Contrast Sensitivity in Eyes with Central Scotoma: Effect of Stimulus Drift

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SIGNIFICANCE: In the field of visual rehabilitation of patients with central visual field loss (CFL), knowledge on how peripheral visual function can be improved is essential. This study presents measurements of peripheral dynamic contrast sensitivity (with optical correction) for off-axis viewing angles in subjects with CFL.
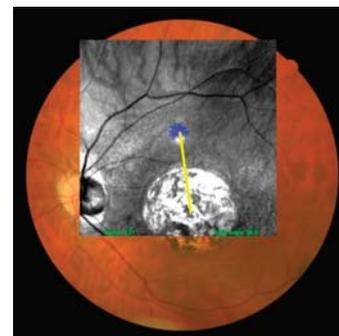
PURPOSE: Subjects with CFL rely on a peripheral preferred retinal locus (PRL) for many visual tasks. It is therefore important to ascertain that contrast sensitivity (CS) is maximized in the PRL. This study evaluates the effect of stimulus motion, in combination with optical correction, on CS in subjects with CFL.

METHODS: The off-axis refractive errors in the PRL of five young CFL subjects were measured with a COAS open-view Hartmann-Shack aberrometer. Low-contrast (25% and 10%) and high-contrast resolution acuity for stationary gratings was assessed with and without optical correction. High-contrast resolution was also measured for gratings drifting at 7.5 Hz (within a fixed Gaussian window). Furthermore, resolution CS was evaluated for both stationary and moving gratings with optical correction for a total of two to three spatial frequencies per subject.

RESULTS: High-contrast resolution acuity was relatively insensitive to stimulus drift motion of 7.5 Hz, whereas CS for gratings of 0.5 cycles per degree improved with drift for all subjects. Furthermore, both high- and low-contrast static resolution improved with optical correction.

CONCLUSIONS: Just as for healthy eyes, stimulus motion of 7.5 Hz enhances CS for gratings of low spatial frequency also in the PRL of eyes with CFL. Concurrently, high-contrast resolution is unaffected by the 7.5-Hz drift but improves with off-axis optical correction. This highlights the importance of providing optimal refractive correction for subjects with CFL and that stimulus motion can be used to further enhance CS at low spatial frequencies.

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Although the central ±5° of the visual field does not account for much more than 2% of the total visual field, loss of function in this region is devastating. This study investigates the possibility to improve the remaining peripheral vision of people with central scotomas through stimuli motion in combination with optical correction.

Several different ocular conditions can result in an absolute central scotoma and a central visual field loss. The most common cause of central visual field loss is macular degeneration, which is one of the leading causes of irreversible visual impairment in the world.[1,2] The condition predominantly affects the elderly, but central visual field loss can also result from juvenile forms of macular degeneration, such as Stargardt disease or cone-rod dystrophy, as well as from diseases affecting the optic nerve, for example, Leber hereditary optic neuritis or tumors impinging on prechiasmal locations of the visual pathways. With central visual field loss, simple tasks such as reading, recognizing faces, and a host of other activities become much more challenging because of the loss in ability to discern fine spatial details.[3–5] In order to see, patients with central visual field loss use areas in the peripheral retina, so-called preferred retinal loci.[6,7]

Peripheral vision is in many aspects worse than healthy central vision. The spatial resolution capacity at eccentric locations is limited by the coarser spacing of the cones and ganglion cells,[8–12] and high-contrast resolution acuity can therefore not exceed the neural Nyquist frequency. Because the neural Nyquist limit is often lower than the optical bandwidth in the periphery, peripheral high-contrast resolution is generally insensitive to optical errors and does not improve with increasing image quality.[13–15] However, for spatial frequencies below the neural Nyquist limit, the presence of optical errors can severely affect the peripheral visual function, such as low-contrast resolution acuity.[13,16] These characteristics of peripheral high- and low-contrast resolution acuity can be expressed as a contrast sensitivity function; the peripheral resolution contrast sensitivity function shows an abrupt cutoff at the neural Nyquist frequency, and an off-axis refractive correction mainly improves contrast sensitivity at lower spatial frequencies.[14,17] However, at the eccentric preferred retinal locus of some subjects with central visual field loss, the correction of off-axis refractive errors has also been shown to improve peripheral high-contrast resolution.[16,18] This is possible because the high spatial frequency cutoff, as well as the overall contrast sensitivity, of subjects with central visual field loss is often reduced compared with the peripheral contrast sensitivity of healthy eyes.[19–21]

It is well established that visual performance depends also on the temporal properties of the stimulus and not only on the contrast and spatial frequency content. For example, for normally sighted subjects, image motion can enhance the perception of blurry images,[22] and slow drifting eye movements increase the visibility of low and medium spatial frequencies.[23] The spatiotemporal contrast sensitivity function can therefore be considered to give a more comprehensive characterization of the sensitivity of the visual system to temporally modulated stimuli of varying spatial frequency and contrast.[24–26] In central vision, motion corresponding to approximately 5 to 10 cycles per second (Hz) enhances contrast

sensitivity at low spatial frequencies, whereas motion in excess of 10 Hz leads to a reduction in contrast sensitivity, as well as the high-contrast cutoff.[24,26] In the periphery of healthy eyes, Wright and Johnston[27] found that contrast sensitivity of stationary as well as counterphase flickering and drifting gratings reduced in a uniform linear manner from the fovea to 12° eccentricity; they therefore speculated that the effect of stimulus motion was homogenous over the visual field. A recent study confirmed that the effects of stimuli motion on peripheral contrast sensitivity are similar to those in the fovea; Venkataraman et al.[28] showed that drift motion of 5 and 10 Hz improved contrast sensitivity for gratings of low spatial frequency (0.5 and 1.0 cycles per degree [cpd]) and that 15-Hz drift led to a decrease in contrast sensitivity at higher spatial frequencies. The only difference with respect to the foveal spatiotemporal contrast sensitivity function appears to be that the peripheral high-contrast resolution is less reduced by stimulus motion; moderate amounts of motion can actually lead to improvements.[29–31] The effect of stimulus motion on contrast sensitivity in people with central visual field loss is not known; however, image jitter and scrolled text have been shown to improve word recognition and reading rates.[32–34] Legge et al.[32] evaluated the effect of scrolled text also for subjects with normal vision and found that they experienced reduced reading rates, whereas subjects with central visual field loss read 15% faster with scrolled text.[32,33] Larger improvement in contrast sensitivity may thereby be achieved for subjects with central visual field loss than for subjects with normal vision by altering the temporal characteristics of the stimuli.

This study sought to examine the effect of stimulus motion on high-contrast resolution and contrast sensitivity in five subjects with central visual field loss. The measurements were performed in the peripheral preferred retinal locus with off-axis refractive correction to achieve as high contrast sensitivity as possible for all spatial frequencies. We also measured the effect of the optical correction on the resolution cutoff at different contrast levels.

METHODS

Five subjects with longstanding (stable) central field loss participated in the study, after obtaining informed consent. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the regional ethics committee. Upon recruitment, the off-axis refractive correction in the subjects' preferred retinal locus was determined with a COAS-HD VR aberrometer for natural pupils; the refraction was determined from the second- and fourth-order spherical Zernike coefficients of a circular wavefront inscribed within the natural elliptical pupil. This optical correction was implemented with trial lenses for all subjects, except for subject S5 who was already fully corrected for the eccentric viewing angle with the habitual contact lenses. Fixation stability and preferred retinal locus location were also evaluated using a spectral Optical Coherence Tomographer/Scanning Laser Ophthalmoscope (Opko Health, Inc., Miami, FL). During the fixation test, subjects were asked to look toward the center of a white square target (2° width and height) for a period of 20 seconds with the fellow eye occluded. Fixation stability in terms of the bivariate contour ellipse area encompassing 68% of fixation points was calculated according to the method described by Steinman,[35] using the formula: bivariate contour ellipse area = $2.28\pi\sigma_H\sigma_V(1 - \rho^2)^{1/2}$, where σ_H and σ_V are the SDs of the horizontal and vertical fixation positions, and ρ is the product moment correlation of these two components. In addition, fundus photography was performed using a Canon CR-2 Plus Retinal Camera (Canon Inc., Japan).

All subjects had developed central visual field loss at an early age and as such were well aware of the location of their preferred retinal locus and the required direction of gaze needed to align this with the stimulus. They also had normal cognitive ability and part- or full-time employment. Details of diagnosis, age, off-axis refraction, preferred retinal locus location, and fixation stability for each subject are summarized in Table 1. Fundus photographs with fixation stability overlay are presented in Fig. 1, showing the position of the preferred retinal loci with respect to other retinal landmarks.

Stimuli and Apparatus

Gabor gratings were used as stimuli for both cutoff and contrast sensitivity measurement; the size of the Gaussian window was held constant ($\sigma = 1.6°$), and the orientation of the gratings was either 45° or 135° to reduce measurement variation during the peripheral vision evaluation.[36] Moving stimuli were generated by modulating the phase of the sinusoidal wave so that the grating drifted within the fixed Gaussian envelope; therefore, the retinal area stimulated remained fixed, irrespective of whether the grating was drifting.

TABLE 1. Summary of tested eye, diagnosis, age (+ age when diagnosed), off-axis refraction, PRL location (with horizontal and vertical directions in parentheses), and fixation stability (in terms of BCEA) for all subjects

Subject	Eye	Diagnosis	Age (age when diagnosed) (y)	Refraction	PRL location	BCEA (arcmin^2)
S1	Right	Stargardt	25 (10)	−1.00/−3.50 × 167	34.2° Inferior-nasal (horizontal: 8.6°, vertical: 33.1°)	5059
S2	Right	Leber optic neuropathy with photocoagulation scar in macula	50 (22)	−2.00 DS	6.0° Superior-nasal (horizontal: 5.1°, vertical: 3.1°)	5374
S3	Right	Pituitary tumor postoperative	45 (14)	−1.75/−1.25 × 75	12.9° Inferior-nasal (horizontal: 12.5°, vertical: 3.1°)	8001
S4	Left	Cone dystrophy	27 (10)	−2.25/−2.50 × 10	10.4° Inferior-temporal (horizontal: 10.1°, vertical: 2.3°)	4344
S5	Left	Stargardt	41 (6)	−9.50/−1.00 × 180 corrected with contact lenses	12.0° Inferior-temporal (horizontal: 1.6°, vertical: 11.9°)	5012

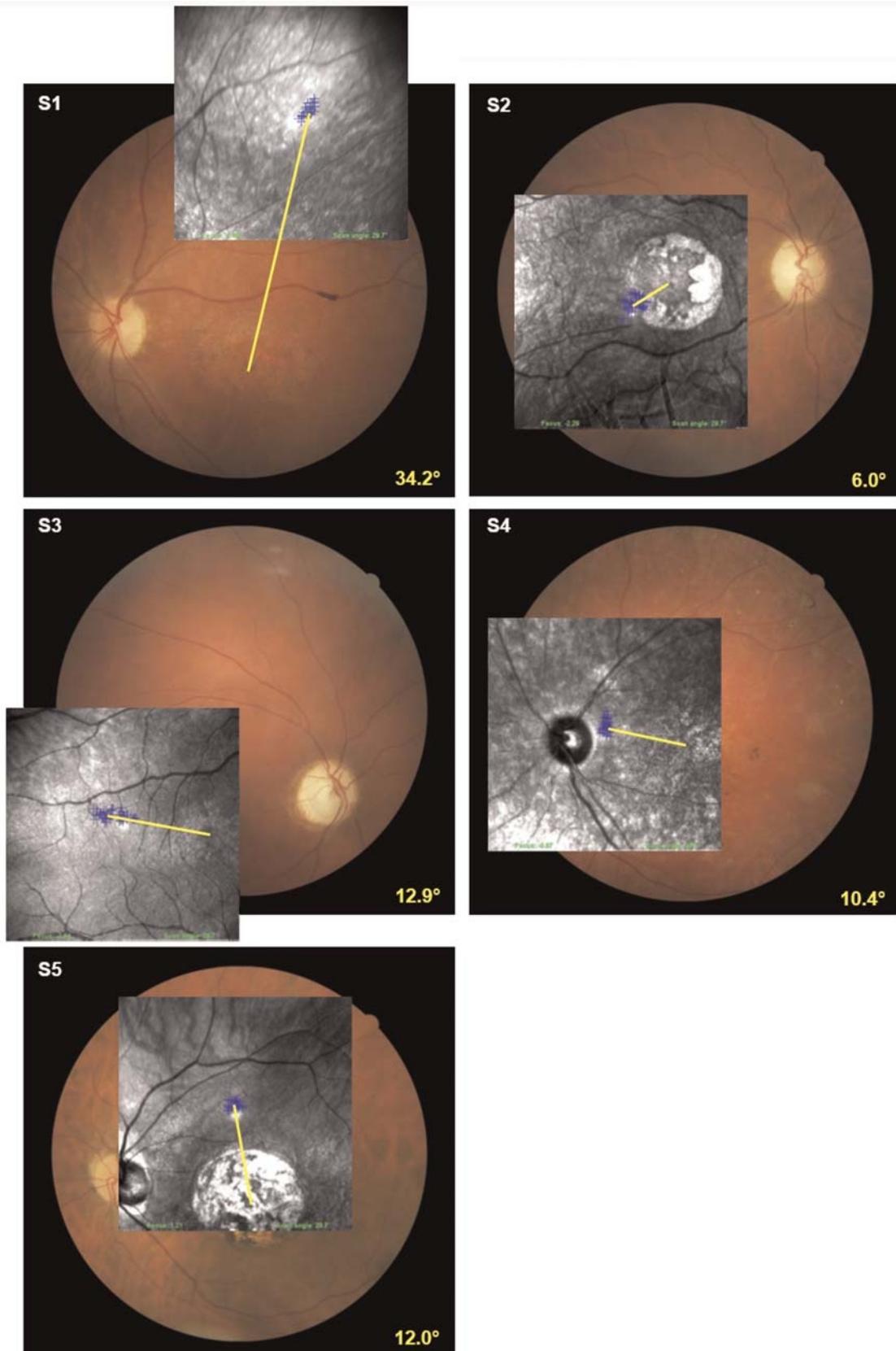BCEA = bivariate contour ellipse area; PRL = preferred retinal locus.

FIGURE 1. Fundus photographs with an overlay of the scanning laser ophthalmoscope fixation-stability images for all subjects. Details of the approximate distance (the yellow line section in degrees) to the preferred retinal locus (marked as a group of blue crosses) from the center of the nonfunctional macula are shown in the lower right corner of each photograph.

Drift velocity was specified in terms of temporal frequency, the number of cycles of the grating passing a fixed retinal location per second (cps or Hz). The direction of movement was always toward the nonfunctional macula. All measurements were conducted in the subjects' preferred eye and favored preferred retinal locus (if more than one existed) as specified in Table 1; the other eye was occluded with an IR filter. The stimuli were presented on a gamma-corrected analog CRT monitor (Nokia 446Xpro; Nokia Display Products, Finland) driven by a Linux PC (Dell PC running Linux [open source]) with a 10-bit NVIDIA graphic card. The mean luminance of the stimuli was 51.5 cd/m^2, and the rest of the room was in darkness. The monitor was 2 m away from the subject. The grating stimuli used for cutoff evaluation corresponded to 1.8 to 0.0 logMAR (75 equi-log spaced spatial frequencies ranging from 0.5 to 30 cpd, corresponding to 0.0167 to 1.00 in decimal Snellen visual acuity). For contrast sensitivity measurements, the stimuli contrast ranged from 100% to 0.4%, (64 levels equidistant in log-space). The size and spatial frequency of the stimuli were adjusted to compensate for spectacle magnification: $M = (1 - \alpha F)^{-1}$, where α is the vertex distance from the trial lens to the eye, and *F* is the spherical equivalent of the lenses; trial lenses were oriented parallel to the plane of the stumuli.

Each measurement consisted of 50 trials; the stimuli were presented for 500 milliseconds accompanied by an auditory cue. MATLAB and Psychtoolbox[37,38] were used for stimulus generation, presentation, and implementation of the psychophysical algorithms. The subjects were asked to identify the orientation of the stimulus and enter responses with a keypad; no feedback regarding correctness of the responses was given. Both the cutoff and the contrast sensitivity tasks involved a two-alternate forced-choice procedure. A Bayesian adaptive approach, the Psi method,[13,39] was used in determining the successive stimuli and in the calculation of final threshold. A guess rate of 50% and a lapse rate of 5% were set. In order to facilitate fixation, a "star" in the form of eight white paper stripes radiating outward was placed around the monitor. The subjects used this star to hold their scotoma in a fixed position so that they could make sure to view the monitor with their preferred retinal locus also when no stimulus was visible on the screen. During the vision evaluation, subjects were instructed to take regular breaks between the trials to refixate whenever required; note that the presentation of the stimuli was initiated by the subject. Furthermore, fixation stability was monitored during measurements using a Tobii X2-30 eye tracker (Tobii Pro, Sweden).

Experimental Protocol

After an initial period of training to familiarize the subjects with the psychophysical procedures, the measurement of cutoff and contrast sensitivity was conducted in two stages. First, cutoff was measured at three contrast levels (100%, 25%, and 10%), with and without off-axis refractive correction, for static stimuli (0 Hz). Thereafter, high-contrast cutoff was measured with drifting stimuli (7.5 Hz) with refractive correction. The order of temporal frequencies was randomized. Second, contrast sensitivity was determined (always with refractive correction) for both 0 and 7.5 Hz at two to three spatial frequencies chosen to be roughly equi-spaced in log scale, between 0.5 cpd and the stationary high-contrast cutoff. The order in which the different spatial and temporal frequencies were tested was randomized. A total of 21 cutoff measurements (three contrast levels × three repetitions, with and without correction for static stimuli, and at 100% contrast with off-axis refractive correction for 7.5-Hz drift) and 12 or 18 contrast sensitivity

measurements (two or three spatial frequencies × two temporal frequencies × three repetitions with Rx) were performed. The exact number of contrast sensitivity measurements depended on the high-contrast cutoff of the subject. Although the duration of a single measurement was relatively short (lasting approximately 2 minutes), the large number of measurements necessitated that these were conducted over the course of 2 consecutive days. In addition, adequate rest was given between measurements to avoid fatigue.

RESULTS

Resolution Acuity

The grating resolution cutoff acuities obtained for each subject in high (100%), 25%, and 10% contrast are given in Table 2. For comparison the last column presents the corresponding average values in the 10° nasal visual field of eyes with normal visual function (obtained from contrast sensitivity function measurements in healthy eyes).[28] The second row of Table 2 shows that stimulus drift had no conclusive effects on the high-contrast cutoff acuity. The third row shows that stationary high-contrast cutoff improved for all five subjects (although to a minor degree for S1 and S3) following correction of off-axis refractive errors at the preferred retinal locus. Similarly, all subjects showed improvements also for 25% contrast with correction; in particular, subjects S4 and S5 were unable to see the gratings at 25% without correction but were able to see them with off-axis correction. At 10% contrast, only subject S2 was able to resolve the gratings without correction; with correction in place, both subject S3 and S5 could also perform the measurements. Subjects S1 and S4 could not resolve the 10% gratings, neither with nor without correction.

Contrast Sensitivity

The contrast sensitivity curves for stationary (0 Hz indicated by blue circles) and drifting (7.5 Hz indicated by red triangles) gratings for each individual subject are shown in Fig. 2. The lines are drawn between the mean values of the contrast sensitivity measurements, as well as between the mean values of the 100% and 25% resolution cutoff measurements. As stated in the methods, contrast sensitivity was measured at one or two additional spatial frequencies, besides 0.5 cpd. Subsequently, subjects with a high-contrast cutoff below approximately 4 cpd (S1, S3, and S4) were tested at 0.5 cpd and one additional spatial frequency; the other two subjects were tested at two additional spatial frequencies. Despite the variation in appearance of the curves for the five subjects, log contrast sensitivity without stimulus drift (blue curves) tended to have a bandpass shape (contrast sensitivity decrease at low and high spatial frequencies), whereas with target motion the red curves show a more low-pass shape (no contrast sensitivity decrease at low frequencies but decrease at high spatial frequencies). Also worth noting is the increase in contrast sensitivity for movement of 7.5 Hz for the lowest spatial frequency grating tested (0.5 cpd); this being evident for all subjects. The open blue squares (□) indicate the cutoff measurements for 10% contrast for subjects S2, S3, and S5. For subjects S2 and S3, the measurements of 10% cutoff were ambiguous as their maximum log contrast sensitivity was close to 1.0 (i.e., 10% threshold). It was therefore possible for the 10% cutoff values to fall on either side of the contrast sensitivity peak as can be seen by the blue squares in Fig. 2. The 10% cutoff measurements commenced at 0.5 cpd; this also being the lowest spatial frequency used when presenting stimuli, and subsequently

TABLE 2. Summary of resolution acuities (in logMAR, take $10^{(-logMAR)}$ to convert to decimal Snellen acuity) at different contrast levels in the PRL of the five subjects (S1–S5)

Resolution acuity	S1 34° −2.8 D	S2 6° −2.0 D	S3 13° −2.4 D	S4 10° −3.5 D	S5 12° −10.0 D	Normal 10°
100% With Rx						
Stationary	1.22	0.66	1.27	1.12	0.80	0.43
Drifting	1.26	0.66	1.42	1.08	0.77	0.42
Difference	**−0.04**	**0.00**	**−0.15**	**0.04**	**0.03**	**0.01**
100% Stationary						
Without Rx	1.25	0.74	1.32	1.72	1.52	—
With Rx	1.22	0.66	1.27	1.12	0.80	0.42
Difference	**0.03**	**0.09**	**0.05**	**0.61**	**0.72**	—
25% Stationary						
Without Rx	1.56	1.04	1.64	>1.80	>1.80	—
With Rx	1.41	0.93	1.32	1.26	0.95	0.55
Difference	**0.15**	**0.11**	**0.32**	**>0.54**	**>0.85**	—
10% Stationary						
Without Rx	Not measurable	1.77	>1.80	Not measurable	>1.80	—
With Rx	Not measurable	1.59	1.64	Not measurable	1.00	0.62
Difference	Not measurable	**0.18**	**>0.16**	Not measurable	**>0.80**	—

The PRL eccentricity and spherical equivalent are given for each subject on the first row. The last column presents reference normal values.[28] Positive differences represent improvement with stimulus drift (second row, 7.5 Hz for S1–S5 and 5 Hz for the normal data) or correction (third to fifth row). When cutoff was not measurable without correction, the minimum theoretical difference is shown; the maximum-measurable logMAR was 1.8 logMAR (0.48 cpd or 0.016 in decimal Snellen acuity). BCEA = bivariate contour ellipse area; PRL = preferred retinal locus.

the lowest value that could be measured, which explains the two divergent values at 0.5 cpd for subject S3.

Effects of Stimulus Motion

A summary of the changes in log contrast sensitivity with movement is given in Table 3. For comparison, the last column presents the corresponding average values in the 10° nasal visual field of eyes with normal visual function.[28] As can be seen from both Fig. 2 and Table 3, contrast sensitivity improved with movement of 7.5 Hz for stimuli of 0.5 cpd for all subjects. Regarding the intermediate spatial frequencies, contrast sensitivity improved significantly for subject S2 at both additional spatial frequencies tested, whereas a decrease was seen for the second lowest spatial frequency for subjects S1 and S5. We did not observe any conclusive effects of temporal frequency on the high-contrast cutoff for these subjects, with the exception of S3 who showed a reduction in high-contrast cutoff for drifting gratings (Table 2).

DISCUSSION

This study shows that stimulus motion generally enhances contrast sensitivity at the preferred retinal locus of subjects with central field loss; the changes in contrast sensitivity with motion of 7.5 Hz are most pronounced for low spatial frequencies. This is likely because stimulus motion prevents the fading of low spatial frequency objects, as has been shown when comparing foveal contrast sensitivity between eyes with natural microfluctuations and with artificial stabilization.[40] In addition, off-axis optical correction improved resolution for both high- and low-contrast static stimuli.

As seen in previous studies investigating peripheral contrast sensitivity, the present study included only a few subjects, mainly because of the large number of measurements performed and the long testing time. For this reason, and because of the heterogeneity of the underlying cause of central visual field loss, formal tests of statistical difference were deemed inappropriate. Nonetheless, the individual results were repeatable and showed similar trends across all five subjects, and the improvements in contrast sensitivity at low spatial frequency with stimulus motion were comparable to those observed in studies on healthy individuals both in the fovea[24–26] and in the periphery.[27,28] In addition, the stationary contrast sensitivity functions for the five subjects in the present study display a similar pattern of interindividual variation as in earlier studies on contrast sensitivity in low vision.[19–21]

Stimulus motion equivalent to a drift of 7.5 Hz did not affect the high-contrast cutoff on the whole, with the exception of subject S3, who showed a lower cutoff. This may be due to the underlying cause of the central visual field loss for this subject (optic atrophy after pituitary tumor treatment), resulting in a generally depressed contrast sensitivity function with worse high-contrast cutoff than the other four subjects. Nonetheless, the insensitivity of the high-contrast cutoff to movement has also been reported earlier by Lewis et al.,[30] Rosén et al.,[13] and Venkataraman et al.,[28] who all found that high-contrast resolution acuity in the periphery was relatively unaffected by drift motion up to approximately 15 Hz in healthy subjects. This is opposite to foveal studies, in which stimulus motion reduces the neural response because of temporal summation processes that lead to a decrease in the perceived contrast.[26,40,41] However, the sampling limited nature of the peripheral high-contrast cutoff could be the reason behind its insensitivity to moderate drift
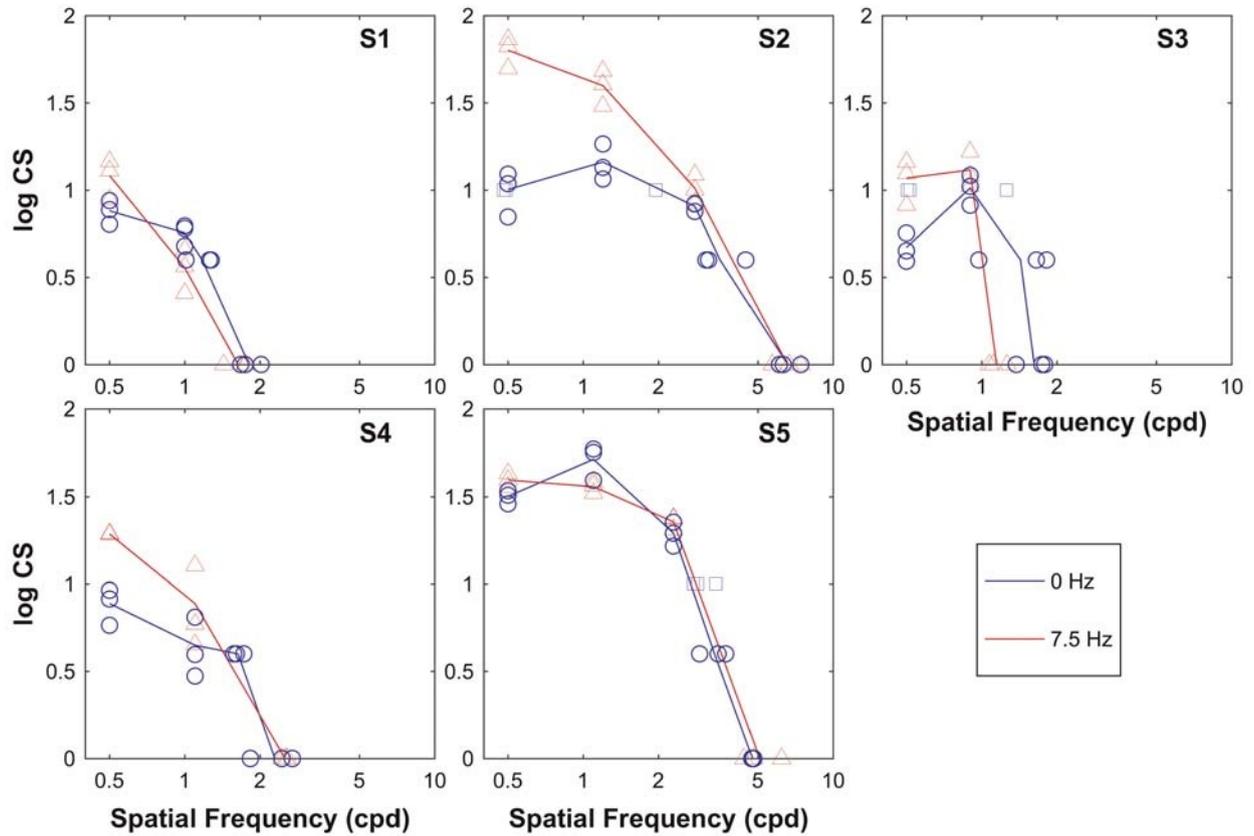
FIGURE 2. Log contrast sensitivity functions (logCS) for subjects S1 to S5. The blue line sections denote stationary contrast sensitivity, and red lines denote contrast sensitivity for 7.5 Hz. The individual measurement points for the three repeated contrast sensitivity measurements are shown as open blue circles (○) and as open red triangles (△) for 0 Hz and 7.5 Hz, respectively. Similarly, the measurement points for the stationary 100% and 25% cutoff are plotted with the same symbols. The 10% cutoff values (where measurable) are shown as open blue squares (□).

motion.[28] In the present study, even though the high-contrast cutoff was contrast limited in at least three of the subjects without optical correction, there were no changes in the high-contrast cutoff with stimulus motion when these subjects wore their optical correction; the reason for this may be the relatively low temporal frequency of 7.5 Hz used.

With optical correction, the stationary high-contrast cutoff improved significantly for at least three of the five subjects, which is in line with the results of Gustafsson,[42] Gustafsson and Unsbo,[43] Lundström et al.,[16] and Baskaran et al.,[18] who also saw improvements in high-contrast resolution acuity in subjects with central visual field loss following the correction of refractive errors in the preferred retinal locus. Other studies evaluating the effect of

optical errors on peripheral high-contrast resolution acuity have found contradictory results.[15,44–46] However, those studies were conducted on subjects with normal macular function. The dissimilarity in peripheral visual function between subjects with central visual field loss and healthy subjects is a likely cause for these differences; as seen in Table 2, the subjects with central visual field loss in this study had lower contrast sensitivity and more reduced high-contrast cutoff compared with the healthy subjects in a similar study by Venkataraman et al.,[28] even though the latter study was conducted at similar eccentricities as the preferred retinal loci in the current study (with the exception of S1 whose preferred retinal locus was located ~34° from the nonfunctional macula). The peripheral high-contrast resolution acuity can thereby be

TABLE 3. Summary of the differences in contrast sensitivity (logCS) for stationary versus gratings drifting at 7.5 Hz at different spatial frequencies (cpd = cycles per degree, take cpd/30 to convert to decimal Snellen acuity)

SF	S1 34° −2.8 D	S2 6° −2.0 D	S3 13° −2.4 D	S4 10° −3.5 D	S5 12° −10.0 D	Normal 10°
0.5 cpd	0.20	0.80	0.39	0.41	0.09	0.40
SF2 (0.9–1.2 cpd)	−0.21	0.44	0.10	0.22	−0.15	0.27
SF3 (2.3–2.8 cpd)	Not measured	0.10	Not measured	Not measured	0.07	0.08

The last column presents reference normal values.[28] Positive values indicate improvement in CS with movement. Note that all subjects wore off-axis refractive correction during CS measurements. CS = contrast sensitivity; SF = spatial frequency.

contrast limited for subjects with central visual field loss and optical correction serves to reduce this limitation by improving image contrast. Optical correction also gave improvements in the cutoff at 25% contrast for all subjects and at 10% contrast in those subjects for which 10% cutoff was measurable. The observed improvements in visual acuity were clearly the largest for those subjects with higher off-axis refractive errors; the average improvement with off-axis correction expressed as total scalar power for subjects S2 to S5 was greater than 0.08, 0.10, and 0.08 logMAR/D in 100%, 25%, and 10% contrast, respectively, which is comparable to 0.07 logMAR/D at 10% contrast for healthy subjects in the 20° nasal visual filed.[47] This finding stresses the importance of correcting the peripheral optical errors in subjects with central visual field loss to improve their resolution acuity also at low-contrast levels. Furthermore, as the contrast sensitivity curves are lower than those for healthy subjects, this is a further incitement for the correction of off-axis refractive errors in order to maximize contrast. A dependence of low-contrast resolution acuity on optical defocus has been noted earlier also for subjects with normal vision.[13,18]

All five subjects had well-trained preferred retinal loci with relatively more stable fixation (bivariate contour ellipse area values of 4344 to 8001 arcmin[2]) compared with some earlier low-vision studies.[48,49] The bivariate contour ellipse area values were larger than for healthy subjects fixating foveally (100 to 650 arcmin[2] according to Crossland and Rubin[50]). This was expected as subjects with macular disease have been shown to have larger fixation instability, mainly due to increased amplitude of microsaccades and slow drifts.[51] Larger eye movements would alter the velocity of the stimulus on the retina, but as long as these are similar for both stationary and drifting gratings, any difference in vision can be attributed to the drift of the stimuli. For the subjects in this study, the average eye movements during the psychophysical measurements were between 0.45° and 0.66° and 0.50° and 0.66° for stationary and drifting stimuli, respectively. As shown in the example in Fig. 3, the eye movements were similar between stationary and drifting gratings, and the subjects were acting as their own controls. We thereby conclude that the improved vision in the preferred retinal locus found in our study was due to the temporal frequency of the drifting stimuli.

The implications of these findings are that stimulus motion is integral in ameliorating some of the effects of reduced contrast sensitivity experienced by subjects with central visual field loss. Pan and Bingham[22] also suggested that motion-based information could counteract the effects of deficits in sensitivity at high spatial frequencies; thus, it may allow patients with low vision to recognize moving objects more readily than stationary objects. Modalities in which scrolled or jittered text is used as a method of enhancing visual performance and reading speed should consider the temporal frequency characteristics of stimulus motion. Unfortunately, the previous studies examining the effect of image motion on reading and word recognition[32–34] did not specify the speed of motion. The speed either was chosen as the "most comfortable" speed for reading for the subject[33] or was given in terms of drift speed in words per minute,[32] or interjitter interval,[34] making comparisons with the present study impossible. The fundamental spatial frequency of the text samples used by Watson et al.[34] were reported to be approximately 0.25 or 0.50 cpd, depending on viewing distance, which is of a similar magnitude as the lowest spatial frequency grating used in the present study. It is perceivable that the temporal characteristics of stimulus motion in the other two studies[32,33] happened to coincide with the "optimal" temporal frequency for the predominating spatial frequency of the reading text, although without this information we are left to speculate.
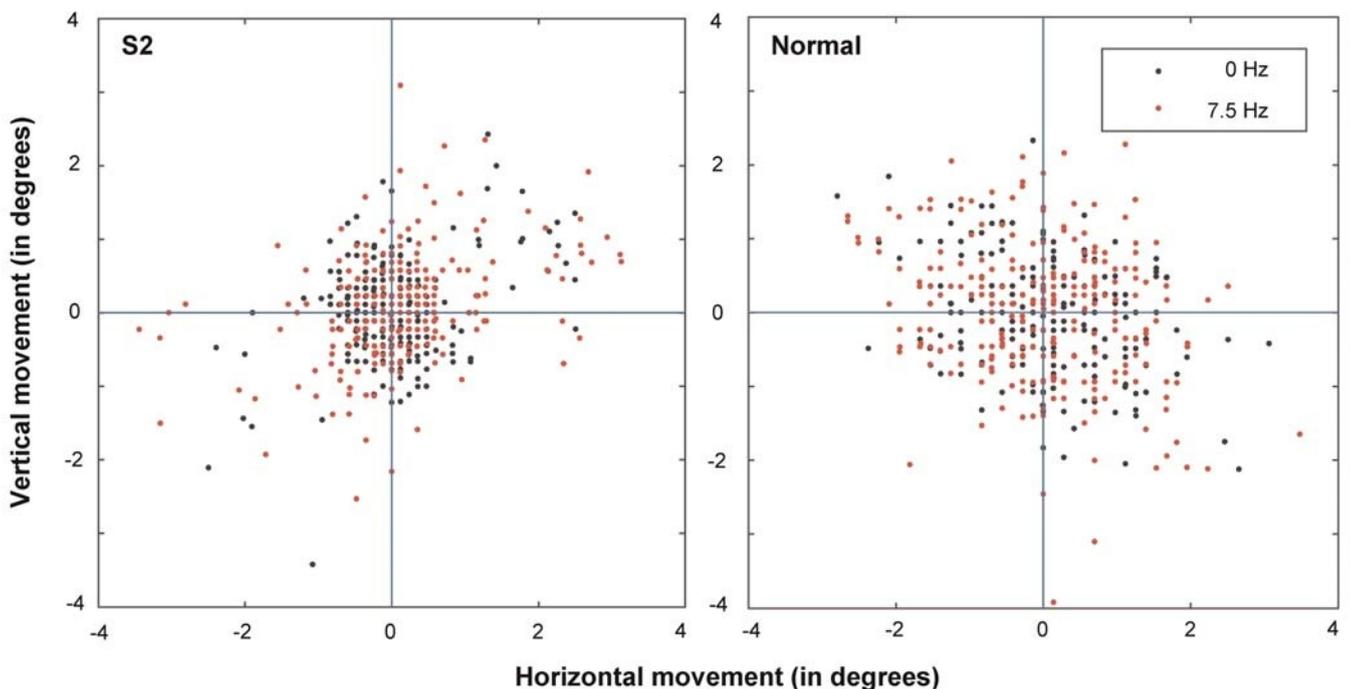

FIGURE 3. Examples of eye-tracker data recorded during the peripheral vision evaluation. The scatterplots show eye movements during two contrast sensitivity measurements at 0.5 cpd; black dots show the deviation in fixation horizontally and vertically for stationary gratings (0 Hz), and red dots are for drifting gratings (7.5 Hz). The left graph is for subject S2 in this study, and for comparison, an example for a subject with healthy vision is shown to the right (data obtained in the 10° nasal visual field on one subject, with the same task but aided by a foveal fixation target[28]).

To our knowledge, this is the first study in which contrast sensitivity under conditions of drift motion have been measured on young subjects with long-standing central visual field loss. The results highlight that stimulus motion corresponding to 7.5 Hz has a beneficial and significant effect on contrast sensitivity for objects of low spatial frequency, as well as the importance of fully correcting off-axis refractive errors in subjects with central visual field loss in order to also maximize resolution acuity. Naturally, further studies should be conducted in order to investigate whether these benefits can also be seen in subjects with age-related macular degeneration.

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