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**Accommodation stimulus-response function and retinal image quality**

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## **ABSTRACT**

Accommodation stimulus-response function (ASRF) and its relationship to retinal image quality were investigated using a modified wavefront sensor. Ten subjects were presented with six vergence stimuli between 0.17 D and 5 D. For each vergence distance, ocular wavefronts and subjective visual acuity were measured. Wavefronts were analysed for a fixed 3-mm pupil diameter and for natural pupil sizes. Visual Strehl ratio computed in the frequency domain (VSOTF) and retinal images were calculated for each condition tested. Subjective visual acuity was significantly improved at intermediate vergence distances (1 D and 2 D;  $p < 0.01$ ), and only decreased significantly at 5 D compared with 0.17 D ( $p < 0.05$ ). VSOTF magnitude was associated with subjective visual acuity and VSOTF peak location correlated with accommodation error. Apparent accommodation errors due to spherical aberration were highly correlated with accommodation lead and lag for natural pupils ( $R^2 = 0.80$ ) but not for fixed 3-mm pupils ( $R^2 < 0.00$ ). The combination of higher-order aberrations and accommodation errors improved retinal image quality compared with accommodation errors or higher order aberrations alone. Pupil size and higher order aberrations play an important role in the ASRF.

## INTRODUCTION

The classical accommodation stimulus-response curve is S-shaped (Morgan, 1944). It shows a lead of accommodation at distance, a cross-over point close to the tonic level or resting point of accommodation, a linear portion with a slope of less than one and a break -off- point at the clinical amplitude of accommodation (Charman, 1982, Charman, 1999).

Most studies that have measured accommodation stimulus-response have used auto-refractometers (see Chen, Schmid & Brown, 2003, for a review). More recent studies have used PowerRefractors based on photo-retinoscopy (Schaeffel, Weiss & Seidel, 1999, Seidemann & Schaeffel, 2003) or wavefront sensors (Hazel, Cox & Strang, 2003, Plainis, Ginis & Pallikaris, 2005). The methods used to correct individual refractive errors prior to accommodation measurement include subjective distance refraction (McBrien & Millodot, 1986, Bullimore, Gilmartin & Royston, 1992, Abbott, Schmid & Strang, 1998), retinoscopy (Gwiazda, Thorn, Bauer & Held, 1993, Gwiazda, Bauer, Thorn & Held, 1995), auto-refraction (Rosenfield, Desai & Portello, 2002) and a calibration procedure using a PowerRefractor combined with retinoscopy (Schaeffel et al., 1999, Seidemann & Schaeffel, 2003). Correction of refractive errors can either be done with spectacles (Gwiazda et al., 1993, Gwiazda et al., 1995, Chen & O'Leary, 2000), contact lenses (Rosenfield & Gilmartin, 1987, Rosenfield & Gilmartin, 1988, Bullimore et al., 1992, Rosenfield et al., 2002) or both (Jiang & White, 1999). When spectacles are used, lens effectivity formulas are needed to calculate effective stimulus and response values (Gwiazda et al., 1993, Abbott et al., 1998, Mutti, Jones, Moeschberger & Zadnik, 2000). Techniques to stimulate accommodation include Badal lens systems (e.g. Seidel, Gray & Heron, 2003, Plainis et al., 2005), distance induced (e.g. McBrien & Millodot, 1986) or lens-induced stimulation (e.g. Gwiazda et al., 1993). Accommodation stimulus-response has also been measured under binocular (e.g.

McBrien & Millodot, 1986, Bullimore et al., 1992), monocular (e.g. Gwiazda et al., 1993, Jiang & White, 1999, Rosenfield et al., 2002) or both viewing conditions (e.g. Ramsdale, 1979, Seidemann & Schaeffel, 2003).

While there has been a large range of methodologies employed, as well as a striking variability of measured lags as noted by Seidemann & Schaeffel (2003) reduced accommodation response in myopes has been reported by many studies (see Chen et al., 2003, for a review). The associated increase in retinal blur during near work in myopes has been suggested to provide a cue to eye growth and ultimately to lead to myopia development (Gwiazda et al., 1993). One important aspect of accommodation lag at near is the associated retinal image quality, which often is described as the retinal blur-circle in various models of myopia development (Flitcroft, 1998, Hung & Ciuffreda, 2000). While retinal blur is an essential part of the hypothesis and is thought to result from accommodation errors, little is known about the quality of the retinal image at various levels of accommodation. Seidemann and Schaeffel (2003) have simulated retinal image quality for various levels of accommodation lag for a diffraction-limited eye and found surprisingly poor letter contrast on the retina. However for real eyes, there are several other factors that can influence retinal image quality including the natural variation in pupil size (Ward & Charman, 1985, Hazel et al., 2003, Plainis et al., 2005) and higher order aberrations (Hazel et al., 2003, Plainis et al., 2005).

Compared with most autorefractors, the PowerRefractor has the advantage of using the entire pupil area to derive its measurement, thereby taking into account pupil size and pupil constriction during accommodation (Choi, Weiss, Schaeffel, Seidemann, Howland, Wilhelm & Wilhelm, 2000). However, it does not give insight into the eye's wavefront aberrations. A

wavefront sensor can do both and was used by Hazel et al. (2003) who found significant differences between fixed 2.9 mm pupil data versus natural pupil data, particularly for their myopic subjects. They concluded that accommodation accuracy is largely influenced by higher-order aberration levels. Plainis et al. (2005) recently supported this conclusion by showing that the one-to-one stimulus/response slope should not be considered as ideal since higher-order aberrations, especially spherical aberration, can influence the actual accommodation demand.

A number of studies have investigated changes in higher-order aberrations with accommodation (Atchison, Collins, Wildsoet, Christensen & Waterworth, 1995, He, Burns & Marcos, 2000, Hazel et al., 2003, Ninomiya, Fujikado, Kuroda, Maeda, Tano, Y. & Mihashi, 2003, Cheng, Barnett, Vilupuru, Marsack, Kasthurirangan, Applegate & Roorda, 2004a). The most consistent finding of these studies is the change of spherical aberration in the negative power direction with accommodation. Several studies concerning visual performance have noted a relationship between spherical aberration and defocus (Jansonius & Kooijman, 1998, Wilson, Decker & Roorda, 2002, Applegate, Marsack, Ramos & Sarver, 2003, Cheng, Bradley & Thibos, 2004b). In the presence of spherical aberration, a certain amount of defocus is beneficial in order to optimise retinal image quality. It is therefore likely that spherical aberration plays a role in the accommodation (defocus) response of the eye when measuring the accommodation stimulus-response curve.

In this study we analyse some of the previously employed methods to measure accommodation stimulus-response. We then use a wavefront sensor to investigate the effects of pupil size, higher order aberrations, monocular and binocular fixation on retinal image quality during accommodation stimulus-response. We predict visual performance based on

wavefront aberrations and compare this with subjectively measured visual acuity at a range of accommodation levels.

## **METHODS**

### **Subjects**

Ten subjects, five females and five males, participated in the experiment. The participants' mean age was 27 years, ranging from 22 to 36 years. Subjects were selected to have no significant ocular disease, normal binocular vision (i.e. heterophoria within normal limits), anisometropia less than 0.50 D (best sphere) and similar visual acuity in each eye (i.e. < 1 line difference). Five subjects were emmetropes and five were myopes. Mean refractive error (best sphere) of the myopes and emmetropes was  $-2.25 \text{ D} \pm 0.85$  and  $+0.05 \text{ D} \pm 0.19$  respectively. Mean refractive astigmatism for the group was  $-0.30 \text{ D} \pm 0.45$ . All subjects had greater than 5 D of accommodation and achieved clear vision of the letter charts for all accommodation levels.

### **Distance refraction**

Correction of refractive errors prior the measurement of accommodation response is important, especially when subjects with different refractive errors are tested. For each of the subjects, we performed a slit lamp examination and subjective refraction of both right and left eyes followed by a binocular balance test. Chart luminance during both subjective refraction and accommodation measurements was set to approximately  $140 \text{ cd/m}^2$  to ensure similar pupil sizes. Subjective refractions were performed at a distance of 4 meters and then  $-0.25 \text{ D}$  was added to the result so as to correct the eyes for a far point at infinity. The on-campus ophthalmic dispensing laboratory enabled us to provide all subjects (both myopes and emmetropes) with the appropriate spectacle correction determined this way within less than

20 minutes. Subjects with any refractive error wore their spectacle correction during the accommodation measurements.

The standard clinical procedure of subjective refraction determines the best spherical lens to be the lowest negative power lens or highest plus power lens to achieve optimal visual acuity. This clinical procedure of subjective refraction will potentially lead to slightly more plus power than required, within the range of the depth-of-focus of the eye. The far point of the eye corrected in this manner is known as the hyperfocal distance (Thibos, Hong, Bradley & Applegate, 2004). Based on subsequent estimates of depth-of-focus for our subject group we estimate the resultant error from the hyperfocal distance to be close to the clinical accuracy of  $\pm 0.125$  D for subjective refraction, when 0.25 D power increments are utilized.

### **Spectacle lens effectivity**

For spectacle lens corrected subjects, effectivity formulas must be used to correct for apparent stimulus and response values. Mutti et al. (2000) presented the thin lens formula for correcting the accommodation response. To correct the apparent stimulus and response values, Mutti et al.'s (2000) thin lens formula can be used for both conditions. The instrument output and the inverse of target distance have to be replaced within the formula to calculate corrected response and corrected stimulus respectively. Thereby the instrument output ( $RawAR$ ) and the refractive error ( $RX$ ) have to be calibrated for the corneal plane. The thin lens formulas that correct for spectacle lens effectivity are:

$$(1) \quad AS = \frac{1}{\frac{1}{\frac{1}{DLE - DTE} + LENS} - DLE} - RX_{cornea}$$

$$(2) \quad AR = \frac{\frac{1}{\frac{1}{\frac{1}{RawAR_{cornea}} + DLE} - DLE} - RX_{cornea}}{\frac{1}{1 + LENS}}$$

Where  $AS$  and  $AR$  are the corrected accommodation stimulus and response respectively,  $RX_{cornea}$  is the refractive error at the corneal plane (as correction),  $DLE$  is the vertex distance in meters,  $DTE$  is the distance from the target to the cornea in meters (both  $DTE$  &  $DLE$  are positive),  $LENS$  is the signed dioptric power of the lens in front of the eye and  $RawAR_{cornea}$  is the spherical equivalent of the instrument reading calibrated for the corneal plane.

We use Mutti et al.'s (2000) thin lens formula because it can be applied to all types of induced accommodation demands (i.e. negative-lens induced, distance induced and positive-lens induced). This is not the case for all formulas that have been presented in the past (Gwiazda et al., 1993, Gwiazda et al., 1995, Abbott et al., 1998, Chen & O'Leary, 2000, He, Gwiazda, Thorn, Held & Vera-Diaz, 2005). Response formulas, which do not take into account changes in target distance, will overestimate accommodation responses for distance and positive-lens induced accommodation demands. For example, the calculated (i.e. corrected) accommodation response for the most myopic subject of our study (spherical equivalent = -3.125 D) and a 5 D accommodation demand would be 0.34 D higher using Gwiazda et al.'s (1993) formula compared with Mutti et al.'s (2000) formula, whereas the corrected accommodation stimulus of both the Gwiazda et al. (1993) and Mutti et al. (2000) formulas is the same.

### **Accommodation stimulus**

Since spectacle lens effectivity changes the uncorrected accommodation stimulus, subjects with different refractive errors would each be provided with different effective accommodation stimuli depending on the magnitude of their refractive errors. For example the effective accommodation stimulus of an emmetrope and a spectacle corrected -6.00 D myope, differs by as much as 0.54 D for a +4 D apparent accommodation stimulus and a vertex distance of the spectacle lens of 13 mm. One method of compensation is to calculate the uncorrected accommodation stimuli for each spectacle-lens and target-distance combination for each subject. In this way the effective accommodation stimuli for all subjects can be the same. We have calculated our apparent accommodation stimuli so that the corrected accommodation stimuli were +1 D, +2 D, +3 D, +4 D, and +5 D for every subject. For example, target distances ranged between 94 cm and 100 cm to induce 1 D of accommodation stimulus for this group of subjects.

### **Data collection procedure**

A Complete Ophthalmic Analysis System (COAS, WaveFront Sciences, Inc.) was used for accommodation and wavefront aberration measurements. The COAS wavefront sensor was modified to present external fixation targets at various distances from the eye via a beam splitter between the eye and wavefront sensor. The normal fixation target inside the wavefront sensor was switched off. A beam splitter allowed both monocular and binocular fixation of targets, which were presented to induce accommodation stimuli of 0.17 D (i.e. 6 m target distance), 1 D, 2 D, 3 D, 4 D, and 5 D. The fixation target at the 6 m stimulus distances was a 0.4 logMAR letter in the centre of a high contrast Bailey-Lovie logMAR chart. For the near conditions (i.e. 1 D to 5 D) the fixation targets were high contrast Bailey-Lovie logMAR charts on slide films with diffuse background illumination. For each condition the beam splitter

could be adjusted to enable the alignment of the letter in the centre of the chart with the measurement axis of the instrument (i.e. the instrument's fixation spot). A different logMAR chart, appropriately scaled for the size of the letters, was used at each of the stimulus distances. The setup allowed the subjects' head to be positioned normally in the headrest. The subject was instructed to focus on the letter at the centre of the 0.4 logMAR line and keep it "as clear as possible" during the wavefront measurements. All subjects reported achieving "clear vision" of the letter charts for all accommodation levels up to 5 D. All subjects' responses were measured for both monocular and binocular fixation conditions. The order of the testing (i.e. monocular/binocular) was randomized between subjects to avoid systematic bias. For each of the six stimulus conditions, 6 x 25 frames (i.e. 150 measurements) of ocular wavefront measurements were acquired. The right eye was used for all monocular measurements while the left eye was covered using an eye patch during this test condition.

### **Subjective visual acuity during accommodation**

Following the monocular accommodation measurements, subjective visual acuity was determined at each stimulus distance. Subjects were instructed to read up to the smallest visible line on the Baily-Lovie chart and then continue guessing until a full line was incorrectly read. The measured visual acuity in logMAR (0.02 logMAR steps) at the six stimulus distances was noted for every target distance. Each Baily-Lovie logMAR chart contained a different configuration of optotypes so as to avoid learning effects. Letter size at each of the stimulus distances was not affected by differences in spectacle lens minification between emmetropic and myopic subjects because the corrected stimulus distances also ensured equivalent target sizes for each of the spectacle-lens and target-distance combinations.

## Data analysis

The wavefront data was fitted with a 7<sup>th</sup> order Zernike expansion and exported for further analysis. Wavefronts were fitted with Zernike polynomials for both a fixed 3 mm entrance pupil size as well as for each subject's natural pupil sizes during the various accommodation conditions. The 3 mm fixed entrance pupil was chosen because it was close to the minimum diameter of natural pupil sizes of all subjects at the various accommodation levels. This diameter also approximates the measurement region used by many autorefractors. The wavefronts of both monocular and binocular accommodation were corrected for spectacle lens effectivity and the stimulus-response curves, based on the Zernike  $Z_2^0$  defocus term, were plotted for the fixed 3 mm entrance pupil size as well as the natural pupil sizes. For both fixed 3-mm pupil and natural pupil sizes the best spherical lens was calculated from each of the  $Z_2^0$  defocus terms of the 150 wavefront measurements and then averaged.

After the defocus terms of the wavefronts were corrected for spectacle lens effectivity, the corrected accommodation stimuli were subtracted from the corrected accommodation (defocus) responses to derive the leads and lags of accommodation. To average Zernike polynomials from 150 measurements of natural pupil sizes, the average pupil size based on the COAS measurements of pupil size for each accommodation stimulus condition was calculated. Then the 150 wavefronts were rescaled according to the average pupil size of the sample using the method described by Schwiegerling (2002) and the Zernike coefficients were averaged.

The relative contribution of spherical aberration to accommodation lead and lag was also investigated for each stimulus distance and compared as a function of accommodation stimulus for both fixed and natural pupils. Using primary and secondary Zernike spherical

aberration terms ( $Z_4^0, Z_6^0$ ), the dioptric equivalent of the balancing defocus in those terms was calculated by extracting components related to  $r^2$ . Note that this dioptric value does not represent Seidel spherical aberration, which is normally defined as the difference between dioptric powers of the pupil centre and pupil edge, but represents the apparent (i.e. measured) defocus shift caused by Seidel spherical aberration. In the context of this study we call these values the apparent accommodation leads and lags due to spherical aberration because they are an artefact of the measurement method. The effect of pupil size on apparent accommodation lead and lag due to spherical aberration during each series of 6 x 25 measurements at each accommodation stimulus was also investigated. Apparent accommodation lead and lag due to spherical aberration was plotted as a function of changing accommodation stimulus and changing pupil size. For each accommodation level, the slope of the regression line of pupil size versus apparent accommodation lead and lag due to spherical aberration was calculated.

To investigate metrics of image quality, the visual Strehl ratio of the optical transfer function (VSOTF) (Cheng et al., 2004b, Thibos et al., 2004) was derived from the averaged wavefronts for each of the six accommodation levels for both 3-mm and natural pupils. Also the location of the peak of the VSOTF and the depth-of-focus, based on the 80% level of the peak (Marcos, Moreno & Navarro, 1999), were calculated by adjusting the defocus component of the wavefronts (Cheng et al., 2004b, Collins, Buehren & Iskander, 2005). The change in dioptric range was simulated by adjusting the defocus component (in 0.125 D steps) of the measured wavefront error for a range of  $\pm 2$  D. Data points then were fitted with a spline function and the magnitude and location of the peak of the VSOTF was identified.

Retinal images of a letter E (0.4 logMAR) were reconstructed using the wavefronts for both fixed 3-mm and natural pupil sizes. Retinal images and the VSOTF were also reconstructed for the leads and lags of accommodation alone (i.e. eliminating all higher-order aberrations), as well as with the higher-order aberrations alone (i.e. eliminating all leads and lags). Retinal images and VSOTF then were compared for the fixed 3-mm pupil and the natural pupil size data.

### **Statistical analysis**

Two-way analysis of variance (ANOVA) and Bonferroni post-hoc tests were performed to investigate differences between the fixed versus natural pupil size analyses as well as monocular versus binocular accommodation. One-way repeated measures ANOVA's and Bonferroni post-hoc tests were performed for the slopes of apparent accommodation error due to spherical aberration versus pupil size, subjective visual acuity, VSOTF and DOF results.

### **RESULTS**

The accommodation stimulus response function was significantly influenced by pupil size and higher order aberration levels. Subjective visual acuity was best at intermediate distances and became worse at 5 D stimulus level compared with 0.17 D. Comparisons between subjective visual acuity and retinal image metrics calculated from natural pupils showed better agreement than image metrics calculated from fixed 3 mm pupils. Apparent accommodation errors due to spherical aberration accounted for most of the measured leads and lags when natural pupils were considered. Under binocular conditions, the accommodation error was smaller than with monocular fixation.

### **Accommodation stimulus-response function**

The accommodation response showed a significantly shallower stimulus-response curve (i.e. more lead and more lag) for monocular fixation compared with binocular fixation (two-way ANOVA interaction  $p < 0.001$ ). This was the case for the natural pupil size analysis (Figure 1, top) but not for the fixed 3-mm pupil size analysis (two-way ANOVA interaction  $p = 0.53$ ) (Figure 1, bottom). We also found slightly, but significantly smaller pupil sizes for binocular accommodation compared with monocular accommodation (two-way ANOVA pupil size  $p < 0.001$ ).

A significantly shallower stimulus-response curve was found with natural pupils compared with fixed 3-mm pupils for both monocular and binocular fixation (both had two-way ANOVA interaction  $p < 0.001$ ). For example, the monocular 5 D accommodation stimulus produced a group mean lag of accommodation of  $+0.91 \text{ D} \pm 0.23$  for the natural pupil analysis and  $+0.46 \text{ D} \pm 0.27$  for the fixed 3-mm pupil analysis (see Table 1 for all stimulus levels).

### **Apparent accommodation errors due to spherical aberration**

For both pupil size analyses, apparent accommodation errors due to spherical aberration (Figure 2) changed significantly from negative to positive (i.e. lead to lag) with accommodation stimulus level (both two-way ANOVAs  $p < 0.001$ ). The slope of change was significantly larger for natural pupils (Figure 2, top) compared with 3-mm fixed pupils (two-way ANOVA interaction  $p < 0.001$ ) (Figure 2, bottom). Leads and lags of accommodation (calculated from Zernike  $Z_2^0$  defocus) were highly correlated with apparent accommodation leads and lags due to spherical aberration ( $R^2 = 0.80$ ) for natural pupils (Figure 3, top) indicating that a large proportion of accommodation leads and lags was due to the effects of

spherical aberration. No correlation was found ( $R^2 < 0.00$ ) for the fixed-3-mm pupil analysis (Figure 3, bottom).

Figure 4 shows a representative example (subject 10) of the interaction between pupil size, apparent accommodation error due to spherical aberration and accommodation stimulus level. As the accommodation stimulus level increased, the apparent accommodation leads and lags due to spherical aberration typically shifted from negative to positive while pupil size concurrently decreased. The effect of pupil size variation on apparent accommodation leads and lags due to spherical aberration within a particular accommodation stimulus level became more pronounced with increasing accommodation stimulus level, as evidenced by the increased slope fitted to the data at the higher stimulus levels (Figure 4). This is an unexpected result, since spherical aberration effects would normally be expected to be more sensitive to pupil size changes in larger pupils. One-way repeated -measures ANOVA revealed a significantly increasing slope of the regression line of pupil size versus spherical aberration effect with increasing accommodation level (one-way ANOVA  $p = 0.014$ ). This increase in the slope of apparent error due to spherical aberration versus pupil size occurred despite an overall decrease of the entrance pupil size by about 1 mm from far to near stimulus levels (i.e. pupil constriction with accommodation).

### **Visual Acuity and VSOTF**

Subjective visual acuity (Figure 5, top & bottom) was significantly better at intermediate stimulus levels (1 D and 2 D) compared with the 0.17 D stimulus level (Bonferroni multiple comparisons; 0.17 D versus 1 D  $p < 0.001$ ; 0.17 D versus 2 D  $p < 0.01$ ), and was also significantly worse at the 5 D stimulus level compared with the 0.17 D stimulus level (Bonferroni multiple comparisons; 0.17 D versus 5 D  $p < 0.05$ ). A group mean difference of

about one line (0.112 logMAR) was found between the highest and lowest acuity (1 D versus 5 D stimulus levels). Visual acuity at the 3 D and 4 D stimulus levels was similar to that achieved at the far stimulus level (0.17 D), while the visual acuity at the 5 D stimulus level was slightly worse (0.032 logMAR) (Table 1) than that at the 0.17 D stimulus level.

The VSOTF for the natural pupil size analysis showed better correlation with subjective visual acuity ( $R = 0.56$ ,  $p < 0.10$ ) than did the VSOTF for the fixed 3mm pupils ( $R = 0.43$ ,  $p > 0.10$ ). The most noticeable difference between the pupil size analyses was shown at the 0.17 D stimulus level, with the 3-mm pupil analysis showing increased over-estimation of the VSOTF compared with the natural pupil result (Figure 5, top). Correlation between the peak of the VSOTF and visual acuity was  $R = 0.56$  ( $p < 0.10$ ) and  $R = 0.38$  ( $p > 0.10$ ) for natural and fixed 3-mm pupils respectively. Again the change was largest for the 0.17 D stimulus level (Figure 5, bottom). The group mean change of VSOTF and peak of VSOTF with stimulus level showed a steady decrease with increasing accommodation level for the fixed 3-mm pupils (Bonferroni multiple comparisons; 0.17 D versus 2 D and 3 D  $p < 0.01$ ; 0.17 D versus 4 D and 5 D  $p < 0.001$ ) (Figure 5). However the change in VSOTF for natural pupils with accommodation level was more consistent with changes in subjective visual acuity, showing a slight increase at the 1 D stimulus level followed by a decrease thereafter (Bonferroni multiple comparisons; 0.17 D versus 3 D  $p < 0.05$ ; 0.17 D versus 4 D and 5 D  $p < 0.001$ ).

In Table 1 all VSOTF, peak of VSOTF, depth-of-focus (DOF), visual acuity, apparent lead and lag due to spherical aberration, and lead/lag (i.e. based on  $Z_2^0$  defocus) results for each of the six accommodation levels are summarized for both fixed 3-mm and natural pupil sizes. The calculated depth-of-focus of the eyes for both pupil conditions (fixed 3-mm & natural) was slightly larger at near, but the increase was not significant (all multiple comparisons

$p > 0.05$ ). The correlation between lead and lag of accommodation and the location of the peak of the VSOTF is shown in Figure 6. There was a significant correlation ( $R = 0.75$ ,  $p < 0.01$ ) between the location of the VSOTF peak and lead/lag error of accommodation. Therefore 75% of the variance in accommodation lead/lag error was associated with the peak location of the VSOTF.

### **Retinal image reconstruction**

The effect of accommodation lead and lag on retinal image quality is shown for a representative subject (subject 3) in Figure 7. Not surprisingly, image reconstruction using the fixed-3mm pupil data shows a generally better retinal image (Figure 7, left column) compared with larger natural pupils (Figure 7, centre left column). For the 3-mm pupil data, vision is best at distance and then continues to worsen for closer target distances (also shown by the VSOTF; left column). For the natural pupil data however (Figure 7, centre left column), in agreement with the visual acuity results, retinal image quality is best at the 1 D stimulus level and then becomes slightly worse than the 0.17 D stimulus data for closer targets. It is worth noting that the decrease in retinal image quality appears to be mainly due to a loss in letter contrast rather than a loss in “clarity”.

To examine the relative roles of defocus and higher order aberrations we have also reconstructed retinal images for the same accommodation lead and lag levels without higher-order aberrations (Figure 7, centre right column) and defocus errors (Figure 7, right column). For the 5 D stimulus level, VSOTF is three to ten times better when higher-order aberrations and defocus errors are combined compared with the conditions where either component is excluded.

## **DISCUSSION**

We found that pupil size, binocular fixation and higher-order aberration levels have a significant impact on accommodation stimulus-response curves. Accommodation errors and spherical aberration effects with natural pupils were significantly different to those calculated for the fixed pupil size. Subjective visual acuity was best for intermediate target distances. The VSOTF showed moderate correlation with visual acuity while the location of the peak of the VSOTF showed good correlation with accommodation error, suggesting that accommodation response “errors” serve to optimize the retinal image quality

### **Accommodation stimulus-response**

Based on the natural pupil size analysis, the accommodation lead and lag results in this study were within the range of values reported previously using autorefractors. We found that the analysis of a fixed sub-aperture of the natural pupil size can lead to significant differences in the accommodation stimulus response curve compared with natural pupil size data. These results are in agreement with Hazel et al. (2003) and Plainis et al. (2005) who also found that accommodation accuracy is influenced by pupil size and higher-order aberration levels. Hazel et al. (2003) also compared their wavefront sensor results with the Shin-Nippon autorefractometer and found significant differences between the two instruments for pupil size analyses and refractive error groups. However, variations with accommodation as measured by the wavefront sensor were similar for the two refractive error groups. Collins (2001) found that the Canon Autorefractometer R-1 reading, which is not expected to account for changes in pupil size or higher-order aberrations is significantly affected by spherical aberration. The question then arises of how to interpret the results taken from autorefractors. This is an important issue for the results of studies that have compared different refractive error groups. Is a sub-aperture of the natural pupil size appropriate to investigate leads and lags and is the accommodation

responses calculated from paraxial optics or including higher-order aberrations more appropriate?

We would argue that the accuracy of representation of the retinal image should determine the most appropriate description of the eye's optics at different accommodation levels. Therefore analysis of accommodation response should be based on natural pupil data because it takes into account the full optical information to estimate retinal image quality. Accommodation leads and lags alone appear not to be good estimators of visual performance during accommodation. There can be little doubt about the superiority of wavefront sensors in providing more detailed information about the optics of the eye compared with autorefractometers. Therefore many of the conclusions from previous work based upon autorefractors should be evaluated with this in mind.

With the wavefront sensor, we found nearly equal monocular and binocular responses for the fixed 3-mm pupil analysis, but a significantly steeper binocular stimulus-response slope when natural pupil sizes were used. Ramsdale (1979) using a laser optometer, reported nearly equal responses for binocular and monocular accommodation fixation. Seidemann & Schaeffel (2003) found a small improvement with binocular compared to monocular accommodation using the PowerRefractor, that reached significance only for the 5 D stimulus level. While we investigated the effects of binocular versus monocular fixation on the accommodation stimulus-response curve, we did not extend this analysis to the interaction of higher-order aberrations and retinal image quality. This is a complex issue when factors such as binocular summation and ocular dominance during binocular accommodation are considered. Therefore our results on binocular accommodation have to be evaluated with this in mind. As expected, we found significantly smaller pupil sizes for binocular, compared with monocular conditions

and this is the likely explanation for reduced accommodation errors in binocular conditions because of the reduced effects of spherical aberration and higher-order aberrations within the smaller pupils.

### **Apparent accommodation errors due to spherical aberration**

While we have based the analysis of retinal image metrics and retinal image reconstruction on all lower and higher-order aberrations, we have limited the detailed investigation of higher-order aberrations to spherical aberration. This was done because spherical aberration is a major contributor to higher-order aberrations, it shows the most systematic change with accommodation (Atchison et al., 1995, He et al., 2000, Hazel et al., 2003, Ninomiya et al., 2003, Cheng et al., 2004a) and it has been shown to affect the best focal plane (Jansonius & Kooijman, 1998, Wilson et al., 2002, Applegate et al., 2003, Cheng et al., 2004b, Plainis et al., 2005). We found a shift of spherical aberration from positive to negative with increasing accommodation levels as others have found previously (Atchison et al., 1995, Hazel et al., 2003, Ninomiya et al., 2003, Cheng et al., 2004a, Plainis et al., 2005). In agreement with Plainis et al. (2005), we also found a clear association between spherical aberration and accommodation errors under natural pupil conditions. He, Gwiazda, Thorn, Held & Vera-Diaz (2005) recently reported no correlation between spherical aberration and accommodation lag. However, the wavefront aberrations were measured only at the resting state of accommodation and not at the accommodation level under investigation.

Earlier studies using laser optometers showed significantly shallower stimulus-response functions under low luminance conditions (Johnson, 1976, Tucker & Charman, 1986) and this has been attributed to the inability of the visual system to use high spatial frequency components under low luminance conditions (Tucker & Charman, 1986). Therefore the best

accommodation response would be expected for high luminance conditions. Some studies that have presented large accommodation errors (Gwiazda et al., 1993, He et al., 2005) have used luminance levels that were high enough to allow good acuity, but low enough for pupil dilation (note that the distance-induced and positive lens-induced slopes of these studies should be shallower because of the spectacle lens effectivity formulas applied). An explanation for the shallow slopes found in these studies is the increased effect of spherical aberration associated with larger pupils for both distance and near focus conditions. We have shown the effect of spherical aberration on the apparent accommodation response using a wavefront sensor in this study and there is evidence that autorefractors are also affected by this factor (Collins, 2001).

The different pupil size analyses showed that the apparent accommodation lead and lag is an artefact of the measurement technique and is largely dependent on pupil size (i.e. central versus all pupil optics). In contrast to the expected increase in accommodation response to negative spherical aberration, for the natural pupil sizes the measured accommodation lag increased when negative spherical aberration increased. This is related to the interaction between Zernike defocus and Zernike spherical aberration. Negative spherical aberration in Zernike terms has a balancing positive defocus component to maintain orthogonality. The positive defocus required to balance the negative spherical aberration leads to the Zernike defocus term becoming more negative. This creates an apparent lag of accommodation if Zernike defocus is considered in isolation. To further highlight the effect of this apparent accommodation lag we have also calculated accommodation lead and lag for a 2 mm pupil diameter for the same subject (subject 3 data in Figure 7). The equivalent accommodation errors in defocus for a 2 mm versus natural pupil for the 0.17 D, 1 D, 2 D, 3 D, 4 D, and 5 D accommodation stimuli were (2 mm pupil= -0.17 D, +0.26 D, +0.11 D, -0.01 D, +0.03 D, and

+0.02 D) and (natural pupil = -0.34 D, +0.04 D, +0.45 D, +0.61 D, +0.80 D, and +1.02 D) respectively. This shows that the paraxial focus (i.e. central pupil) is close to the retina, but as the pupil gets larger, the effects of higher order aberrations alter the apparent leads and lags of accommodation. This factor affects the results of both wavefront sensors and autorefractors, but in different ways. The “accommodation” response in the wavefront error obtained from a wavefront sensor is not the best sphere derived from the second order terms of the Zernike polynomial, but is probably better represented by Seidel defocus. Autorefractors that sample in regions of the entrance pupil and not the whole pupil will also create errors in the estimation of the accommodation response.

### **Visual Acuity and VSOTF**

We found maximum visual acuity was achieved at the 1-m stimulus distance and this coincided with the maximum level of the VSOTF, the peak of the VSOTF as well as the minimum level of apparent accommodation error due to spherical aberration for the natural pupil data of this group of subjects. The fact that the VSOTF peak showed better agreement with subjective visual acuity than did the VSOTF based on the mean accommodation response (see Figure 5), may be explained by microfluctuations that could temporarily bring the image to the best focus (Plainis, Ginis & Pallikaris 2005) as well as trough the depth of focus of the eye. This could allow the visual system to reach acuity levels that correspond to the best achievable retinal image quality at a particular accommodation level. Under-correction of the subjective refraction could have not been the reason for the decrease of visual performance at the far distance in this study because all subjects were corrected within  $\pm 0.12$  D for infinity and the distance accommodation stimulus of 0.17 D was larger than the 0.12 D of potential under correction due to clinical accuracy. The change in visual acuity with vergence distance has been reported previously (Johnson, 1976, Heron, Furby, Walker, Lane

& Judge, 1995). Johnson (1976) found increased visual resolution for intermediate target distances between 2 m and 50 cm and our data confirms this finding. Johnson (1976) attributed variations in visual acuity with stimulus distance primarily to errors in accommodation. Heron et al. (1995) also reported increased visual acuity in the range 1.2 -1.6 m for some observers but no relationship between individual stimulus response characteristics and visual acuity was found. He speculated that aberrations are the most likely cause for the variation in visual acuity since studies have shown decreased aberrations at intermediate distances (van den Brink, 1962, Denieul, 1982).

The variation in VSOTF derived for natural pupil sizes in this study showed some correlation ( $p < 0.1$ ) with variations in subjective visual acuity. Given the limited range of visual acuity in this study (about 1 line), we were surprised at how well the VSOTF predicted visual acuity. These results support previous findings that have identified the VSOTF as a good estimator of high contrast visual acuity performance (Cheng et al., 2004b, Marsack, Thibos & Applegate, 2004, Thibos et al., 2004). However we did not find a one to one relationship between accommodation error and best retinal image quality based on the location of the VSOTF peak (slope 0.43). Several factors probably contribute to this finding. Depth-of-focus of the eye will probably allow the accommodation error to reach a level which is just less than a perceptible or tolerable loss of visual performance. Our estimates of depth of focus based on 80% of the visual Strehl ratio can account for some, but not all of this accommodation error. Other factors such as chromatic aberration and the wavelength that is preferentially focussed during accommodation (Kruger, Nowbotsing, Aggarwala & Mathews, 1995, Thibos et al., 2004) and the natural microfluctuations of the eye (Collins, Davis & Wood, 1995, Plainis et al., 2005) will almost certainly contribute to the tolerable level of accommodation error.

## **Retinal image reconstruction**

The effect of the combination of higher-order aberrations and accommodation error on the retinal image quality (reconstructed E targets) in this study was striking. While there was some loss of image quality at far and near stimulus distances compared to intermediate distances, the level of visual performance was not markedly worse at near. It is well known that the interaction between spherical aberration and defocus can improve visual performance in contrast to the individual effects of these aberrations (Woods, Bradley & Atchison, 1996, Jansonius & Kooijman, 1998, Wilson et al., 2002, Applegate et al., 2003, Cheng et al., 2004b). Our data, in agreement with Plainis et al. (2005), suggests that this interaction plays an important role in the measured errors of accommodation stimulus-response curves. The word error in this context is confusing though, since this apparent accommodation “error” in the presence of spherical aberration and other higher-order aberrations does actually improve retinal image quality compared with zero accommodation error. It is clear that visual performance would be better without spherical aberration and defocus. Yet if spherical aberration is present, then defocus can improve visual performance and therefore the traditionally measured lag of accommodation alone is not a good estimator of the performance of the visual system during accommodation. Therefore studies that have used autorefractors to compare accommodation stimulus- response as a function of refractive error should be evaluated with this in mind. Although the VSOTF decreased slightly at near stimulus distances, we did not find significant retinal image degradation in terms of visual acuity. As shown in the example of Figure 7, the loss in retinal image quality appeared to be characterised primarily by a loss of letter contrast rather than a loss in letter “clarity” and this characteristic was found consistently for most of our subjects. When binocular fixation is considered the image degradation at near is likely to be of lesser magnitude.

In summary, subjective visual acuity was best at intermediate accommodation levels and only became significantly worse at the nearest (5 D) accommodation level compared with the far (0.17 D) level. Changes in retinal image quality metrics, such as the VSOTF with natural pupil sizes showed general agreement with changes in visual acuity and the location of the peak VSOTF value also influenced the accommodation response. Autorefractors which base their results on fixed pupil diameters will not accurately represent the true optical characteristics of the eye during accommodation stimulus-response measurements. The use of wavefront sensors with analysis conducted using natural pupil sizes should provide more accurate estimates of the optical and visual performance of the eye across a range of accommodation levels. However the results of wavefront sensors can also be misleading, if the interactions between lower and higher order aberrations are not considered. Binocular accommodation results with natural pupils are different to those acquired under monocular conditions and with fixed pupils.

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## FIGURE/TABLE CAPTIONS

Table 1: Group mean ( $\pm$ SD) pupil size, accommodation lead and lag based on Zernike defocus  $Z_2^0$ , apparent accommodation lead and lag based on Zernike spherical aberration ( $Z_4^0$  and  $Z_6^0$  terms), subjective visual acuity (obtained through natural pupil sizes), VSOTF, peak of VSOTF and depth-of-focus (DOF calculated from the 80% level of the VSOTF peak) for the six accommodation stimuli are shown.

## Accommodation Stimulus/Response Function

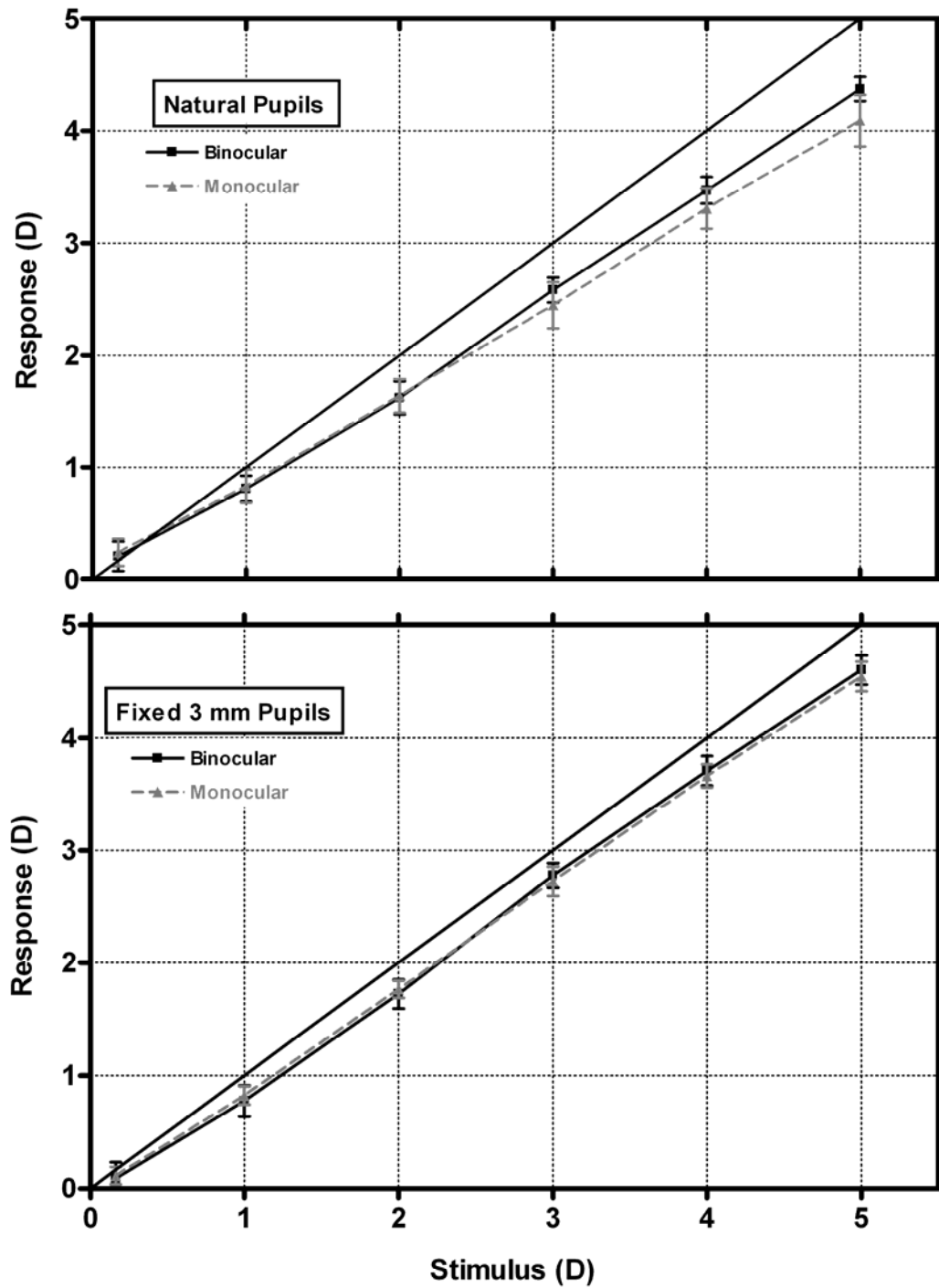


Figure 1: Accommodation stimulus response functions (ASRF) ( $\pm$ SEM) for natural pupils (top panel) and fixed 3-mm pupils (bottom panel) are shown. Dashed and solid lines indicate monocular fixation and binocular fixation respectively.

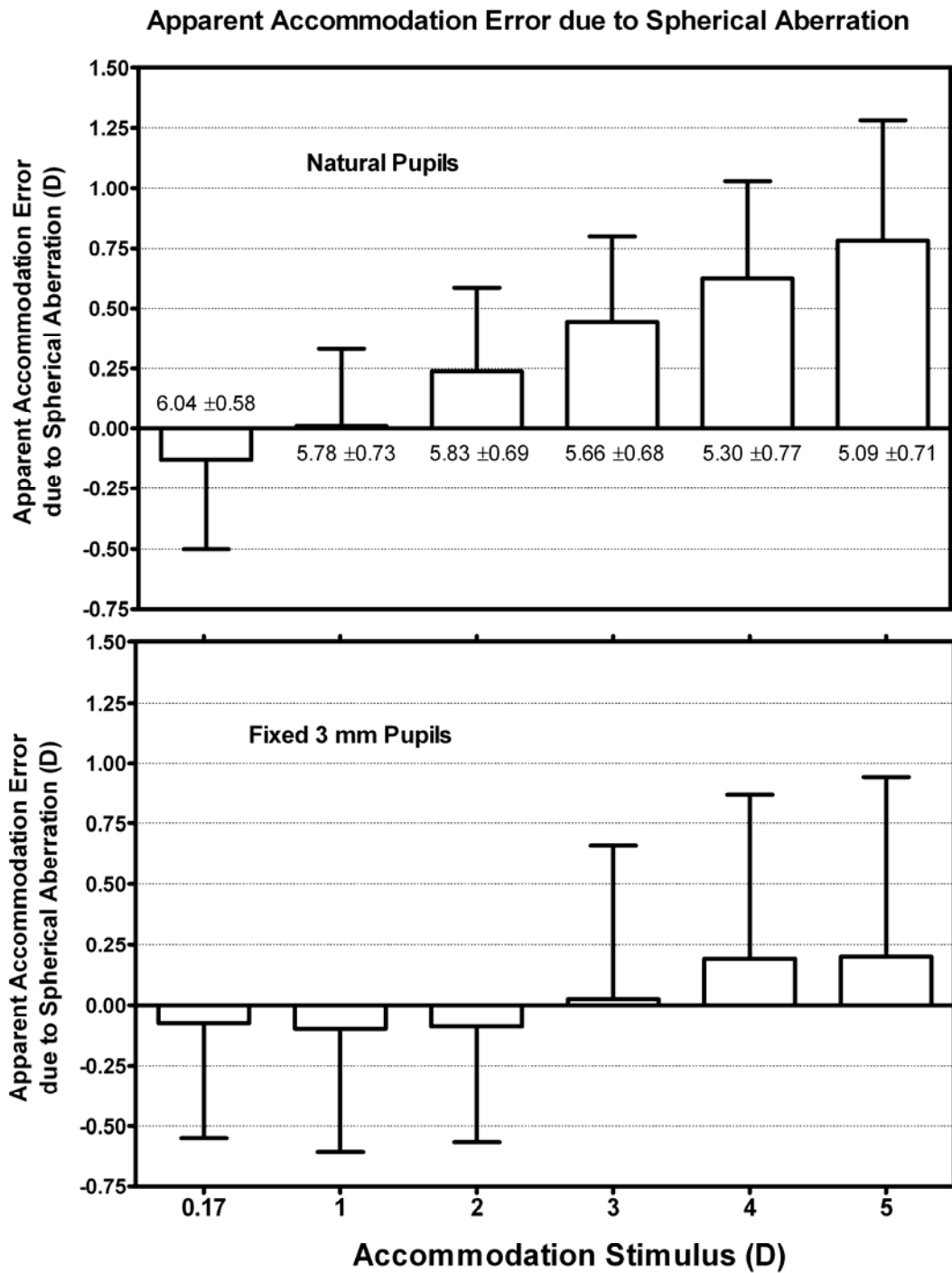


Figure 2: Group mean change ( $\pm$ SD) of apparent accommodation error due to spherical aberration (D) with accommodation stimulus level for natural pupil sizes (top panel) and fixed 3-mm pupils (bottom panel). Group mean natural pupil sizes ( $\pm$ SD) are shown at each accommodation stimulus level of the top panel.

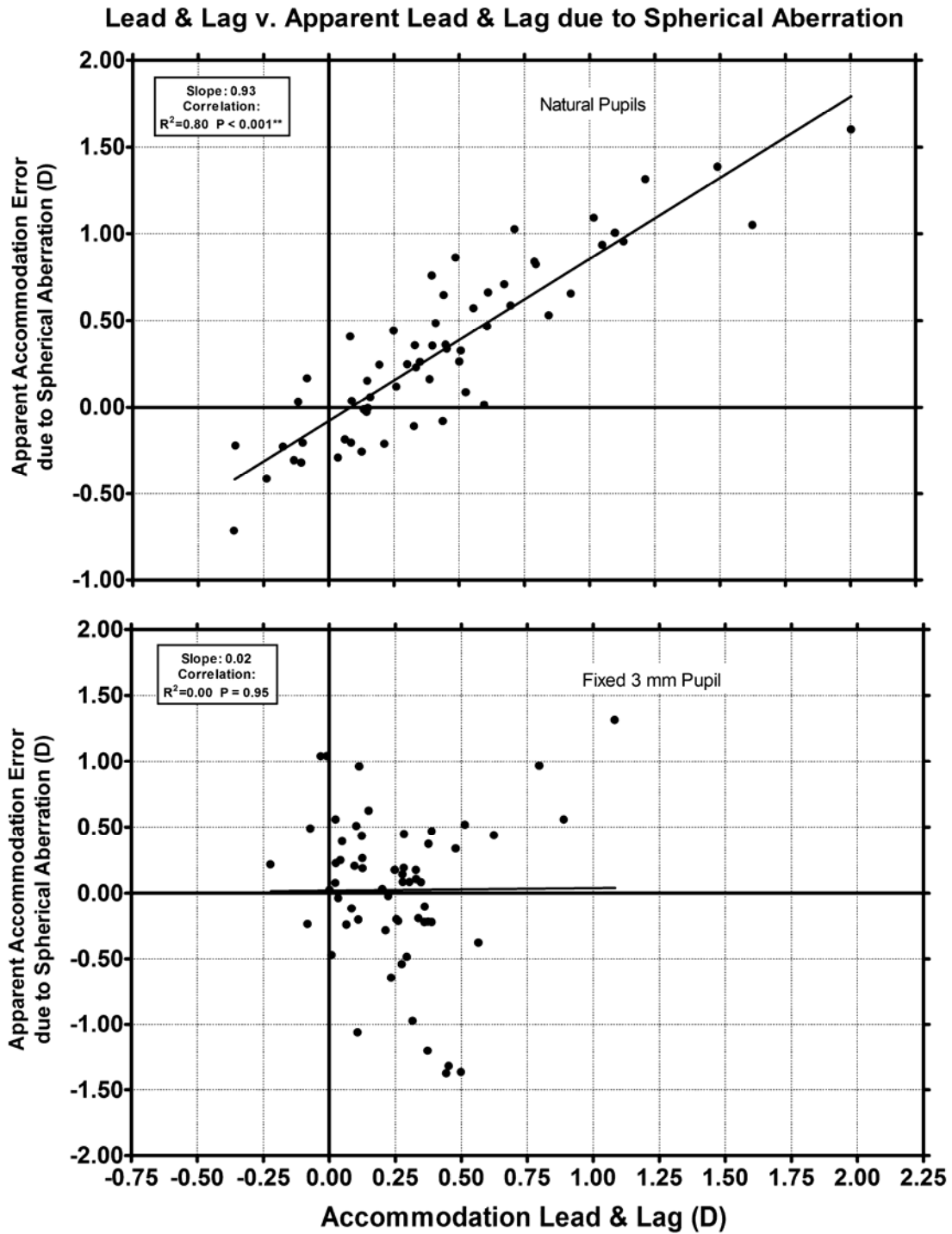


Figure 3: For all accommodation stimulus levels combined, the correlation between apparent accommodation error based on Zernike spherical aberration ( $Z_4^0$  and  $Z_6^0$  terms) and accommodation lead and lag (based on the Zernike  $Z_2^0$  defocus term) is presented. Top panel

shows the results of the natural pupil analysis and bottom panel shows the fixed 3-mm pupil analysis.

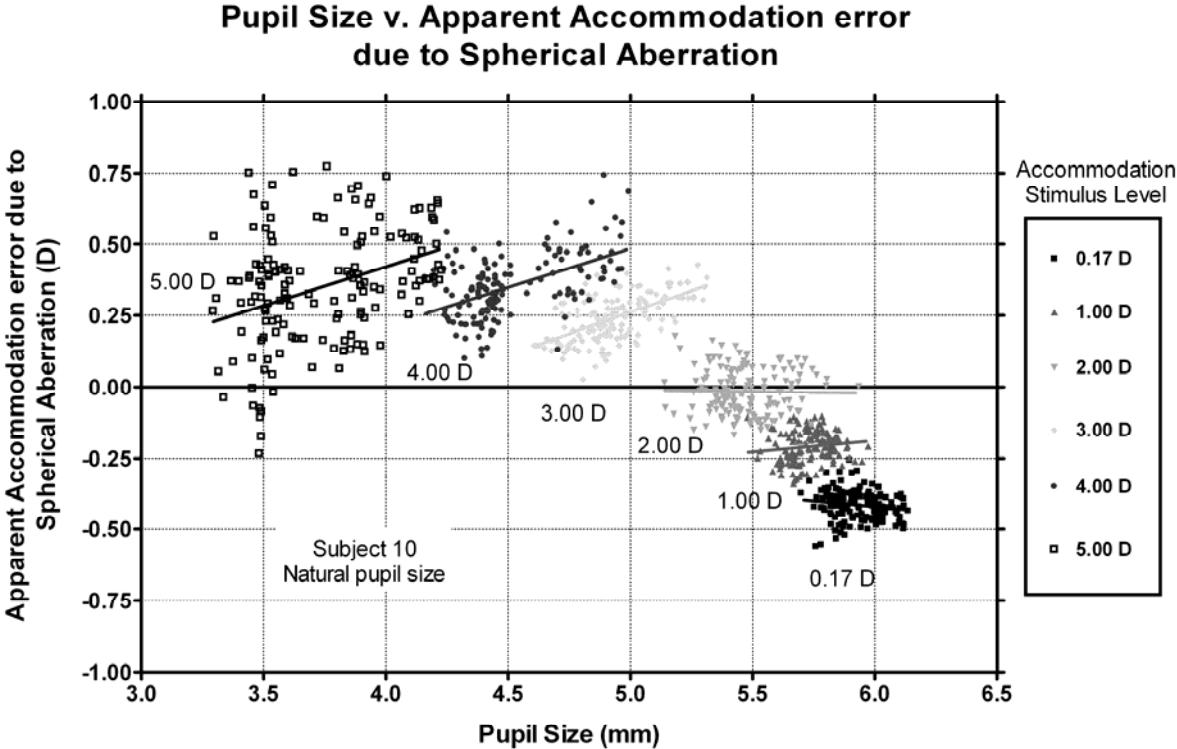


Figure 4: A representative example (myopic subject 10) of the association between pupil size, apparent leads and lags due to spherical aberration and accommodation stimulus level is presented. For each accommodation level, all 150 measurements of spherical aberration effects and pupil size are plotted. Note the increase in slope between apparent accommodation error and pupil size despite an overall pupil constriction with increasing accommodation levels. Stimulus levels are shown alongside each data set.

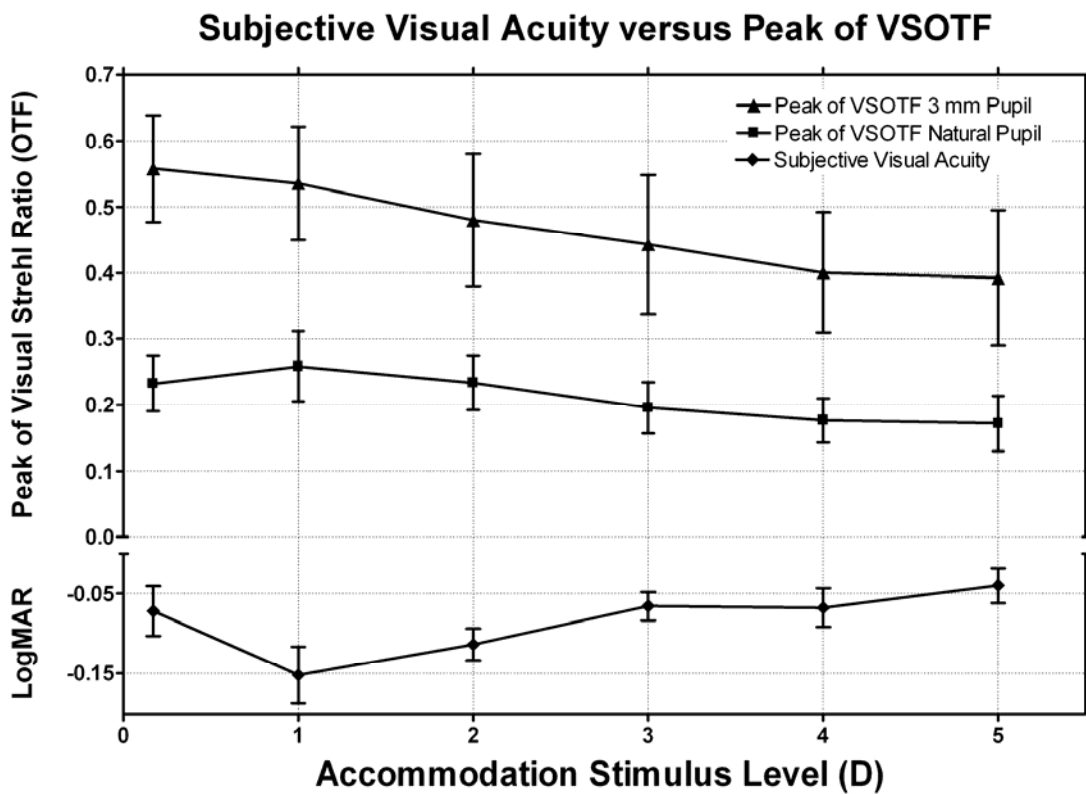
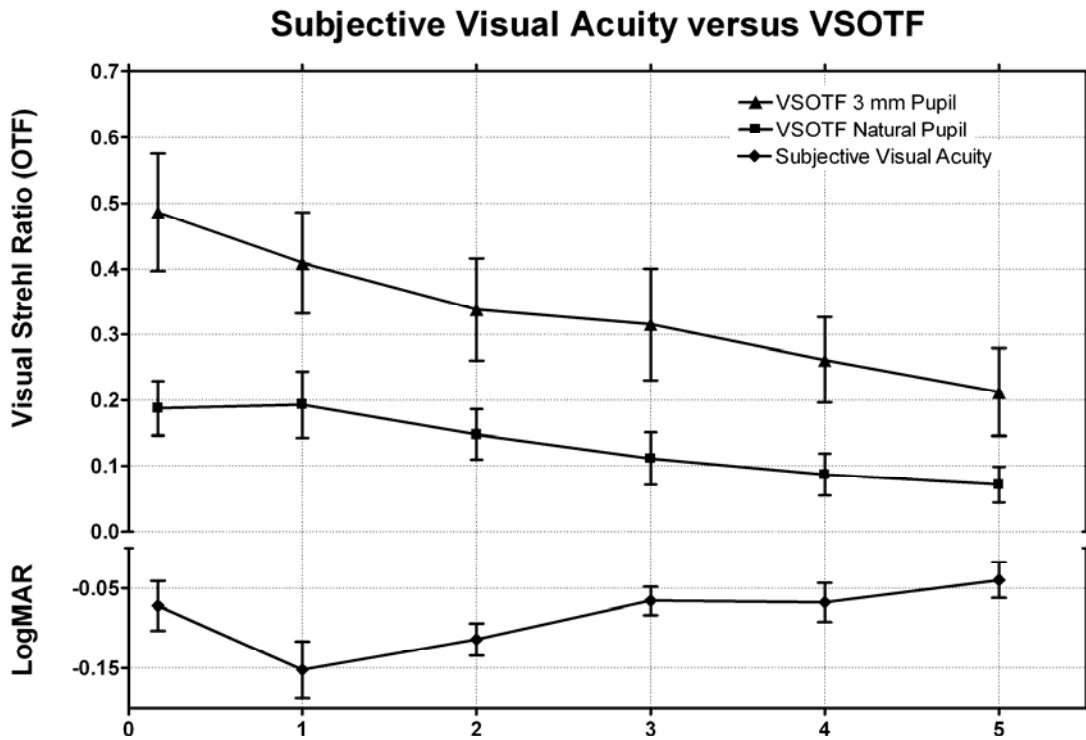


Figure 5: The group mean ( $\pm$ SD) VSOTF for both fixed 3-mm (top) and natural pupil sizes (centre) are shown along with the group mean ( $\pm$ SD) subjective visual acuity (bottom). The change in VSOTF for natural pupil data follows a similar pattern to changes in visual acuity

( $R = 0.56, p < 0.10$ ). The VSOTF of fixed 3-mm pupils shows a poorer correlation with visual acuity, particularly at the far stimulus level (0.17 D) ( $R = 0.43, p > 0.10$ ).

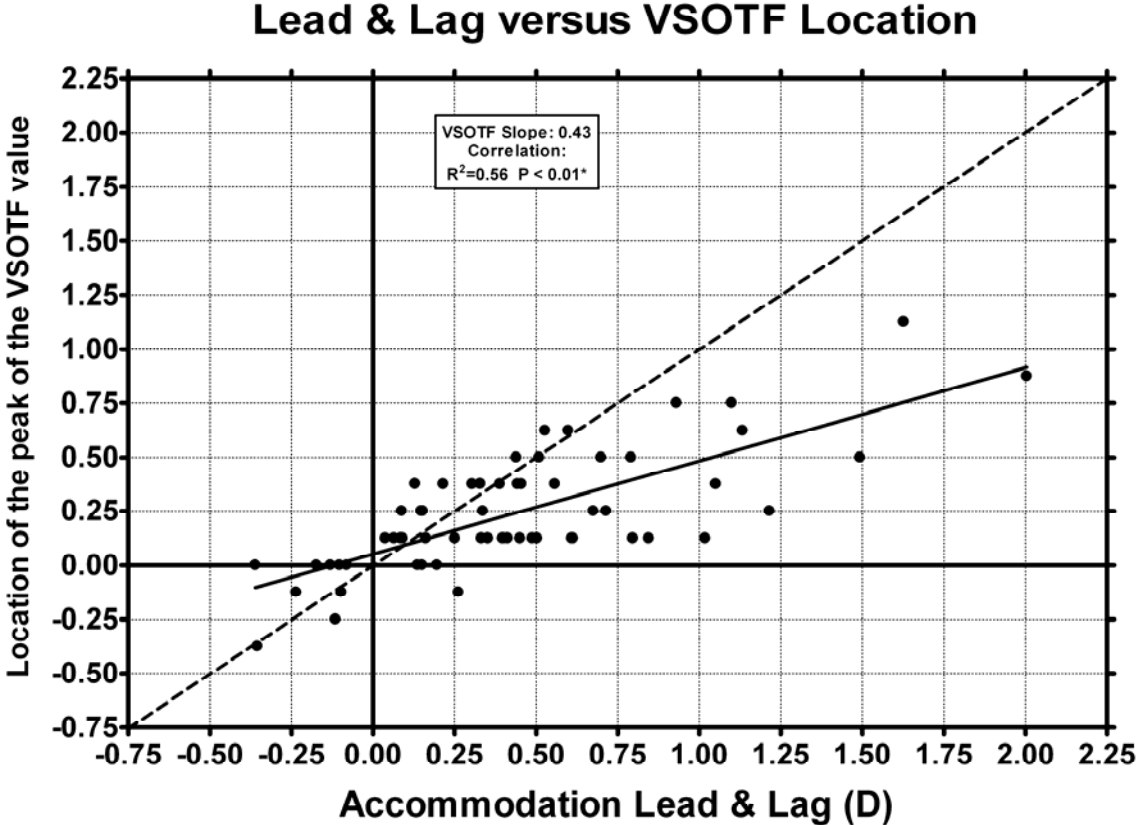


Figure 6: Correlation between lead and lag of accommodation and the location of the peak of the VSOTF. The dashed line represents the one to one relationship between accommodation error and peak of the VSOTF.























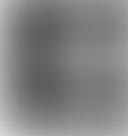

Fixed 3 mm Pupil (All Aberrations)	Natural Pupils (All Aberrations)	Natural Pupils (Defocus only)	Natural Pupils (HO-Aberrations only)
VSOTF = 0.65  600 cm Lag = +0.01 D	Pupil = 6.59 VSOTF = 0.12  600 cm Lead = -0.34 D	VSOTF = 0.08  600 cm Lead = -0.34 D	VSOTF = 0.18  600 cm Lead/Lag = 0.00 D
VSOTF = 0.39  100 cm Lag = +0.24 D	Pupil = 5.23 VSOTF = 0.26  100 cm Lag = +0.04 D	VSOTF = 0.95  100 cm Lag = +0.04 D	VSOTF = 0.33  100 cm Lead/Lag = 0.00 D
VSOTF = 0.29  50 cm Lag = +0.36 D	Pupil = 6.13 VSOTF = 0.09  50 cm Lag = +0.45 D	VSOTF = 0.06  50 cm Lag = +0.45 D	VSOTF = 0.11  50 cm Lead/Lag = 0.00 D
VSOTF = 0.35  33 cm Lag = +0.30 D	Pupil = 5.93 VSOTF = 0.07  33 cm Lag = +0.61 D	VSOTF = 0.03  33 cm Lag = +0.61 D	VSOTF = 0.06  33 cm Lead/Lag = 0.00 D
VSOTF = 0.32  25 cm Lag = +0.33 D	Pupil = 5.57 VSOTF = 0.08  25 cm Lag = +0.80 D	VSOTF = 0.02  25 cm Lag = +0.80 D	VSOTF = 0.05  25 cm Lead/Lag = 0.00 D
VSOTF = 0.23  20 cm Lag = +0.38 D	Pupil = 5.49 VSOTF = 0.09  20 cm Lag = +1.02 D	VSOTF = 0.009  20 cm Lag = +1.02 D	VSOTF = 0.03  20 cm Lead/Lag = 0.00 D

Figure 7: Retinal image reconstructions, accommodation errors, pupil sizes and VSOTFs' for a myopic subject (subject 3) are shown at various accommodation levels. Fixed 3-mm pupil data (left panel) shows best retinal image quality at 6-m distance. Retinal image quality for natural pupil data (other three panels) is generally best at 1-m distance and gets worse for both further and closer distances. With increasing accommodation levels retinal image quality deteriorates substantially for only defocus (centre right panel) and only higher-order aberrations (right panel). Retinal image quality for both defocus and higher-order aberrations combined maintains reasonably stable at a ratio in the area of 0.1.