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Modulation transfer functions and contrast sensitivity through low vision telescopes

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Telescopes are coherently coupled to the eye. Because their wavefront aberrations may be altered by the optics of the eye, especially by accommodation, some researchers question the ability of their modulation transfer functions (MTF) to predict changes in contrast sensitivity functions (CSF) through them. We measured the CSFs of visually normal and aphakic subjects through telescopes. We found that MTF appears to be useful for ranking the telescopes, and accommodation appears to improve focus and partly balance wavefront errors. Our results suggest that cascading (multiplying the contrast of the instrumental MTF with the unaided CSF at each spatial frequency) is useful for predicting visually aided CSFs to within 4 dB.

I. Introduction

Telescopes and telemicroscopes are commonly prescribed as low vision devices, with some models specifically designed and marketed for such use. Unfortunately, manufacturers do not disclose proprietary design specifications for optical correction, nor tolerances for fabrication. Indeed, previous studies from this laboratory confirm the common experience that the optical quality of low power telescopes and telemicroscopes varies greatly within and across model and manufacturer.[1,2] Although Loshin and White[3] studied the effect of low vision telescopes on the contrast sensitivity of subjects with age-related macular degeneration, they considered only the angular magnification.

Little is known about the significance of these variations in optical quality to visual performance because of the interaction of the eye with the optical wavefronts of visual instruments. This interaction occurs because visual instruments produce aerial images that are coherently coupled to the eye, in contrast to nonvisual optical instruments that form images on diffusing surfaces, such as film or ground glass. Because the wavefront aberrations of visual instruments may be modified by the eye, predictability of visual performance through these devices may be confounded, even for very simple tests of visual performance like contrast sensitivity. Although the contrast sensitivity, measured at threshold, may have limited applicability to the performance of suprathreshold visual tasks, there are many low contrast real-world scenes and ocular conditions that result in near threshold retinal images.

The fact that the wavefront aberrations of coherent images formed by one optical component may be increased or reduced by a subsequent optical component in the system makes aberration balancing, that is, having the several components of an optical system produce mutually opposing aberrations, the fundamental method of lens design. For example, a high quality photographic lens has small aberration sums and an MTF that cannot be predicted by cascading the MTFs of the individual lens elements. However, the MTF of a complex optical system can be predicted by cascading the MTFs of the several individual components of the system, provided all intermediate images are formed on diffusing surfaces. Cascading also can be used with coherently coupled systems, such as a visual device and the eye, provided one or the other component is diffraction-limited.[4,5] A simple cascading of the instrumental MTF and the MTF of the eye, in any case, may not be an adequate predictor of visual performance through low vision devices because it neglects both the ability of the eye to accommodate for best focus and the neural signal processing that determines visual perception. To the extent that the visual system operates in a nonlinear range, it cannot be cascaded.[6] These constraints raise the question of whether the MTFs of visual instruments are predictive of any kind of visual performance obtained through them. In particular, how does the MTF of a visual

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instrument affect the contrast sensitivity function (CSF), an analogous psychophysical measure. Reports of others on this issue do not agree.

The value of the MTF or other objective measures of optical quality of visual devices in predicting visual performance was supported by Barton[7,8] who found that the MTF is a reliable and effective test for afocal visual instruments. He refers to observations that show that instruments that look good have higher MTFs than instruments that are not so good, but he provides no data. Fedorova and Fedorova,[9] in a visual detection study, measured the limiting spatial frequency of square-wave targets at each of nine contrast levels, through five telescopes that ranged from 4× to 15×. Five observers took part in the tests. The authors were able to derive a formula for predicting the limits of visual resolution to a periodic target as a function of contrast, of an eye through an instrument, given the MTF of the instrument.

Giles[10,11] found that the effect of one and two wavelengths of instrumental wavefront spherical aberration, coma and astigmatism, on the total system (including the eye), closely approximated the theoretically calculated MTF of the total system. In separate experiments, with seven observers, he measured Ronchi grating detectability and square-wave contrast thresholds with the U.S.A.F. three-bar resolution target presented at five contrast levels. His data suggest that, except for coma, the eye accommodates for best focus. Mouroulis[12] found that contrast sensitivity measurements can be successfully applied to the testing of visual instruments. Several other papers have supported the use of MTF criteria for evaluating visual instruments.[13,14]

On the other hand, a failure of instrument MTF to predict visual performance was observed by Overington and Gullick.[5] They tested three pairs of 10 × 50 binoculars with similar MTFs in an aircraft detection range experiment. The MTF of one pair was degraded with a phase plate, the second had a large amount of veiling glare introduced, and the third pair was left unaltered. No significant difference in detection ranges by the different observers, using any one of the pairs of binoculars, was found. They concluded that the MTF combination of binocular optics plus eye optics did not predict even relative performance between binoculars in this complex task.

The strongest position against the predictive value of the MTF of visual devices is that of Burton and Haig[15,16] who found insignificant correlations between the instrumental MTF and threshold contrasts through the instrument. They conclude that the MTF is inapplicable to the assessment of afocal visual systems[17] due to the factors noted above, namely, coherent coupling, adjustment of focus by the eye, and the perceptual system.

We report the results of tests designed to differentiate between the effect on the CSF of statically and dynamically coupled telescopes and eyes. Static coupling was obtained through the use of aphakic subjects. Their ability to modify the wavefront aberrations of the device in a positive or negative way is limited to the fixed curvatures of a rigid cornea and their corrective lenses. Young visually normal subjects have dynamic crystalline lenses that may minimize the wavefront aberrations of visual devices by accommodating for best focus. CSFs were measured in three conditions: unaided, and through two four-power telescopes; an Eschenbach model 4141/412 with a relatively poor MTF, and a Walters model LHW-400 of higher MTF.

II. Methods

A. Apparatus

1. *CSF*

A Vision Metrics PC pattern generator produced vertical sine wave gratings on a Joyce monitor with a P-4 (white) phosphor. The monitor was located at a distance of 4.6 m (−0.22 diopter [D]) from the subject. A 20-cm diam circular cutout in a sheet of translucent vellum masked the field of view to 2.5°. The mean screen luminance was adjusted to 300 cd/m^2.

2. *Telescope Compensator*

Ideal conditions for comparing CSFs through telescopes with unaided CSFs are: (a) The range of spatial frequencies and the angular size of the display presented to the unaided and aided eye should be the same. Telescopes reduce the apparent range of spatial frequencies and increase the angular size of the display by a factor equal to their angular magnifications. Compensation for the reduced spatial frequency range is complicated by the limited bandwidth of most raster display systems, which imposes an upper limit on alias-free spatial frequencies.[18] In our experiment, this upper limit and the desired angular size of the display establish the viewing distance for the unaided CSF tests. For our system the maximum spatial frequency was about 30 cycles per degree (cpd) at a viewing distance of 4.6 m and field size of 2.5°. Without the compensator, described below, telescopic magnification of four-power would limit the maximum apparent spatial frequency to 7.5 cpd. (b) The wavefront aberrations at the eye for CSF testing should be the same as those which determined the MTFs. Because the MTFs were measured with the telescopes focused for infinity and because aberrations depend on object/image conjugates, CSF testing should be conducted with the telescopes also adjusted to infinity. This condition conflicts with the following requirement. (c) The vergence (stimulus to accommodation) at the eye should be the same in the unaided and aided conditions to maintain equivalent accommodative/refractive states with the same ocular aberrations. Because the monitor is not at infinity, an afocal telescope will amplify the vergence at the eye by a factor approximately equal to the square of the magnification, thereby, placing inappropriate demands on accommodation.

We compensated for the effects of magnification by introducing in front of the afocal telescope a pair of high quality photographic objectives, combined back to back so that the angular magnification of the compensator and telescope was approximately unity. The components of the compensator were nominal 35- and 135-mm Nikon lenses. The angular magnifications of the compensated Eschenbach system (E_C) and Walters system (W_C) were measured to be 1.09× and 1.1×, respectively.

The compensator obviated the problems of spatial frequency shifts and retinal image size differences noted above. Furthermore, by adjusting the spacing between the compensator lenses, we were able to set the vergence input to the afocal telescope to produce an output vergence at the eye equal to the vergence of the directly viewed display monitor. For example, the appropriately spaced compensator lenses produce a virtual image of the display monitor at a distance of nearly 70 m (optical infinity) from the telescope. The resultant −0.014-D input vergence at the four-power telescope is amplified by a factor of ~16, to −0.22 D at the eye. A dioptometer, calibrated against the Joyce monitor located 4.6 m away, was used to set the appropriate compensator lens spacing. As noted below, the MTFs of the coherently coupled compensator and telescope were used in the analysis of the CSF results.

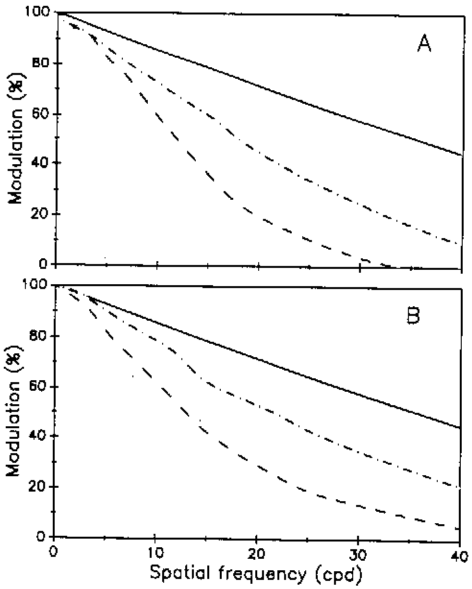

Fig. 1. (A) The MTFs of the Eschenbach (- - -) and Walters (-·-·-) telescopes selected for CSF tests, compared with the diffraction-limited (——) MTF; (B) MTFs of the telescopes coupled to the compensator; E_C (- - -), W_C (-·-·-). Tests made with a 3-mm exit pupil.

B. Procedure

A repeated measures experimental design was used. The CSFs of visually normal and aphakic subjects were measured in three conditions: unaided, with a telescope of relatively poor MTF coupled to the compensator (E_C), and with a telescope of higher MTF (W_C) coupled to the compensator. Tests were monocular, through a 3-mm pupil, with the subject's current lens correction. Unaided tests were made with a 0.1 neutral density filter that approximated the light transmittance losses of the telescope–compensator systems. We maintained a vergence at the eye of −0.22 D for all conditions.

One set of spatial frequencies for all test conditions was presented on the display monitor. Because the angular magnifications of the three test conditions differed slightly and because spatial frequency was under digital control, the spatial frequencies at the eye were not identical for the three test conditions (see Table I).

We used a contrast sensitivity test program written specifically for the PC pattern generator.[19] The psychophysical procedure was a temporal two-alternative forced-choice double staircase method.[20] The stimulus and interstimulus intervals were 500 ms each. The mean luminance of the screen was the same with the pattern and when blank. At the start of the trials, which were well above threshold, a correct response by the subject lowered the contrast for the next trial by 3 dB; an incorrect response raised it by 9 dB, where 20 dB equals 1 log unit. The program collected data at the reversal points after the subject made two errors for a particular staircase. Subsequent correct responses lowered contrast by 1 dB; incorrect responses raised it by 3 dB. The staircases for different spatial frequencies were independent and randomly interleaved. The total number of trials, of course, varied depending on the subject's responses.

Table I. Spatial Frequencies Presented in the Three Conditions of Test

Condition	Spatial frequency (cpd)					
Unaided	3.11	6.00	9.11	12.00	16.00	20.00
E_C	2.84	5.50	8.34	10.99	14.66	18.32
W_C	2.82	5.46	8.28	10.92	14.56	18.20

A test comprised ten reversals at each spatial frequency for one condition. At the end of a test, means and standard deviations were computed in log-contrast domain using decibels. Tests were repeated for each of the conditions in a random sequence. A minimum of ten tests (or 100 reversals) per condition were run on each subject. Several subjects completed as many as 150 reversals for each condition.

C. Subjects

Three aphakic and five young visually normal subjects were tested. CSF was measured monocularly with the subject's preferred eye. Two of the aphakic subjects wore gas-permeable contact lenses, the third had intraocular implant lenses. The five visually normal subjects were from 25 to 28 years old. Their mean amplitude of accommodation, measured by introducing minus lenses until the 20/20 line blurred, was 7.3 D, SD = 0.9.

D. MTFs of Telescopes

We selected the two four-power telescopes, out of twenty-four that were measured, with the highest and

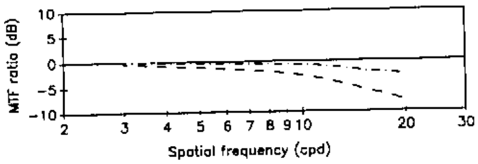

Fig. 2. MTFR curves or the ratio of the MTF of the telescope/compensator systems with respect to the diffraction-limited MTF: E_C (- - -), W_C (- · - · -).

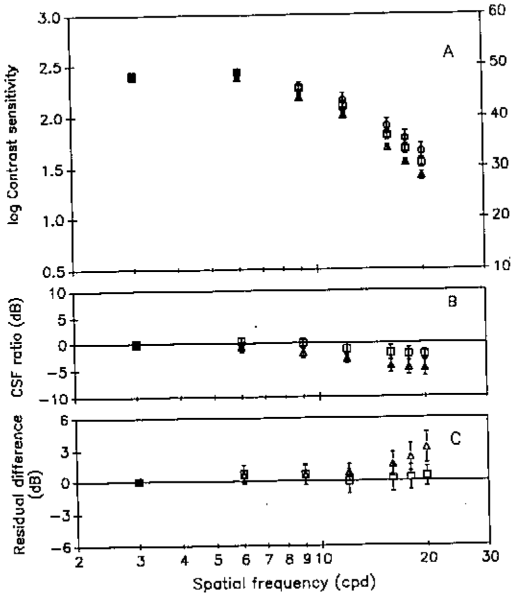

Fig. 3. (A) Mean CSFs of five visually normal subjects, with standard error bars indicated, for the unaided (circles), E_C (triangles), and W_C (squares) conditions; (B) mean CSFRs, with standard error bars, of these subjects; (C) residual differences between the mean CSFRs and MTFRs. The zero line corresponds to predicted CSF based on cascading MTF and CSF. Positive values may be described as a gain in sensitivity, negative values as a loss.

lowest on-axis MTFs (see Fig. 1). An instrument employing an electrooptic Fourier method was used to measure the MTFs.[21] The spatial frequencies, reported below, are all in the image space of the telescopes, as presented to the subject. At 20 cpd, the highest spatial frequency at which the CSF was measured, the modulation transfer of the Walters telescope was 58% compared with 12.7% for the Eschenbach. These values correspond to contrast attenuations of 1.7 and 15 dB with respect to the diffraction-limited contrast, respectively. The 13.3-dB difference in contrast in the image of a 20-cpd pattern is the maximum obtainable with these telescopes alone. However, because the telescopes must be coherently coupled to the compensator for the CSF tests, we remeasured the MTFs. The MTFs of the coupled systems are 53% and 29% at 20 cpd. The attenuation is 2.64 dB for the W_C system and 7.87 dB for the E_C system. The difference, thus, is reduced to 5.23 dB (0.26 log unit) and is less at lower spatial frequencies.

Figure 2 represents the modulation transfer function ratios (MTFR) between the telescope/compensator and the diffraction-limited MTFs. We evaluated the CSFs measured through the telescopic systems by comparing them to a criterion CSF based on cascading the MTFRs with the unaided CSFs. The differences between the criterion and aided CSFs indicate the extent of failure of cascading to predict CSF.

III. Results

A. Visually Normal Subjects

The mean CSFs of the five visually normal subjects, in the three test conditions, are shown in Fig. 3(A). Because the data points for the three conditions were at slightly different spatial frequencies we used Lagrangian interpolation to compute the sensitivity at a common set of spatial frequencies (3, 6, 9, 12, 16, 18, and 20 cpd) for each subject.

We computed the ANOVA for a repeated measures, two-factor design of test condition by spatial frequency, on the logarithmically transformed mean sensitivities. The analysis indicates significant effects of test condition, $F(2,8) = 5.85$, $p < 0.05$; spatial frequency, $F(6,24) = 274.29$, $p < 0.001$; and test condition by spatial frequency, $F(12,48) = 3.99, p < 0.001$. The last reflects the greater attenuation of high spatial frequencies by the telescopes.

We also computed an ANOVA at each spatial frequency, as described by Keppel.[22] There is a significant main effect ($p < 0.05$), that is, the means of the unaided, Eschenbach, and Walters CSFs differ at 18 and 20 cpd (see Table II). This table also lists the F/ratios and probabilities obtained from a comparison of pairs of means. Above 12 cpd, the means of the Eschenbach CSFs differ significantly from the unaided (U vs E_C). There are no significant differences between the mean CSFs for the Walters compared to unaided (U vs W_C). A comparison of the Eschenbach to the Walters (E_C vs W_C) reveals significant differences in sensitivities for spatial frequencies of 9 cpd and higher with probabilities that range from <0.01 to <0.05.

We show in Fig. 3(B) the contrast sensitivity function ratios (CSFR), or algebraic differences in decibels, between the aided and unaided test conditions. They are structurally analogous to visuograms.[23] These curves would lie on the horizontal 0-dB line only if the telescope systems were diffraction-limited and could be cascaded with the CSF of the visual system. As a figure of merit, the area below the 0-dB line, bounded by the CSFR, indicates sensitivity losses with the device; areas above the 0-dB line indicate gains in sensi-

Table II. Summary of Significant *F*/Ratios for CSFs of Visually Normal Subjects

Source	df	Spatial frequency (cpd)				
		9	12	16	18	20
All	2,4	—	—	—	7.14*	7.24*
U vs E_C	1,4	—	10.11*	10.57*	9.75*	8.79*
U vs W_C	1,4	—	—	—	—	—
E_C vs W_C	1,4	40.84**	4.79**	8.85*	11.82*	6.86*

* $p < 0.05$; ** $p < 0.01$.

tivity. The Eschenbach system produces greater sensitivity losses across all measured spatial frequencies than the Walters system. The latter shows slightly lowered contrast sensitivities at spatial frequencies above 9 cpd.

Figure 3(C) shows the residual differences (δ) computed from the data illustrated in Figs. 2 and 3(B), where δ = CSFR − MTFR. Cascading would predict that these points lie on the 0-dB line. Positive decibel differences indicate higher contrast sensitivity than predicted by cascading. The sensitivities through the W_C system very nearly correspond to the function predicted by cascading. However, better-than-predicted contrast sensitivities result at high spatial frequencies through the E_C system.

B. Aphakic Subjects

The mean CSFs for the three aphakic subjects are shown in Fig. 4(A). They are lower than the CSFs of the visually normal subjects. The results of a two-factor ANOVA are similar to those for the visually normal subjects, except that for the simple main effect, that is, the differences between the test conditions, the value of $F(2,4) = 4.36, p < 0.01$. Spatial frequency and the interaction between test condition and spatial frequency were significant at $p < 0.001$. A comparison of pairs of means indicated significant differences ($p < 0.05$) only between the unaided and Eschenbach CSFs at spatial frequencies from 12 to 20 cpd.

The CSFRs shown in Fig. 4(B) indicate that the aphakic subjects, like the visually normal subjects, have relatively larger contrast sensitivity losses through the E_C system compared with the W_C telescope system. The sensitivity losses through the E_C system, at spatial frequencies above 12 cpd, are greater for the aphakic than for the visually normal subjects. However, as shown in Fig. 4(C), the residual errors between the MTFRs and the CSFRs are within 2 dB of zero, or nearly equivalent to the cascaded effect.

IV. Discussion

The MTF of the Eschenbach/compensator system exhibits contrast attenuations, with respect to the diffraction-limit, of 2–8 dB between 9 and 20 cpd, as shown in Fig. 2. A much smaller reduction in contrast, no more than 2 dB up to 20 cpd, is shown by the Walters/compensator system. The initial expectation, therefore, is for the E_C system to more severely degrade the CSF. Indeed, the CSFs of four out of the five visually normal and all the aphakic subjects were more severely degraded by the E_C system. Thus, even with MTF differences of <6 dB, it appears to be possible to rank the E_C system poorer on the basis of CSF tests. The results of the ANOVA confirm the significant ($p < 0.05$) reduction in CSFs caused by the E_C system at spatial frequencies above 9 cpd.

The residual difference data for the visually normal subjects, shown in Fig. 3(C), however, indicate that the CSF through the E_C system is better than predicted by cascading, at the high spatial frequencies, and maximally so (by 3.2 dB, S.E. = 1.4 dB) at 20 cpd. Cascading would predict a loss in contrast sensitivity at 20 cpd equal to the 7.9-dB attenuation in modulation of the E_C system (see Fig. 2). Better-than-predicted CSFs may be due to fortuitous aberration balancing by the ocular surfaces and appropriate accommodative changes in the lens to obtain best focus. But these factors appear not to be totally effective in compensating for the wavefront aberrations of the E_C system.

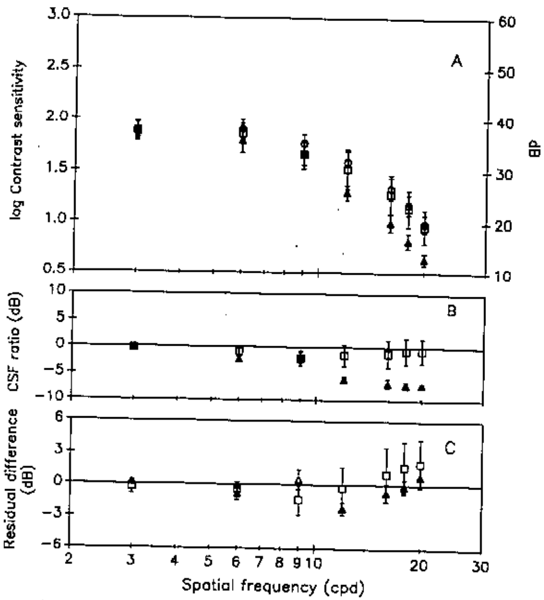

Fig. 4. (A) Mean CSFs of three aphakic subjects, with standard error bars indicated, for the unaided (circles), E_C (triangles), and W_C (squares) conditions; (B) mean CSFRs, with standard error bars, of these subjects; (C) residual differences between the mean CSFRs and MTFRs. The zero line corresponds to predicted CSF based on cascading MTF and CSF. Positive values may be described as a gain in sensitivity, negative values as a loss.

The W_C system produces a CSF within 0.7 dB of the cascaded result across all spatial frequencies. The slight MTF attenuation of the W_C system, a maximal 2.6 dB at 20 cpd, suggests why it was not possible to show statistical differences between the unaided and W_C CSFs. It appears that a condition for cascading, namely, the coupling of a diffraction-limited optical device with the eye, was very nearly satisfied by the W_C system, and the predicted outcome was obtained. The ocular components and accommodation appear to have provided a well-focused retinal image of the sine wave grating.

In the case of the aphakic subjects, the CSFR of the E_C system is depressed more than the corresponding CSFR of the visually normal subjects, except at 9 cpd. The 12-cpd data point of the residual difference plots, in Fig. 4(C), deviates the most with respect to the zero line. Nevertheless, this plot indicates that the CSF measured through the E_C system is nearly equivalent to the cascaded values at all other spatial frequencies. This is consistent with the inability of the aphakic subjects to accommodate for best focus. The W_C system results in CSFs that show gains of ~2 dB at the high spatial frequencies.

Coherently coupled visual systems can produce a best-focus image that is defocused in the static eye. The aberrations (contrast) in this image may be greater or smaller than determined by the telescope alone due to interaction with the wavefront aberrations by the ocular refractive surfaces of visually normal and aphakic subjects. Aberration balancing and negligible retinal image defocus are necessary for the aphakic subjects to show gains in their CSFs; a fortuitous coincidence. The visually normal subjects can accommodate in an effort to bring these conditions about, provided that the defocused image is within the range of accommodation. Why, then, were not the departures from the cascaded predictions greater? In general, based on the results shown in Figs. 3(C) and 4(C), the mean CSFs of both the visually normal and aphakic subjects, measured through both telescopic systems, are within 2.5 dB of the cascaded values at all spatial frequencies. The standard errors are greatest (~2.6 dB) at 16 cpd for the aphakic subjects with the W_C system.

A possible explanation for the limited ability of the visually normal subjects to overcome aberrations and defocus errors by accommodation is that sinusoidal gratings are poor stimuli for accurate accommodation.[24,25] Charman notes that accommodative lag may cause errors in focus of sinusoidal gratings.[26] He found that, under favorable circumstances, considerable compensation for astigmatism and field curvature of a telescope may be achieved through the exercise of accommodation. However, accommodation to the image field may only be accurate to ~0.5 D.[27] Also, the 500-ms stimulus duration may have been too brief to permit accurate accommodation. Of course, the subjects did have a parafoveal stimulus to accommodation in the edge of the 2.5° mask that surrounded the sine wave gratings.

Finally, the question of whether MTF is a useful predictor of CSF requires us to establish a criterion or tolerance on the accuracy with which cascading must predict CSF to be useful. Higgins *et al.*[28] studied CSF test–retest reliability using forced-choice and method-of-adjustment procedures. They report that each method produced similar mean sensitivities and they show 99% confidence limits from initial test to retest for a sample of twenty eyes. However, they do not suggest acceptable tolerances. The closest we were able to come to finding a criterion was a statement by Tomlinson and Mann,[29] citing a personal communication from Applegate, that differences in CSFs of <0.2 log unit (or 4 dB) are unlikely to be clinically significant. In our study, cascading the instrumental MTF with the unaided CSF would have predicted CSF to within 4 dB at 88 out of 96 data points (eight subjects, measured through two telescopic systems at six spatial frequencies).

There presently are no standards on the optical performance of low vision devices. Our results indicate that the MTF of low vision devices should be included in such standards when they are formulated and be among the criteria used by clinicians in selecting and prescribing low vision devices.

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