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Effect of induced transverse chromatic aberration on peripheral vision

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Transverse chromatic aberration (TCA) is one of the largest optical errors affecting the peripheral image quality in the human eye. However, the effect of chromatic aberrations on our peripheral vision is largely unknown. This study investigates the effect of prism-induced horizontal TCA on vision, in the central as well as in the 20° nasal visual field, for four subjects. Additionally, the magnitude of induced TCA (in minutes of arc) was measured subjectively in the fovea with a Vernier alignment method. During all measurements, the monochromatic optical errors of the eye were compensated for by adaptive optics. The average reduction in foveal grating resolution was about 0.032 ± 0.005 logMAR/arcmin of TCA (mean ± std). For peripheral grating detection, the reduction was 0.057 ± 0.012 logMAR/arcmin. This means that the prismatic effect of highly dispersive spectacles may reduce the ability to detect objects in the peripheral visual field.

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1. INTRODUCTION/PURPOSE

Chromatic aberration is the largest optical error in the healthy human eye, apart from refractive errors. Despite its magnitude, the negative impact of chromatic aberration on foveal visual quality is relatively small [1,2]. However, transverse (or lateral) chromatic aberration (TCA) increases in the peripheral visual field; away from the achromatic axis there will be an angular offset between the principal rays of different wavelengths that is independent of the size of the pupil. Very little is known about this peripheral TCA in the human eye. Therefore, the aim of this study is to investigate the effect of TCA on peripheral vision.

Peripheral visual function is important for many daily tasks, such as detection, orientation, and locomotion, and becomes crucial in traffic situations. Furthermore, several recent studies have shown that the peripheral image quality might affect the growth of the eye and, thereby, the progression of myopia, although the underlying mechanisms of this regulation are not known [3,4]. Additionally, the optical quality in the peripheral visual field is particularly important for people with large central visual field loss, who are depending on the periphery for all visual tasks.

Previous studies of peripheral vision and the effect of optical errors have mainly concentrated on monochromatic errors. To the best of our knowledge, there are only three studies that have evaluated the magnitude of peripheral chromatic aberrations, longitudinal or transverse. The two studies by Rynders *et al.* and Jaeken *et al.* found the longitudinal chromatic aberration (LCA) to be relatively constant with eccentricity, which was in agreement with theoretical simulations [5,6]. Contrary to LCA, objective measurements of TCA are complicated: TCA induced to the incoming light into the eye cannot be detected directly as the second pass out of the optics of the eye will induce TCA of the opposite sign. Therefore, the only study on peripheral TCA was subjective; Ogboso and Bedell used a subjective Vernier alignment method to measure TCA over the ±60° horizontal peripheral visual field and found the magnitude of TCA to increase with eccentricity [7]. This is in agreement with theoretical predictions of a nearly linear increase in TCA with eccentricity; Thibos predicted the TCA from a modified reduced-eye model to be 5 arcmin in the 20° nasal visual field [8]. This number is close to the peripheral high-contrast resolution acuity in the same location when the refractive errors are corrected [9,10]. Thibos concluded that "The aberration… [TCA]… probably has negligible effect on peripheral acuity but may act to limit aliasing of peripheral patterns" [8]. Aliasing occurs when the details in the image on the retina are of higher spatial frequency than the sampling density of the retina. This means that the presence of the stimulus

can be detected through the Moiré pattern without resolving the actual details (such as the orientation of the lines for a grating stimulus). This detection through aliasing will depend on the quality of the retinal image and will be ultimately limited by the ability of the retina to detect the lower contrast of the Moiré pattern. As the neural sampling density decreases toward the periphery [11,12], aliasing is more common in peripheral vision, especially if optical errors are corrected to improve image quality. Peripheral detection acuity can thereby be optically limited at the same time as peripheral resolution acuity is limited by the retinal sampling density [9–16]. Cheney *et al.* have investigated peripheral detection with an interferometric setup and found improvements when the TCA of the peripheral eye was avoided by monochromatic stimulation [17]. However, stimuli that are generated directly on the retina through interference have extremely high contrast and no LCA, which may exaggerate the effect of TCA. Therefore, it is not clear how more natural peripheral detection tasks are affected by TCA.

Besides the natural TCA of the peripheral eye, many people are also experiencing additional peripheral TCA induced by their spectacle lenses. The induced TCA is especially large for high-index glasses with high dispersion and may be evident to the wearer when looking through the edges of the spectacles, or while using glasses with prismatic power. Foveally, the contrast reduction because of additional TCA is evident in contrast sensitivity measurements [18–21], as well as in visual acuity; spectacle-induced TCA of around 5–7.5 arcmin reduces the visual acuity by 0.1 logMAR [22,23]. However, it is not known how this further increase of TCA affects peripheral visual function.

The aim of this study is to evaluate whether or not peripheral vision is degraded by additional TCA, as predicted by theory. This is accomplished by measuring the detection acuity loss in the 20° nasal visual field as a function of TCA induced horizontally by high dispersive prisms. The results will increase our understanding of the optical limitations to peripheral vision. Additionally, knowing the extent to which TCA degrades peripheral visual performance is important when designing spectacles. For comparability with earlier studies, the resolution acuity loss for central vision is also measured. Because the TCA experienced by the subject will depend both on the prism power and on the properties of the stimulus, the current study includes foveal subjective measurements of the magnitude of induced TCA. To isolate the effect of the chromatic aberrations, foveal and peripheral refractive errors, as well as high-order monochromatic aberrations, are corrected during the measurements.

2. METHODS

The effect of additional TCA, induced by prisms, was evaluated in four subjects under full correction of monochromatic optical errors. In all subjects, three separate measurements were performed monocularly on the right eye. First, the TCA perceived by the subjects was measured foveally by a subjective Vernier alignment procedure. The effect of induced TCA was then studied in the fovea by resolution acuity and, finally, in the 20° nasal visual field by detection acuity. During all three tests, the subjects sat in a chin rest and used the right eye to view test stimuli shown on a monitor via an adaptive optics (AO) system. For the foveal measurements, the left eye was occluded. In the peripheral measurements, the left eye was shown a Maltese cross, located the same distance from the eye as the stimuli, to control the angle of fixation. The schematic setup is shown in Fig. 1. The position of the fixation target was corrected for the deviation angle of the corresponding prism. The measurements were performed in a dark room with natural pupils.

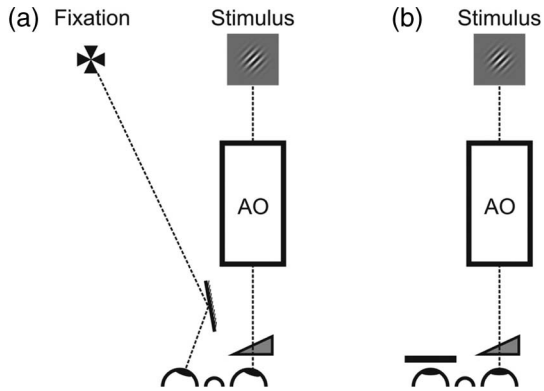

Fig. 1. Measurement setup for studying the effect of prism-induced transverse chromatic aberration (TCA) in the right eye (schematic illustration seen from above). The stimuli were seen via an adaptive optics (AO) system that compensated for monochromatic aberrations [24]. Peripheral detection acuity was measured with an external fixation target (a), and foveal resolution acuity with an occluded left eye (b).

A. Subjects

Four subjects between 28 and 35 years old participated in the study. The subjects consisted of one myope (S3: –2.50 D) corrected with soft contact lenses during the measurements, and three emmetropes (S1, S2, and S4). All subjects had a best corrected visual acuity of 0.0 logMAR or better, no strabismus, minor heterophoria, and normal results in the Ishihara color vision test. All subjects were experienced in psychophysical testing and gave written informed consent before participating in the study. The experimental procedures conformed to the Declaration of Helsinki and were approved by the regional ethics committee of Stockholm.

B. Prisms

Prisms were used to induce different magnitudes of TCA for the subjects. The prisms were manufactured in a high-dispersion glass (Rodenstock Cosmolit) with Abbe number or constringence $V_d = 32$ and refractive index $n_d = 1.67$ (1.679 for 480 nm, 1.668 for 546 nm, and 1.658 for 643 nm). The prisms were mounted in trial case lens holders and aligned horizontally in a lens holder in front of the right eye of the subject. Five prism powers were measured for all subjects: from 9.5 and 4.5 Δ base in (BI), over a planar lens to 4.5 and 9.5 Δ base out (BO). The order of the measured prisms was randomized for each subject. For three of the subjects (S1, S2, and S3), two additional prism powers, 2.0 and 6.25 Δ BO prisms, were used to test the peripheral detection acuity and get a better estimate of the magnitude of induced TCA needed to correct the natural TCA of the eye in the 20° nasal visual field.

C. Monochromatic Optical Correction

An adaptive optics system was used to correct the monochromatic aberrations in the respective measurement angle of the right eye of the subjects [24]. During peripheral testing, additional trial lenses mounted in front of the right eye supported the AO system in the correction of the peripheral refractive errors (low-order aberrations). Theses lenses were placed in the same lens holder as the prisms and aligned perpendicular to the axis of the AO system to avoid inducing any additional TCA. In these cases, the spectacle magnification was compensated for when performing the psychophysical tests. Throughout all tests, the AO system was running live in a continuous closed loop correcting both (remaining) low- and high-order aberrations, and the total residual aberrations did not exceed a root-mean-square error of 0.15 μm for a pupil diameter of 5 mm.

D. Screens and Psychophysics

The stimuli were presented in 10 bit grayscale resolution on a gamma-calibrated 19 in. CRT monitor (manufacturer, AOC; model, 9Glr; resolution, 1600 × 1200 pixels). The monitor was placed at 2.6 m distance from the right eye. The monitor was controlled by the Psychophysics Toolbox extension for Matlab [25]. Furthermore, the spectrum of the calibrated monitor can be seen in Fig. 2.

E. Vernier Alignment (Induced TCA)

A version of the Vernier alignment method by Rynders *et al.* [26] was applied to determine the induced TCA foveally for all prisms. The procedure utilizes a method of adjustment: the black bars of a cross on top of a red background were placed unaligned. The subject was then asked to make the bars appear aligned with the bars on top of the surrounding blue background with the help of a keypad (see Fig. 3). Herein, the subject was instructed to follow an iterative procedure, i.e., passing the threshold point and returning, until the subject judged the alignment as best match. From the measured Vernier displacement, the TCA as a function of prismatic power was calculated. Additionally, the TCA in the direction perpendicular to the prismatic gradient was used as a control, mainly to confirm that the prism was mounted correctly. Three repetitions were made, and the order of the prisms was randomized within each repetition.

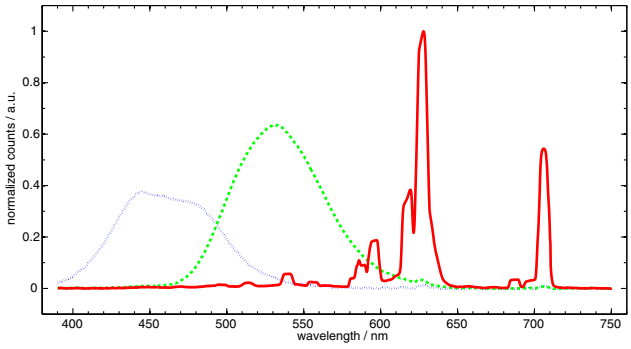

Fig. 2. Spectrum of the calibrated CRT screen with the three RGB color channels shown (R, solid; G, dashed; and B, dotted line). The magnitude of induced TCA will depend on the applied combination of stimulus spectrum, spectral sensitivity of the eye, and prismatic power.

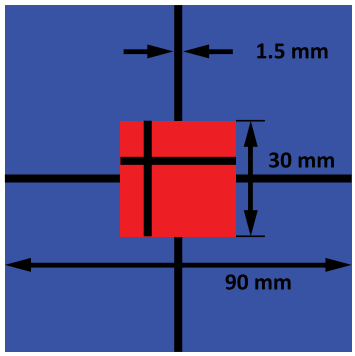

Fig. 3. Stimulus for the foveal Vernier alignment method. The task of the subject is to move the black bars in the center red square until they appear aligned with the horizontal and vertical lines on the surrounding blue background. From the remaining displacement of the bars, the magnitude of induced TCA can be calculated. The stimulus is viewed from a distance of 2.6 m, and the bars are moved with a step size of 0.23 mm (corresponding to about 0.3 arcmin).

F. Foveal Resolution Acuity

To determine foveal resolution acuity with different magnitudes of TCA, high-contrast Gabor gratings were used with a Gaussian envelope of 0.8° standard deviation and an average gray luminance of 51 cd/m^2. The gratings were oblique, leaning either 45° or 135°, and were displayed in a two-alternative forced-choice method, in which the subject was asked to report the orientation of the grating via a keypad. The spatial frequency of the gratings was varied according to the Bayesian method of Kontsevich and Tyler [27]. The psychometric threshold was estimated in 50 trials. The grating stimuli were presented for 500 ms accompanied by an auditory cue. No feedback about the correctness of the answer was given to the subject. Three repetitions were made, and the order of the prisms was randomized within each repetition.

G. Peripheral Detection Acuity

The peripheral detection acuity with different magnitudes of TCA was measured with the same grating stimuli, and in a similar way as in the resolution measurement. However, a two-interval forced-choice psychophysical procedure was implemented for the detection acuity. In this procedure, each trial consisted of two intervals, separated in time and indicated by two different auditory cues. The grating stimulus was shown in one of the intervals, and the other interval presented a blank screen homogenously set to the average luminance of the Gabor gratings. The subjects were asked to report whether the grating was present in the first or the second interval. The subject was not required to tell the orientation of the gratings, as for the foveal resolution task, but merely to detect the presence of stimulus, which can be done via aliasing of gratings with high spatial frequency.

3. RESULTS

The magnitudes of induced TCA and the effect of induced TCA on foveal resolution, as well as on peripheral detection, are presented separately for the four subjects in Figs. 4–6.

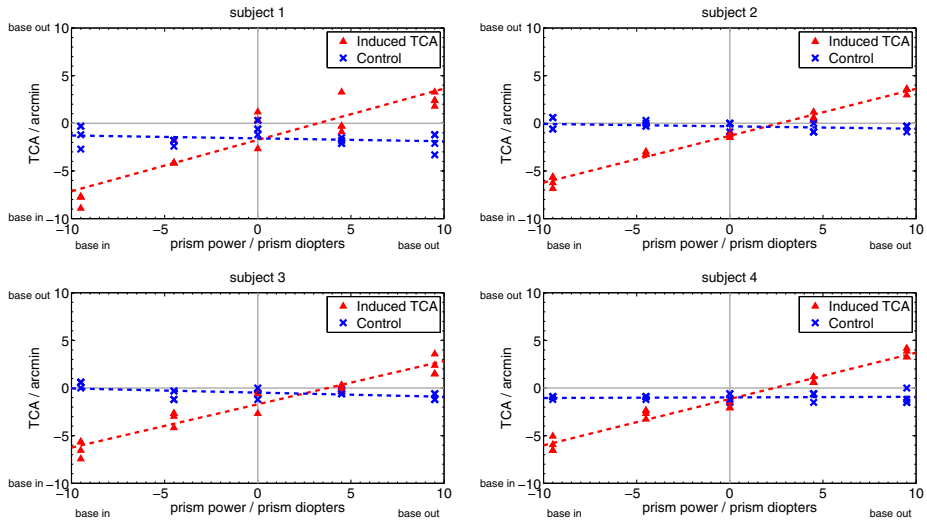

Fig. 4. Foveal TCA (red triangles) in arcmin induced by trial lenses with varying prismatic power ($V_d = 32$ and refractive index $n_d = 1.67$) shown for four subjects. The control (blue crosses) shows the induced TCA in the direction perpendicular to the prismatic gradient. The markers denote individual measurement values, and the lines are linear fits of those values. The average magnitude of induced TCA is 0.49 ± 0.03 arcmin/Δ.

First, the results of the foveal Vernier alignment, which evaluates the magnitude of TCA induced by the prisms, are shown in Fig. 4. As can be seen, the measured TCA was in the range of 0.45 to 0.54 arcmin/Δ with an average of 0.49 ± 0.03 arcmin/Δ (average and standard deviation of four subjects). Moreover, the data were highly correlated with the prism power ($r \geq 0.96$, Pearson correlation coefficient) for the individual subjects. In the remainder of the paper, this average increase of TCA with prism diopters (0.49 arcmin/Δ) will be considered to be the actual TCA induced optically to the eye in both foveal and peripheral vision. This average increase will also be used when relating the resolution and detection results to the magnitude of induced TCA. In the control experiment of the Vernier alignment, where TCA was measured perpendicular to the direction of the prismatic gradient, no effect of the induced prisms was seen; as expected, the best fitted blue line in Fig. 4 is very close to flat for all subjects, and the average increase in TCA was -0.02 ± 0.02 arcmin/Δ.

Second, the foveal sensitivity in grating resolution acuity to TCA is presented in Fig. 5. Here, all three measurement series are presented separately for each subject. The data for each subject were pooled, and a least square fit of a v-shaped function was then executed (black line in Fig. 5). The fit coefficients are given in Table 1. In this table, the slopes toward the left ("BI")

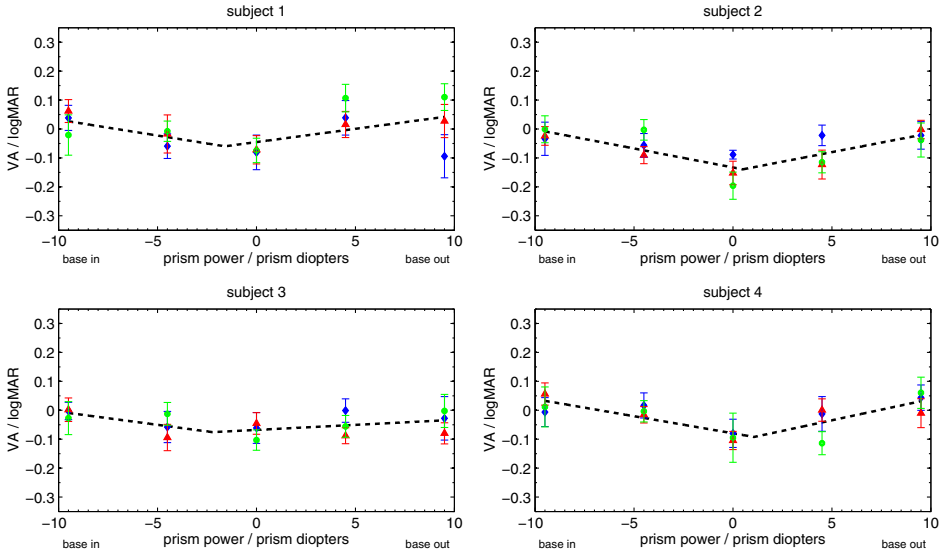

Fig. 5. Grating resolution acuity in logMAR in the fovea measured over induced prism power shown for four subjects. The black line shows the least square fit of the pooled data of the three measurement series (blue diamonds, red triangles, and green circles), and the error bars represent the standard deviations of the psychometric function for the individual series. The individual fit coefficients are given in Table 1.

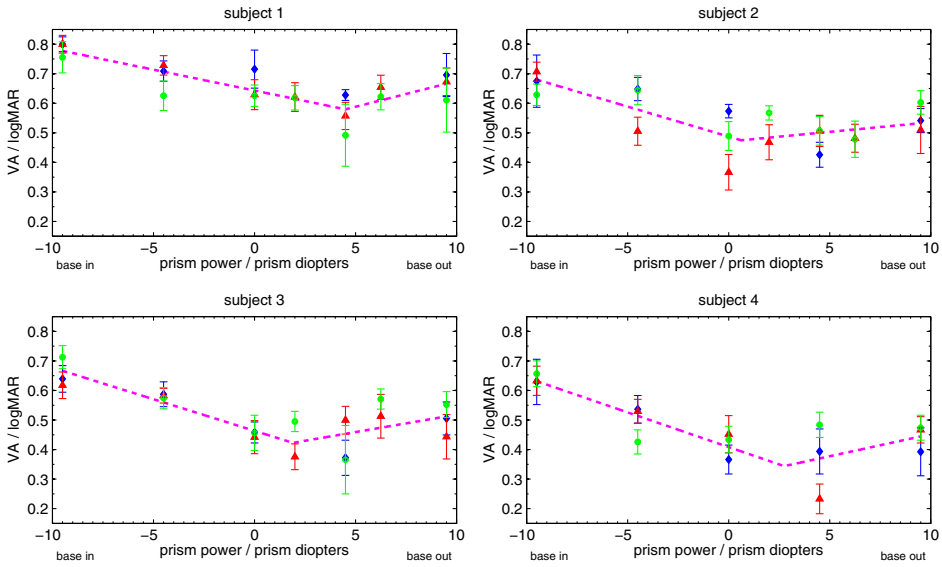

Fig. 6. Grating detection acuity in logMAR in 20° nasal visual field measured over induced prism power shown for four subjects. The magenta line shows the least square fit of the pooled data of the three measurement series (blue diamonds, red triangles, and green circles), and the error bars represent the standard deviations of the psychometric function for the individual series. The individual fit coefficients are given in Table 1.

in Figs. 5 and 6 are denoted as "slope when increasing the natural TCA" because BI prisms are expected to increase the already existing TCA of the eye (will be referred to as BI slope in this article). Similarly, slopes toward the right mainly include BO prisms, which represent an overcorrection of the natural TCA of the eye (referred to as BO slope). The average sensitivity to TCA in the fovea was calculated to be 0.011 ± 0.002logMAR/Δ for BI slope, and 0.010 ± 0.005 logMAR/Δ for BO slope. Although these slopes are very low, the fitting of the v-shaped function gives significantly smaller residual errors compared to fitting a straight line to the data (average residual absolute error of 0.03 and 0.05 logMAR, respectively).

Third, the peripheral sensitivity in grating detection acuity to TCA for all subjects is shown in Fig. 6. Similar to Fig. 5, all three measurement series are presented separately for each subject. Note that Subject 4 was not measured with the additional prisms of 2.0 Δ and 6.25 Δ. The data were pooled and a least square fit of a v-shaped function was executed in the same way as for the foveal measurements. The average sensitivity to TCA in 20° nasal visual field was 0.020 ± 0.004 logMAR/Δ for BI slope, and 0.013 ± 0.005 logMAR/Δ for BO slope (fit coefficients are given in Table 1). Note that the induced TCA that gave the best peripheral acuity was shifted BO, compared to the fovea. This shift toward BO meant that fewer data were available to calculate the slope in that direction. The slope for peripheral detection acuity with BI prisms is about twice the slope measured for foveal resolution, and the fitting of the v-shaped function, therefore, also gives significantly smaller residual errors compared to fitting a straight line to the data (average residual absolute error of 0.04 and 0.63 logMAR, respectively).

Table 1. Individual Fitting Parameters of the V-Shaped Function to Describe the Effect of Prism-Induced TCA on Foveal and Peripheral Visual Acuity for Four Subjects (S1-S4)[a]

	Subject	Slope When Increasing the Natural TCA (BI)/(logMAR/Δ)	Slope When Overcorrecting the Natural TCA (BO)/(logMAR/Δ)	Prism Power for Best Vision/Δ	Best Vision/ logMAR
Fovea	S1	−0.011	0.009	−1.59	−0.06
	S2	−0.013	0.013	0.50	−0.14
	S3	−0.009	0.003	−2.22	−0.08
	S4	−0.012	0.015	1.07	−0.09
	Average	-0.011 ± 0.002	0.010 ± 0.005	-0.56 ± 1.59	-0.09 ± 0.03
Periphery 20° nasal visual field	S1	−0.014	0.017	4.50	0.58
	S2	−0.020	0.007	0.62	0.47
	S3	−0.021	0.012	1.90	0.42
	S4	−0.023	0.015	2.75	0.34
	Average	-0.020 ± 0.004	0.013 ± 0.005	2.44 ± 1.63	0.45 ± 0.10

[a]The orientation of the prisms is denoted with a negative sign for base in (BI) aligned prisms, and results in a negative slope. Similarly, base out (BO) prisms are positive.

Finally, visual acuity was directly related to the induced TCA by combining the grating acuity measurements with those of the Vernier alignment. For this conversion, the mean slope of 0.49 arcmin/Δ from the Vernier alignment method was used, but the displacement caused by the natural foveal TCA was ignored. Furthermore, the measured TCA from the Vernier alignment was reduced by a factor of $1/\sqrt{2}$ to acknowledge the 45° rotation of the gratings relative to the prismatic gradient during the visual acuity measurements. Figure 7 shows the foveal and peripheral visual acuity as a function of induced TCA separately for each subject. The average sensitivity to TCA in the fovea was computed to be (0.032 ± 0.005) logMAR/arcmin for increasing the natural TCA of the eye (BI slope), and (0.029 ± 0.014) logMAR/arcmin for overcorrecting the natural TCA (BO slope). In the periphery, the average sensitivity to TCA was (0.057 ± 0.012) logMAR/arcmin for BI slope, and (0.036 ± 0.013) logMAR/arcmin for BO slope.

4. DISCUSSION

This study examined the effect of induced TCA on peripheral vision. A combination of stimuli spectrum and prism material, which induced 0.49 arcmin of TCA per prism diopter, was applied. This combination decreased the foveal resolution acuity by 0.032 logMAR/arcmin of induced TCA, whereas the peripheral detection acuity was decreased by 0.057 logMAR/arcmin. Furthermore, the magnitude of the natural TCA in the eye may be derived from these measurements.

A. Effect of Stimulus Properties on Induced TCA

The TCA induced by a prism is often estimated by taking the prismatic power divided by the Abbe number of the material. For the prisms in this study, one prism diopter would correspond to an angular difference of 1.07 arcmin between blue (F 486 nm) and red (C 656 nm) light. However, this estimation is assuming single wavelength colors and is not taking the spectral sensitivity of the eye into consideration. A simple theoretical convolution of the monitor spectrum with the ocular sensitivity suggests a reduction of induced TCA. Indeed, the Vernier alignment method showed that the actual magnitude of TCA induced to the eye was about 0.49 arcmin/Δ. To verify that this 50% reduction of induced TCA can be explained by the spectrum of the monitor, together with the ocular sensitivity, separate Vernier alignment measurements were performed with blue (470 nm) and red (626 nm) light emitting diodes instead of monitor phosphors as illumination. All three subjects (S4 + two other subjects) of this separate test showed sensitivity very close to 1 arcmin/Δ with the diodes, compared to the measured 0.49 arcmin/Δ when a monitor was used.

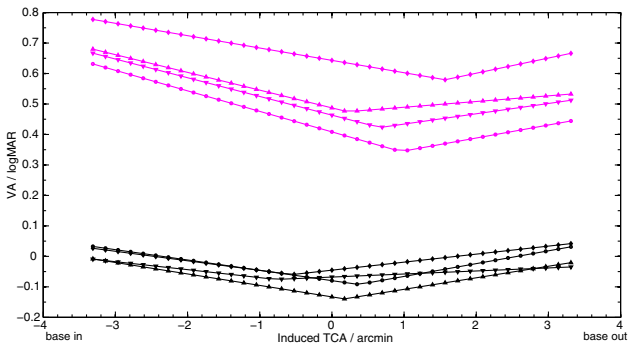

Fig. 7. Grating detection acuity in 20° nasal visual field (upper purple lines) and grating resolution acuity in the fovea (lower black lines) as a function of induced TCA in arcmin, shown for four subjects: diamonds (S1), triangles up (S2), triangles down (S3), and circles (S4); note that these markers are not representing any data points, but merely used to distinguish between subjects. Here, the grating acuity measurements (Figs. 5 and 6) are combined with the magnitude of induced TCA (Fig. 4). The average peripheral sensitivity to base in (BI) induced TCA is 0.057 ± 0.012 logMAR/arcmin compared to 0.032 ± 0.005 logMAR/arcmin in the fovea.

The dependence on illumination spectrum means that the TCA and, thereby, the blur in the retinal image caused by a certain prism will vary for different viewing conditions. Furthermore, it should be noted that the reduction in peripheral detection would have been even larger with a stimulus where the luminance variation of the grating is oriented parallel to the axis of the prisms (the same argument is equally applicable to the foveal resolution results). It is therefore important to express the reduction of visual acuity as a function of induced TCA in minutes of arc, instead of a function of prism diopters.

B. Effect of Induced TCA on Foveal Vision

Earlier studies on how induced TCA reduces the foveal resolution acuity have not measured the magnitude of induced TCA for their specific stimuli [18–23]. The numbers given in the introduction, i.e., that the visual acuity is reduced 0.1 logMAR by around 5 to 7.5 arcmin of spectacle-induced TCA, have been estimated only from the stated Abbe number of the used prisms. In other words, the reduction in foveal resolution may be larger than the 0.02 to 0.01 logMAR/arcmin estimated earlier. Indeed, our results suggest a somewhat higher sensitivity of 0.032 logMAR/arcmin.

C. Effect of Induced TCA on Peripheral Vision

The effect of induced TCA on peripheral vision was evaluated using grating detection acuity in the 20° nasal visual field. The detection task for the periphery was chosen because it is optically limited, similar to foveal resolution. This is in contrast to peripheral high-contrast resolution, which is limited by the sampling density of the retinal ganglion cells and, therefore, does not improve when the image quality on the retina is improved [28]. Furthermore, in daily life, it is more common to use the peripheral vision for detection tasks, whereas resolution tasks are mainly carried out by our active foveal vision.

When comparing the reduction in vision because of induced TCA between the fovea and the periphery, it is apparent that the peripheral detection shows a much higher sensitivity: BI slope 0.057 logMAR/arcmin compared to 0.032 logMAR/arcmin. Perhaps surprising at first, it may be understood from the difference in shape between the foveal resolution contrast sensitivity function (CSF) and the peripheral detection CSF. In this study, we have measured the highest visible spatial frequency for high-contrast gratings, i.e., the cutoff when the CSF is equal to one. When the induced TCA reduces the contrast in the image on the retina, this can be thought of as translating the

CSF downward, resulting in a lower cutoff frequency. The change in cutoff frequency will then depend on the slope of the CSF in that spatial frequency region; a flatter curve gives a larger change. Earlier studies have shown that the peripheral detection CSF with its aliased parts becomes flatter under optical correction than the foveal CSF (see Fig. 6 of [15]), which would explain the larger effect of induced TCA on peripheral detection. It should be noted that this flattening of the peripheral detection contrast sensitivity curve does not require adaptive optics correction; it is evident already with spectacles for correcting the peripheral refractive errors [15].

The peripheral grating detection acuity reduction of 0.057 logMAR/arcmin of induced TCA means that the prismatic effect of a 10 D spectacle lens potentially worsens the detection acuity in 20° off axis by more than 0.1 logMAR [29]. This number should be related to the visual functions in the 20° nasal visual field; best refractive corrected detection acuity in 100% contrast is around 0.4 logMAR, whereas the high-contrast resolution acuity stays close to 1 logMAR, also with refractive errors present [10,28]. In other words, TCA induced by high-power spectacles may hamper the ability to detect objects in the peripheral visual field when refractive errors are corrected. This study has evaluated only high-contrast acuity, i.e., maximum detectable spatial frequency, and there may be effects of induced TCA on the contrast sensitivity for lower spatial frequency as well. Extra care should be taken in situations where the peripheral refractive errors of the eye are meant to be corrected by the spectacles, for example, as is the case when designing spectacles to improve the remaining peripheral vision for people with central visual field loss [30,31]. In an earlier study on this patient group, it was found that the improvements in peripheral vision with such spectacles can be up to 0.2 logMAR [31]. Our findings imply that the success of spectacles for people with central visual field loss will depend on appropriate choices of the prism reference point (where the TCA is zero), the prismatic power, and the applied lens material (Abbe number).

D. Magnitude of the Natural TCA

The peripheral detection acuity data in Fig. 6 show a clear worsening of vision with increasing BI prisms. However, for the BO prisms, the trend is less clear as there seems to be a region of best vision without any well-defined minimum. For most subjects, vision also varied more for these prisms, and the optimum acuities measured were around 0.45 logMAR, which corresponds to 11 cycles per degree. This is clearly in the aliasing zone, but not as high as suggested by earlier studies on peripheral detection [15,32]. Most likely, we are entering a region where the TCA is no longer the main limitation to peripheral detection. Possible limitations here may be neural, as well as optical, in the form of LCA and remaining monochromatic higher-order aberrations. The flatter region implies that the v-shaped curve suggested by theory is not optimum, and the goodness of the fit for the BO prisms is much less than that of the BI prisms, as can be seen in Fig. 6.

The results from the Vernier alignment test performed with the planar lens (0 Δ) are also measures of the natural foveal TCA of the individual eyes. For the subjects of this study, the foveal TCA seems to range from close to no TCA up to about 2 arcmin of BI TCA (meaning that the short wavelengths will end up at the retina more toward the nasal side than the longer wavelengths), which is in agreement with having the visual axis of the eye located more nasally in the visual field than the achromatic axis [33]. Several other studies have also been investigating the magnitude of the foveal TCA ending up with similar values ranging up to about 3 min of arc over the visual spectrum [7,26,33–35].

It should be noted that the foveal TCA estimates of the individual subjects, found with the Vernier alignment method in Fig. 4, were not replicated by the prism power for optimal vision in the resolution acuity measurements with varying prismatic power in Fig. 5. This implies that the technique is not sensitive enough to estimate the natural foveal TCA, probably because of the slow reduction in foveal vision with increasing TCA (0.032 logMar/arcmin). However, for the peripheral detection acuity, the slope goes up to 0.057 logMar/arcmin, which suggests that it may be possible to estimate the off-axis TCA of the eye through this technique. In the results of Fig. 7, the best peripheral detection acuity is achieved for around 1 arcmin of induced BO TCA, which is, indeed, in the same direction as suggested by theory; the natural TCA of the eye in 20° nasal visual field corresponds to the one induced by a BI-aligned prism and, consequently, should be corrected by a BO prism. However, theory is suggesting about 5 arcmin of BI TCA in the 20° nasal visual field when using a blackbody radiator [8], and, although this value should be lowered for a CRT monitor, our finding of 1 arcmin BI TCA is smaller than anticipated. Still, it should be noted that we do not know how large an intersubject variability to expect; one earlier study on peripheral TCA measured subjectively by Ogboso and Bedell found TCA values ranging from 3.9 arcmin BO to 5.3 arcmin BI in the 20° nasal visual field [7].

5. CONCLUSIONS

This study shows that the peripheral grating detection acuity, in the 20° nasal visual field, is reduced by more than 0.05 logMAR/arcmin of TCA induced to the eye. The magnitude of induced TCA, as measured subjectively for stimuli presented on a computer monitor, is linearly correlated with the applied prismatic power by a factor of 0.49 arcmin/Δ. This number is less than the theoretical prediction from the Abbe number, and, therefore, the reduction of visual acuity is expressed as a function of induced TCA in minutes of arc, instead of prism diopters. The results indicate that peripheral vision is more sensitive to induced TCA than foveal vision (0.057 ± 0.012 logMAR/arcmin compared to 0.032 ± 0.005 logMAR/arcmin). This means that the prismatic effect of highly dispersive spectacles with high power can induce additional TCA large enough to lower the peripheral detection acuity. For example, the reduction with a 10 D lens can be more than 0.1 logMAR in 20° off axis. Therefore, inducing additional peripheral TCA should be avoided, especially in situations where the peripheral refractive errors of the eye are corrected, e.g., for people with central visual field loss.

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29. This number was obtained by assuming a thin lens located 14 mm in front of the eye. Light that reaches the eye in 20° off axis is entering the lens 5 mm away from the optical center. In this location, the lens will give a prismatic effect of $5\ \Delta$. If the lens is made of high dispersive material, such as the prisms in this study, $5\ \Delta$ is equivalent to inducing about 2.5 arcmin of TCA, which translates into 0.14 logMAR ($2.5\ \text{arcmin} * 0.057\ \text{logMAR/arcmin}$).
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