Quick contrast sensitivity measurements in the periphery

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Measuring the contrast sensitivity function (CSF) in the periphery of the eye is complicated. The lengthy measurement time precludes all but the most determined subjects. The aim of this study was to implement and evaluate a faster routine based on the quick CSF method (qCSF) but adapted to work in the periphery. Additionally, normative data is presented on neurally limited peripheral CSFs. A peripheral qCSF measurement using 100 trials can be performed in 3 min. The precision and accuracy were tested for three subjects under different conditions (number of trials, peripheral angles, and optical corrections). The precision for estimates of contrast sensitivity at individual spatial frequencies was 0.07 log units when three qCSF measurements of 100 trials each were averaged. Accuracy was estimated by comparing the qCSF results with a more traditional measure of CSF. Average accuracy was 0.08 log units with no systematic error. In the second part of the study, we collected three CSFs of 100 trials for six persons in the 20° nasal, temporal, inferior, and superior visual fields. The measurements were performed in an adaptive optics system running in a continuous closed loop. The Tukey HSD test showed significant differences ($p < 0.05$) between all fields except between the nasal and the temporal fields. Contrast sensitivity was higher in the horizontal fields, and the inferior field was better than the superior. This modified qCSF method decreases the measurement time significantly and allows otherwise unfeasible studies of the peripheral CSF.

Introduction

Peripheral visual acuity is severely degraded compared to central vision (Low, 1951). There are both neural and optical reasons for this worsening of vision in the periphery. Neurally, the density of ganglion cells decreases (Curcio & Allen, 1990) whereas, optically, peripheral refractive errors differ from those of central vision (Ferree, Rand, & Hardy, 1931), and higher order aberrations are larger (Thibos, Cheney, & Walsh, 1987; Williams, Artal, Navarro, McMahon, & Brainard, 1996; Atchison & Scott, 2002; Lundström, Gustafsson, & Unsbo, 2009; Lundström, Mira-Agudelo, & Artal, 2009). Most studies argue that the peripheral field is specialized for motion perception, detection, low spatial frequencies, and low contrast and that peripheral resolution is insensitive to optical blur (cf. Brown, 1972; Millodot, Johnson, Lamont, & Leibowitz, 1975;

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Thibos, Walsh, & Cheney, 1987; Wood, 2002; Brooks, Tyrrell, & Franks, 2005; Schieber, Schlorholtz, & McCall, 2009; Atchison, Mathur, & Varnas, 2013). Despite poorer acuity, the quality of peripheral vision still has an impact on several important areas of vision research. First, peripheral vision is used extensively by patients with central visual field loss (Crossland, Culham, Kabanarou, & Rubin, 2005). Second, the optical quality on the peripheral retina might contribute to the enigmatic myopia development process (Smith, 2011). Third, a reduction in peripheral vision may be the first indication of serious diseases, such as glaucoma. Fourth, if the peripheral optical errors are corrected, detection acuity is improved as detection by aliasing becomes possible (Anderson, 1996; Wang, Thibos, & Bradley, 1997). Fifth, good peripheral vision is important for many daily tasks, such as locomotion, scene recognition, and driving (Wood, 2002; Lemmink, Dijkstra, & Visscher, 2005; Larson & Loschky, 2009).

The most complete way to describe spatial vision and its limits is to use the contrast sensitivity function (CSF) as it covers all possible combinations of stimuli contrast and spatial frequency. A number of studies describing CSFs for the periphery have previously been published (Virsu & Rovamo, 1979; Johnston, 1987; Rovamo, Virsu, & Näsänen, 1978). Most of these studies have assumed that peripheral resolution is insensitive to optical blur and have therefore not corrected for the peripheral optical errors. However, we have recently shown that even relatively small amounts of optical errors affect low contrast resolution acuity in the periphery (Rosén, Lundström, & Unsbo, 2011). As such, the published studies may not accurately reflect the neural limits to the CSF but rather vision limited by optical errors.

There is one study of peripheral contrast sensitivity published by Thibos, Still, and Bradley (1995) in which the refractive errors were corrected for one subject. It revealed interesting differences in the shape of the CSF compared to that of central vision, which had not been reported in the studies without optical correction. The most important difference is that the CSF for peripheral resolution (but not detection) suffers a sharp and sudden cutoff at a spatial frequency corresponding to the sampling density of the ganglion cells.

Although the study by Thibos et al. (1995) did correct refractive errors, higher order aberrations were not corrected. Because aberrations can degrade low contrast acuity (Rosén, Lundström, & Unsbo, 2012a), the measurements of a neurally limited CSF need to eliminate or bypass higher order aberrations as well. Interference fringes created directly on the retina have previously been used to bypass the optical errors and assess peripheral high contrast resolution and detection acuity (Thibos, Cheney et al., 1987). A modification of the interference fringe method allows the creation of fringes at any contrast level and, thus, CSF measurements (Williams et al., 1996). However, the method is complicated, can only be used for monochromatic light, and requires scaling calculations to compensate for laser speckles, all making it less than ideal to use. Conversely, the advent of adaptive optics in vision science (Liang, Williams, & Miller, 1997) has allowed correction of monochromatic higher order aberrations on normal, polychromatic targets. This is what was used in the current study.

Compared to other visual metrics, the CSF has the disadvantage of taking a much longer time to sample. This has been the main reason for us to use low-contrast resolution acuity in earlier studies (Rosén et al., 2011; Rosén et al., 2012a; Rosén, Lundström, & Unsbo, 2012b). However, a recently published Bayesian adaptive method to quickly estimate the CSF, quick-CSF (qCSF; Lesmes, Lu, Baek, & Albright, 2010) holds great potential (Lesmes, Wallis, Jackson, & Bex, 2012). The qCSF method uses a predefined parameterization of the shape of the CSF for central vision. However, the CSF shape characteristic of central vision does not accurately describe the peripheral CSF. To enable peripheral usage, we have modified the qCSF method by implementing a parameterization with the characteristics of the peripheral CSF as measured by Thibos et al. (1995).

The first goal with the current study is to make certain that the modified qCSF gives repeatable and valid measurements of the peripheral CSF together with correct estimations of the confidence interval of the predictions. The second goal, after the method is validated, is to estimate the peripheral CSF with adaptive optics correction in different fields: in the 20° nasal, temporal, inferior, and superior visual fields. These measurements give new knowledge of the neural limits to the peripheral CSF.

Methods

Setup and subjects

The study consists of two parts: verification and field measurements. In both parts, the peripheral optical errors of the subjects were measured and corrected in an adaptive optics system. The characteristics of the system and its use in peripheral vision testing have been described in detail earlier (Rosén et al., 2012a). To briefly summarize, the fellow eye (left) was used to keep fixation, and the monochromatic aberrations of the right eye were corrected in a continuous closed loop throughout the psychophysical experiment. The chromatic aberrations of the eyes were not corrected. The psychophysical routines were

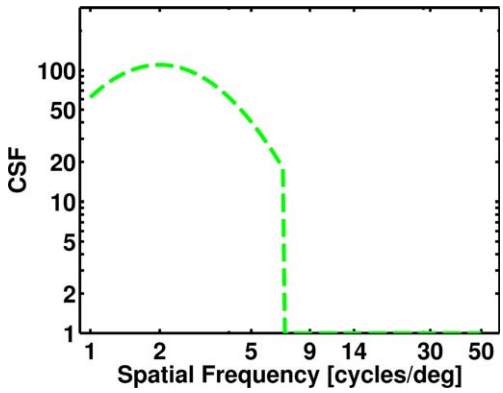

Figure 1. A CSF curve using the new peripheral parameterization with $a = 110$, $b = 2$, $c = 2.2$, and $d = 7$.

implemented in Matlab and the Psychophysics toolbox on a calibrated CRT screen using 1,024 gray levels. The stimuli consisted of grayscale Gabor patches oriented either 45° or 135° with a standard deviation of the Gaussian hull of 0.8°. The stimuli were presented for half a second, and the psychophysical procedure utilized a two-alternative forced choice in which the subjects had to respond on a keypad to indicate the orientation of the gratings. In the verification part, three subjects were tested extensively, with a total time spent per subject of about 10 hr. For the field measurements, we had six subjects who were measured for about 90 min each. Written informed consent by the subjects was obtained beforehand; the study conformed to the tenets of the Declaration of Helsinki and was approved by the Regional Ethics Committee in Stockholm.

Adapting qCSF to peripheral measurements

The main idea of the qCSF algorithm is that the CSF curve can be parameterized. As such, instead of measuring the contrast sensitivity at every spatial frequency, the shape of the curve is assumed a priori to be described by four parameters that, when varied, can describe every possible shape the CSF can take. Different combinations of parameter values are assigned a certain probability, creating a four-dimensional probability density function (pdf). For reasons of computational ease, this pdf is discretized. The psychophysical Bayesian method is similar to the Ψ-method as described by Kontsevich and Tyler (1999) for investigating the two-dimensional psychometric function: after each trial, the pdf is updated using Bayes' rule. Then, the next stimulus is chosen out of all possible combinations of spatial frequency and contrast such that the response by the subject will result in the largest reduction in the uncertainty of the pdf. The use of qCSF for central vision has been described in detail earlier by Lesmes et al. (2010).

We made two major changes to adapt qCSF to peripheral vision: a new parameterization and confidence interval estimations. Both will be described in detail below. The new parameterization is required to account for the sharp cutoff in peripheral resolution acuity described by Thibos et al. (1995), in which the sudden reduction in CSF is larger than what a second-order polynomial can capture. However, for reasons of computational complexity, only four parameters could be used. Therefore, the low-frequency truncation used for central qCSF was removed as initial testing showed few signs of such truncation in the periphery where the peak frequency is lower. Additionally, we set the lower bound of the spatial frequency range rather high, to 1 cycle per degree. The four parameters used were a, the peak contrast sensitivity; b, the spatial frequency of the peak; c, the bandwidth of the curve; and d, the high-frequency truncation. The equation used to describe the logarithmic CSF is

$$logCSF = \begin{cases} \text{if } freq < d: \left(\log_{10} a - \log_{10} 2 \left[\dfrac{(\log_{10} freq - \log_{10} b)}{(c(\log_{10} 2)/2)} \right]^2 \right) \\ \text{if } freq > d: 0 \end{cases}$$

with the spatial frequency in cycles per degree as *freq*. The "if" statements of the equation reflect the cutoff frequency characteristic for peripheral resolution: the logCSF is zero whenever *freq* is higher than the parameter d.

A graph showing the resulting CSF from one combination of parameter values is shown in Figure 1. The ranges of the parameters were set to be 32 values between 2 and 256 for a, 28 values between 1 and 12 for b, 27 values between 1 and 9 for c, and 41 values between 2 and 50 for d. Therefore, the pdf contains a total of 991,872 possible combinations of CSF parameters that were all assigned a probability, which was then updated after each trial. The stimuli space was set to contain 50 different spatial frequencies between 1 and 50 cycles per degree and 64 contrast sensitivity levels between 1 and 256. Both parameters and stimuli were distributed evenly in logarithmic space. The resulting pdf describes the probability of different combinations of parameters. However, we are interested in knowing the range of possible contrast sensitivity values for each spatial frequency. Therefore, for every possible combination of parameters, the corresponding contrast sensitivity at each spatial frequency can be calculated. It is then possible to estimate an expectation value of the contrast sensitivity at each spatial frequency independently; i.e., the shape of the resulting CSF is not limited to being described by one set of parameters. From that, the total area under

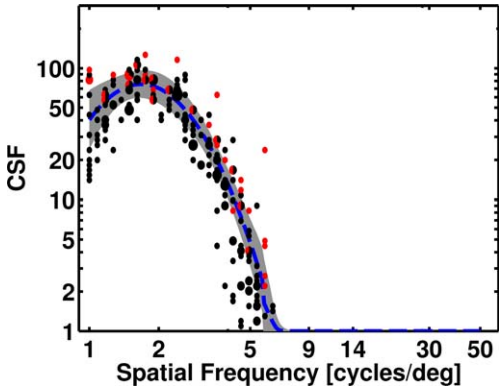

Figure 2. An example of one CSF measurement taken with 200 trials 20° nasally for subject 1 with adaptive optics correction. Black dots represent correct answers and red dots incorrect answers, and the size represents the number of trials at that contrast and spatial frequency. The blue dashed curve is the expectation value of the contrast sensitivity at each spatial frequency, and the gray area shows the 95% confidence interval of that curve. The convergence on a per trial basis can also be seen in the attached movie.

logCSF (AULCSF) can be calculated using the trapezoid method with both the spatial frequency and the contrast sensitivity in logarithmic values. The lower bound for spatial frequency was set to 1 cycle per degree. Besides calculating the expectation value, it is possible to provide a range of contrast sensitivity values that cover a large proportion of the pdf for that particular spatial frequency. We used that to estimate the 95% confidence interval. For example, if 95% of the pdf for a certain spatial frequency lies between a contrast sensitivity of 30 and 50, that becomes the estimated 95% confidence interval. Similar calculations give the 95% confidence interval of the AULCSF. An example of one CSF estimation can be seen in Figure 2.

Verification

The verification data were collected for three subjects in the 20° nasal visual field as well as at 10° and 30° for subject 2 and at 20° with two diopters of defocus added for subject 1. In the non-defocused conditions, all eyes were continuously corrected with the adaptive optics system. For each individual and circumstance, eight qCSFs were measured with 200 trials per measurement and each qCSF measurement taking 5 min. Additionally, traditional CSF measurements were performed by keeping the spatial frequency constant and estimating the contrast sensitivity with the Ψ-method (Kontsevich & Tyler, 1999). Three spatial frequencies were chosen at 25%, 50%, and 75% of the interval between 1 cycle per degree and the cutoff frequency, the latter being determined from a peripheral visual acuity measurement (under high contrast, estimating the spatial frequency cutoff with the Ψ-method). At each of the three spatial frequencies, contrast sensitivity was measured four times using 50 trials per measurement. The subjects were given ample time to rest between tests. All tests for a single person and a single circumstance took several hours and were spread out over the course of at least 2 days. The results of the measurements were quantified in terms of the AULCSF and the contrast sensitivity at the three chosen spatial frequencies.

The purpose of the verification was to estimate the precision and accuracy depending on the number of qCSF measurements and the number of trials used. Additionally, we wanted to see if there was any systematic error in the qCSF estimation and whether the estimated 95% confidence interval was accurate. To determine the precision, the "true" AULCSF and the contrast sensitivity at the three spatial frequencies were defined as the average of all eight qCSF measurements using the full 200 trials for each subject and circumstance. These true values were then compared with estimates that were recalculated under the assumption that the measurements stopped at 50, 100, 120, 150, and 200 trials using one to eight qCSF measurements in all possible combinations (drawn without replacement) to calculate a mean value. For each such estimate, we calculated $\log_{10}$ *estimation* − $\log_{10}$ *true value*, the root mean square (RMS) of which is reported in the results section as precision.

The accuracy was determined in a similar manner as precision; we compared the average estimation of all eight qCSF measurements for each of the three spatial frequencies to the average contrast sensitivity estimated by the Ψ-method (the "true" value). The accuracy RMS was calculated as for precision but describes the average deviation between the qCSF estimation and the Ψ-method (the intermeasurement difference for qCSF is described by the precision). In this comparison, we also investigated whether there was a systematic error, i.e., an overestimation or underestimation from the qCSF compared to the Ψ-method, by taking the sign of the error ($\log_{10}$ *estimation* − $\log_{10}$ *true value*) into account. Finally, the AULCSF estimated by fewer than 200 trials were also analyzed to see any systematic error compared to the true AULCSF with 200 trials.

Field measurements

In addition to verifying the modified qCSF method for peripheral vision, this study also used the method to estimate the 20° peripheral CSF in different fields. The purpose of these measurements was threefold: to find asymmetries based on gaze direction that were not due

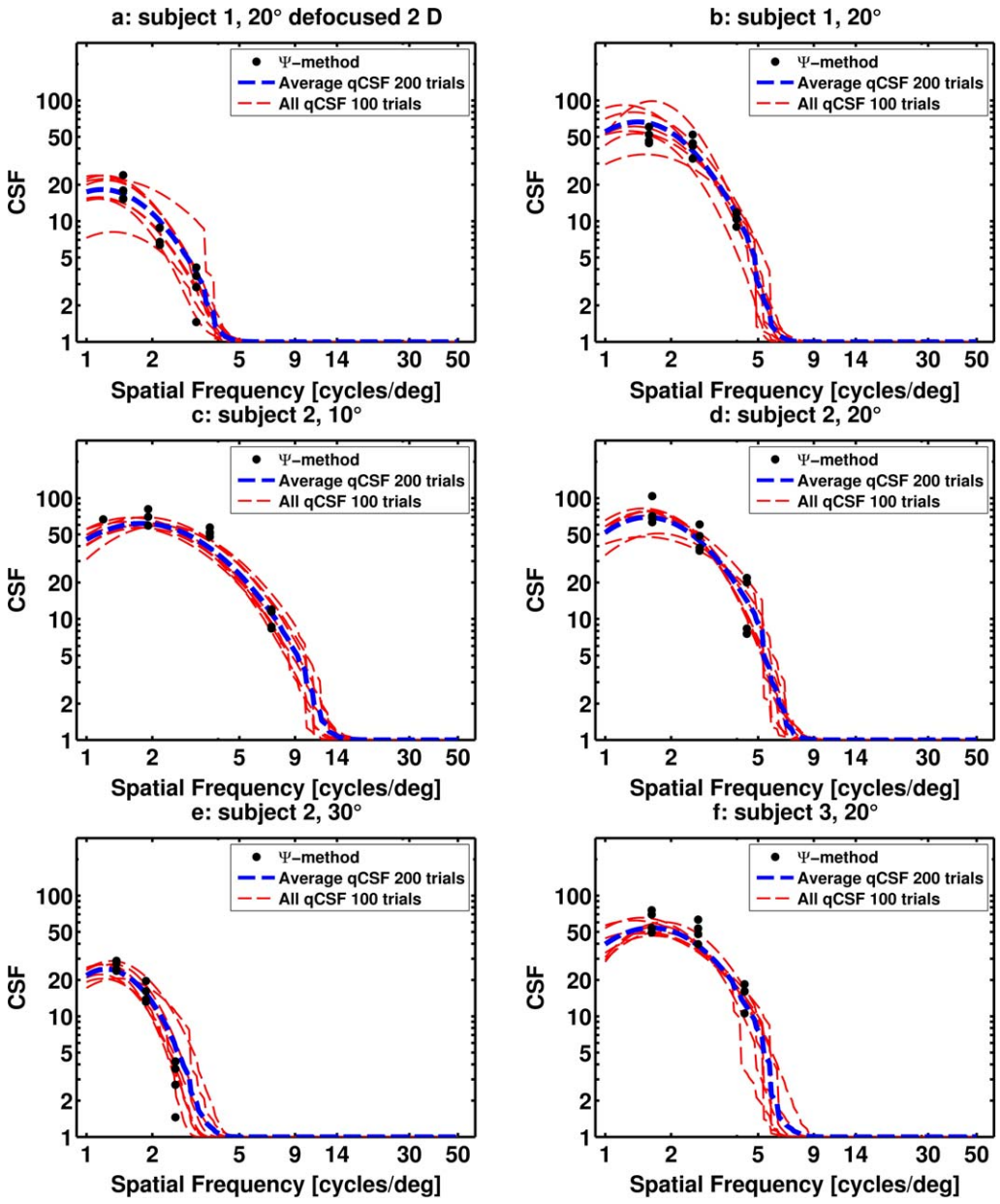

Figure 3. (a–f) Average qCSF for eight measurements with 200 trials (thick blue), the eight separate qCSF measurements with 100 trials (thin red), and the estimation of contrast sensitivity with the Ψ-method (black dots). The verification conditions were (a) subject 1 defocused 2 D in the 20° nasal visual field, (b) subject 1 in the 20° nasal visual field, (c) subject 2 in the 10° nasal visual field, (d) subject 2 in the 20° nasal visual field, (e) subject 2 in the 30° nasal visual field, and (f) subject 3 in the 20° nasal visual field.

to optical asymmetries, to assess the magnitude of the intersubject variation in peripheral visual function, and to collect normative data regarding the peripheral CSF. The field measurements were collected for six subjects in the 20° nasal, temporal, inferior, and superior fields of the right eye. Based on the verification results, we decided to conduct three qCSF measurements of 100 trials each at every field. The total measurement time for 12 qCSF measurements and four alignments of the subjects in the adaptive optics system was about 90 min. The AULCSF data was analyzed using mixed-effect ANOVA with the six subjects as random effects and the four fields as fixed effects. The Tukey HSD test was used to determine which of the fields differed from each other, and $p < 0.05$ was chosen as significance level.

Verification results

Figure 3a through 3f gives an indication of the precision and the accuracy of using qCSF in the periphery with 100 trials. The black dots show the 4×3

	50 trials	100 trials	120 trials	150 trials	200 trials
1 qCSF	0.17	0.121	0.11	0.108	0.105
2 qCSF	0.122	0.082	0.075	0.072	0.069
3 qCSF	0.101	0.065	0.059	0.054	0.051
4 qCSF	0.088	0.053	0.049	0.043	0.04
5 qCSF	0.08	0.045	0.041	0.035	0.031
6 qCSF	0.073	0.039	0.035	0.027	0.023
7 qCSF	0.068	0.033	0.03	0.021	0.015
8 qCSF	0.063	0.027	0.023	0.013	0

Table 1. RMS precision of contrast sensitivity estimation of individual spatial frequencies, depending on the number of qCSF measurements (rows) and the number of trials per qCSF measurement (columns). *Notes*: The values are in log units, so a precision of 0.1 and a "true" contrast sensitivity of 50 would mean that the estimate of the subject could have been $10^{0.1} = 26\%$ larger, i.e., 63.

estimations of contrast sensitivity with the Ψ-method, the thick blue line shows the average expectation value of the CSF at all spatial frequencies for all eight qCSFs with 200 trials, and the thinner red lines show the expectation value of the CSF at each spatial frequency for the eight individual qCSF estimations taken with 100 trials.

The precision of the estimated contrast sensitivity at the three individual spatial frequencies is shown as the RMS of $\log_{10}$ *estimation* − $\log_{10}$ *true value* for all conditions in Table 1. For example, when three separate qCSF measurements with 100 trials each are used, the RMS precision was 0.065 log units (i.e., $10^{0.065} = 16\%$). As a comparison, the RMS precision using the Ψ-method was worse: 0.098 log units.

The precision of the estimated AULCSF can be seen in Table 2. The values shown are the RMS precision in area units. To put the values in perspective, average AULCSF for the 20° nasal visual field was 0.9 area units. The accuracy and systematic error can be seen in Table 3. The RMS accuracy is calculated similarly to RMS precision, but because it is the average for all eight qCSF estimates, only one row is needed. The average accuracy remains fairly constant and is below 0.1 log units even with just 50 trials. The small negative systematic error means that the modified qCSF method, on average, estimates vision to be slightly worse than the Ψ-method and that the AULCSF will be slightly worse than what is estimated after 200 trials.

Field measurements results

Based on the verification results, we decided to conduct three qCSF measurements of 100 trials each for the field measurements. The average AULCSF in the 20° inferior/superior/nasal/temporal visual field was 0.67/0.46/0.90/0.87 area units with a mean intrasubject standard deviation of 0.058/0.035/0.047/0.073 and an intersubject standard deviation of 0.10/0.11/0.086/0.11. Mixed-effect ANOVA revealed a significant effect of field, and the Tukey HSD test showed that all fields differed significantly from each other with the exception of nasal versus temporal. The average CSFs for the six persons in the different fields are shown in Figure 4. As can be seen, contrast sensitivity was highest in the horizontal fields, and the inferior field was better than the superior.

Discussion

Peripheral psychophysics is more tiring for the subject than central psychophysics due to the need to maintain fixation and split attention and the presence of aliasing (Thibos, Walsh et al., 1987). Therefore, in all peripheral psychophysics, it is paramount to keep the number of trials to a minimum as long as precision and accuracy is maintained. The qCSF method, adapted to

	50 trials	100 trials	120 trials	150 trials	200 trials
1 qCSF	0.087	0.069	0.068	0.067	0.061
2 qCSF	0.064	0.047	0.045	0.044	0.04
3 qCSF	0.055	0.037	0.033	0.033	0.03
4 qCSF	0.05	0.03	0.026	0.026	0.023
5 qCSF	0.046	0.026	0.021	0.021	0.018
6 qCSF	0.044	0.022	0.016	0.016	0.013
7 qCSF	0.042	0.019	0.011	0.012	0.009
8 qCSF	0.04	0.017	0.006	0.007	0

Table 2. RMS precision for estimation of AULCSF depending on number of trials and qCSF measurements.

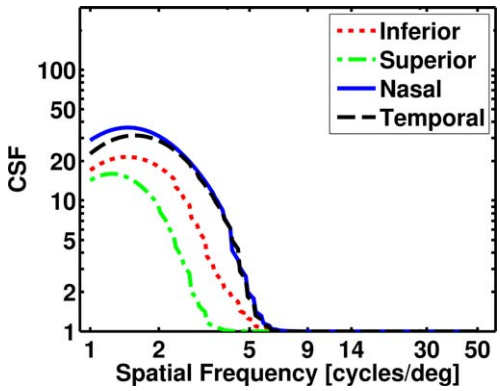

Figure 4. Contrast sensitivity in four different 20° visual fields measured for six subjects under adaptive optics correction.

peripheral vision evaluation, presents an acceptable compromise that allows for larger studies on contrast sensitivity—something that has previously been precluded by the long measurement time.

The verification measurements presented in this study show that the modified qCSF method is both precise and accurate. Accuracy describes how much the measured qCSF contrast sensitivities deviate from the results of the Ψ-method. As the accuracy is stable around 0.08 log units, this provides a limit on how good precision is needed and thereby a guideline of how many trials and qCSF measurements it is reasonable to conduct. In our opinion, one to three peripheral qCSF measurements with 100 trials for each condition tested represent the ideal compromise between time and precision.

Furthermore, if only a single qCSF measurement is taken, the estimated 95% confidence interval for the contrast sensitivity at individual spatial frequencies, as well as for the AULCSF, can be used as an indicator of the certainty of the measurement as described in the Methods. To investigate whether this estimated confidence interval could also capture the variation between different qCSF measurements and AO correction sessions, we computed how often the confidence interval contained the "true" contrast sensitivity (defined as the average of all eight qCSF measurements with 200 trials). For estimations with 100 trials, 94% of the qCSFs had the true contrast sensitivity within the 95% confidence interval. When the "true" contrast sensitivity was defined as the average of the Ψ-method estimates, the fraction within the 95% confidence interval dropped to 87%. The size of the 95% confidence interval was, on average, ±0.22 log units for 100 trials. A similar comparison was made for the AULCSF, in which 94% of the estimates were within the 95% confidence interval with an average size of ±0.11 area units for 100 trials. Therefore, it is possible to perform measurements with just a single qCSF and use the size of the confidence interval as a tool to verify the measurement.

The fourth parameter to describe the CSF, the high-frequency cutoff, is not always needed. If the width of the curve is narrow enough, the more traditional shape of a second-order curve can describe the peripheral CSF. In the field measurements, we had a total of 72 qCSF measurements. Out of those, 52 required the fourth parameter; the other 20 had a combination of parameters in which the high frequency cutoff lay beyond that produced by the three other parameters. Out of these 20 measurements, 11 were in the superior visual field and five in the inferior. Conversely, only two and three measurements in the nasal and temporal field, respectively, did not utilize the high frequency cutoff parameter. Therefore, we concluded that the fourth parameter is beneficial to include in the majority of cases. It should be noted that the parameterization used is specific for peripheral resolution. If, e.g., peripheral detection is to be tested, an alternative parameterization is needed, one that can describe the transition from second-order to linear curve at the cutoff frequency for resolution and with which detection is still possible in the aliasing zone (Thibos et al., 1995). Such parameterization could be done in future research.

The field measurements of the six subjects gave a similar magnitude of peripheral CSF as the earlier study published by Thibos et al. (1995) even though they used one very experienced subject with refractive correction. In comparison, our subjects were fully corrected for monochromatic errors and less experienced in peripheral psychophysics. With regards to the different fields, there is a substantial body of literature that describes a nasotemporal asymmetry in peripheral vision, see, e.g., Fahle and Schmid (1988) or Silva et al. (2010). Curiously, that was the only pair of fields for which we failed to find a significant difference. One possible explanation is that we have corrected the optical nasotemporal asymmetry. However, a nasotemporal asymmetry was also described with regards to

	50 trials	100 trials	120 trials	150 trials	200 trials
Accuracy of contrast sensitivity (log units)	0.088	0.08	0.08	0.074	0.073
Systematic error of contrast sensitivity (log units)	−0.022	−0.015	−0.010	−0.012	−0.003
Systematic error of AULCSF (area units)	−0.020	−0.008	−0.004	−0.004	0.00

Table 3. RMS accuracy and systematic error for estimation of contrast sensitivity at individual spatial frequencies compared to the Ψ-method and systematic error for the AULCSF compared to the estimate with 200 trials, depending on the number of trials.

ganglion cell density by Curcio and Allen (1990) with twice the density in the nasal compared to the temporal retina. The findings were corroborated in studies of visual resolution of high contrast gratings in the periphery (Anderson, Wilkinson, & Thibos, 1992; Beirne, Zlatkova, & Anderson, 2005). They explained the asymmetry through a visual streak in the nasal retina. Because no effort was made on our part to localize the visual streak, it may be that the stimuli were placed outside of it. However, none of the subjects exhibited the asymmetry, and it seems unlikely that we missed the streak for every person. Other explanations might be the oblique orientation of the grating stimuli, the wavelength spectrum of the stimuli, or the relatively close distance to the optic disc; Anderson et al. (1992) and Beirne et al. (2005) used other grating orientations, less polychromatic light, and measured at 25° eccentricity. On the other hand, the inferior-superior asymmetry, as reported in several publications, e.g., by Edgar and Smith (1990), was still present when the optical errors were corrected in the current study.

The results of the field measurements can be used as nominal data when finding the optimum refractive correction in off-axis angles. In highly aberrated eyes, it is recommended that metrics are employed that take neural factors into account (e.g., VSOTF in Marsack, Thibos, & Applegate, 2004). As very little data has previously been available on the neural characteristics in the periphery (e.g., typical CSFs with no optical errors imposed), many studies of peripheral optics present refraction data solely based on the second order Zernike coefficients. In addition to being known as a poor metric for central vision, this metric is even more problematic in the periphery because the pupils are elliptical and the higher order aberrations, particularly coma, are larger.

To conclude, the modified qCSF method allows fast assessment of functionally relevant peripheral vision. For reasons of measurement time, earlier studies have focused primarily on the high frequency cutoff either for high or low contrast. However, the qCSF evaluates vision also at low spatial frequencies and contrasts, the importance of which the current literature, e.g., on driving performance (Schieber et al., 2009), stresses. Additionally, being able to quickly and accurately measure the peripheral CSF can be important in a clinical setting, for example, to diagnose and monitor the progression of glaucoma, which reduces peripheral contrast sensitivity. It could also be of importance for measurement of patients with age-related macular degeneration for whom it is not necessarily the reading of high contrast letters that is the most important visual function but rather tasks such as face recognition and navigation in which objects of lower contrast need to be seen.

Keywords: peripheral vision, contrast sensitivity, adaptive optics, qCSF

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