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Peripheral resolution and contrast sensitivity: Effects of stimulus drift

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ABSTRACT

Optimal temporal modulation of the stimulus can improve foveal contrast sensitivity. This study evaluates the characteristics of the peripheral spatiotemporal contrast sensitivity function in normal-sighted subjects. The purpose is to identify a temporal modulation that can potentially improve the remaining peripheral visual function in subjects with central visual field loss. High contrast resolution cut-off for grating stimuli with four temporal frequencies (0, 5, 10 and 15 Hz drift) was first evaluated in the 10° nasal visual field. Resolution contrast sensitivity for all temporal frequencies was then measured at four spatial frequencies between 0.5 cycles per degree (cpd) and the measured stationary cut-off. All measurements were performed with eccentric optical correction. Similar to foveal vision, peripheral contrast sensitivity is highest for a combination of low spatial frequency and 5–10 Hz drift. At higher spatial frequencies, there was a decrease in contrast sensitivity with 15 Hz drift. Despite this decrease, the resolution cut-off did not vary largely between the different temporal frequencies tested. Additional measurements of contrast sensitivity at 0.5 cpd and resolution cut-off for stationary (0 Hz) and 7.5 Hz stimuli performed at 10, 15, 20 and 25° in the nasal visual field also showed the same characteristics across eccentricities.

1. Introduction

A thorough knowledge of the peripheral visual function is important for a complete understanding of our visual system. The direct applications are enhancement of vision for people with central visual field loss and better understanding of the development of myopia. Compared to the fovea, the periphery is characterized by reduced neural sampling (Curcio & Allen, 1990; Curcio, Sloan, Kalina, & Hendrickson, 1990) and degraded optics (Gustafsson, Terenius, Buchheister, & Unsbo, 2001; Lundström, Gustafsson, & Unsbo, 2009; Mathur, Atchison, & Scott, 2008). Foveal vision is largely limited by optical errors and the foveal CSF shows a gradual loss in sensitivity with increasing spatial frequency in accordance with the optical modulation transfer function of the eye. However, in the periphery high contrast resolution acuity cut-off is sampling-limited (Rosén, Lundström, & Unsbo, 2011; Wang, Thibos, & Bradley, 1997) and the peripheral resolution CSF is therefore characterized by an abrupt drop at the cut-off spatial frequency (Rosén, Lundström, Venkataraman, Winter, & Unsbo, 2014; Thibos, Still, & Bradley, 1996). In spite of the reduced neural sampling, detection thresholds and low contrast resolution in the periphery are dependent on the contrast of the retinal image and hence proper eccentric optical correction is needed during evaluation (Cheney, Thibos, & Bradley, 2015; Rosén et al., 2011, 2014; Wang et al., 1997).

In addition to visual field location, the CSF is also known to be dependent on the temporal characteristics of the stimulus and hence a more thorough measure is the spatiotemporal CSF surface (Daly, 1998; Kelly, 1985; Robson, 1966; Wright & Johnston, 1983). The visual environment contains an abundance of moving objects both in the line of sight and particularly in the peripheral visual field. Additionally, our eyes are never completely motionless; micro-movements help prevent the fading of visual stimuli. The foveal CSF of an eye with artificial stabilization for motion will be severely reduced and it is shown that the CSF of a stabilized eye evaluated with targets moving at a velocity equivalent to the eye's drift motion (about 0.15 degree/s) resembles the stationary CSF of an unstabilized eye (Kelly, 1985). It is well documented that the shape of the foveal CSF varies for different temporal frequencies (Daly, 1998; Robson, 1966). Temporal-modulated stimuli give rise to changes in both the cut-off spatial frequency and the peak of the foveal CSF. Contrast sensitivity at low spatial frequencies is enhanced when the stimulus motion corresponds to about 5–10 cycles per second (cps or Hz). Increasing the stimulus motion beyond 10 Hz results in reduced contrast sensitivity and the foveal

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cut-off is shifted to lower spatial frequencies (Daly, 1998; Kelly, 1985).

It should be noted that peripheral vision differs from central vision in many aspects of motion processing, such as velocity discrimination (McKee & Nakayama, 1984), critical flicker frequency (Hartmann, Lachenmayr, & Brettel, 1979), reaction time and perceived velocity for slow moving targets (Tynan & Sekuler, 1982), as well as detection thresholds for speed change (Traschütz, Zinke, & Wegener, 2012). Different studies on the effect of temporal frequency on peripheral vision do not agree fully. One study reported that the variations in contrast sensitivity with temporal modification were uniform from the fovea and out to 12° eccentricity, suggesting that the sensitivity to temporal parameters is homogeneous throughout the visual field (Wright & Johnston, 1983). However, recent reports on peripheral high contrast resolution cut-off have shown that drifting gratings and stationary gratings give similar thresholds, which is not the case in the fovea (Lewis, Rosén, Unsbo, & Gustafsson, 2011; Rosén et al., 2011). Furthermore, two reports (Anderson, 1996; R.S. Anderson, Detkova, & O'Brien, 1995) state that peripheral resolution of stimuli of different contrasts is stable until around 10 Hz, whereas another report (S.J. Anderson, Drasdo, & Thompson, 1995) states that peripheral resolution is stable for contrasts above 10% for temporal frequencies up to 24 Hz. This lack of consensus could be because previous studies have focused on different regions of the spatiotemporal CSF. To get a clearer picture on the effects of temporal modification on peripheral vision, both cut-off and contrast sensitivity should be evaluated for a range of temporal frequencies. Such elaborate measurements will be helpful in determining whether modulating the visual stimulus temporally can have implications in improving peripheral vision in subjects with central vision loss. This paper focuses on the changes in peripheral CSF with temporal frequencies to investigate if the pattern of CSF changes is similar to the foveal model. Grating resolution cut-off and contrast sensitivity measurements were performed for both stationary and drifting gratings up to 15 Hz in the 10° nasal visual field of normal-sighted eyes. Additional sets of measurements on low spatial frequency contrast sensitivity and resolution cut-off were conducted at eccentricities out to 25° in the nasal visual field in order to evaluate the variation across eccentricities.

2. Methods

Three of the authors (S1, S2 and S3, aged 31–43 years), who are experienced subjects in psychophysical evaluation of peripheral vision, participated in the first set of measurements. A second set of measurement was performed on one of the author (S1) and in two more subjects (S4 and S5, aged 27 and 28 years) who were naïve to the purpose of the study and were inexperienced in performing psychophysical measurements. All subjects had normal visual function and no ocular diseases. S1, S3 and S4 were emmetropic while S2 and S5 were myopic (−2.50DS and −3.00 DS respectively) and were corrected with soft contact lenses. The study protocol adhered to the tenets of the Declaration of Helsinki, approved by the regional ethics committee, and informed consent was obtained from the subjects.

3. Stimuli and apparatus

For both peripheral resolution cut-off and contrast sensitivity evaluations, the stimulus was a sinewave grating enveloped in a Gaussian window of 1.6° standard deviation. As the measurements were made in the horizontal visual field meridian, the grating was oriented obliquely at either 45° or 135° to avoid bias towards certain orientations (Venkataraman, Winter, Rosén, & Lundström, 2016). For the moving stimuli, the drift was produced by dynamically altering the phase of the sinewave within the stationary Gaussian envelope; the stimulus thereby stimulated the same retinal area independent of whether it was moving or stationary. The temporal drift was quantified in terms of the number of grating-cycles passing a certain retinal location per second (cps or Hz). The direction of movement was always towards the fovea. A Hartmann-Shack wavefront sensor was used to determine the eccentric optical corrections based on the second order Zernike values. All psychophysical measurements were performed with appropriate trial lenses to correct for these eccentric refractive errors.

A high contrast Maltese cross was used as an external foveal fixation target for the right eye to control the measurement angle. Additionally, the fixation stability was monitored using a Tobii X-30 eye tracker. The subject was seated 2 m from the foveal fixation target and the monitor used to present the stimuli. The monitor was an analogue cathode-ray-tube monitor (Nokia 446Xpro) driven by a Linux PC with a 10-bit NVIDIA graphic card. It was calibrated to give a linear response in luminance with the mean luminance of the stimuli set to 51.5 cd/m^2. The entire range of the luminance table (0–103 cd/m^2) was used to present stimuli for the high contrast resolution cut-off measurements. Due to the insufficient number of displayable low-contrast stimuli to estimate the CSF (even with the high-end 10-bit graphic card), we redefined the gamma curve of the monitor to display a narrower range of luminance values in smaller steps. The contrast sensitivity measurements could thereby utilize the central 1/8th (luminance between 45 and 58 cd/m^2) of the original color look up table interpolated to 10-bit resolution.

The stimuli set for resolution acuity cut-off consisted of gratings corresponding to 0.0–1.8 logMAR (75 levels equidistant in log-space), which is equivalent to spatial frequencies of 30–0.5 cycles per degree (cpd). For contrast sensitivity measurements, stimulus contrast ranged between 12.5% and 0.4%, corresponding to a contrast sensitivity of 8–256 (64 levels equidistant in log-space). The extent and spatial frequency of the stimuli were scaled to compensate for the spectacle magnification: $M = 1/(1 - aF)$ where a is the vertex distance from the trial lens to the eye and F is the spherical equivalent of the lenses. Each stimulus was presented for 500 ms accompanied by an auditory cue. The generation and presentation of the stimuli and the implementation of the psychophysical algorithms were carried out in Matlab and Psychtoolbox (Brainard, 1997; Pelli, 1997). In the 2-alternative forced choice procedure, the subjects identified the orientation of the gratings and responded with a keypad. No feedback was given about the correctness of the response. A Bayesian adaptive approach was used to choose the successive stimuli and to calculate the final threshold (Kontsevich & Tyler, 1999; Rosén et al., 2011). A guess rate of 50% and a lapse rate of 5% were set. The threshold estimation consisted of 50 trials and took about 2 min.

4. Experiment protocol

Resolution cut-off and contrast sensitivity were evaluated for four temporal frequencies: 0, 5, 10, and 15 Hz with three repetitions. The first set of measurements was conducted on three subjects in the 10° nasal visual field of the right eye with the left eye occluded. The order of temporal frequencies and repetitions was randomized for the resolution measurements. The contrast sensitivity measurements were performed at four spatial frequencies; the lowest spatial frequency (SF1) was 0.5 cpd (equivalent to 1.8 logMAR) and the other three spatial frequencies (SF2, SF3 and SF4) were chosen to be equi-spaced in log scale between 0.5 cpd and the measured stationary cut-off spatial frequency. The testing-order of spatial and temporal frequency combinations was randomized. In total, 12 high contrast resolution cut-off measurements (4 temporal frequencies × 3 repetitions) and 48 contrast sensitivity measurements (4 spatial frequencies × 4 temporal frequencies × 3 repetitions) were performed. The entire set of measurements was spread across two days because peripheral measurements demand proper attention and fixation with adequate breaks given after every three measurements to avoid fatigue.

A second set of measurements were performed on S1, S4 and S5 to evaluate the effect of stimulus drift across different visual field eccentricities. Based on the results of the first set of measurements at 10° eccentricity, only low spatial frequency (0.5 cpd) contrast sensitivity and high spatial frequency cut-off were evaluated with stationary gratings and with temporal drift of 7.5 Hz. The same stimuli and psychophysical protocol as explained above were used, and the measurements were performed over eccentricities from 10° to 25° in the nasal visual field in 5° steps. The measurement orders were randomized. In total, 24 high contrast resolution cut-off measurements (4 eccentricities × 2 temporal frequencies × 3 repetitions) and 24 contrast sensitivity measurements (4 eccentricities × 2 temporal frequencies × 3 repetitions) were performed.

5. Results

The peripheral resolution acuity cut-off at the four temporal frequencies for each subject is presented in Fig. 1. The average cut-off spatial frequency for stationary stimuli (0 Hz) was 13.0, 11.9 and 8.9 cpd (corresponding to 0.36, 0.40 and 0.53 logMAR respectively) for subjects S1, S2 and S3 respectively. It can be seen from Fig. 1 that there is no direct relation between the change in resolution cut-off and the temporal frequencies. The changes in resolution cut-off for 5 and 10 Hz compared to 0 Hz are within the measurement variation in all three subjects. For 15 Hz, S1 and S3 had a small reduction compared to 0 Hz, whereas S2 does not show such changes.

The CSF curves in the 10° nasal visual field are shown in Fig. 2. The values of cut-off spatial frequency are taken from the resolution measurements and the logarithm of the contrast sensitivity

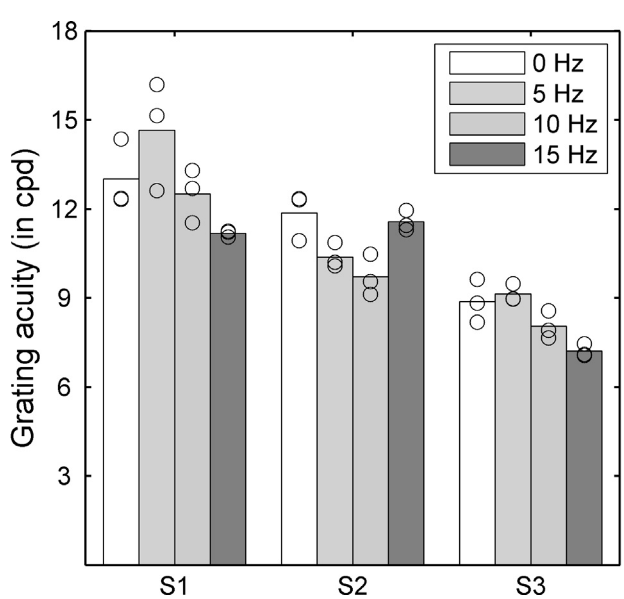

Fig. 1. Grating resolution acuity cut-off in the 10° nasal visual field at four different temporal frequencies for subjects S1-S3. Open circles represent individual measurements and columns represent the mean values.

(log CS) values for the other four spatial frequencies are from the CS measurements. As stated in the methods, these four spatial frequencies were chosen to be equi-spaced in log scale between 0.5 cpd (SF1) and the measured stationary cut-off for each individual subject; SF2 was close to 1.0 cpd in all three subjects, SF3 was around 2–3 cpd and SF4 was around 4–6 cpd. The CS values were repeatable and the maximum standard deviation of the three repetitions was 0.13 log CS. It is worth noting that the variation in the shape of the CSF curve for the different temporal frequencies is very similar between subjects. For all three subjects, the highest contrast sensitivity with stationary gratings was found at SF3. For drifting gratings, the highest contrast sensitivity shifted towards lower spatial frequencies, and for 15 Hz drift SF1 showed the highest contrast sensitivity for all three subjects. From the individual values plotted on Fig. 2, it can be clearly seen that in the low spatial frequency region, the 5 Hz and 10 Hz (red and green markers) drift produces a substantial increase in the contrast sensitivity compared to stationary stimuli (black markers).

The maximum change in log CS with moving stimuli was seen for the spatial frequency of 0.5 cpd (SF1), where CS improved with all temporal modulations compared to stationary stimuli. On average, an improvement of 0.39 ± 0.09, 0.34 ± 0.03 and 0.16 ± 0.05 log CS was seen for 5, 10 and 15 Hz respectively. SF2 also showed improvements with both 5 and 10 Hz modulation (0.27 ± 0.03 and 0.21 ± 0.08 log CS). On the contrary, a considerable decrease in CS was noted for both SF3 (−0.27 ± 0.05 log CS) and SF4 (−0.29 ± 0.04 log CS) with 15 Hz drift.

In the second set of measurements, the resolution cut-off and contrast sensitivity for 0.5 cpd at eccentricities between 10° to 25° showed similar changes between stationary (0 Hz) and drifting gratings (7.5 Hz) in all three subjects. In all eccentricities, the high contrast resolution cut-off did not vary between stationary gratings (0 Hz) and drifting gratings (7.5 Hz) (Fig. 3). The improvement in contrast sensitivity with 7.5 Hz drift compared to the stationary gratings (0 Hz) was also uniform across eccentricities (Fig. 4).

6. Discussion

This study shows that contrast sensitivity in the 10° nasal visual field is enhanced at low spatial frequencies (0.5 and 1.0 cpd) with temporal drift of 5–10 Hz. At higher spatial frequencies, there was a decrease in contrast sensitivity with 15 Hz drift. The improvement in contrast sensitivity at 0.5 cpd with 7.5 Hz drift was similar across eccentricities from 10° to 25°.

Most previous studies on peripheral contrast sensitivity evaluation (Anderson, 1996; R.S. Anderson et al., 1995; S.J. Anderson et al., 1995; Thibos et al., 1996), included only a few subjects; mainly because of the long and challenging measurements. The present study also only included three subjects for each set of measurements. However, the individual results were repeatable and the same trend was observed across all subjects. Furthermore, the results agree well with other similar studies. For example, Wright and Johnston (Wright & Johnston, 1983) also reported that the contrast sensitivity decreased with 8 and 16 Hz motion for the spatial frequencies of 2 and 6 cpd, but improved for lower spatial frequency (0.25 cpd) in the fovea and out to 12° eccentricity. Those results were found with counterphase-modulated gratings, but the same study also confirmed that the effect of temporal frequency were similar for drifting gratings and counterphase gratings in both fovea and periphery, though the absolute value for contrast sensitivity was approximately 0.3 log units better for drifting gratings compared to counterphase gratings. Earlier reports also confirm that high contrast resolution cut-off (up to 15 Hz) is similar for stationary and counterphase gratings in the peripheral visual

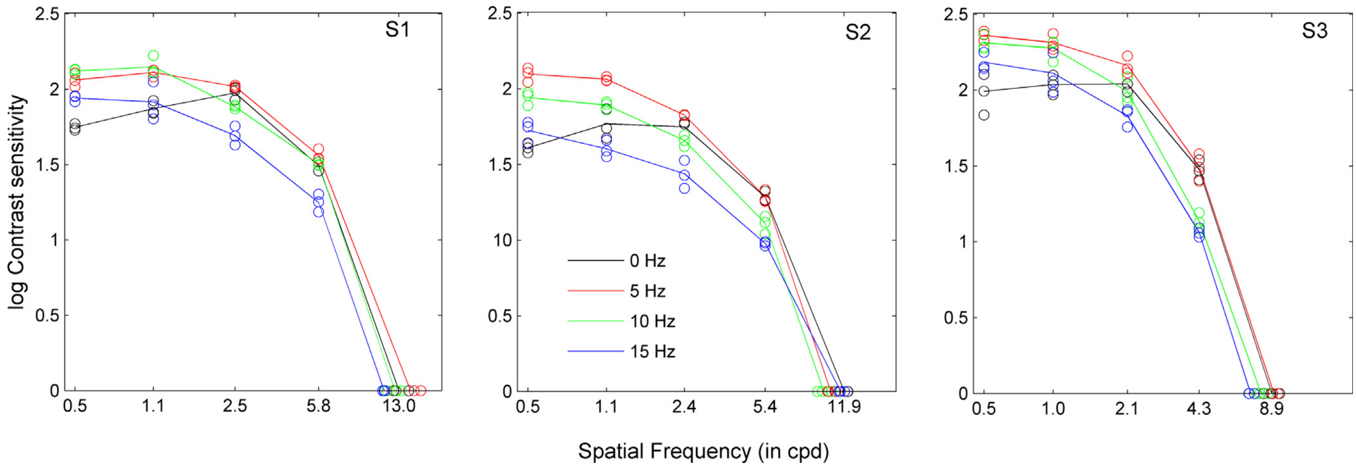

Fig. 2. The logarithm of the contrast sensitivity in the 10° nasal visual field in three subjects for 4 different spatial and temporal frequencies. Markers represent the three repetitions and lines represent the average. The spatial frequency values for log CS = 0 were obtained from the resolution cut-off measurements shown in Fig. 1.

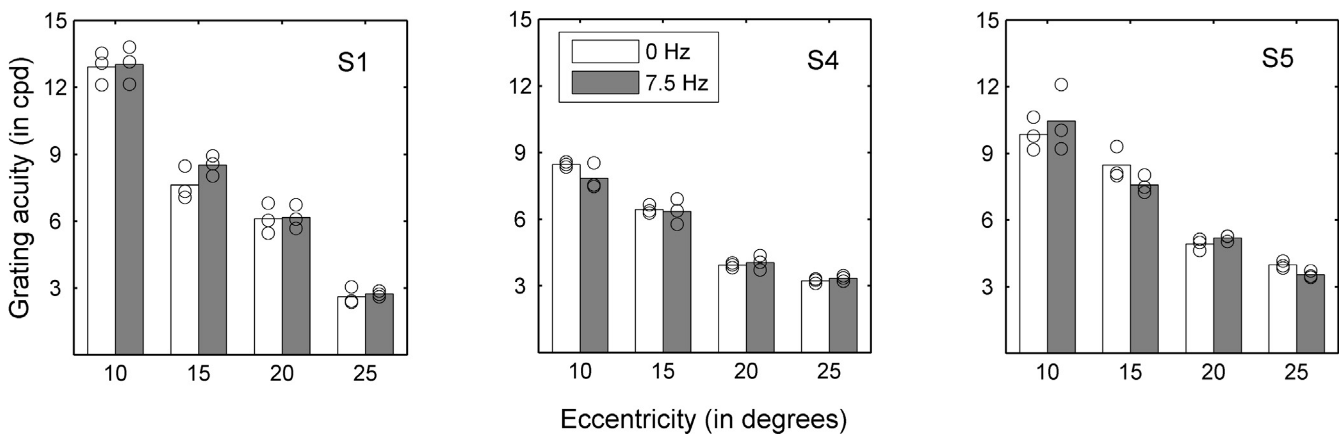

Fig. 3. High contrast resolution acuity cut-off in different eccentricities with stationary (0 Hz) and drifting gratings (7.5 Hz). Open circles represent individual measurements and columns represent the mean values.

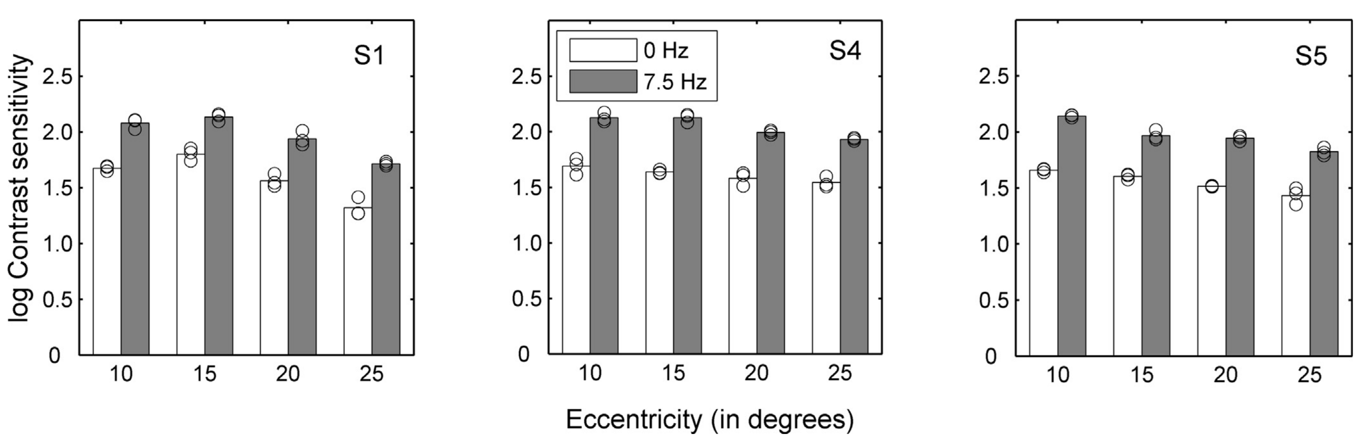

Fig. 4. The logarithm of the contrast sensitivity (log CS) for 0.5 cpd stationary (0 Hz) and drifting (7.5 Hz) gratings in different eccentricities. Open circles represent individual measurements and columns represent the mean values.

field (Anderson, 1996; R.S. Anderson et al., 1995; Lewis et al., 2011; Rosén et al., 2011).

Except for the resolution cut-off, the changes in peripheral CSF with stimulus drift found in this study were similar to that of the foveal CSF reported earlier. The stationary CSF in 10° nasal visual field is a band-pass function of the spatial frequency, with the peak located around 2–3 cpd for all subjects. With drifting gratings, the CSF alters to a low-pass function as shown in Fig. 2. This behavior is similar to that of foveal vision which also shows a low-pass spatial response at high temporal frequencies (Burr & Ross, 1982; Daly, 1998; Kelly, 1985). The low spatial frequency (0.5–1.0 cpd) and low to medium temporal frequency (5–10 Hz) combination results in the highest contrast sensitivity in 10° nasal visual field. This is very similar to foveal vision that also has optimal contrast sensitivity for low spatial frequency stimuli modulated between 5 and 10 Hz (Daly, 1998). The second set of experiments was therefore performed with 7.5 Hz stimulus. The 7.5 Hz drift improved contrast sensitivity at 0.5 cpd in all four eccentricities between 10° and 25° nasally.

The effect of temporal drift on peripheral CSF can be understood from the neural properties beyond the fovea. The fall-off at low spatial frequencies of the stationary CSF is explained by the center-surround antagonism of the receptive fields. For these spatial frequencies, the receptive fields are more effectively stimulated by stimuli moving at moderate temporal frequencies. Whereas, for the higher spatial frequencies, contrast sensitivity drops as the perceived contrast is decreased when the drift exceeds the temporal summation duration of the neurons (Burr & Ross, 1982; Kelly, 1985; Robson, 1966). However, irrespective of the marked reduction in contrast sensitivity with 15 Hz drift, the cut-off spatial frequency did not vary largely in the current study. This can be explained in terms of the sampling limited nature of the peripheral resolution cut-off; the apparent loss of contrast produced by the moving stimuli does not affect the peripheral cut-off, as it is not contrast limited. The peripheral high contrast cut-off is thereby less affected by stimulus motion than foveal vision, but would obviously decrease when the temporal frequency is sufficiently high.

The present findings on peripheral resolution acuity and contrast sensitivity with drifting gratings can be of importance for subjects with central visual field loss. In the peripheral visual field of normal subjects, low temporal frequencies of around 5–10 Hz improve contrast sensitivity for low spatial frequencies without any negative effects on the higher spatial frequencies due to the sampling limited peripheral resolution cut-off. We recently also found that the CSF changes with stimuli drift found in the current study also occur in subjects with central visual field loss (e-abstract, Venkataraman, Lewis, & Lundström, 2016). An improvement in contrast sensitivity for low spatial frequency targets with drift could be a mode to improve their remaining visual function. For example, low contrast sensitivity has been shown to be one of the limiting factor for reading in low vision subjects (Rubin & Legge, 1989). Actually, scrolling or jittering text have already been shown to give promising effects on reading in people with central vision loss (Gustafsson & Inde, 2004; Harvey & Walker, 2014; Watson et al., 2012). A combination of proper magnification and drifting text (such as 0.5 or 1.0 cpd target drifting at 5 or 10 Hz) should thereby accentuate the lower spatial frequency components, making reading easier in the peripheral visual field.

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