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THE EFFECT OF INSTRUMENTAL SPHERICAL ABERRATION
ON VISUAL IMAGE QUALITY

by

Kevin P. Lyons

B. S. University of Rochester

(1980)

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science
in the Center for Imaging Science
Rochester Institute of Technology

April 1995

Signature of the Author _____

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CENTER FOR IMAGING SCIENCE
ROCHESTER INSTITUTE OF TECHNOLOGY
ROCHESTER, NY

CERTIFICATE OF APPROVAL

M.S. DEGREE THESIS

The M.S. Degree Thesis of Kevin P. Lyons
has been examined and approved by the
thesis committee as satisfactory for the
Master of Science degree

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4-6-95

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by
Kevin P. Lyons

Submitted to the
Center for Imaging Science
in partial fulfillment of the requirements
for the Master of Science Degree
at the Rochester Institute of Technology

ABSTRACT

The effect of instrumental spherical aberration has been examined by constructing telescopes with approximately 1, 2, and 3 waves of aberration. Contrast sensitivity and resolution results have been obtained, as well as information on the preferred focus in the presence of aberration. The results show that an appropriately defined integral of the instrumental MTF, called MTF_a, is the best candidate among image quality metrics for describing the observed degradation in performance as well as the preferred focus. For pupil diameters less than about 3 mm, these results support the assertion that the aberrations of the eye are of little importance in visual instrument optical design and testing.

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Lastly, I am eternally grateful to my wife, Dr. Judith Mevs, for keeping a very busy household running smoothly during my studies. Her ability to juggle the needs of our children, her work and this graduate student is noteworthy and will not be forgotten.

Dedication

I dedicate this thesis to my wife, Dr. Judith Mevs, for her unwavering support during my six years of study at RIT.

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CHAPTER 1

INTRODUCTION

Subjective performance in the presence of instrumental aberrations has been studied in the past by several investigators.¹⁻¹³ Work has concentrated on the subjective effects of astigmatism, coma and chromatic aberrations in visual instruments and their correlation with objective image quality metrics. The assumption was usually made that the image quality at the retina was an adequate predictor of subjective performance. If the optical designer could characterize the instrument - eye system, then image quality predictions could be made in advance, without worrying about the effects of neural processing that occur after imaging at the retina.

Most studies rely on the use of perceptually simple tasks to measure the subjective response; such as contrast sensitivity, resolution, or discrimination between aberrated and unaberrated targets.³ Contrast sensitivity experiments measure the contrast threshold of an instrument - eye system as a function of spatial frequency. An aberrated wavefront will increase this threshold. Resolution tests measure the limit of acuity, utilizing three - bar targets, sometimes as a function of contrast. These studies reduce the influence of purely perceptual factors and reveal the influence of instrumental effects.

There can be problems with predictions of image quality based on predictive models. The eye's optics are not totally understood, so modeling a system that includes the eye can lead to potential errors. Previous studies concerning the optical properties of the eye reveal different levels of aberrations, either as a result of natural inter-observer variations or limitations of the experimental apparatus^{14,21,24}. Also, there can be variations

in the accommodative response among observers. Particularly, there are differences in the “resting state” of the eye, which is the preferred focus state of the eye. This difference in resting state can influence overall image quality. In addition, there have been cases where the retinal image quality has not been a good predictor of subjective performance. The neural processes that occur after the retina can influence the perceived image quality and hinder efforts to predict degradation based on optical calculations. For example, when Giles studied the effects of spherical aberration he concluded that “the eye somehow compensates for spherical aberration somewhat better than a simple accommodative defocus predicts.”³ Giles is suggesting that there is a coherence of coupling between the optics of the eye and the instrument or that the eye-brain system is compensating for the aberration. Van Heel designed a lens that canceled the spherical aberration of the eye, and reported no change in subjective performance.¹⁵ This suggests that there is no coherence of coupling below a certain pupil diameter, which seems to contradict the conclusion of Giles.

The refractive system of the eye influences final image quality through both defocus from accommodation and aberrations. If aberrations of the eye coherently couple with the wavefront of the instrument, image quality can be affected. For this study, pupil sizes are $\leq 3\text{mm}$. Most investigators have concluded that aberrations at this pupil size are less than a quarter wave, so defocus is the largest contributor to image quality. The eye can then be thought of as a diffraction limited, variable focus system. Since the degrading effect of some instrumental aberrations can be minimized with defocus, the goal is to find an objective image quality metric that predicts correctly the accommodative response in the presence of aberrations.

The “accommodative response” is explained as follows. Each image quality metric is optimized in the presence of spherical aberration when defocus is added to the wavefront. This defocus can be converted to diopters of power for the eye-instrument system. One can now imagine each objective metric to be a separate “image” that the eye may choose to focus on in image space. The graph below illustrates the relative magnitude of each metric as focus is changed in a system with 3 waves of spherical aberration.

Figure 1.1: Through focus curves of objective metrics

The location of each metric’s peak (in terms of waves of defocus) can be converted to a position in image space. Zero waves of defocus corresponds to the position of paraxial focus. If the preferred plane of focus can be identified in the presence of aberration, this would be of help in the automated (observerless) testing of visual instrumentation by

defining the appropriate focus position at which performance should be measured. Objective metrics that have been studied include the Strehl ratio, R_{84} (the radius that contains 84% of the point spread function energy), the rms wavefront and the limited integral of the MTF, called the MTFa. The limits of integration of MTFa have been defined to be between the frequency limits of 5 to 24 cycles per degree¹². So far, the evidence favors the MTFa as the preferred metric for the accommodative response.¹⁶ The MTFa metric has not been tested adequately in the presence of spherical aberration until now.

If the accommodative response can be explained in terms of the preference for a particular objective metric it may also be reasonable to investigate the correlation between subjective degradation and the degradation of the metric. This would be of some help to the optical designer when comparing the relative effect of different aberrations on perceived image quality.

Previous studies that attempted to characterize the effect of spherical aberration have not been conclusive. The earliest study known is that of Coleman et al¹⁷, who attempted to quantify the choice of focus, and the degradation created by spherical aberration. His focus experiment resulted in the conclusion that the eye prefers paraxial focus for systems with greater than 1/4 wave of spherical aberration. This is difficult to explain, since one would expect the plane of best focus to shift from the paraxial plane in the presence of spherical aberration. Coleman's other study¹ on degradation resulted in the conclusion that "the reduction in image contrast produced by the common aberrations is great." Such a general statement is of little use to the optical designer in assessing the specific influence of spherical on subjective image quality. Other details would have been helpful in assessing the value of Coleman's results, such as specific focus settings

and a better description of aberration levels. The small pupil diameter used in his experiment (0.6 mm) was not useful for assessing the eye's influence at the more typical pupil diameters of 2 to 3 mm.

Giles's study³ concluded in general that the eye accommodated at the plane of minimum wavefront variance, but the spherical aberration fit to his data was the least successful (astigmatism and coma were better). In addition, the Giles data indicate that the 1.3 waves of spherical were mixed with 1 wave of coma, and 2.6 waves of spherical were mixed with 1.4 waves of coma. Spherical aberration was not studied in isolation.

Burton and Haig⁷ attempted to measure the degradation of images viewed on a monitor through aberrated telescopes. They concluded that there was no correlation between MTF and subjective image quality. They attempted to explain the lack of correlation by suggesting that the spherical aberration of the eye coherently coupled with that in the telescopes to affect the results. The magnitude of spherical aberration of the telescopes was not quantified, nor was there an attempt to correlate subjective data at other focus positions. Therefore this study was not useful in assessing the eye's accommodative response. Other studies^{9,10} by these authors were concerned with establishing a just-noticeable difference in image quality and therefore did not concern themselves with larger aberration values.

The vision and optometry community has also been concerned with the effect of spherical aberration, whether due to the eye alone, or due to external visual aids. Smith¹⁸ studied the spherical aberration of aphakic eyes corrected with intra-ocular lenses. He calculated the magnitude of the spherical aberration of the eye with different aspheric lens designs. In his study he calculated the accommodative response using the minimum of the variance of the wave aberration function as a focusing criteria. In addition, Smith did

not actually measure the degradation that resulted from calculated values of spherical aberration. He referred instead to the work of both Bauer¹⁹ and Burton & Haig¹⁰, who measured the visual tolerance to spherical aberration. Bauer constructed 3 zero power lens systems with different levels of spherical aberration and measured the reduction in visual acuity (using Landolt C's as targets) that resulted for pupil diameters of 4.4 to 5.8 mm. However in this study the pupil sizes were less than 3 mm and the aberrations of the eye are small. Bauer assumed that the eye focuses on the circle of least confusion and therefore did not investigate other alternatives for the accommodative response. As with the Burton & Haig study, this work focused on a tolerance for a just-noticeable difference, and did not study the effects of larger spherical aberration values.

Hemenger et al²⁰ studied the role of spherical aberration in contrast sensitivity loss with radial keratotomy. He proposed that the loss of retinal image quality could be the result of a change in the spherical aberration of the post - RK cornea. He compared MTF calculations to measured CSF degradation for 4 subjects and concluded that for some subjects the increase in spherical aberration of the cornea does reduce retinal image quality, but other subjects do not correlate. He chose the image plane to be that where the MTF at 22.4 c/degree is at a maximum.

The work described above concerning spherical aberration does not answer some basic questions about its effect on instrumental image quality. First, what is the relationship between the magnitude of spherical aberration and the resulting perceived degradation in image quality? Previous work did not isolate this aberration or it did not adequately quantify its magnitude. Second, can subjective degradation be predicted in terms of an objective metric such as MTF_a, the Strehl ratio, RMS wavefront or R_{84} ? If there is a correlation between one of these metrics and subjective degradation, can it be

explained simply in terms of the accommodative response of the eye? Other investigators assumed that the eye accommodated to a specific plane such as the minimum RMS wavefront focus without verifying this experimentally¹⁹. Even if such assumptions were reasonable for small aberration magnitudes, no attempt was made to establish accommodation choices at higher levels of spherical. Usually attempts at correlation studied only one metric in the presence of defocus without analyzing other candidates for correlation. Lastly, how significant is the coherence of coupling at pupils less than 3 mm diameter? An attempt will be made to answer these questions in a way that will provide useful recommendations to the optical designer.

CHAPTER 2

Apparatus and Methods

2.1 The Telescopes

The experiments comprised observations of various targets through specially constructed telescopes that presented known amounts of spherical aberration ($0-3 \lambda$), and negligible amounts of other aberrations over the central part of the field. Contrast thresholds were measured with sinusoidal targets and resolution thresholds were measured with USAF 3-bar targets. An attempt was also made to measure the choice of focus in the presence of these aberrations. Six different Keplerian telescope systems were assembled from six off-the-shelf achromatic doublets of known design prescription.

A typical optical layout is shown in figure 2.1.

Figure 2.1: Telescope optical layout

A detailed list of the optical prescription for each telescope is located in the appendix.

Table 2.1 is a listing of the Gaussian parameters.

Table 2.1
Gaussian properties of telescopes

<u>nominal spherical aberration</u> (waves)	<u>exit pupil diameter</u> (mm)	<u>Magnification</u>	<u>fl objective</u> (mm)	<u>fl eyepiece</u> (mm)
0	3.0	3.1	80	25
1	3.0	3.1	80	25
2	2.9	3.0	60	20
3	3.2	2.5	50	20
0	2.2	2.5	50	20
1	2.2	2.5	50	20

Table 2.1 shows that the gaussian properties of some of the telescopes are the same. They do have different amounts of spherical aberration because the orientation of the lenses was changed or the entrance pupil size was changed. Specifically, the objective of the 1λ scope was reversed to create the 3 mm pupil control telescope. The 1λ , 2.2 mm pupil telescope was created by reducing the entrance pupil size of the 3λ scope. The 2.2 mm pupil control telescope was constructed by reversing the objective in the 1λ scope. Table 2.2 shows the design aberrations. The aberrations are represented in terms of the coefficients of the wavefront aberration polynomial:

$$W(r,\theta) = W_{11}r(\sin\theta) + W_{20}r^2 + W_{40}r^4 + W_{22}r^2(\sin^2\theta) + W_{31}r^3(\sin\theta) + \text{higher orders}$$

↑
tilt

↑
defocus

↑
spherical

↑
astigmatism

↑
coma

The field dependent aberration values are shown at a 3 degree semi-field angle in eye space. Two pupil sizes were required in order to assess the contribution of the eyes' aberrations to the degradation observed.

Table 2.2

Design values of telescope aberrations

<u>spherical</u>		<u>coma</u>	<u>astigmatism</u>	<u>axial color</u>	<u>lateral color</u>
W_{40}	W_{40}	$W_{31}(\lambda)$	W_{22}	∂W_{20}	∂W_{11}
(λ)	(diop)		(λ)	(λ)	(λ)
0.15	0.17	-.21	0.44	-0.26	0.48
1.16	1.2	-.05	0.17	-0.19	0.40
2.18	2.5	-.16	0.36	0.02	0.02
3.18	3.2	-.04	0.36	0.02	0.09
0.19	0.40	-.24	0.16	-0.09	0.04
0.73	1.5	-.01	0.17	0.01	0.06

The available targets used for the medium and high frequencies actually subtended less than the intended 2 degrees in object space. As a result, off axis aberrations were less than those listed above for some targets. The low frequency target filled the entire field, so aberration content was higher at the edge of the target. The observer tended to concentrate on the center of the field, so the influence of off axis aberrations was low. The table below lists the aberrations at the edge of the targets.

Table 2.3
Aberration magnitudes at edge of target

<u>Telescope</u>	<u>Aberrations @</u> <u>target edge (waves</u> <u>@ 550 nm)</u>		
	<u>low frequency</u>	<u>medium frequency</u>	<u>high frequency</u>
0.7 waves W_{40}	W_{31} : 0.02	W_{31} : 0.01	W_{31} : 0.00
	W_{22} : 0.29	W_{22} : 0.06	W_{22} : 0.01
1.2 waves W_{40}	W_{31} : 0.28	W_{31} : 0.08	W_{31} : 0.04
	W_{22} : 0.74	W_{22} : 0.06	W_{22} : 0.02
2.2 waves W_{40}	W_{31} : 0.23	W_{31} : 0.06	W_{31} : 0.03
	W_{22} : 0.71	W_{22} : 0.05	W_{22} : 0.01
3.2 waves W_{40}	W_{31} : 0.05	W_{31} : 0.03	W_{31} : 0.01
	W_{22} : 0.60	W_{22} : 0.13	W_{22} : 0.03

The two telescopes with less than 0.2 wave spherical were used as the control telescopes against which the performance of the aberrated telescopes was compared. The other telescopes have approximately 1, 2 and 3 waves of undercorrected third order spherical aberration. These aberration values were measured experimentally, as is described in following section.

The lenses were assembled in precision machined barrels which provided for good alignment and easy replacement of lenses. Such replacement was necessary in this experiment because aberration conditions had to be recreated for different observers at different stages of the experiment. The tube extension that holds the aperture stop also acts as a retaining ring for the objective lens; no cement was used. The eyepiece barrel was moveable to allow focusing, and could be locked in place with a screw mechanism that did not cause lens motion upon engaging. This was verified when the transmitted wavefront of the telescopes (as viewed on an interferometer) did not change when the locking screw was tightened. Figure 2.2 illustrates the mechanical layout of the telescopes.

Figure 2.2: Telescope barrel assembly

As shown in figure 2.2, a shifted stop was utilized in order to minimize off axis aberrations. Table 2.4 shows the reduction in coma and astigmatism that resulted from shifting the stop.

Table 2.4

Aberration reduction resulting from shifted stop at 3 degrees in eye space

<u>W40</u>	<u>W31:</u> <u>no shift</u>	<u>W31:</u> <u>shifted stop</u>	<u>W22:</u> <u>no shift</u>	<u>W22:</u> <u>shifted stop</u>
1.1	0.83	0.05	0.60	0.17
2.2	0.99	0.03	0.50	0.36
3.1	2.68	0.04	0.95	0.36

Figures 2.3 and 2.4 show the actual telescope components used for this experiment.

Figure 2.3: 1λ , 2λ , and 3λ telescopes

Figure 2.4: Telescope barrel, aperture plate holder, aperture plate

2.1.1 Telescope calibration

Before assembly, the focal length, back focus and front focus of the individual lenses were tested on a precision nodal slide bench. All lenses were found to be within 0.1 mm of specification. This served as an indirect verification of the telescope magnifications used in this experiment. Values of spherical aberration, axial coma and axial astigmatism were measured utilizing a Twyman - Green interferometer illuminated with a He-Ne laser at 632.8 nm in a double-pass configuration. Figure 2.5 shows the interferometer set-up.

Figure 2.5: Twyman - Green interferometer

A photograph of the equipment is shown below.

Figure 2.6: Hardware for Twyman - Green interferometer

The telescope was aligned in the interferometer by first nulling out the fringe pattern of the empty interferometer test cavity. The telescope was then placed in the test arm and tipped, translated and focused until a symmetric fringe pattern was observed. The test mirror near the telescope was then tipped to produce the vertical fringes required for data collection. The telescope was not moved after the initial alignment described above.

A CCD camera and frame grabber hardware was used to acquire the fringe pattern that was imaged on a transparent screen. WISP software analyzed the interferogram and calculated the seidel aberrations. Table 2.5 lists the measured on-axis aberrations for each telescope. The magnitude of spherical aberration is very close to the predicted values. The magnitude of coma and astigmatism is small, which verifies that the lenses

were well aligned. If coma was present in the wavefront due to lens to lens misalignment, no amount of telescope tilting in the interferometer cavity would have canceled the comatic wavefront and produced the symmetric wavefronts observed. The interferometer cavity was measured without the telescope in the beam to verify that the system errors are too small to affect the aberration magnitudes significantly.

Table 2.5

Measured wavefront errors converted at 550 nm

<u>Telescope</u>	<u>W_{40} (waves)</u>	<u>W_{31} (waves)</u>	<u>W_{22} (waves)</u>
3 mm pupil; control	0.15	0.17	0.07
3 mm; 1.1 wave	1.27	0.09	0.14
3.2 mm; 2.1 waves	2.15	0.12	0.05
3mm; 3.1 waves	3.17	0.23	0.12
2.2 mm; 0.73 wave	0.78	0.19	0.20
2.2 mm control	0.09	0.23	0.15
interferometer cavity	0.16	0.06	0.10

An example of graphical output from WISP software is shown in figure 2.7.

Figure 2.7: Wisp output

2.2 Targets and Illumination

The target illumination system that was used for CSF and resolution data collection is shown in Figure 2.8.

Figure 2.8: Illumination fixture layout

A photograph of the illumination system is shown below, where the telescope in a V-groove mount can be seen in the foreground.

Figure 2.9: Illumination fixture hardware

Light from a 400 watt Xe arc lamp, after filtering out the UV and attenuating to the desired level, was focused through a variable beamsplitter. Two flashed opal diffusers were placed in the two arms. The target was in contact with one of the two diffusers. The two diffusers were seen through a nominally 50-50 beam combiner. A collimating lens presented the object at infinity for the telescopes. The collimator was a well

corrected doublet of 300 mm focal length, operating at about F/30, thus not contributing any measurable spherical aberration.

2.2.1 Alignment of telescopes in target illumination fixture

The telescope v-groove mount was aligned to the target by first placing a cylindrically shaped He-Ne laser in the mount and tipping and translating the mount until the beam was retro-reflected. Some small height difference remained in the beam because the laser was a different diameter than the telescope barrels. The collimating lens was then placed in the laser beam and translated until the beam returned to its original position. The collimating lens was focused on the target by placing an autocollimator in the v-groove and moving the collimating lens until the target appeared to be in focus. For the 300 mm fl collimating lens an estimated focusing error of 1 mm resulted in an image position error of only 0.01 diopters.

A close-up of the mounted telescope with a correcting lens in front of the eyepiece is shown in figure 2.10. This correcting lens was used to cancel the known sphere errors of each observer.

Figure 2.10: Telescope mounted in illumination fixture

The apparent contrast of the target could be adjusted by rotating the variable beamsplitter. The variation in total luminance (sum of both diffusers as seen through the beam combiner) over the angular range of the beamsplitter was less than 15%. This variation was minimized in order to prevent the observer from receiving clues relating to the setting of the beamsplitter, and therefore the contrast setting. Figure 2.11 shows the variation in total luminance over the full 360 degree rotation range of the beamsplitter in terms of the voltage reading of a power meter.

Figure 2.11: Beam power as a function of beamsplitter angle

In order to minimize luminance variations, the beamsplitter was used in the angular range of 140 to 300 degrees. The nominal target luminance was 150 cd/m^2 . Such a luminance is expected to produce a pupil size larger than 3 mm^{22} , so the exit pupil is determined by the telescope. This was verified through direct observation of the observers' eye pupil while looking at the target. A neutral density filter placed just after the light source was used to equate the apparent luminance of the targets at the two pupil sizes.

2.2.2 Target and Contrast Calibration

The targets used for the first part of the experiment were photographically produced sinusoidal transparencies, and a positive USAF three-bar target. Figure 2.12 is an example of a sinusoidal target.

Figure 2.12: Sinusoidal target

Calibration of the apparent contrast of this target involved measuring the intensities of each arm of the illumination fixture as a function of beamsplitter angle. The transmittance T_0 and the contrast V of the each target also had to be measured. These quantities were used to calculate the apparent contrast (C) of the image. A simplified schematic of the illumination fixture is shown below.

Figure 2.13: Schematic for contrast calculation

The target transmittance has a sinusoidal variation superimposed on the average transmittance:

$$T = T_0 (1 + V \cos kx)$$

where T_0 = average transmittance of target

and V = contrast of target

The total intensity of the combined beams is

$$I_{\text{tot}} = I_1 T_0 (1 + V \cos kx) + I_2 = [I_1 T_0] + I_2 + [I_1 T_0 V \cos(kx)]$$

This can be reduced to

$$I_{\text{tot}} = I_0 [1 + C \cos(kx)]$$

The apparent contrast observed is

$$C = (I_1 T_0 V) / (I_1 T_0 + I_2)$$

$$\text{and } C = V / (1 + R / T_0)$$

$$\text{where } R = I_2 / I_1$$

A detector was placed in the beam after the two beams recombined. The intensities I_1 and I_2 were measured separately as a function of beamsplitter angle. R was calculated from these measurements. T_0 and V were measured for each target using a CCD camera to image the transmissive sinusoidal targets on a monitor. “Imlab” software was used to digitize a frame and record an intensity trace of the sinusoid. Initially background levels in the image were measured by blocking the light source and storing the resulting data set. A 100% luminance level was also recorded with no target over the light source. The background noise was subtracted from both the 100% level data set and the target data set. The software then calculated the ratio of the target to the 100% level. This provided transmittance information over many periods of the sinusoid. This transmittance

measurement was calibrated by measuring the transmittance of Kodak ND filters with known densities. Very good agreement resulted from this comparison. Average transmittance (T_0) of each target was calculated by calculating the average of the maximum and minimum values of T :

$$T_0 = (I_{\max} + I_{\min})/2$$

The contrast V was calculated by recording the maximum and minimum transmittance and performing the following calculation:

$$V = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$$

Figure 2.14 shows the data acquisition steps required to obtain a transmission curve for the sinusoid.

Figure 2.14: Target signal for contrast calibration

Because there is a pronounced variation in total intensity from 0 to 50 degrees (beamsplitter position), as shown in figure 12, an effort was made to keep all

observations out of this zone. If a threshold appeared to be in this region, more neutral density filters were added to the non-target arm of the fixture. This had the effect of shifting a particular contrast setting to another beamsplitter setting that was out of the region of variation. If such filters are added the final contrast is recalculated:

$$C = V/(1 + [R \cdot T_n]/T_0)$$

T_n = transmittance of the added filter

If the contrast threshold appeared to be at or below the minimum contrast setting of the beamsplitter, additional filtering was added to the target arm of the fixture. This had the effect of moving the threshold up away from the minimum angle of the beamsplitter. This change was incorporated into the calculation by multiplying the average transmittance of the target (T_0) by the transmittance of the added filter.

2.2.3 Sinusoidal Gratings

The sinusoidal targets were intended to cover the frequency range of 5-20 c/degree in the eye space. Because of the different telescope magnifications involved (2.5X - 3.1X) and the range of targets available, a range of 4-22 c/degree was observed. The spatial frequencies of the sinusoidal gratings were measured with a Nikon toolmakers' microscope. The spatial frequencies were converted to units of cycles per degree using information about the focal length of the collimating lens (300 mm) and the magnification of each telescope:

$$\text{cycles/degree} = (\text{cycles/mm} \cdot \text{fl}) / (180/\pi \cdot \text{mag.})$$

The following table lists the spatial frequencies that were observed in this experiment.

Table 2.6

Target spatial frequency in eye space

<u>telescope</u>	<u>frequency (c/deg)</u>		
	<u>low</u>	<u>medium</u>	<u>high</u>
3 mm pupil control	3.9	8.7	20.6
1.2 waves W40	3.9	8.7	20.6
2.2 waves W40	4.1	9.1	21.5
3.2 waves W40	4.9	8.8	22.4
2.2 mm pupil control	4.9	8.8	22.4
0.7 wave W40	4.9	8.8	22.4

The targets had the following number of periods visible in the field of view:

Table 2.7
number of periods visible in sinusoid

<u>Telescope</u>	<u># periods</u>		
	<u>low frequency</u>	<u>medium frequency</u>	<u>high frequency</u>
3 mm pupil control	31	32	32
1.2 waves W40	31	32	32
2.2 waves W40	33	32	32
3.2 waves W40	31	20	26
2.2 mm pupil control	31	20	26
0.7 wave W40	31	20	26

It is important to have at least 10 periods so that the target approximates infinite extent to the observer's eye per studies by Howell³⁴.

Table 2.8 lists the angular size (in eye space) of each target in the field of view.

Table 2.8
Target sizes in eye space

	<u>target size</u> (full field; deg.)		
<u>telescope</u>	<u>low frequency</u>	<u>medium frequency</u>	<u>high frequency</u>
3 mm pupil control	8.1	2.3	1.3
1.2 wave	8.1	2.3	1.3
2.2 wave	8.4	2.2	1.2
3.2 wave	6.5	3.0	1.4
2.2 mm pupil control	6.5	3.0	1.4
0.7 wave	6.5	3.0	1.4

2.3 Focusing the telescopes

In this experiment the focus of each telescope was pre-set and kept constant. The focusing experiment that will be described later illustrates the variability associated with observer selection of focus. It is because of this variability that the focus was pre-set. The 3λ telescope had a second pre-set focus position tested. A second focus setting was chosen because it was not clear which focus would be optimum for visual testing at such a large aberration level. The performance of the telescope at both focus settings will be compared in a section that follows.

Due to depth of focus limitations, the telescopes had to be focused in the following way, using the interferometer. The telescopes were placed in the test arm of the Twyman-Green interferometer and focused until the minimum rms wavefront condition was observed. When the minimum rms wavefront was reached, the eyepiece was locked into place with a screw on the side of the telescope barrel. The separation of the top surface of the eyepiece and the barrel of the telescope was recorded. This position of minimum rms position could be used as an objective reference point for other focus settings. It is known that this minimum rms position is separated from paraxial focus by power that is equal but opposite in magnitude to the spherical aberration present:

$$\delta W_{20} = -W_{40}$$

Once the position of paraxial focus is known, the other metrics can be located in image space with respect to it. By converting waves of defocus to diopters defocus, the position of paraxial focus could be calculated:

$$\delta W_{20} = 1/2 * h_e^2 * \delta D \quad \text{equation \#1}$$

where δW_{20} = defocus (m)

h_e = exit pupil radius (m)

and δD = diopters of defocus (1/m)

Once the defocus is expressed in terms of diopters (δD), the linear shift of the eyepiece can be calculated using the paraxial lens makers formula:

$$1/s_1 + 1/s_2 = 1/f_e \quad \text{equation \#2}$$

s_1 = object distance (the object is the primary image produced by the objective)

s_2 = virtual image distance = $1/\delta D$ (from previous calculation)

f_e = focal length of the eyepiece

The focal length (f_e) is known and the virtual image distance (s_2) was calculated using formula #1 ($1/\delta D$). The object distance (s_1) is then calculated. The difference between the object distance and the eyepiece focal length is the focus shift required to place the telescope at paraxial focus. For example:

$$f_e = 25 \text{ mm}$$

$$W_{40} = 1.17 \text{ waves} = 6.435 \times 10^{-7} \text{ m}$$

$$h_e = 1.53 \times 10^{-3} \text{ m}$$

$$1/2 * h_e^2 = 1.1552 \times 10^{-6} \text{ m}^2$$

$$\delta D = .557$$

$$1/\delta D = 1.795 \text{ m} = 1795 \text{ mm}$$

$$1/(-1795 \text{ mm}) + 1/s_1 = 1/25 \text{ mm}$$

$$\text{therefore the object distance } (s_1) = 24.657 \text{ mm}$$

$$(25 \text{ mm} - s_1) = .343 \text{ mm} = 0.014''$$

Therefore the eyepiece needs to be moved out by a distance of 0.014 inch to place the telescope at paraxial focus. When the telescopes were used at this paraxial focus it was

clear that the eye would not prefer to set focus here in the presence of spherical aberration.

Since previous studies have shown that the eye prefers to place the image at -1 diopters²³, it was decided to place this minimum rms wavefront image there. Such a focus setting would place the other objective metrics in question within the eye's accommodative range. A 1 diopter shift of the minimum rms image was calculated for each telescope based on the focal length of each eyepiece. Equations 1 and 2 (listed above) were used for this calculation. For example, using the following parameters, the eyepiece shift for the 1 wave telescope is calculated:

focus setting at minimum rms wavefront: 0.495"

focal length of eyepiece: 25 mm

image distance for -1 diopter : -1000 mm

$1/(-1000 \text{ mm}) + 1/s_1 = 1/25 \text{ mm}$

object distance (s_1) = 24.390 mm

$(25\text{mm} - 24.390\text{mm}) = 0.610 \text{ mm} = 0.024''$

$0.495'' - 0.024'' = 0.471''$

eyepiece shift = .024"

Each eyepiece was moved in by the amount that was calculated using the procedure outlined above. At this focus setting, the critical image quality metrics are all within the accommodative range of an observer. Table 2.9 lists the focus settings for each telescope

in terms of the separation between the outer surface of the eyepiece and the rear surface of the barrel.

Table 2.9

Mechanical focus settings; eyepiece flange to barrel

<u>Telescope</u>	<u>paraxial focus setting</u>	<u>min RMS at -1 diopter</u>
	(inches)	(inches)
3 mm pupil control	0.323	0.299
1.2 waves W_{40}	0.509	0.471
2.2 waves W_{40}	0.498	0.467
3.2 waves W_{40}	0.440	0.404
2.2 mm pupil control	0.206	0.191
0.7 wave W_{40}	0.443	0.418

Table 2.10 lists the positions of the various metrics for each focus position.

Table 2.10

Position of image metrics

IMAGE POSITIONS

	R84	min RMS	MTFa	Paraxial
2.2 mm pupil control	-1D	-1D	-1D	-1D
3 mm pupil control	-1D	-1D	-1D	-1D
0.73 wave	-.89D	-1D	-1D	-1.67D
1.1 waves W40	-.89D	-1D	-1D	-1.57D
2.2 waves W40	-.78D	-1D	-1D	-2.14D
3.2 waves W40	-.77D	-1D	-1.4D	-2.37D
3.2 waves W40 (shifted focus)	+0.52D	+0.33D	-0.2 D	-1D

2.4 Observers and methods

There were 3 observers, from 25 to 40 years old, using their dominant eye for the observations. Observer 1 had better than 6/6 uncorrected acuity. Observer 2 was a -2D myope with no astigmatism, and observer 3 required -0.5D sphere correction. All had perfect near vision at 25 cm while wearing their corrective lenses. Sphere correction was made possible with a diopter lens mounted in front of the eyepiece for the contrast threshold and the resolution threshold experiments.

2.4.1 CSF data collection

The first part of the experiment consisted of contrast sensitivity experiments taken at the frequencies listed in table 6, using the variable contrast fixture described in the previous section. A random double staircase was used to collect the data. The experiment was controlled by a personal computer which determined the contrast for the presentations, prompted the observers to look and then relax, and recorded the data. The observers had 8 seconds in which to place their eye at the exit pupil and give their response. The staircases had a total of 50 observations, the last 20 of which were used for the threshold calculation. The contrast step was halved after the first 20 observations. The appropriate step size as well as the high and low initial contrast values were determined empirically after some trial runs. These values generally varied for the different aberration conditions, spatial frequencies, and observers. The observers trained for a total of more than two experimental sessions, and had several incomplete sessions of less than 50 observations under the different aberration conditions in order to establish the staircase step and the high/low values.

A typical staircase data set is shown in the following figure.

Figure 2.15: Staircase data

A staircase run lasted around 20 minutes; no more than 3 runs were taken in a single day to avoid fatigue. The observers were allowed to stop the experiment whenever they wished in order to rest. The observers were instructed to rest their eyes on an illuminated white card whenever possible between observations. Counting training sessions, there were approximately 75 staircase runs performed in total.

With a grating near threshold, the field appears totally unstructured, so it is difficult for the observers to maintain a consistent accommodative response. Thus the gratings were flanked by two dots (placed on the other diffuser) which were seen at high

contrast when the target was being viewed at low contrast. These dots provided some accommodative clue to help guide the accommodation in the neighborhood of the grating image. Of course, since they were normally imaged outside the fovea they were not a perfect accommodative clue, nor were they meant to be. Even if it was somehow possible to superimpose the dots on the grating image, the resulting clue might have been confusing, at least for the 2λ and the 3λ scopes. This is because the high frequencies contained in the dots are imaged optimally at a different focal plane than the grating.

2.4.2 Three bar resolution data collection

The second part of the experiment involved viewing the three bar resolution target at contrast levels of 0.02, 0.1, 0.2 and 0.3 for all the telescope/focus setting combinations used in the CSF portion of the experiment.

Figure 2.16: Three-bar target

Each observer was given unlimited time to view the target and report the smallest group that was resolvable to establish a resolution threshold. The three-bar target was placed in the same position on the illumination fixture as the sinusoidal targets. No accommodative clues were required for this portion of the experiment because the target was always well above the contrast threshold. The charts of interest were placed near the center of the field of view, minimizing any off-axis aberrations. Resolution thresholds were the same in the vertical and horizontal chart orientations, indicating that astigmatism was not present in the wavefront. The spatial frequency was known for each group on the target and converted to cycles/degree in the eye space when telescope magnification and collimator focal length were taken into account.

CHAPTER 3

Results and Discussion

3.1 Contrast sensitivity experiment

Seven contrast sensitivity curves were taken at 3 spatial frequencies each, for each of the 3 observers. The primary data set consisted of contrast sensitivity for a control telescope and telescopes with 1.2, 2.2 and 3.2 waves of spherical with a 3 mm pupil. A secondary data set consisted of contrast sensitivity for a control telescope and a telescope with 0.7 wave of spherical with a 2.2 mm pupil. Collecting data for two controls with different pupil sizes made it possible to assess the contribution of the eye's aberrations to perceived image quality.

Some data sets appeared to be inconsistent with previous results and were remeasured. Observer GZ's results proved to have high variability and were not consistent enough to include in group averages. As will be explained in the focus experiment section, this observer appeared to prefer accommodate very close, so placing the various image metrics around -1 diopter resulted in errors in accommodation and inconsistent results.

Figures 3.1 through 3.3 show the log of the CSF plotted as a function of spatial frequency for the 3 mm pupil telescopes. In order to reduce and make presentable the

information contained in the CSF graphs, interpolated CSF curves were plotted according to the relation:

$$\log(\text{CSF}) = af + b$$

It should be emphasized that this linear fit cannot be extrapolated to frequencies lower than 4 cycles/degree, since it is known that the CSF of the eye drops at frequencies below this value.

Figure 3.1: CSF of 3 mm pupil telescopes; Observer KL

Figure 3.2: CSF of 3 mm pupil telescopes; Observer ZM

Figure 3.3: CSF of 3 mm pupil telescopes; Observer GZ

Figures 3.4 through 3.6 show the CSF results for the 2.2 mm pupil telescopes.

Figure 3.4: CSF for 2.2 mm pupil telescopes; Observer KL

Figure 3.5: CSF for 2.2 mm pupil telescopes; Observer ZM

Figure 3.6: CSF for 2.2 mm pupil telescopes; Observer GZ

The table below lists the slopes (a) and intercepts (b) for the interpolated CSF curves:

Table 3.1

Slope and intercept values for interpolated CSF curves

<u>condition</u>	<u>observer 1</u>		<u>observer 2</u>	
	<u>a</u>	<u>b</u>	<u>a</u>	<u>b</u>
3 mm control	-0.046	2.80	-0.061	3.22
1.2 λ	-0.051	2.79	-0.061	3.12
2.2 λ	-0.591	2.76	-0.067	3.02
3.2 λ (std. focus)	-0.065	2.72	-0.065	2.88
3.2 λ (shifted focus)	-0.044	2.52	-0.064	2.83
2.2 mm control	-0.049	2.87	-0.064	3.18
0.7 λ	-0.047	2.81	-0.068	3.10

A seventh CSF curve was measured with the 3 wave telescope set at a different focus position. This was done because the proper choice of focus for such a large aberration is not obvious. The results of this measurement will be discussed later in this section. The graphs of CSF show a clear downward trend as the aberration level increases, except for

GZ's results which show an increase in CSF for the 1 wave telescope. This part of the experiment was repeated for this observer, and the variation in results illustrated the fact that the threshold criteria for this observer was not constant. As a result, GZ's data was not included in averaged results. If GZ's results were included in the data, the results would be very similar; removing his data just helped to reduce the overall variability of the data.

It can be seen that the maximum CSF value (of the control) varied from observer to observer. Each observer has an individual peak CSF capability. The aberrated curves fall below this maximum CSF curve, but one cannot compare directly (among observers) the CSF values when talking about visual performance in the presence of aberrations.

3.1.1 CSF degradation

A more meaningful measure is the CSF degradation, which is the ratio of the aberrated CSF to the control CSF. This ratio was calculated at three spatial frequencies of 4, 9, and 22 cycles per degree. Figure 3.7 shows the degradation of two observers.

Figure 3.7: CSF degradation for individuals

Observer KL's results are sufficiently similar to observer ZM's to permit averaging of the results. This averaging has also been applied to the three bar results in the section describing resolution degradation.

Figure 3.8: Average CSF degradation

Figure 3.9 shows the degradation of the (2.2 mm pupil) 0.7λ telescope. It is similar to the (3 mm pupil) 1.2λ degradation (also shown).

Figure 3.9: Average 0.7λ , 1.2λ degradation

With reference to the question of the influence of the eye's aberrations with a 3 mm pupil, the CSF data for the control telescopes can now be compared. A t-test was performed to check for statistically significant differences in the data.

Table 3.2

t values ($\alpha = 0.95$) for unaberrated telescope CSF values

OBSERVER	FREQUENCY		
	LOW	MEDIUM	HIGH
KL	0.86	0.27	6.8
ZM	0.95	2.75	9.65

t - critical = 2.02

There seems to be a significant difference for the high frequency data, but on average the data is similar. This suggests that the aberration content of the eye remains small at the 3 mm pupil size. Figure 3.10 shows the comparison between CSF's for the 2 pupil sizes.

Figure 3.10: CSF comparison of control telescopes

If the eye is diffraction limited at 2.2 and 3 mm pupils, it could have as much as 1 wave of spherical aberration. The 0.7 wave and 1.2 waves CSF results show a small but

detectable degradation. An improvement in CSF was never observed. This indicates that coherence of coupling is not significant, since coherence could result in improved image quality if aberrations canceled each other.

Figure 3.11 shows the average 3λ CSF degradation for the two focus positions.

Figure 3.11: 3λ shifted focus degradation

This focus shift was required for the following reason. It was unclear where the focus should be set due to the large aberration level, and a second setting was used in case the first setting was not preferred. A t-test of the 3.2 wave CSF values before and after the focus shift indicate that there was little change in average CSF for one observer (ZM) but a statistically significant difference for the other observer (KL). On average, the difference between the two focus settings is not large. This shows that there is relatively little sensitivity to the focus setting for the highly aberrated telescope.

Table 3.3

t values ($\alpha = 0.95$) for 3λ shifted focus CSF values

OBSERVER	FREQUENCY		
	LOW	MEDIUM	HIGH
KL	7.24	4.36	22.39
ZM	0.77	7.84	0.22

t - critical = 2.02

As a general guide for the optical designer, the subjective CSF degradation can be shown as a function of W_{40} . The degradation was averaged over all frequencies for 2 observers.

Figure 3.12: Average contrast degradation

3.1.2 CSF correlation to objective metrics

In order to obtain the amount of objective degradation, WISP software was used to calculate the magnitude of MTFa, R_{84} , Strehl ratio and the rms wavefront. The nominal zernicke coefficients of each telescope were used as input to the program since interferometry verified that the lenses were aligned properly with little residual aberrations. MTFa was calculated for the frequency range of 4 to 23 c/degree, since this was the approximate range of target frequencies observed. WISP provides MTF data on a normalized scale. This scale was converted to cycles/degree by calculating the cutoff frequency in terms of cycles/degree:

$$v_{\text{cutoff}} = (d/\lambda) * (\pi/180)$$

Where d is the diameter of the exit pupil of each telescope and λ is taken to be $5.5 * 10^{-4}$ mm.

Figure 3.13 shows the MTF curves for each telescope at the plane of peak MTFa.

Figure 3.13: MTFa limits (vertical lines)

Figure 3.14 shows the correlation between CSF degradation and the degradation of the metrics MTFa, R_{84} , Strehl ratio and wavefront variance. Because the normalization (by the unaberrated result) applies to both subjective and objective quantities, the results from the 2.2 mm pupil experiment can be included on the same graph.

Figure 3.14: CSF correlation to metrics

Table 3.4 summarizes the correlation coefficients and the slopes for the graphs above:

Table 3.4

Correlation coefficients for CSF vs. objective metric degradation

	<u>MTFa</u>	<u>Strehl</u>	<u>R_{r4}</u>	<u>wavefront variance</u>
R ²	0.98	0.93	0.93	0.94
slope	0.92	0.64	0.85	-7.89

These metrics all correlate well with subjective CSF degradation. MTFa shows the best correlation, both in terms of R² fit and the slope of the line. The MTFa correlation provides a nearly 1 to 1 relationship between subjective and objective degradation. This is understandable in that the contrast of sinusoids was being observed. It is important to note that similar conclusions result if correlations are calculated based on individual results instead of average results. For example, all the observers had the best correlation to MTFa.

An additional attempt at correlation was made by comparing CSF degradation to the MTF degradation at each frequency observed. The MTF was calculated at the focus setting that resulted in a peak MTF value for each frequency. This assumes that the eye

would maximize each frequencies' MTF individually through accommodation. A plot of the correlation is shown below.

Figure 3.15: MTF/CSF correlation

This shows that using MTF data at individual frequencies to relate objective to subjective performance will result in weaker correlation. Another way to illustrate this is to replot both the observed CSF degradation and the calculated MTF degradation as a function of frequency.

The results are shown below.

Figure 3.16: Predicted vs. measured degradation

The results show that there tends to be more degradation at the lowest frequency than the MTF calculation would predict. There is better agreement between the two metrics at the medium and high frequencies observed. It is this variation as a function of frequency and the general disagreement of the 0.7 wave telescope data that results in lower correlation.

3.2 Three-Bar experiment results

Resolution thresholds were measured for six telescope aberration and pupil conditions plus a shifted focus condition for all three observers. The data was collected as described in the “methods” section. The results for each observer are shown below.

Figure 3.17: Resolution threshold; Observer KL

Figure 3.18: Resolution threshold; Observer ZM

Figure 3.19: Resolution threshold; Observer GZ

2.2 mm pupil results are listed below.

Figure 3.20: Resolution thresholds; 2.2 mm pupil

3.2.1 Resolution degradation

Unaberrated resolution thresholds are different for each observer and it is reasonable to look at degradation instead. The degradation is defined as the ratio of the aberrated 3-bar threshold to the control 3-bar threshold frequency.

Figure 3.21: Average three-bar degradation

Figure 3.22 shows similar degradation between the 0.7λ and 1.2λ scopes.

Figure 3.22: 0.7λ , 1.2λ resolution degradation

It can be seen that there is much less degradation than was measured in the CSF experiment. This is probably due to the fact that the target was usually seen at a high contrast setting. The image energy was spread out longitudinally, but there was still a large amount of contrast that kept the bars visible. Only at 0.02 contrast was there a large difference in degradation among the aberration levels.

The 3 bar results also indicate that the aberrations of the 3 mm eye have little effect on subjective image quality as compared to a 2.2 mm pupil.

Figure 3.23: Control telescope resolution threshold

In addition, the two focus positions for the 3 wave telescope did not show any significant differences in terms of resolution degradation. It would be difficult to observe the degrading effect of a shifted focus when the overall degradation is so small.

Figure 3.24: 3λ shifted focus resolution degradation

As with the CSF results, performance is not highly dependent on focus position.

Overall resolution degradation can be shown as a function of W_{40} :

Figure 3.25: Average resolution degradation

3.2.2 3-bar correlation to objective metrics

Correlation was calculated for 3 bar degradation vs objective metrics. The results are shown below:

Figure 3.26: Three-bar/metrics correlation

The table below is a summary of the correlation coefficients and slopes of the above graphs:

Table 3.5

Correlation coefficients for 3-bar resolution vs. objective metric degradation

	<u>MTFa</u>	<u>Strehl</u>	<u>R_{r4}</u>	<u>wavefront variance</u>
<u>R²</u>	0.96	0.99	0.98	0.79
<u>slope</u>	0.35	0.25	0.33	-2.76

All the metrics show an acceptable correlation, except for the wavefront variance. It must be noted that a comparison with the MTFa is not particularly meaningful because the spatial frequency that corresponds to the resolution limit is typically outside the MTFa limits. Correlation of resolution degradation is most appropriate when comparing to a degradation based on the ratio of observed and predicted threshold resolutions. An objective prediction of maximum observable frequency is necessary in order to correlate subjective vs. objective performance. In order to do this, the contrast threshold (inverse CSF) for observer 1 was plotted along with the MTF of each telescope. The estimated MTF of the eye was backed out of the inverse CSF plot since the eye optics were already included in the optics MTF curve. The MTF was multiplied by the average contrast used in the 3-bar experiment, since calculated MTF's assume unit contrast in the target. The

intersection point of these two curves should show the limiting frequency observed. Giles used a similar process.

Figure 3.27: Resolution threshold predictions

A comparison between three bar degradation and objective frequency degradation is shown below.

Table 3.6

Measured vs predicted resolution threshold

<u>Telescope</u>	<u>calculated</u> <u>maximum frequency</u>	<u>observed</u> <u>maximum frequency</u>
3 mm control	52	38.9
1.2 waves	45	38.9
2.2 waves	30	35.6
3.2 waves	25	32.7
2.2 mm control	49	38.3
0.7 wave	49	38.3

The procedure over estimates thresholds for the low aberration telescopes and under estimates thresholds for the high aberration telescopes. The correlation coefficient of 0.90 for the objective/subjective resolution plot is satisfactory, but the small slope illustrates the fact that much less degradation was observed than was predicted.

Figure 3.28: Observed vs. predicted three-bar degradation

3.3 Focus Setting Experiment

In this experiment, an attempt was made to provide an answer to the question whether there is an image quality metric that the optimizes for accommodation. There are several ways of performing an experiment of this sort. If one seeks to answer the question of where the eye accommodates in the presence of spherical aberration, then the most obvious way is to measure the accommodation using an infrared or laser optometer, while the observer looks through the aberrated telescope (and presumably accommodates at the preferred focus). In such an experiment, the eyepiece focus must be fixed; but this implies that an arbitrary decision must be made regarding the vergence difference between competing metrics and the resting state. In relating the accommodation

measurement to the preferred image quality metric, the additional assumption must be made that the resting state of the observer exerts little or no influence; otherwise, if the accommodation response is a compromise between the resting state and the focal plane that optimizes the metric that we seek, we cannot determine what the metric is. Stated differently, if the optimum value of a particular metric happens to be close to the resting state of the observer, a bias of unknown magnitude exists in favor of that metric.

An alternative and experimentally simpler way is to ask the observers to focus the eyepiece and then measure the corresponding focus settings. There are two possible ways of performing this experiment, with active accommodation and with paralyzed accommodation. This experiment tried active accommodation. An additional experiment was tried with paralyzed accommodation by Mouroulis using the telescopes from this experiment.

For the active accommodation experiment, the observers viewed a distant building through the telescopes and adjusted manually the focus; appropriate neutral density filters were inserted to ensure eye pupil size larger than 3 mm. Only the 3 mm exit pupil telescopes were used. For each aberration condition, the observation was repeated sixteen times. The initial setting for eight of the observations was strongly myopic, and for the other eight it was strongly hyperopic; however, the observers were allowed to oscillate around the optimum focus before finalizing the setting. This experiment showed that the initial setting of the eyepieces biases the results, despite the oscillatory focusing

procedure (Schober et al²⁵ found a similar bias but without allowing oscillation). Tables 3.7 and 3.8 show the focus results for each observer in terms of the position of some of the optimized objective metrics. With a single exception at 2λ , all observers tended towards more myopic settings from a myopic value.

Table 3.7

Visual focus settings (diopters); initial myopic focus

EYEPIECE OUT					
Observer	telescope	R84	RMS	MTFa	Paraxial
KL	0 wave	-0.5	-0.5	-0.5	-0.5
	1.2 waves	0.0	-0.1	-0.1	-0.7
	2.2 waves	-0.8	-1.0	-1.0	-2.1
	3.2 waves	0.0	-0.2	-0.6	-1.6
ZM		R84	RMS	MTFa	Paraxial
	0 wave	-1.5	-1.5	-1.5	-1.5
	1.2 waves	-1.2	-1.3	-1.3	-1.9
	2.2 waves	-1.7	-2.0	-2.0	-3.0
GZ		R84	RMS	MTFa	Paraxial
	0 wave	-4.4	-4.4	-4.4	-4.4
	1.2 waves	-4.7	-4.8	-4.8	-5.4
	2.2 waves	-6.4	-6.7	-6.7	-7.7
	3.2 waves	-5.9	-6.1	-6.5	-7.5

Table 3.8Visual focus settings (diopters): initial hyperopic focus

EYEPIECE IN					
Observer	telescope	R84	RMS	MTFa	Paraxial
KL	0 wave	-3.5	-3.5	-3.5	-3.5
	1.2 waves	-1.4	-1.5	-1.5	-2.1
	2.2 waves	-2.5	-2.8	-2.8	-3.8
	3.2 waves	-1.4	-1.6	-2.0	-2.9
ZM		R84	RMS	MTFa	Paraxial
	0 wave	-2.4	-2.4	-2.4	-2.4
	1.2 waves	-2.0	-2.1	-2.1	-2.7
	2.2 waves	-1.3	-1.6	-1.6	-2.7
GZ		R84	RMS	MTFa	Paraxial
	0 wave	-5.8	-5.8	-5.8	-5.8
	1.2 waves	-5.3	-5.4	-5.4	-6.0
	2.2 waves	-7.3	-7.6	-7.6	-8.7
	3.2 waves	-8.0	-8.2	-8.6	-9.6

The average eyepiece settings across all conditions were in the range of -1.5D for observers KL and ZM, but around -6D for observer GZ. Occasional observers have been known to present extreme instrument myopia²⁵, so the results of observer GZ are not implausible, although they are unrepresentative of the population. This is the reason that the results of observer GZ from the averaging discussed in the previous section.

The large range of preferred focus shown in Table 3.7 and 3.8 preclude any conclusions regarding the accommodative response. For this reason the experiment was

repeated, but this time the eyepiece was not reset for each observation; the setting for the first observation was the average determined from the previous experiment for each observer. Also, two artificial targets were used. The first target was a random, non-overlapping dot pattern, which has a relatively flat spatial frequency spectrum (peaking only near the zero frequency). the second target was a difference of Gaussians (DOG), whose spatial frequency spectrum peaked at 10c/deg, with the 50% points at approximately 5c/deg and 20 c/deg; this type of target has been shown to be useful in studies of accommodation²⁶. A focus correction for the finite target distance was employed (focus shift = $f_c^2/[\text{object distance}]$). The target luminance was around 30cd/m² for the DOG, and around 100cd/m² for the dots.

In the absence of aberrations, the eyepiece focal setting gives directly the location of the paraxial focal plane, which can then be taken as the preferred focal setting (or accommodative effort). But when spherical aberration is present, there are several alternative image planes, and determination of the paraxial focal plane after a focus adjustment by the observer does not, by itself, give any information on what focal plane the observer chose. In order to infer anything from this kind of measurement, aberrated and unaberrated cases must be compared. An assumption may be made that the same accommodative effort would be preferably maintained in the presence of aberration as in the absence of aberration. Therefore, the image quality metric whose optimum value lies closest to the vergence obtained for the unaberrated case is to be considered the preferred

one. The results of the Dog and dot tests were similar enough to permit averaging the results. Table 3.9 lists the average focus results. Table 3.10 lists the standard deviation of the focus results in order to provide some measure of the repeatability of the results.

Table 3.9

Focus positions of image metrics (diopters); average of 2 targets

Observer	telescope	R84	RMS	MTFa	Paraxial
KL	0 wave	-1.6	-1.6	-1.6	-1.6
	1.2 waves	-0.7	-0.8	-0.8	-1.4
	2.2 waves	-2.0	-2.2	-2.2	-3.3
	3.2 waves	-1.7	-1.9	-2.3	-3.3
ZM		R84	RMS	MTFa	Paraxial
	0 wave	-1.3	-1.3	-1.3	-1.3
	1.2 waves	-1.0	-1.1	-1.1	-1.7
	2.2 waves	-0.7	-0.9	-0.9	-2.0
GZ		R84	RMS	MTFa	Paraxial
	0 wave	-3.7	-3.7	-3.7	-3.7
	1.2 waves	-2.5	-2.6	-2.6	-3.1
	2.2 waves	-5.0	-5.3	-5.3	-6.4
	3.2 waves	-2.0	-2.2	-2.6	-3.6

Table 3.10Repeatability (1σ) of focus settings

<u>observer</u>	<u>control</u>	<u>1.2λ</u>	<u>target: DOG 2.2λ</u>	<u>3.2λ</u>	<u>units = diopters control</u>	<u>1.2λ</u>	<u>target: DOTS 2.2λ</u>	<u>3.2λ</u>
ZM	0.2	0.4	0.5	0.7	0.3	0.2	0.4	0.5
KL	0.2	0.3	0.5	0.8	0.3	0.3	0.3	0.5
GZ	0.4	0.8	0.7	0.8	0.6	0.8	0.9	0.7

This repeatability has two components: that due to the mechanical limitations of moving the eyepiece to the preferred position and the increased uncertainty of focus at higher aberration levels. It can be seen that the latter has some influence on focus since the repeatability generally worsens at higher aberration levels.

This experiment also proved to be inconclusive. Observer ZM was more successful in maintaining a reasonably consistent accommodative effort, but the other observers did not give any consistent result. Observer GZ again gave some strongly myopic settings. Thus, this experiment served to demonstrate the variability to be expected with active accommodation, but did not allow any further conclusion. It is for this reason that the paralyzed accommodation experiment was performed by Mouroulis and 2 new observers with the telescopes from this experiment. The experiment is briefly

described below in order to shed more light on the question concerning the accommodative response.

The accommodation was paralyzed with 1-2 drops of cyclopentolate hydrochloride. Three subjects viewed the dots and the DOG targets and adjusted focal settings as before. The luminance was typical of indoor fluorescent illumination for both targets. By paralyzing the accommodation, the consistency of the results improved and the standard deviation became less than a quarter of a diopter. Also, the difference in settings between the two targets was found negligible, so the DOG target was discarded. The observers repeated each observation five times. The initial eyepiece setting was random.

Table 3.11 gives the results for the 3 observers.

Table 3.11

Paralyzed accommodation results

<u>observer</u>	<u>metric</u>	<u>0λ</u>	<u>1λ</u>	<u>2λ</u>	<u>3λ</u>
1	R ₈₄	-2.4	-2.2	-2.1	-1.9
	rms	-2.4	-2.3	-2.4	-2.1
	MTFa	-2.4	-2.3	-2.4	-2.5
	paraxial	-2.4	-2.8	-3.5	-3.4
2	R ₈₄	-0.4	0.1	0.3	0.8
	rms	-0.4	0.0	0.1	0.6
	MTFa	-0.4	0.0	0.1	0.2
	paraxial	-0.4	-0.6	-1.0	-0.8
3	R ₈₄	0.5	0.6	0.9	1.7
	rms	0.5	0.5	0.6	1.5
	MTFa	0.5	0.5	0.6	1.1
	paraxial	0.5	0.0	-0.5	0.1

Since all metrics are simultaneously optimized at the paraxial focal plane in the absence of aberrations, all the values in column 1 are identical. For the other columns, the optimum focal plane for the MTFa and the rms aberration is practically the same for the 1 λ and 2 λ aberration levels, but not for the 3 λ level²⁷. The preferred metric is the one for which the values in the last three columns are closest to the value in the first (0 λ) column.

It can be seen that observer 1 was consistent in preferring the MTFa. Observer 2 seemed to prefer a focus halfway between the paraxial focus and the MTFa. Finally, observer 3 preferred the MTFa (or rms) for the 1λ and 2λ scopes, but moved closer to the paraxial focus for the 3λ scope.

CHAPTER 4

General Discussion

4.1 Performance degradation and pupil size

In this section we will organize the discussion around the original questions posed in the introduction. The question of how much degradation is observed as a function of aberration is answered in the figures 3.12 and 3.25. In order to extrapolate to other pupil sizes, we need to make an assumption about how the perceptual effect of an aberration is affected by the change in pupil size. For example, if the longitudinal spherical aberration was the perceptually significant quantity, then we could express all our results in diopters and assume that they hold at any pupil size. Unfortunately, we have no evidence in support of such an assumption without performing a much larger experiment.

Let us re-state the above problem in order to clarify it further: If it were possible to determine a just-noticeable tolerance for spherical aberration that is independent of pupil size, how would such a tolerance be expressed? In diopters, wavelengths, or as an angular or transverse term?

There have been two previous attempts to determine tolerances. Haig and Burton¹⁰ gave the tolerance in the form of wave-front aberration as 0.23λ , while Bauer¹⁹ gave it as a longitudinal aberration of 0.26D. Wave-front and longitudinal spherical aberration are related through

$$\delta W_{40} = 1/4 h_e^2 \delta D$$

where h_e is the pupil radius. The Haig and Burton tolerance refers to the W_{40} term alone, without allowance for compensating defocus; it was obtained through a computer simulation, which decouples the effect of accommodation. If defocus is allowed, as would be the case for a coherently coupled instrument, then the tolerance would be expected to rise to about 0.9λ ²⁸ for the same Strehl ratio. Although our experiment was not tailored around determining a minimum detectable tolerance, our results at 1.2λ for a 3.2 mm pupil and 0.7λ for a 2.2 mm pupil show a small but detectable amount of degradation and are therefore in basic agreement with the 0.9λ tolerance.

If we translate the 0.9λ value to the pupil diameters used by Bauer (≥ 4.5 mm), we arrive at a value of $\delta D \leq 0.4D$. This is not too far from the $0.26D$ value for which Bauer found no difference in Landolt acuity. At 6 mm diameter, the 0.9λ wave-front error becomes $0.23D$., which is very close to the $0.26D$ value obtained by Bauer, but is only half of the $0.47D$ value that he calculated theoretically (we note however, that this latter value was obtained on the assumption that the geometrical circle of least confusion is the visually significant quantity, which we know to be untrue from the results of the previous section.)

We may also take the value of $0.26D$ obtained by Bauer, and see whether it agrees with results obtained with smaller pupils. If this value is assumed to hold for any pupil

size, then we obtain a wave-front error of 0.28λ and 0.14λ at 3.2 mm and 2.2 mm pupil diameters respectively. These values are too small, so we must therefore conclude that the perceptual effect of a fixed amount of longitudinal spherical aberration depends on pupil size. If we then assume that the perceptual effect increases with pupil size in the same way as the longitudinal aberration itself (i.e. quadratically), then Bauer's $0.26D$ tolerance becomes 0.6λ , at any pupil size. From our data for 2.2 mm pupil diameter and 0.7λ of aberration, we see that this amount produces a small, although detectable, performance degradation.

Thus it seems that with the approximation involved in these experiments, the value of 0.6λ to 0.9λ is reasonable as a tolerance over a relatively wide range of pupil sizes. Of course, the larger value is practically identical with the Strehl tolerance as derived by Marechal^{28,29} for a general lens system. The above does not imply that the wavefront aberration (as opposed to the transverse or longitudinal ray aberration) has now been proven to be the perceptually significant quantity in the presence of spherical aberration. This is because the approximations involved in the above comparisons are rather crude. We are proposing to accept the 0.9λ as an approximate value for tolerance only in the absence of an experiment specifically designed to address the effect of pupil size.

Finally, these results confirm to some degree the findings of both Van Heel¹⁵ and Giles³, and shed some light into their apparent disagreement. We have seen that if a high-contrast resolution test is used (similar to that of Van Heel), even large amounts of spherical aberration cause a small change in performance. However, a contrast sensitivity test (similar to that used by Giles) reveals the effect of spherical aberration more readily. Thus the disagreement between those two reports can be seen as due, at least in part, to the different targets and visual tasks used.

4.2 Preferred focus

This experiment illustrates the fact that accommodative response in the presence of spherical varies too much to arrive at any solid conclusions. The additional focus experiment with these telescopes helped to tighten the range over which the eye is accommodating. Of the 3 cycloplegic observers, one consistently preferred the plane of optimum MTF_a, another preferred a plane between the optimum MTF_a and the paraxial focus, and the third was in between the two. The tendency to move toward the paraxial focus is not easy to explain, but lends some limited support to the early assertion of Coleman et al¹⁷. Also, a related finding is that of Charman et al³⁰, who found that the refractive state of the eye does not change significantly as the pupil size increases, implying an insensitivity of optimal focus to spherical aberration; we note though that this last study was concerned with the effects of the eye's aberrations only.

The paralyzed accommodation experiment also shows that there is no consistent preferences among observers, but it has narrowed down the preferred focal plane to a region $0.5D$ wide, bracketed by the optimum MTFa on one side and extending towards the paraxial focus. This is important, because all other reasonable image quality metrics (e.g. Strehl, spot diagram, etc.) are optimized on the side of the MTFa that is away from the paraxial focus.

It is to be noted that the paralyzed accommodation experiment determined the plane of optimum image quality for the targets under test. It does not necessarily follow that deviation from this condition provides the stimulus for accommodation, except to the extent that no alternative hypothesis is available. This topic is sufficiently important to be further investigated separately; we consider the conclusions drawn here as only preliminary.

4.3 Correlation with image quality metrics

The results of section 3 show acceptable correlation with all the metrics examined. This is not surprising when only a single aberration is involved; it has already been shown that a true test of correlation must involve aberration combinations. The question of correlation with image quality metrics has been specifically addressed by Mouroulis and Cheng¹⁶, who concluded that the MTFa is the strongest candidate metric,

but noted that it must be tested against spherical aberration. The present results indicate that the MTFa has passed the test of spherical aberration.

The second strongest contender is the Strehl ratio. In the presence of spherical aberration, MTFa and Strehl are optimized at practically the same focal plane. However, for $W_{40} \cong 3\lambda$, the Strehl shows a double peak as a function of focus (see figure X); it is optimum for $W_{20} \cong -2\lambda$ (at which point the MTFa is also optimum), and also at $W_{20} \cong -4\lambda$. If the Strehl ratio was the perceptually significant metric, there would have been no reason for the observers to prefer the peak that lies closer to the paraxial focus ($W_{20} = 0$), and there would have been the expectation to obtain at least some settings around the second optimum peak of the Strehl; but none were found.

Finally, the results provide for a clarification of the conclusion of Giles³, that the eye accommodates at the plane of minimum wavefront variance in the presence of spherical aberration. We have shown that this is approximately true at the 1λ and 2λ levels of aberration, as examined by Giles, but only because the optimum variance and optimum MTFa happen to coincide. At the 3λ level, where the two quantities are optimized separately, our results show that the significant quantity is not the wave-front variance but the MTFa (this has also been shown to be the case for coma and astigmatism¹²).

4.4 Coherence of coupling

The results indicate that coherence of coupling should be considered as unimportant at small pupil sizes. Even 0.7λ of spherical aberration, which is considerably larger than the aberration of a typical eye at 2.2 mm pupil diameter, produced a very small drop in performance. Smaller amounts of aberration, comparable to those of the eye, would produce an even smaller drop in performance; such a drop might be detectable after a long psychophysical experiment with many observations, but would be insignificant under the normal conditions of use of an instrument. A similar conclusion has been reached by Thibos et al³¹ in the case of chromatic aberration. Inter- and intra-observer variation of the ocular monochromatic aberrations are now well established, as is the fact that they are irregular and not well described as third-order spherical^{21,24,32}. Therefore, it would be impossible for the instrument to cancel the aberrations of the eye in any consistent way across observers and observing conditions; only an average response makes sense. Finally, the accuracy of the accommodative response is such that a defocus of magnitude larger than the ocular aberrations is tolerated. For example, Winn et al³³ found that approximately 0.25D of defocus was necessary in order to stimulate accommodation; this translates into 0.7λ for the 4 mm pupil that they used, or 0.4λ at 3 mm. In both cases, the corresponding retinal image degradation is considerably larger than that caused by 0.6 - 0.9λ of spherical aberration

with a defocus term added. For example, the Strehl ratio for $W_{20} = 0.4\lambda$ is 0.58, whereas for $W_{40} = 0.9\lambda$ (with $W_{20} = -0.9\lambda$) the Strehl ratio is 0.83.

CHAPTER 5

Conclusions and Recommendations for Optical Design and Testing

1) The subjective effect of instrumental spherical aberration has been characterized in a way that permits comparison with the effects of other aberrations. The designer may use either the degradation plots for figures 3.12 and 3.25, or the MTFa in attempting to optimize a visually-coupled system at the design stage. The latter method is preferable as it can describe aberration combinations just as easily as individual aberrations.

2) Spherical aberration causes a rather small drop in high contrast resolution, as obtained with three-bar targets. Contrast sensitivity is affected more severely.

3) The tolerance to spherical aberration is in the range $0.6\text{--}0.9\lambda$, expressed as a wavefront aberration, and for pupil diameters from 2 to 6 mm.

4) Although this experiment showed a wide range of focus preferences, the preliminary evidence from the experiment with paralyzed accommodation indicates that the preferred focal plane in the presence of spherical aberration spans a range from the optimum MTFa focus to about half-way through the paraxial focus.

5) For the purposes of optical design, and from the viewpoint of aberration cancellation or coherence of coupling at pupil diameters less than about 3 mm, it suffices to simplify the eye as a diffraction-limited focusing system, which chooses the focus by

optimizing the MTFa. This conclusion, however, arises from data on monocular vision and thus may not be indiscriminately extended to systems for which stereoscopy is the primary function.

6) To the extent that conclusion 4 above holds, it also follows that the choice of focus during automated (observerless) MTF testing of visual instruments should be the plane that maximizes the MTFa. The MTFa has in any case been shown to be the best choice from among the competing metrics for describing the subjective performance of spherical aberration.

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Appendix

Telescope prescription

3 mm pupil control telescope

<u>Surface</u>	<u>Radius</u>	<u>Thickness</u>	<u>Glass</u>	<u>Diameter</u>
Object	Infinity	Infinity		0
Stop	Infinity	35		9.5
2	52.93	7.3	SK11	31.5
3	-37.16	2.2	SF8	31.5
4	-128.45	97.4		31.5
5	33.1	2	SF15	12
6	12.48	3.76	BALKN3	12
7	-15.04			12

1.2 Waves W40 telescope

<u>Surface</u>	<u>Radius</u>	<u>Thickness</u>	<u>Glass</u>	<u>Diameter</u>
Object	Infinity	Infinity		0
Stop	Infinity	35		9.5
2	128.45	2.2	SF8	31.5
3	37.16	7.3	SK11	31.5
4	-52.93	100.9		31.5
5	33.1	2	SF15	12
6	12.48	3.76	BALKN3	12
7	-15.04			12

2.2 Waves W40 telescope

<u>Surface</u>	<u>Radius</u>	<u>Thickness</u>	<u>Glass</u>	<u>Diameter</u>
Object	Infinity	Infinity		0
Stop	Infinity	23		9
2	100.93	2.47	SF5	30
3	27.8	9.99	SK11	30
4	-39.49	75.3		30
5	48.5	1.18	SF8	10
6	8.46	4.39	SSK4	10
7	-13.64			10

3.2 Waves W40 telescope

<u>Surface</u>	<u>Radius</u>	<u>Thickness</u>	<u>Glass</u>	<u>Diameter</u>
Object	Infinity	Infinity		0
Stop	Infinity	45		7.9375
2	89.36	1.5	SF5	18
3	22.47	4.46	SK11	18
4	-32.16	68.8		18
5	13.64	4.39	SSK4	10
6	-8.46	1.18	SF8	10
7	-48.5			10

2.2 mm pupil control telescope

<u>Surface</u>	<u>Radius</u>	<u>Thickness</u>	<u>Glass</u>	<u>Diameter</u>
Object	Infinity	Infinity		0
Stop	Infinity	45		5.5
2	32.16	4.46	SK11	18
3	-22.47	1.5	SF5	18
4	-89.36	63.9		18
5	13.64	4.39	SSK4	10
6	-8.46	1.18	SF8	10
7	-48.5			10

0.7 Wave W40 telescope

<u>Surface</u>	<u>Radius</u>	<u>Thickness</u>	<u>Glass</u>	<u>Diameter</u>
Object	Infinity	Infinity		0
Stop	Infinity	45		5.5
2	89.36	1.5	SF5	18
3	22.47	4.46	SK11	18
4	-32.16	67.88		18
5	13.64	4.39	SSK4	10
6	-8.46	1.18	SF8	10
7	-48.5			10