Effects of Pupil Center Shift on Ocular Aberrations

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PURPOSE. We investigated effects of pupil shifts, occurring with changes in luminance and accommodation stimuli, on refraction components and higher-order aberrations.

METHODS. Participants were young and older groups (n = 20; 22 ± 2 years; age range, 18–25 years; and n = 19, 49 ± 4 years, 45–58 years, respectively). Aberrations/refractions at 4- and 3-mm diameters were compared between centered and decentered pupils for low (background, 0.01 cd/m², 0 diopters [D]), and high (6100 cd/m², 4 or 6 D) stimuli. Decentration was the difference between pupil centers for low and high stimuli. Clinical important changes with decentration were: M at ±0.50 or ±0.25 D, J180 and J45 at ±0.25 or ±0.125 D, HORMS at ±0.05 μm, G(3, 1) at ±0.05 μm, and G(4, 0) at ±0.05 μm.

RESULTS. Because of small pupil shifts in most participants (mean 0.26 mm), there were few important changes in most refraction components and higher-order aberration terms. However, M changed by >0.25 D for a third of participants with 4-mm pupils. When determining refractions from second to sixth order aberration coefficients, the more stringent criteria gave 76/534 (14%) possible important changes. Some participants had large pupil shifts with considerable aberration changes. Comparisons at the high stimulus were possible for only 11 participants because of small pupils. When refractions were determined from second order aberration coefficients only, only 35 (7%) had important changes for the more stringent criteria.

CONCLUSIONS. Usually pupil shifts with changes in stimulus conditions have little influence on aberrations, but they can with high shifts. The number of aberrations orders that are considered as contributing to refraction influences the proportion of cases that might be considered clinically important.

Keywords: accommodation, coma, luminance, ocular aberrations, pupil centration, pupil size, refraction, spherical aberration

We have investigated the effect of luminance and accommodation stimulus on pupil size and position using young and middle aged adult groups.1 With increase in luminance and accommodation, pupil size decreased as expected and there was a mean absolute variation in pupil center position of 0.26 ± 0.08 mm, with a mean nasal shift from the lowest to the highest stimulus condition of approximately 0.12 mm (Fig. 1). Only luminance contributed significantly to the latter shift. There was considerable interindividual variation, with individual shifts up to 0.5 mm. We concluded that in the context of fitting progressive addition lenses, changes in pupil center are not large enough to be of concern.

Aberrations have been compared for different pupil sizes, but usually without taking into account change in pupil center that would accompany real shifts in pupil size.2–3 Walsh and Charman4 considered the effect of 1 and 2 mm decentrations of small pupils on the modulation transfer function; these decentrations are much larger than those in studies of changes in pupil position.1,5–12 Porter et al.10 investigated the errors of measuring the aberrations of eyes dilated with phenylephrine and then surgically corrected through undilated pupils without taking into account the pupil shift between the two conditions. The mean pupil shift was 0.29 ± 0.14 mm in the supero-temporal direction for the undilated condition compared to the dilated condition, which is much higher and in the opposite direction to shifts with luminance changes.1,5–9,12 In a related study, Applegate et al.13 evaluated variation in wave aberration determination due to theoretical pupil location uncertainty up to 0.2 mm; the aberration variation increased as wave aberration and uncertainty increased.

Corneal and ocular aberrations have been compared without taking into account different pupil centers resulting from the different lighting conditions for corneal topographers and aberrometers. Tabernero et al.10 calculated changes in the corneal contribution to aberrations when ocular aberrations were determined at a low light level, giving large pupils, and corneal topography was determined at a high light level, giving a smaller pupil; data for the cornea were referenced to the pupil centers for aberration measures. Absolute changes in pupil center were 0.21 ± 0.11 mm, a little smaller than our values.1

In this study, we use our previous results1 to investigate effects of pupil shifts on aberrations and refraction of the eye when luminance and accommodation stimulus are altered.

METHODS

The study complied with the tenets of the Declaration of Helsinki and was approved by the University Human Research Committee.
Ethics Committee. Experimental methods were described in detail by Mathur et al.1 Participants were staff and students of Queensland University of Technology in good general and ocular health, with best corrected visual acuities \( \geq 6/6 \), spherical equivalent refractions > −3 diopters (D), and cylinder ≤ 0.75 D. There were 20 young participants (mean age, 22 ± 2 years; spherical equivalent, −1.5 ± 0.9 D) and 19 older participants (mean age, 49 ± 4 years; spherical equivalent, −1.8 ± 1.6 D). Pupil images and aberrations were determined with a modified COAS-HD Hartmann-Shack aberrometer (Wavefront Sciences, Inc., Albuquerque, NM, USA) with room lights off and the nontested eyes occluded. A matrix of stimulation conditions were used in which there were 4 luminance levels between 0.01 cd/m² (level 1) and 6100 cd/m² (level 4), of a 12.5° × 11.0° background, and up to 4 accommodation stimulus levels (0, 2, 4, and 6 D) provided by moving the internal target. Three measurements were taken for each luminance-accommodation stimulus combination. Accommodation stimuli were increased until the participant reported that the target could no longer be made clear, up to a maximum of 6 D. Eye images were analyzed using an algorithm that estimated \( x, y \) coordinates of the pupil center relative to the limbus center. Nasal and superior pupil center positions were taken as positive.

To determine uncertainty associated with determining pupil centers, two images at a randomly selected luminance/accommodation combination were analyzed for each of five young and five older participants. Each image was analyzed three times and the absolute distance of the pupil center from the limbus center was obtained. The standard deviations of the three analyses and the absolute difference between the averages for the two images were determined. Across all participant/image combinations, the mean of the standard deviations of three analyses was 0.04 ± 0.03 mm. Across all participants, the mean absolute differences between first and second images was 0.03 ± 0.03 mm. This indicated that pupil shifts determined of 0.05 mm or more are meaningful.

We did comparisons at conditions giving the largest and smallest pupil sizes. The largest pupil sizes occurred for the luminance level 1–0 D accommodation condition, henceforth referred to as the “low stimulus condition.” For most of the younger group the smallest pupil size was determined for the luminance level 4–6 D accommodation condition, and for the majority of the older group the smallest pupil size was determined for the luminance level 4–4 D accommodation condition. Some people could not make the target of the aberrometer appear clear at these accommodation stimuli, and in these cases the determinations were made for 4 D stimulus in one case for the younger group and for 2 D stimulus in eight cases for the older group. The high luminance and high

![Figure 1](image1.png)  
**Figure 1.** Pupil center shifts from the low to the high stimulus condition used in this study for 20 young and 19 older participants. See Methods for further details. Data are from our previous study.¹

![Figure 2](image2.png)  
**Figure 2.** Change in analysis pupil. Black spots and black ring indicate Hartmann-Shack image points and rim of actual pupil. Blue spots and blue ring indicate Hartmann-Shack image points and rim of pupil of interest for the centered case. Red spots and red ring indicate Hartmann-Shack image points and rim of pupil of interest for the decentered case.

![Figure 3](image3.png)  
**Figure 3.** Effective pupil size on decenteration. The actual 3.5-mm pupil does not completely encompass the required 3.0-mm pupil upon decenteration, and the effective decentered pupil size is 2.9 mm.
accommodation combination will be referred to as the “high stimulus condition.”
As pupil sizes were small at the high stimulus condition, we decided to do analyses for 4.0 and 3.0 mm diameter pupils. For the low stimulus condition, we determined the aberrations at these pupil sizes when the data were centered and when they were rereferenced to the pupil center of the high stimulus condition for each participant. For the high stimulus condition, we determined the aberrations when the data were centered and when they were rereferenced to the pupil center of the low stimulus. The rereferencing for the low stimulus condition is particularly relevant as the low stimulus condition, with relatively large pupils, is the one that usually is used to determine aberrations at smaller pupil sizes.

Aberrations up to the sixth order were determined from the positions of the spots (black spots in Fig. 2) in the Hartmann-Shack images using custom software. For analyzing in the centered case, a subset of spots (blue spots overlaid over black spots) was used that matched the pupil size of interest (blue ring). For analyzing in the decentered case, another subset of spots (red spots overlaid on blue and black spots) was selected around the new reference point to match the pupil size of interest (red ring).

Often, analyses were not valid at the high stimulus condition, because the size at which analyses were made (3.0 or 4.0 mm) was not attained either by the natural pupil or by the effective pupil when the effect of decetration was studied. To explain the pupil size limitations further, we

**Figure 4.** Changes in aberrations induced by decentration for the young group with 4-mm pupils with refraction from second to sixth aberration orders. Limits of clinical importance are given by dashed lines, with the more stringent criteria for refraction terms given by small dashes. The low stimulus is indicated by filled circles and the high stimulus is indicated by unfilled circles. The high stimulus results were valid only for participant 20. The large filled circle for ΔM indicates the low stimulus condition for young participant 1.
present two examples. Firstly, the pupil size might be 3.5 mm compared to the reference pupil size of 4.0 mm. Secondly, say the pupil size is 3.5 mm compared to the reference pupil size of 3.0 mm, and a decentration of 0.3 mm is required (see Fig. 3). The effective pupil size = 3.5 – 2 × 0.3 = 2.9 mm. When the effective pupil size was smaller than the reference pupil size, we extrapolated the aberrations of the former to match the latter using our algorithm for this purpose; this was considered to be valid in two cases where the effective pupil sizes were ≤ 0.1 mm smaller than the reference pupil size.

Aberrations were referenced to 550 nm. In the results, we show changes in mean spherical equivalents (ΔM), regular astigmatism (ΔJ180), oblique astigmatism (ΔJ45), higher-order root–mean squared aberrations (ΔHORMS), horizontal coma coefficients (ΔC3,1), and spherical aberration coefficients (ΔC4,0). We have used the ANSI/ISO system of specifying aberration coefficients.14ΔM, ΔJ180, and ΔJ45 were determined by combining second to sixth order aberration coefficients and by considering only the second order aberration coefficients.

RESULTS
Second to Sixth Order Aberration Coefficients Considered for Refraction
Results are shown in Figure 4 (young group, 4-mm pupil), Figure 5 (young group, 3-mm pupil), Figure 6 (older group, 4-
mm pupil), and Figure 7 (older group, 3-mm pupil). Scales have been chosen that include the maximum and minimum values across all group, pupil size, and stimulus combinations. We have chosen the following changes to represent clinically important changes in refraction upon decentration: $M$ at $\pm 0.50 \text{ or } \pm 0.25 \text{ D}$, $J_{180}$ and $J_{45}$ at $\pm 0.25 \text{ or } \pm 0.125 \text{ D}$, and HORMS, $C(3,1)$, and $C(4,0)$ at $\pm 0.05 \text{ m}$. The more stringent refraction criteria were selected as they match prescription intervals. These limits are given in the figures by dotted lines. As mentioned earlier, for many cases, the high stimulus results were invalid because pupil sizes were too small.

All but one participant had valid data, whether centered or decentered, for the low stimulus condition and both pupil sizes. Only one participant had valid data for the high stimulus condition and 4-mm pupils. Several participants had valid data for the high stimulus condition and 3-mm pupils, but only six young and five older participants had valid results for centered and decentered conditions, while three young and eight older participants had valid results for only the centered condition.

Using $M$ as $\pm 0.50 \text{ D with } J_{180}$ and $J_{45}$ as $\pm 0.25 \text{ D}$ gives only 33 important changes, while using the more stringent criteria of $M$ as $\pm 0.25 \text{ D and } J_{180}$ and $J_{45}$ as $\pm 0.125 \text{ D}$ gives only 76 important changes. This is of 534 possible cases with valid

**Figure 6.** Changes in aberrations induced by decenteration for the older group with 4-mm pupils with refraction from second to sixth aberration orders. Limits of clinical importance are given by *dashed lines*, with the more stringent criteria for refraction terms given by *small dashes*. The low stimulus is indicated by *filled circles*. The high stimulus results were invalid for all participants.
Comparisons; that is, where effective pupil size meets the reference size for centered and decentered situations. However, within the important changes were some interesting cases.

For the younger group with 4-mm pupils and the low stimulus condition, and using the more stringent criteria for the refraction components, 25 cases had important changes (Fig. 4). These were spread mainly between $\Delta M$ (nine cases) and $\Delta$HORMS (five cases). The most noticeable change was $\Delta M = -1.1$ D for participant 1, for which there was a decentration of 0.25 mm (large filled circle in Fig. 4). This participant also had $\Delta J_{45} = 0.3$ D.

For the younger group with 3-mm pupils and the low stimulus condition, and using the tighter tolerances for the refraction terms, only 10 cases had important changes (Fig. 5). The most noticeable change was $\Delta M = -1.2$ D for young participant 1 (large filled circle), similar to this person's result for the 4-mm pupil.

For the younger group with 3-mm pupils and the high stimulus condition, valid comparisons were possible for six subjects (Fig. 5), among which there were 13 cases with important changes. The most notable changes were for participant 17 (large open circle), which included $\Delta M = +0.6$ D, $\Delta J_{180} = -1.0$ D, $\Delta J_{45} = +0.5$ D, $\Delta$HORMS at $-0.20$ μm, and $\Delta C(3,1) = +0.28$ μm, which were the largest changes occurring for these aberrations. This participant had a particularly large pupil decentration of 0.35 mm. Interestingly,
aberration changes for the low stimulus condition for this subject were small.

For the older group with 4-mm pupils and the low stimulus condition, and using the more stringent criteria for the refraction terms, seven cases had important changes, three of which involved $\Delta M$ (Fig. 6). For the older group with 3-mm pupils and the low stimulus condition, and using the more stringent criteria for the refraction terms, 14 cases had

**Figure 8.** Changes in refraction components induced by decentration for the young group with 4-mm pupils with refraction from second aberration order. Limits of clinical importance are given by *dashed lines*, with the more stringent criteria for refraction terms given by *small dashes*. The low stimulus is indicated by *filled circles* and the high stimulus is indicated by *unfilled circles*. The high stimulus results were valid only for participant 20. The *large filled circle* for $\Delta M$ indicates the low stimulus condition for young participant 1.

**Figure 9.** Changes in refraction components induced by decentration for the young group with 3-mm pupils with refraction from second aberration order. Limits of clinical importance are given by *dashed lines*, with the more stringent criteria for refraction terms given by *small dashes*. The low stimulus is indicated by *filled circles* and the high stimulus is indicated by *unfilled circles*. For most participants the high stimulus results were invalid. The *large filled circle* for $\Delta M$ indicates the low stimulus condition for young participant 1. The *large open circles* indicate the high stimulus condition for young participant 17.
important changes, most involving the astigmatism terms (Fig. 7).

For the older group with 4-mm pupils and the high stimulus condition, valid comparisons were not possible. For the older group with 3-mm pupils and the high stimulus condition, valid comparisons at the high stimulus condition were possible for five subjects (Fig. 7), among which there were seven cases with important changes.

Only Second Order Aberration Coefficients Considered for Refraction

Group results for the refraction components only are shown in Figure 8 (young group, 4-mm pupil), Figure 9 (young group, 3-mm pupil), Figure 10 (older group, 4-mm pupil), and Figure 11 (older group, 3-mm pupil).

**Figure 10.** Changes in refraction components induced by decentration for the older group with 4-mm pupils with refraction from second aberration order. Limits of clinical importance are given by dashed lines, with the more stringent criteria for refraction terms given by small dashes. The low stimulus is indicated by filled circles. The high stimulus results were invalid for all participants.

**Figure 11.** Changes in refraction components induced by decentration for the older group with 4-mm pupils with refraction from second aberration order. Limits of clinical importance are given by dashed lines, with the more stringent criteria for refraction terms given by small dashes. The low stimulus is indicated by filled circles and the high stimulus is indicated by unfilled circles. For most participants the high stimulus results were invalid.
The number of cases with importance reduced considerably, from 76 (14% of the total 534 cases) with the second to sixth order analysis, to 35 (7%), although the number for ΔM increased from 10/38 to 17/38. Most of this reduction occurred with the 3-mm pupil, for which there were only 11 clinically important values, compared to 44 previously. For the young group in the unaccommodated condition with 4-mm pupils, there were 12 cases of ΔM > 0.5 D.

To consider individual participants, for young participant 1 at 4-mm pupil and the low stimulus condition, there was considerable change in ΔM from −1.1 for second to sixth order aberration coefficients to −0.6 D for second order aberration coefficients only (compare ΔM for Figs. 4, 8, large filled circles), while at 3-mm pupil his results changed even more from ΔM = −1.2 D to only −0.2 D (compare ΔM for Figs. 5, 9, large filled circles). For young participant 17 at 3-mm pupil and the low stimulus condition, ΔM hardly changed (+0.6 to +0.5 D) but ΔM₈₁₈₀ changed from −1.0 to +0.4 D and ΔM₁₄₅ changed from +0.5 to −0.1 D (compare Figs. 5, 9, large open circles).

DISCUSSION

Because of the small pupil centration changes with change in stimulus condition (from low luminance/low accommodation stimulus to high luminance/high accommodation stimulus) for most participants, there were mainly small changes in refraction and higher-order aberrations that would be considered to have no clinical importance. However, for approximately a third of participants with 4-mm pupils, mean spherical refraction changed by more than 0.25 D. There were a few cases where changes in refraction and/or higher order aberrations were considerable.

When determining refractions from second to sixth order aberration terms, the majority of important shifts, 48 of the 76 across both pupil sizes and using the more stringent refraction criteria, occurred for the younger participants. Given the small number of subjects for whom comparisons could be made at the high stimulus condition, the proportion of important shifts under this condition (20/66) was considerable, possibly reflecting considerable higher-order aberrations for some of the centered pupils at this level.

When refractions were determined from second order aberration terms only, the number of clinically important changes in refraction and higher order aberrations was only 37, with only eight values with the 3-mm pupil. Determining refraction using only second order terms probably is better than using more orders at smaller pupil sizes, as higher order terms can be rather “noisy” and have undue influence on refraction.

This study has implications for clinical refraction using aberrometers. Occasionally, pupil sizes might be considerably different during aberrometer refraction and subjective refraction, with accompanying different pupil centers, such as when the subjective measurements are under photopic conditions and the aberrometer measurements are under mesopic lighting conditions. This may give important refraction “errors” with aberrometry, which will be influenced by the number of orders of aberrations considered as contributing to refraction.

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References