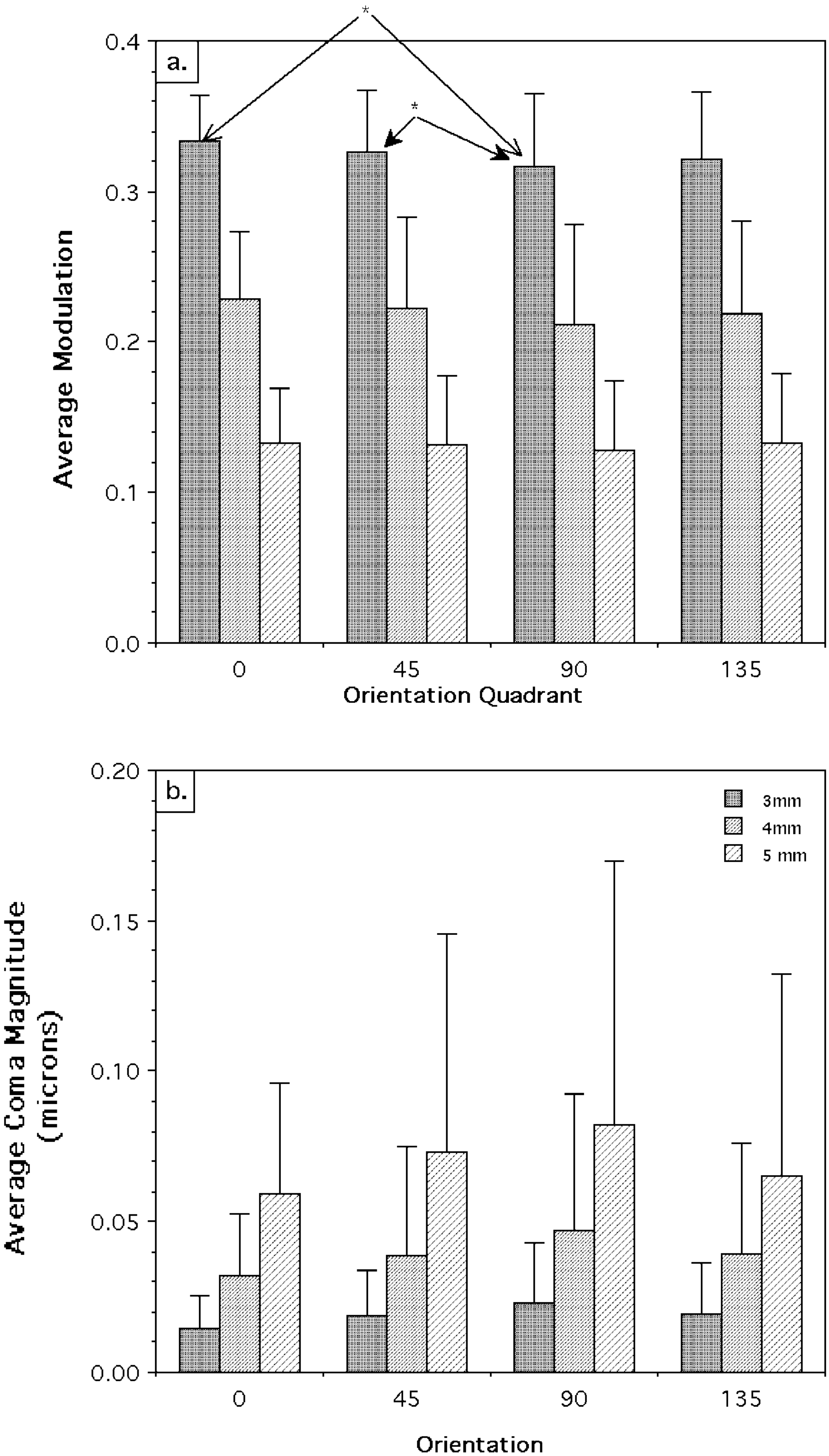

FIGURE 6. (**a**) Average MT up to the diffraction limit for different quadrants and different pupil sizes. *Quadrants that have statistically different MTs for a given pupil size. Error bars are intersubject standard deviations. (**b**) Coma magnitude for different meridians and pupil sizes. Error bars are intersubject standard deviations.

jects was between 2 and 3 mm, with optical quality being poorer for smaller and larger pupils. Campbell and Green[29] measured MTFs in two subjects by comparing contrast sensitivity measured using the eye's natural optics and using interferometry to project gratings directly onto the retina. Their estimates of MTF were best at pupil sizes of 2 to 2.8 mm, with performance declining for larger pupil sizes. They did not, however, measure MTF for smaller pupil sizes than 2 mm. Using double-pass measurements of the retinal image, Guirao et al.[30] showed that average MTFs were poorer as pupil size increased from 3 to 4 mm and then to 6 mm. Walsh and Charman[31] performed an objective version of Howland aberrometry[32,33] on 10 subjects and reported the effects of pupil size on the calculated MTF of one of their subjects. In this subject, MTF for 3 mm was slightly better than for 2- and 4-mm and larger pupils. Other investigators[34] have reported a similar dependence of visual acuity on pupil size, with visual acuity for corrected myopes being best at pupil sizes of 2 to 3 mm and poorer for larger or smaller pupil sizes.

It should be noted that our mean MTFs derived from aberrometry are higher than those previously obtained by the psychophysical method of comparing the contrast sensitivity function (CSF) measured with normal optics and the CSF measured with interferometry bypassing the optics,[29,35] and that they are also higher than those derived from double-pass measurements of point- and line-spread functions.[28,30,35] Our results for 3-mm pupils are close to aberration-based MTF calculations[27] (λ = 590 nm) in 10 subjects.[31] This difference between the results obtained by the three methods has been discussed by other researchers.[27,35]

As might be expected, given that both are indices of image quality, RMS is strongly related to the average height of the MTF, although the relationship is not a perfect monotonic function. The shape and height of the MTF vary, depending on the types of aberrations that are present and on interactions between these aberrations, so that the simple index of RMS is not a perfect predictor of the average height of the MTF. However, RMS can be much more rapidly computed from aberration coefficients than can MTFs and given the relationship between the two indices RMS may serve as a useful summary index of image quality.

Our estimates of optical quality suggest that, with best spectacle correction, some children may be capable of perceiving aliasing by the foveal cone matrix. There are no anatomic data available on foveal cone packing in children of similar age to this study's subjects, preventing direct calculation of the Nyquist frequency in our subjects' age group. It is reasonable however to assume that the Nyquist frequency lies somewhere between that for 45-month-old subjects and that for adults, as shown in Figure 2. Thus, from our data, at the Nyquist frequency, average MT lies somewhere between 0.23 and 0.32 in 3-mm pupils, 0.17 and 0.21 in 4-mm pupils, and 0.09 to 0.11 in 5-mm pupils. Some subjects have higher (and lower) MTs than these averages. Thus, some supra-Nyquist spatial information may reach the fovea of some children of this age group, and they may perceive aliasing of such supra-Nyquist frequencies (i.e., local and global distortions of spatial frequency, orientation, and motion).[13,36] However, a number of additional factors may act to curtail aliasing in children's vision. First, as discussed earlier, light scatter by the ocular media may also lead to a loss of retinal image contrast that cannot be quantified directly through aberrometry. Second, our calculations are based on monochromatic aberrations for light of 550 nm and ignore the additional image degradation that chromatic aberration imposes on polychromatic stimuli (e.g., white light). This is difficult to predict, because different subjects may have different levels of transverse chromatic aberration at the fovea. At the Nyquist frequency with a 2.5-mm pupil, longitudinal chromatic aberration by itself would be expected to attenuate MT by 0.1 to 0.2 log units from the diffraction limits.[37] Third, our MTF calculations are based on perfect correction of spherical and cylindrical refractive errors, and for many young children this is not the case, so that MTFs are slightly attenuated by the effects of defocus and astigmatism. Errors of accommodation may also have the same effect. Fourth, cones attenuate image contrast by averaging light across their apertures, at the fovea.[38] This attenuation may be greater in children than adults, because children's foveal cone apertures summate over a larger area of space, a consequence of children's slightly larger inner segments and shorter axial lengths. However, in children and adults, cone apertures are too small to affect overall MT significantly until spatial frequency is considerably higher than the Nyquist frequency. Using the same techniques as previous investigators have used,[38] we calculated MTFs for foveal cone apertures at 45 months of age and in adulthood, based on previously tabulated anatomic data.[12] At the Nyquist limit for each age group, for 45-month-old children and adults, respectively, foveal cone apertures had MT of 0.85 and 0.84. Thus, these combined factors decrease the likelihood that vision was affected by foveal cone aliasing in this age group.

Comparison with Adult Data

The average MTFs for both children and adults are shown in Figure 2, along with sample standard deviations. Average adult MTFs were slightly below those of children, with the difference increasing as pupil size increased, so that, at some spatial frequencies, the average adult MTF for 5 mm was 0.2 log units below the average for children. Thus, on average, the optical quality of children appears to be slightly better than that of adults, although there is considerable overlap between MTFs for the two samples. This age difference in MTFs should be considered in light of possible concurrent natural changes in pupil size. There is little information on changes in photopic pupil size between 6 years and young adulthood; however, McLachlan and Howland[39] reported that mesopic average pupil size increases in this interval by approximately 0.5 mm in males and is almost unchanged in females. Thus pupil size is unlikely to improve MTFs in young adults, compared with children. Age changes in pupil apodization by the Stiles-Crawford effect might have effects similar to those of changing pupil size and are possible considering the age changes that have been observed in photoreceptors.[11] Although recent researchers have noted that in adults the Stiles-Crawford effect probably plays a minor role in improving contrast sensitivity,[40] to our knowledge the developmental time course of the Stiles-Crawford effect has not been reported in the literature, and existing anatomic data does not appear adequate for modeling changes in the effect.

Previously, investigators have compared CSFs between children of an age similar to those in the present study and adults and found that children have poorer contrast sensitivity.[1,2] One study[1] reported an interage contrast sensitivity difference of 0.15 to 0.3 log units, and another[2] reported an interage contrast sensitivity difference of between 0.1 and 0.6 log units, with the difference dependent on spatial frequency. Given no evidence of an improvement in MTF between childhood and adulthood, these concurrent CSF changes might be attributable to neural and cognitive factors, such as those suggested by Wilson.[7]

Optical Orientation Anisotropy

When MTFs for different orientations are assessed, our results show a slight average meridional anisotropy, with MT being poorest for vertically modulated (i.e., horizontal) gratings and best for horizontally modulated (i.e., vertical gratings). This meridional difference was only significant for 3-mm pupils, and there was considerable intersubject variation in meridional anisotropy. We assessed the possibility that this anisotropy might reflect a difference between horizontal and vertical coma terms. We did not find a similar average meridional anisotropy in coma magnitude, although in our sample, meridional differences in coma magnitude are correlated with meridional differences in the height of the MTF. This correlation is only moderate, as might be expected, in that coma's effects on image quality can be influenced by interactions with other higher order aberrations. There was no evidence of an average oblique effect in the optics of our subjects.

In summary, to the best of our knowledge, no researchers have reported MTFs in children this young. Our results show a dependence of optical quality on pupil size, and a slight average meridional anisotropy at 6 years of age. Average optical quality in this age group is equivalent to or better than that of young adults.

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