Can We Safely Measure Contrast Sensitivity Without Full Optical Correction?

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Changes in the contrast sensitivity function (CSF) often have been used to demonstrate the effects of an experimental treatment or the process of some ophthalmic disease. For example, spatial frequency selective minima (notches) in the CSF have been reported in certain ophthalmic conditions. Similar notches in the CSF of otherwise normal eyes have been predicted from consideration of optical theory, yet surprisingly notches have only recently been reliably demonstrated with astigmatic defocus and spherical defocus. One early study appears to show moderate notches with 2.0D myopic defocus. The authors did not comment on the notches. Other workers have unfortunately often averaged CSFs between subjects or between hyperopic and myopic defocus which would tend to hide any notches.

With carefully controlled experimental conditions (monochromatic stimuli aligned with the foveal achromatic axis and maintained with a bite-bar and head rest, cycloplegia and artificial pupils), Atchison and coworkers demonstrated that the effects of both defocus and pupil size on the CSF could be predicted from subjective measurements of the ocular transverse aberrations. This included multiple notches with both hyperopic and myopic defocus. The depth and spatial frequency of notches were subject to large inter-subject variations.

Reasons for a failure to identify notches in the CSF in earlier studies may include the use of broad-band stimuli (polychromatic), active accommodation and natural pupils, conditions which are common in most experimental and clinical assessments of CSF. Notches in the CSF for polychromatic gratings often appear reduced in depth compared to when measured with monochromatic gratings (see for example figure 1). The spatial frequency and depth of notches is dependent on the level of defocus and pupil size. Since, during a typical CSF measurement without cycloplegia, normal fluctuations in pupil size may be as much as ±0.5mm and normal fluctuations in accommodation may be as much as ±0.5D we might expect that active accommodative and pupillary mechanisms would tend to reduce or smear any notches in the CSF. If the alignment between the eye and the target were to vary between presentations notches may be reduced due to off-axis variations in ocular...
aberrations. Finally, a major contributory factor presumably was insufficient resolution (i.e. number of spatial frequency levels) so that notches could not be distinguished from measurement errors.

Despite these restrictions Apkarian et al.\textsuperscript{5} were able to demonstrate single notches in the CSF with a polychromatic target and no cycloplegia. From their study the level of astigmatism necessary for notches is not clear and, since notches were related to uncorrected astigmatism, notches will only occur with gratings oriented orthogonal to the astigmatism. With spherical defocus, gratings of any orientation can produce notches in the CSF.

If defocus can produce notches in the CSF, could this be the reason for previous reports of medium spatial frequency selective reductions? We doubted the general relevance of defocus-induced notches in the CSF because most experimental and clinical measurements of CSF are not conducted under strict conditions. Hence, we measured the CSF using a polychromatic target, unrestrained head movements, active accommodation (no cycloplegia), natural pupils and spherical defocus to examine the clinical relevance of CSF notches.

**Methods**

Five subjects, the three authors and two naive subjects who were inexperienced observers, were carefully refracted for the 4 metre viewing distance. During contrast sensitivity (CS) measurements the subject was seated, the left eye patched and head and eye movements were not restrained. Subjects monocularly viewed the CS display on a monitor (P4 phosphor) which was under computer control. An adaptive psychometric procedure was used to determine the test contrast levels and to estimate CS. The monitor was masked to give a circular field subtending a visual angle of 2.5\(^{\circ}\) and the surround luminance was approximately matched to the average monitor luminance of 40cd/m\(^2\). Pupils of the subjects’ right eyes ranged between 5 and 6mm under average room illuminance of 2 lux. CS was measured with best correction and myopic spherical defocus in 0.5D steps up to 2D. Spatial frequency of each grating was adjusted for any induced spectacle magnification. Spatial frequencies were measured at approximately 1 cpd intervals. Where the CSF appeared not to be monotonically decreasing repeated measures of CS were made at appropriate spatial frequencies such that each CSF involved up to 40 estimates of CS.

**Results**

All five subjects demonstrated reductions in CS with increasing defocus, though there was considerable inter-subject variability. Examples for two subjects, one experienced (subject NS) and one inexperienced (subject CM) observer, are shown in figures 2 and 3 respectively. Many of the effects of defocus on the CSF apparent in the previous, carefully controlled studies were apparent in our study. Non-monotonically decreasing functions (i.e. notches) were found with almost all levels of defocus for all subjects.

| The spatial frequencies of the notches varied with defocus. For example the first notch in the CSF of subject NS was noted at approximately 11, 6, 4 and 3 cpd for 0.5, 1.0, 1.5 and 2.0D defocus respectively (figure 2). Multiple notches were apparent. For example, with 2.0D defocus there were notches at approximately 3 and 10 cpd in the CSF of subject NS and at approximately 3, 6 and 12 cpd in the CSF of subject CM. The spatial frequencies of the notches varied between subjects. The spatial frequencies of distinct notches in the |
|-------------------------------|---|---|---|---|---|
| CM | DA | DG | NS | RW |
| 0.5 | 13 | 13.5 | 8 | 11 | - |
| 1.0 | 4.5, 6.5 | 8 | 5, 10 | 6 | - |
| 1.5 | 4, 8 | 4, 10 | 8.5, 13 | 4 | 3.5, 6, 8 |
| 2.0 | 3, 6, 12 | 4, 7 | 4, 7.5, 14 | 3, 10 | 3, 6.5 |

Table. Spatial frequency (cpd) of distinct notches (on repeated measurement, lower CS than at a higher spatial frequency) in the CSF of the five subjects for myopic defocus +0.5 to +2.0D.
CSF of all five subjects are summarised in the table. With as little as 0.5D myopic defocus notches were apparent in four of the five CSFs, and the notches were of moderate size (≥0.25 log units). Since the CSFs are non-monotonic, the CS sometimes was better with greater defocus. For example, at 5cpd, subject NS’s CS with 2.0D defocus was better than both 1.0D and 1.5D defocus. Similarly, at 12cpd, subject CM’s CS with 1.5D defocus was better than 1.0D defocus.

**Discussion**

Under conditions which were representative of typical CSF measurements, non-monotonically decreasing reductions in the CSF with myopic defocus were apparent. These notches in the CSF were found with as little as 0.25D myopic defocus in some individuals (figure 2), while greater defocus was required with other subjects before notches were apparent (table). Hence, contrary to our reservations, notches in the CSF are of relevance to the clinician and the experimenter. As it is not possible to predict easily the amount of defocus which will produce notches in the CSF, we recommend that all subjects are carefully refracted prior to CSF measurement.

This advice must be tempered by knowledge of our ability to accurately determine the optimal refraction. In the clinical setting, at least ±0.5D has been reported as the confidence limits of refraction of young normal subjects. Lower levels of reliability would be expected for subjects with reduced visual performance or ophthalmic disease, thus care must be taken in the interpretation of notches in the CSF (i.e. medium spatial frequency selective reduction).

We predict that moderate levels of spherical hyperopic defocus, given sufficient active accommodation and an appropriate stimulus to accommodation, probably will not cause problems with younger subjects. Conversely, presbyopic subjects with limited accommodation probably will show notches in the CSF with hyperopic defocus.

Limitations of our study include our use of a relatively small field of view (2.5°) since off-axis variations in ocular aberrations probably will increase the chance of grating detection with a larger
display. Our low room illuminance and relatively large pupils will have resulted in notches at lower spatial frequencies than with smaller pupil diameters.

Figure 3. CSF for subject CM with varying levels of defocus. A notch in the CSF was apparent even with +0.5D defocus.

References