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Choice of Grating Orientation for Evaluation of Peripheral Vision

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ABSTRACT

Purpose. Peripheral resolution acuity depends on the orientation of the stimuli. However, it is uncertain if such a meridional effect also exists for peripheral detection tasks because they are affected by optical errors. Knowledge of the quantitative differences in acuity for different grating orientations is crucial for choosing the appropriate stimuli for evaluations of peripheral resolution and detection tasks. We assessed resolution and detection thresholds for different grating orientations in the peripheral visual field.

Methods. Resolution and detection thresholds were evaluated for gratings of four different orientations in eight different visual field meridians in the 20-deg visual field in white light. Detection measurements in monochromatic light (543 nm; bandwidth, 10 nm) were also performed to evaluate the effects of chromatic aberration on the meridional effect. A combination of trial lenses and adaptive optics system was used to correct the monochromatic lower- and higher-order aberrations.

Results. For both resolution and detection tasks, gratings parallel to the visual field meridian had better threshold compared with the perpendicular gratings, whereas the two oblique gratings had similar thresholds. The parallel and perpendicular grating acuity differences for resolution and detection tasks were 0.16 logMAR and 0.11 logMAD, respectively. Elimination of chromatic errors did not affect the meridional preference in detection acuity.

Conclusions. Similar to peripheral resolution, detection also shows a meridional effect that appears to have a neural origin. The threshold difference seen for parallel and perpendicular gratings suggests the use of two oblique gratings as stimuli in alternative forced-choice procedures for peripheral vision evaluation to reduce measurement variation.

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Key Words: grating orientation, peripheral vision, resolution, detection, meridional effect, psychophysics, forced-choice procedure

Peripheral visual evaluations are important in many aspects of vision care and research. One instance is central visual field loss, where the visual evaluation has to be performed in the eccentric preferred retinal locus.[1–3] Peripheral evaluation is challenging because of reduced retinal function and large optical errors. Care must therefore be taken when designing the psychophysical procedure to avoid additional uncertainties in the estimated threshold. Spatial visual acuity in the periphery is known to vary with task (resolution or detection),[4–6] field loci (eccentricity and meridian), [7–9] and stimulus properties (orientation of the stimulus).[7–11] For accurate visual evaluation, all three factors should be taken into consideration. However, little is known about the interaction between task and stimulus orientation. In this study, we therefore quantify the difference in detection and resolution thresholds for gratings of different orientations in the peripheral visual field.

Peripheral resolution acuity is well known to be dependent on the orientation of the visual stimuli—known as the meridional effect. Several psychophysical and functional magnetic resonance imaging studies have found that stimuli oriented radially along the meridian are better resolved than stimuli oriented in other directions. [7–11] It has also been reported that the meridional preference for resolution is not caused by refractive errors or other aberrations, hence supporting neural origin.[8,9] The physiological cause for the meridional preference would be that retinal ganglion cell dendritic fields are radially oriented.[12–15] A neural selectivity

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for radial grating orientations also in cortical level has been confirmed by Schall et al.[16] who found that the orientation columns in the visual cortex of cats are wider for the radial orientation than for other orientations. This neural orientation preference will increase the uncertainty and variability of threshold estimations if the alternatives of a forced-choice paradigm are orientated parallel and perpendicular to the meridian. In addition, there might be a response bias when one of the orientations is more easily seen than the others. Peripheral vision is very important for daily activities, such as orientation, movement, and driving. Peripheral vision evaluation is very important in cases such as macular degenerations, myopia development, and progression research. To avoid uncertainties and inaccuracies in the peripheral acuity measurements, appropriate stimuli selection is vital.

Previous studies on the meridional effect have mainly focused on resolution acuity, and little is known about orientation preferences for peripheral detection acuity. Unlike central vision, there is a difference between resolution and detection acuity for peripheral vision: high-contrast resolution is relatively unaffected by optical errors because it is neurally limited,[5,17] whereas detection is affected by optical errors.[5,6] This means that a stimulus with a spatial frequency above the neural sampling limit cannot be resolved. However, the undersampled stimulus undergoes aliasing and can be perceived through its *moiré* pattern with a lower spatial frequency, a lower contrast, and a different orientation.[4,18] The zone of aliasing is dependent on the optical errors in the periphery. Correction of peripheral optical errors enhances the contrast, which improves detection acuity and thereby widens the aliasing zone. Because of the influence of optical errors on peripheral detection acuity, a meridional preference for detection tasks may be a combination of optical and neural orientation sensitivities. The amount and direction of asymmetric optical errors like astigmatism, coma, and transverse chromatic aberration (TCA) can favor the detection of certain orientations over others. The peripheral image quality is dominated by off-axis astigmatism and coma oriented radially, which could lead to poorer detection of perpendicular gratings and hence a larger meridional effect. To reveal neural limitations and evaluate whether the meridional effect is also present for detection tasks, correction of these optical errors is necessary. Therefore, the present study uses a combination of trial lenses, an adaptive optics system, and monochromatic stimuli to correct for the existing monochromatic and chromatic optical errors. In a peripheral detection study by Cheney et al.,[19] the optical errors were surpassed by using circular windowed interferometric stimuli. The reported detection cutoff frequencies were high, and a large meridional preference was reported in white light and was suggested to be purely optical in origin, caused by TCA, as the effect disappeared in green light. However, these results may be caused by the special properties of the interferometric stimuli (such as high retinal image contrast and the presence of TCA in the absence of longitudinal chromatic aberrations), and the meridional preference for detection of noninterferometric stimuli could therefore be very different.

In the present study, we evaluate the peripheral resolution and detection acuities for different orientations in different visual field meridians with optical correction. The detection measurements are also performed in monochromatic light to elude the effects of chromatic aberrations.

METHODS

Two emmetropes (S1 and S2, 29 and 33 years old) and a 2.5D myope (S3, 35 years old) corrected with soft contact lenses participated in the experiments. All three subjects had good general and ocular health and were experienced in peripheral psychophysical measurements. The study protocol was reviewed by the regional ethics committee and followed the tenets of Declaration of Helsinki; written informed consent was obtained from the subjects before the study. All measurements were performed in the right eye at 20-deg eccentricity under adaptive optics correction, and the left eye was used for fixation. White light resolution and detection measurements in eight different visual field meridians were performed on S1, and monochromatic detection measurements in the 20-deg nasal visual field were performed on all three subjects.

Experimental Setup

The psychophysical routines for the evaluation of peripheral resolution and detection were implemented in Matlab and Psychophysics toolbox.[20,21] The stimuli were presented on a calibrated CRT monitor with 10-bit grayscale resolution. The monitor had a mean luminance of 51 cd/m^2 in white light and was 2.6 m away from the subject. High-contrast (100%) Gabor gratings were used to estimate resolution and detection thresholds. The Gaussian filter of the Gabor had a standard deviation of 1.6 deg to always have at least six visible cycles even for low spatial frequency gratings. A custom-built adaptive optics system was used to measure and correct the optical errors in the corresponding visual field locus. The refractive errors were obtained from the second-order coefficients of the wavefront measurements as follows:

$$M = -4\sqrt{3} \times \frac{c_2^0}{r_{pupil}^2},\ J0 = -2\sqrt{6} \times \frac{c_2^2}{r_{pupil}^2},\ J45 = -2\sqrt{6} \times \frac{c_2^{-2}}{r_{pupil}^2}$$

$$Cylinder = -2\sqrt{(J0^2 + J45^2)},\ Sphere = M - \left(\frac{cylinder}{2}\right)\ and$$

$$axis = 0.5*\text{atan}\left[\frac{\text{J45}}{\text{J0}}\right]$$

The refractive error in each field locus was corrected with trial lenses and adjusted for the distance to the stimulus monitor. The remaining refractive errors as well as the higher-order aberrations were corrected by the adaptive optics running in continuous closed-loop during the measurements. Total residual amount of aberrations was maintained around 0.1 μm for a pupil diameter of 5 mm. The details of the system and its use in peripheral visual evaluations have been described in detail earlier.[22] For detection acuity measurements in green light, a narrow band green filter from Thorlabs (with a peak transmission of 70% at 543 nm and a bandwidth of 10 nm) was used in the path between the CRT monitor and the adaptive optics system to render the light nearly monochromatic. All the measurements were done with natural pupils.

Resolution and Detection Acuity Measurements

Resolution and detection acuity measurements in white light were performed on subject S1 in eight visual field meridians: temporal (T), superior-temporal (ST), superior (S), superior-nasal (SN), nasal (N), inferior-nasal (IN), inferior (I), and inferior-temporal (IT). Fig. 1 represents the visual field meridians tested as well as the gratings of four orientations: horizontal, vertical, left and right oblique. The orientations of gratings mentioned in the following sections are all relative to the visual field meridian tested, with 0 deg denoting gratings parallel with the tested meridian (i.e., oriented radially in the visual field), 90-deg gratings perpendicular to the meridian, and 45- and −45-deg gratings with an oblique orientation relative to the meridian. All eight meridians were tested in one session, and the order of the meridian was randomized. Adequate breaks were given in-between measurements to avoid fatigue. The sessions were repeated thrice for both detection and resolution measurements separately, and the average acuity values were used for further analysis. Detection acuity in monochromatic light was measured with three repetitions in all three subjects in the 20-deg nasal visual field. For these measurements, only gratings oriented parallel and perpendicular to the visual field meridian (horizontal and vertical) were used.

Psychophysical Procedure

All resolution and detection acuities were measured by varying the spatial frequency of the grating stimulus with Bayesian adaptive psychophysical procedures.[6,23] A modified four-alternative forced-choice task was used to determine the resolution acuities for all four grating orientations in a combined psychophysical procedure by interleaving the psychophysical algorithms for each orientation. The lapse rate was set to 5%, and the threshold was estimated at 60% correct responses. The gratings of all four orientations were presented in random order in 120 trials, with 30 trials for each orientation. After each trial, the response was collected and processed separately based on the orientation to evaluate the individual resolution acuity thresholds for each orientation. The subject's task was to identify the orientation of the grating and respond with the corresponding key on a keypad. When no orientation of the stimulus is perceived or when the stimulus is not seen at all, the subject was asked to press a fifth key, which then assigned a random response through a computer-generated guess. This was done to avoid any response bias, and this method has been shown to be more precise in threshold estimation provided that the subject has good compliance.[24] The grating stimuli were presented for 500 ms accompanied by an auditory cue. The size and spatial frequency

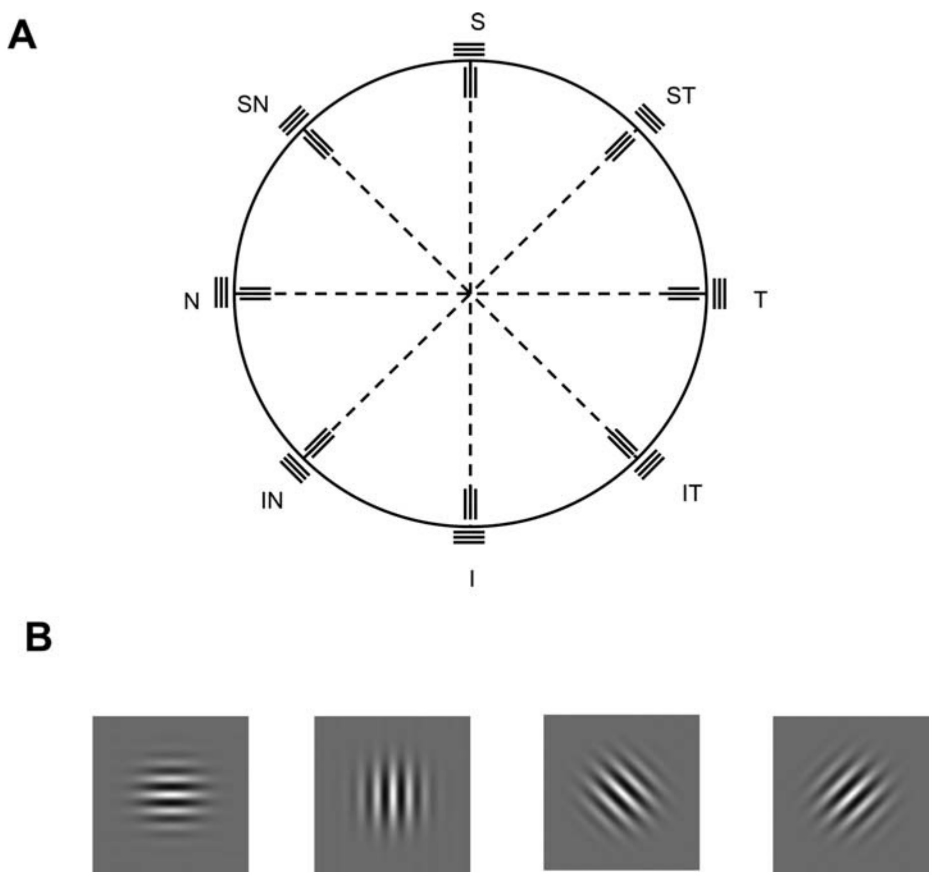

FIGURE 1.

(A) Schematic representation of the eight visual field meridians tested: temporal (T), superior-temporal (ST), superior (S), superior-nasal (SN), nasal (N), inferior-nasal (IN), inferior (I), and inferior-temporal (IT). The solid circle represents the 20-deg eccentricity. The center of the circle denotes the central visual field. The lines inside and outside the circle represent the parallel (0-deg relative orientation) and perpendicular (90-deg relative orientation) grating orientations, respectively. The 45- and −45-deg relative orientations (not shown) are gratings oriented obliquely with respect to the 0- and 90-deg relative orientations. (B) The four orientations of gratings used (horizontal, vertical, left oblique, and right oblique).

of the presented stimuli were adjusted to compensate for the spectacle magnification (*m*): *m = 1/(1 - aF)* where *a* is the vertex distance from the trial lens to the eye and *F* is the spherical equivalent of the lenses. The measurement time for each location was about 10 min including the alignment of the subject's eye in the adaptive optics system.

Detection acuity measurements were evaluated in an interleaved procedure similar to the resolution measurements, except for that this was a two-interval forced-choice procedure (threshold estimated at 72.5% correct responses). The grating stimulus was presented in one of two time intervals, both accompanied by an auditory clue. The subject was asked to respond in which interval the grating was presented. The random guess button was not used in this case. The total measurement time for each test location was longer than that of resolution caused by the two intervals. For the detection measurements in green light, only two orientations of the gratings were interleaved (parallel and perpendicular), with 50 trials for each orientation. The thresholds for both resolution and detection are noted as logMAR and logMAD, respectively (logarithm of minimum angle of resolution or detection, in minutes of arc minutes). Unpaired t-tests were used to compare the differences in acuities between different orientations.

RESULTS

The trial lenses used to correct the refractive error at each corresponding visual field locus obtained from the wavefront sensor are given in Table 1. The log acuities for different orientation gratings in white light for the different visual field meridians in 20-deg eccentricities are shown for subject S1 in Fig. 2. The resolution acuity is better for the parallel gratings (0-deg relative orientation), worst for perpendicular gratings (90-deg relative orientation), and intermediate for the oblique orientations (45- and −45-deg relative orientation) (Fig. 2A). The average difference between parallel and perpendicular grating resolution acuity was 0.16 ± 0.05 logMAR. Similarly, detection acuity was also better for the parallel gratings and worst for the perpendicular gratings (Fig. 2B), with an average difference of 0.11 ± 0.09 logMAD. Note that the detection acuity was better than the resolution acuity in all visual field meridians for all grating orientations (average difference was 0.14 log acuity with a standard deviation of 0.07), suggesting that the stimuli were in the aliasing zone. During detection tasks, the subjects experienced aliasing, manifested as seeing the stimulus but not being able to identify its orientation. The resolution and detection acuities reported for gratings of different orientations in this section are the average values of three measurements except for the resolution acuity for parallel gratings in the ST meridian where only one data point was included in the analysis, as the threshold estimation was not converging in the other two measurements. The standard deviations in acuity estimates were 0.04 logMAR and 0.07 logMAD for resolution and detection, respectively. The average differences between parallel and perpendicular and two oblique gratings for resolution and detection acuities are summarized in Table 2.

TABLE 1.

Trial lens prescription (sphere/cylinder × axis) used to correct the peripheral refractive errors in 20-deg eccentricity

Subject	Location	Trial lens prescription
S1	T	+0.25/-0.75 × 100
S1	ST	+0.0/-0.50 × 30
S1	S	+0.50/-1.50 × 165
S1	SN	+1.25/-1.75 × 130
S1	N	+0.75/-1.50 × 90
S1	IN	+0.50/-1.50 × 45
S1	I	+0.25/-1.50 × 5
S1	IT	+0.25/-1.25 × 145
S2	N	+0.25/-1.50 × 80
S3	N	+0.00/-3.00 × 85

The peripheral refractive error values were obtained from the Hartmann-Shack measurements. See Fig. 1 legend for the abbreviations.

The detection acuities at 20-deg nasal visual field for parallel and perpendicular gratings measured in green light are shown in Fig. 3. The meridional preference still existed in the monochromatic detection measurements; the detection acuities in green light are better for the parallel gratings compared with perpendicular gratings in all the subjects. The average difference between the parallel and perpendicular grating is 0.10 ± 0.04 logMAD, which is similar to the average difference seen in the detection acuity in white light (0.11 ± 0.09 logMAD).

DISCUSSION

This study shows that both peripheral resolution and detection acuities have a meridional preference; the acuity is better for gratings oriented along the meridian. In agreement with earlier studies,[8–11] resolution in white light showed a significant meridional effect. The parallel-perpendicular difference for the resolution task was 0.16 logMAR, and this difference was slightly lesser (0.11 logMAD) for the detection task. Green light detection measurements also showed a meridional effect of 0.10 logMAD.

Validation of Optical Quality

The presence of the meridional effect even in green light (eliminating the influence of chromatic aberrations) indicates that both resolution and detection acuities are using neural channels with orientation selectivity. To rule out any contribution of residual optical errors that could have caused this meridional effect, postanalysis of the peripheral modulation transfer function (MTF) was performed. For the green light measurements, MTF is limited only by diffraction and remaining residual optical errors through the elliptical pupil. For each visual evaluation, the wavefront aberrations were averaged for the time of the session, and the MTFs for parallel and perpendicular orientations were calculated for an elliptical pupil size of 5 mm in major diameter and 5 mm * cos(20 deg) in minor diameter (elliptical because of the 20-deg peripheral viewing). For a spatial frequency of 10 cpd (0.48 logMAR), which is close to the acuity limits in this study, the average image contrast rates for the measurements in green light of the three subjects were 87 ± 3% for parallel and 83 ± 6% for perpendicular orientations. The residual optical asymmetries or pupil asymmetries are not responsible for the found meridional effect as the image contrast was similar for both parallel and perpendicular gratings. Example MTFs of two of the

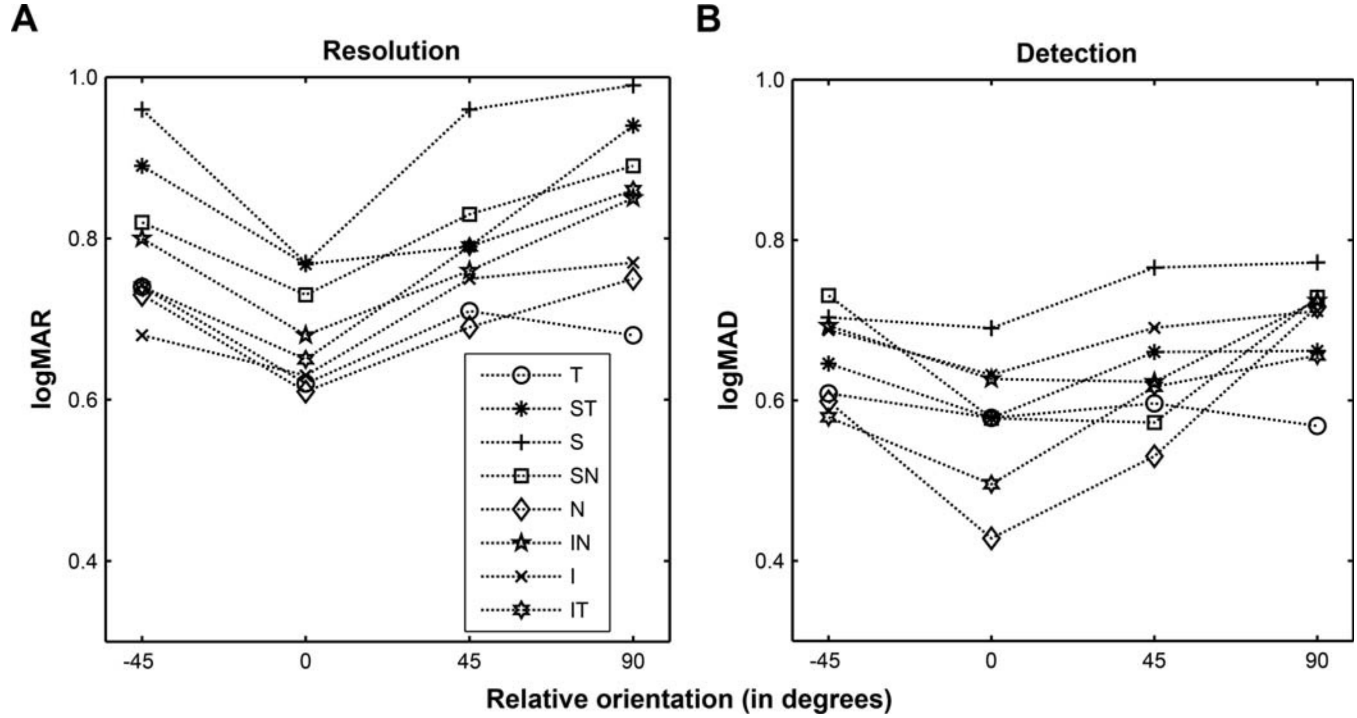

FIGURE 2.

White light resolution (A) and detection (B) acuities in logMAR and logMAD in eight different visual field meridians at 20-deg eccentricity for subject S1. Acuities are for gratings oriented parallel (0 deg), perpendicular (90 deg), and two oblique orientations (+45 and −45 deg) relative to the visual field meridian. See Fig. 1 legend for the abbreviations.

measurements are shown in Fig. 4; note that the two measurements had different MTF profiles but similar image contrast levels for parallel and perpendicular gratings at the acuity limit and also the same meridional effect.

The meridional asymmetries in the spectacle magnification could also lead to meridional effect if the parallel gratings are more magnified than the perpendicular gratings. However, this possibility is unlikely as the trial lenses used were only of low power; the maximum difference between the spectacle magnification for parallel and perpendicular orientations is less than 5%, which will lead to an acuity difference of about 0.02 logMAR only. Considering the above-mentioned factors, meridional effect seen in the present measurements seems to have a neural basis.

Neural Orientation Selectivity

Radial orientation preference of retinal ganglion cells and higher-level neurons are well documented in the literature.[12–15] This neural orientation selectivity is clearly seen for the resolution task as parallel gratings are transmitted in a more efficient neural channel than perpendicular gratings. In addition to providing meridional effect for resolution tasks, the orientation of the dendritic field can also affect detection. However, the detection of a grating in the aliasing zone is not restricted to one orientation channel alone because the aliased pattern will contain different orientations. Hence, a perpendicular grating that has undergone aliasing can be detected not only by the neural channel for that orientation but also, to some degree, by the more efficient channel for the parallel orientation, resulting in a reduced meridional effect for detection. This can be seen from the measurements as the difference between resolution and detection acuities was more for perpendicular than parallel gratings. On average, detection acuities were 0.18 and 0.13 log acuity better than resolution for perpendicular and parallel gratings, respectively.

One possible reason why the neural orientation selectivity is higher for radial orientations could be long-term adaptation to the existing optical errors in the periphery. The off-axis astigmatism of the human eye usually causes one line focus to be radially oriented. If the radially oriented line focus is the one closest to the retina, the parallel gratings will have a better image quality than the perpendicular gratings and it is possible that a long-term adaptation has occurred to the more easily seen parallel orientation, thereby resulting in a higher neural sensitivity for the parallel orientation. For subject S1, the parallel line focus was closest to the retina for the unaccommodated state only in six of the eight

TABLE 2.

Average difference between acuities of gratings with different orientations of white light for subject S1

Relative orientations (in degrees)	Resolution (in logMAR)	Detection (in logMAD)
0 and 90 (parallel and perpendicular)	0.16 ± 0.05 (p = 0.002)	0.11 ± 0.09 (p = 0.023)
−45 and 45 (two oblique)	0.01 ± 0.05 (p = 0.824)	0.02 ± 0.07 (p = 0.631)

The p values from the unpaired t-test are given in the parentheses.

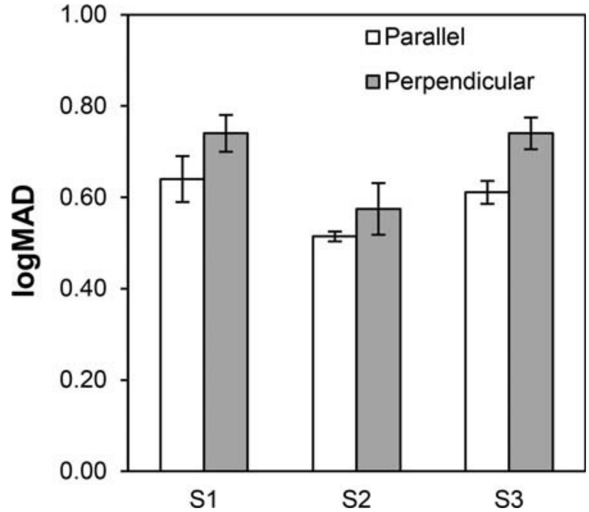

FIGURE 3.
Detection acuity in logMAD at 20-deg nasal visual field for parallel (0-deg relative orientation) and perpendicular (90-deg relative orientation) gratings in monochromatic light (543 nm with a bandwidth of 10 nm). The error bars indicate 1 standard deviation.

measured meridians despite seeing a clear meridional effect in all meridians. In addition, the perpendicular line focus will be closest to the retina at instances depending on object vergence and accommodative state. Hence, we believe that long-term adaptation to the existing optical errors is not the main reason for the meridional effect seen in the periphery.

Stimulus Properties and Detection Acuity

In the present study, sinusoidal gratings were used in a Gaussian window (Gabor gratings). Sinusoidal gratings are a common stimulus choice for research on peripheral vision,[5,6,18,25,26] suitable for evaluating detection and resolution acuity and contrast sensitivity. The advantage with a Gaussian window is that it is well defined in both spatial frequency and spatial extent. However, the Gaussian window also reduced the contrast of the stimuli; at the radius of 1 standard deviation, the Gaussian window reduces the contrast by $e^{-0.5}$—this means that the contrast in the center of the stimulus has been reduced to about 55% at 1 standard deviation away from the center. At this contrast level, the stimuli are still clearly visible (corresponding to a contrast sensitivity level of 1/0.55 = 1.8). The peripheral detection values reported in the current study are similar to the values reported in the earlier studies (~10 cpd) that used sinusoidal gratings with either a Gaussian window or a cosine bell window.[6,25,27] However, studies that used sinusoidal gratings in a circular window have reported better detection values (~20 to 30 cpd).[4,5,28] These better detection cutoffs can be caused by the well-known edge effect; a grating within a sharp window contains a wider range of spatial frequencies and the edge is visible even when the gratings are not.[29,30] Moreover, if the circular window gives rise to a difference in luminance between the stimulus and the background, then it will be unclear whether the estimated thresholds are for detection of stimulus itself or detection of luminance (where the threshold is determined by Ricco law).

The difference in detection thresholds for gratings with different windows might also affect the quantification of the meridional

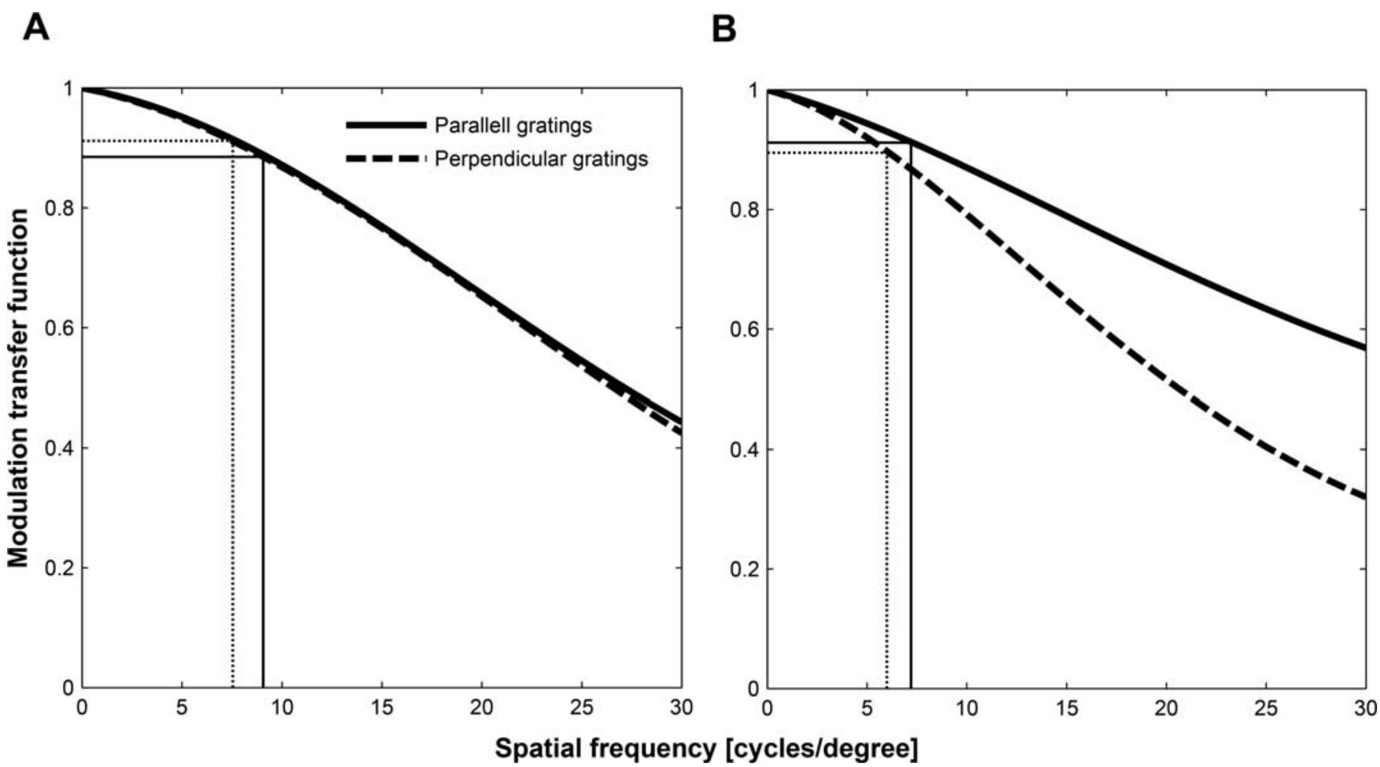

FIGURE 4.
Modulation transfer function calculated with residual optical errors for elliptical pupil. A and B are from green light detection measurements of subjects S2 and S3, respectively; both measurements had the same meridional effect (0.10 logMAD). The vertical and horizontal lines represent acuity values and the corresponding image contrast, respectively.

effect. A meridional effect for detection in monochromatic light was found in the present study as well as in the study by Atchison et al.,[25] both using Gaussian windowed gratings. On the contrary, Cheney et al.[19] reported no meridional effect in monochromatic light when the measurements were performed with interferometric stimuli with a circular window. Furthermore, they reported a very large meridional effect for white light; the parallel and perpendicular grating detection values were about 25 and 40 cpd, respectively. While comparing these values with those of the previously mentioned studies, it should be noted that interferometric stimuli will have much higher retinal image contrast and the effect of TCA is exaggerated in white light because of the absence of longitudinal chromatic aberrations.

The detection acuity reported in the present study for green light is slightly worse than that for the white light because of the luminance difference caused by the green filter (70% transmission). In green light, a meridional effect of 0.10 logMAD was found, which is somewhat lower than the values reported in a study by Atchison et al.[25] (0.20 logMAD), where the measurements were done with optimal refractive correction in monochromatic light on one subject. The smaller meridional effect in the present study is not unexpected as we corrected the higher-order aberrations in addition to the refractive correction, which reduced the optical limitations on the detection of perpendicular gratings further.

Choice of Stimulus Orientation

Previous studies have used either the two oblique gratings[22,31–34] or the parallel-perpendicular gratings[4,6,28] as the alternate choices for peripheral resolution measurements. For detection measurements, either one orientation (parallel[4]) or random presentation of two orientations of gratings (parallel and perpendicular[6,27,28] or two oblique orientations[18]) were used in the two alternate interval choice procedure. Considering the differences between parallel and perpendicular grating acuity found in the current study, it becomes clear that there might be inconsistencies in the threshold estimation when this combination of orientations is used during a forced-choice procedure.

In summary, the magnitude of the difference in both resolution and detection acuities of different grating orientations indicates the importance of appropriate choice of visual stimuli during peripheral psychophysical evaluations in both clinical and research scenarios. Two alternative forced-choice procedures for evaluating the peripheral visual acuity with gratings oriented with ±45 deg to the measured meridian will reduce the variation in threshold estimation compared with using parallel and perpendicular gratings. Two interval forced-choice procedures could use only one grating orientation, keeping in mind that a grating parallel to the visual field meridian will produce better acuity than a perpendicular grating.

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