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THE CONTRAST ACUITY ASSESSMENT (CAA) TEST

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THE CONTRAST ACUITY ASSESSMENT (CAA) TEST

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Executive Summary

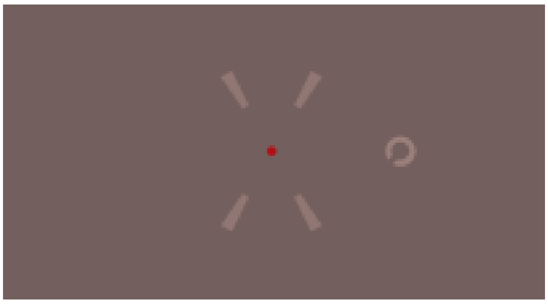
Background: The results of a recently completed study of visual performance in Photorefractive Keratectomy (PRK) and Laser Assisted In-situ Keratomileusis (LASIK) subjects, suggests that the majority of these individuals do not differ significantly from the normal population in terms of visual performance. The study included the measurement of scattered light within the eye, contrast sensitivity, high and low contrast letter acuity, contrast thresholds for detection and gap orientation discrimination and mean visual search times. However, approximately 10% of the post-surgery subjects tested were identified as "outliers", (more than 1.5 times the interquartile range above the upper quartile), by the contrast acuity test (gap orientation discrimination). The degradation of retinal image quality in the outliers has been attributed to an increase in both intraocular light scatter and ocular aberrations following surgery. The other tests appeared to be less sensitive to changes in visual performance, only identifying those individuals with extreme increases in scatter and/or aberrations. Poor performance for such a task has safety implications in aviation where the rapid interpretation and processing of information is vital. This is particularly critical under low (mesopic) ambient illumination when the enlarged pupil diameter increases the influence of both scatter and aberrations on the retinal image.

The existence of a significant number of outliers points to the urgent need for a screening test that is sensitive to the presence of scattered light and aberrations. A glare source was not incorporated in the test design since under some conditions a glare source can produce an improvement in visual performance compared to the no glare situation as a result of pupil constriction. In addition, scatter originating from within the retinal image of the object of regard, often causes more visual degradation than scatter from a peripheral glare source.

With this in mind, we have designed and validated a contrast acuity test that can be used to assess the subject's dynamic visual performance under photopic and mesopic light adaptation. Analysis of Contrast Acuity Assessment (CAA) data for an individual relies on the "standard" contrast acuity observer, derived from measurements in normal subjects. The CAA test parameters (target size, light level and effective visual field) are based on a detailed study of modern flight deck instrumentation design. Target size is scaled to increase with increasing target eccentricity to reflect the reduced resolving power of the retina with increasing distance from the fovea. This was determined from assessment of 64 normal subjects under both photopic and mesopic conditions in order to maximise the sensitivity of the test to the presence of increased scatter and aberrations, and to simplify interpretation of the data.

Method: Measurements were carried out a number of discrete eccentricities either side of the visual axis (0, ±1.25°, ±2.5°, ±5°) presented in a random order using a four-alternative, forced-choice procedure to determine the threshold for contrast. The subject was required to press one of four buttons to indicate the position of the gap in the ring, upper left, upper right, lower left, lower right. A correct answer resulted in a reduction in stimulus contrast. If the gap could not be resolved, a guess was made with an incorrect guess resulting in an increase in stimulus contrast.

Figure a: The stimulus configuration for the CAA test at 2.5 degrees



Contrast thresholds for gap acuity discrimination were obtained in 64 normal subjects under photopic and mesopic conditions and were found to be approximately 24% and 48% respectively. The variance of these measurements provides an estimate of the range of threshold contrast variation that describes the normal "standard" contrast acuity observer, (see figure b).

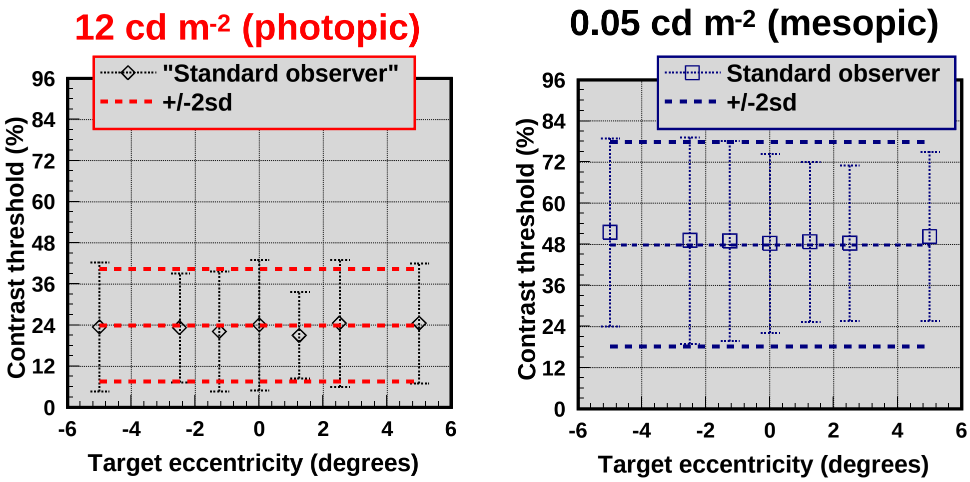


Figure b: Definition of the "standard" contrast acuity observer for the stimulus parameters selected for the CAA test. The graphs show mean thresholds based on measurements in 64 normal subjects (dotted lines). The dashed lines indicate the ±2sd range.

Results: Seven PRK and seven LASIK subjects were examined to validate the test with the data generally falling into one of two categories. Many of the subjects were identified as having good visual performance by the CAA test, with contrast threshold data clustered around the "standard" observer (see figure c). All such patients were asymptomatic. A few subjects showed an increase in contrast thresholds indicating reduced visual performance. Increased scatter and aberrations tend to cause a characteristic peak in contrast thresholds around the fovea and parafoveal region (see figure d). In one subject, poor visual performance was only found under mesopic conditions when the pupil was large. This finding emphasises the importance of examining refractive surgery patients under night time lighting conditions. In some patients the more peripheral regions of the cornea contribute significantly to increased aberrations and scattered light and this can only be revealed under conditions that cause full pupil dilation.

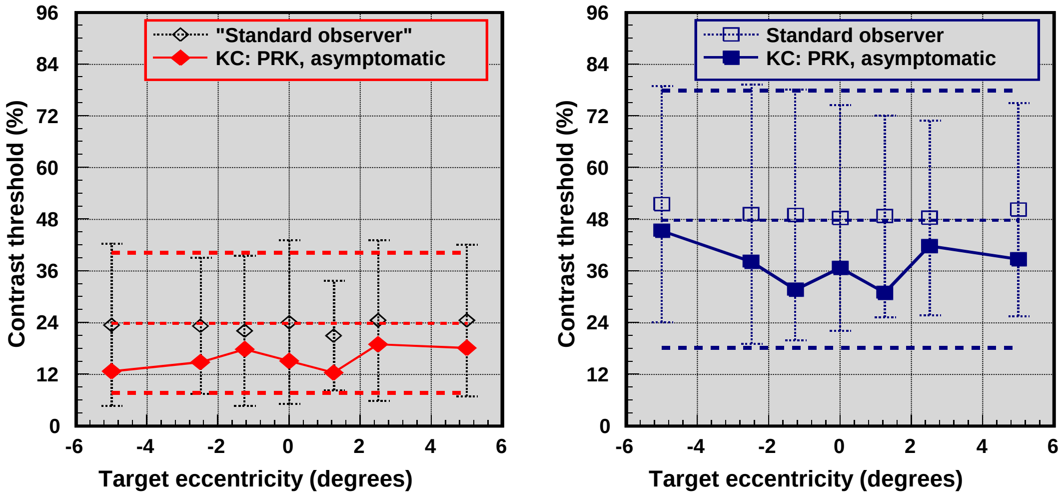


Figure c: Example CAA test data in an asymptomatic subject after recovery from photorefractive keratectomy. Results are shown for both photopic (left) and mesopic (right) conditions of light adaptation. Contrast thresholds are lower than the "standard" observer indicating better than average visual performance at both light levels.

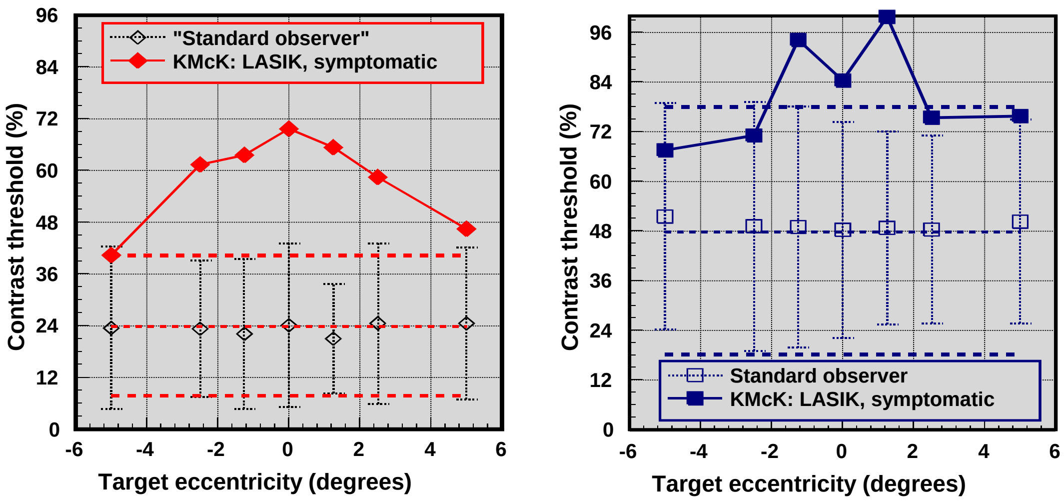


Figure d: Example CAA test data in a symptomatic subject after recovery from LASIK. Results are shown for both photopic (left) and mesopic (right) conditions of light adaptation. Contrast thresholds were consistently higher than the "standard" observer indicating poor visual performance at both light levels. The greatest discrepancy occurred foveally, implicating both scatter and aberrations.

Conclusions: The majority of refractive surgery patients have good visual performance as indicated by the CAA test and can in fact perform better than the standard observer. A small percentage of subjects suffer from reduced visual performance as indicated by the CAA test, i.e. their data fall outside the normal range ±2sd. These patients are not necessarily symptomatic, perhaps because they do not commonly encounter visually demanding conditions.

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1 INTRODUCTION

Previous work undertaken at City University, for the UK Civil Aviation Authority, examined the effect of photorefractive keratectomy (PRK) and laser assisted in-situ keratomileusis (LASIK) on intraocular light scatter and visual performance. Custom designed, computer-based techniques were utilised in this study (Barbur *et al.*, 1999; Chisholm et al., 2000) (see also CAA report on *The effect of laser refractive surgery on visual performance and its implications for commercial aviation*, August 2000). It was initiated after a number of reports pointed to an increase in intraocular light scatter during the recovery period post-PRK. However, the findings from the City University study suggest that when group data are compared, intraocular light scatter levels do not differ significantly between the refractive surgery groups and the control group (average follow-up times of 136 weeks post-PRK and 16 weeks post-LASIK).

This same study also measured a number of other indices of visual performance including contrast thresholds for target detection and for gap orientation discrimination (i.e. a contrast visual acuity task), using a Landolt ring target. An estimate of both high and low contrast acuity was made using a LogMAR letter chart, (log. minimum angle of resolution). Visual search performance was also investigated by measuring the relationship between visual search times and target contrast. Following the removal of significant 'outliers', the contrast acuity threshold data[1] revealed a statistically significant difference between the refractive surgery groups and the control group ($p<0.05$). This reduction in performance was very small and unlikely to be significant for non-simulated, real-world visual tasks. The other measures of visual performance (i.e., contrast detection thresholds, low contrast acuity and visual search performance), showed no such deficit. A number of outliers (more than 1.5x outside the interquartile range), were identified in each experiment (approximately 11% of LASIK patients and 12% of PRK patients), the majority of whom were also outside the normal range for the contrast acuity test. The contrast acuity test was the only measure of performance to reveal any statistically significant difference between subject groups. In addition, all symptomatic patients turned out to be outliers for this test.

The results of the initial City University studies suggest that the majority of PRK and LASIK subjects do not differ significantly in visual performance from the normal subject group. Based on these findings these subjects should be considered safe as pilots in commercial aviation (after the follow-up times stated in the methods section). However, a significant number of outliers were found in both refractive surgery groups and therefore an efficient form of visual assessment is required. The outliers demonstrate a large reduction in contrast acuity thresholds due to increased intraocular scatter and/or irregular aberrations of the cornea and lens, important enough to cause concern in commercial aviation and other employment where good vision is essential. One might expect that flight simulators would provide one of the best methods of assessing visual performance in aviation. However, there are a number of inherent difficulties in using such techniques as demonstrated by studies that have examined vision and driving – despite what appears to be an obvious association, only a very weak correlation has been established between driving accident rates and poor high contrast vision (Road Research Laboratory, 2000). This is largely because of the enormous number of factors that affect overall performance

[1] Note: contrast acuity is the lowest contrast between stimulus and background, at which a stimulus can be discriminated

in complex visual tests. Similarly skills involved in piloting an aircraft draw on a number of different, interacting inputs in addition to high contrast (Snellen) vision. These include motor skills, the ability to focus attention, spread and maintain attention, rapid speed of judgement, familiarity with the flight deck, etc. Further it is very difficult to score flying performance using a method amenable to statistical analysis. As a result, it is difficult to isolate the effects of reduced visual performance from other tasks relevant to overall performance, unless a group of experienced pilots underwent surgery and their performance was then reassessed, a study unlikely to receive ethical approval. Such difficulties were hinted at by the results of the visual search test developed for the initial study, which was designed to mimic more complex visual search tasks. Analysis of the parameters involved in determining visual search performance revealed a number of important factors in addition to target contrast, such as search strategy, glimpse duration during fixations, memory length for storing previously visited locations in the visual field, fatigue and learning.

2 CONSIDERATION OF TEST REQUIREMENTS

In designing a robust test that specifically reflects the loss of contrast acuity in post-refractive surgery patients, it is essential that the test is based on criteria that relate to the critical visual stimuli employed in typical flying tasks. The Scientific Peer Advisory and Review Services of the American Institute of Biological Sciences, in their report on PRK, strongly recommended that any test to evaluate visual function following refractive surgery should include parameters other than high contrast acuity alone, ideally using measures tailored to the visual tasks involved. They recommended the inclusion of luminance, contrast and spatial frequency factors in target choice, in order to reveal those conditions that show increased sensitivity to the presence of light scatter and irregular aberrations. They also suggested that pupil size and the effect of glare should be considered. Although it seems sensible to incorporate a glare source to mimic the effect produced by runway approach lights for example, a point source within the field chosen to simulate the luminance of car headlights at 100 feet has been shown to improve contrast sensitivity relative to the no-glare situation, as a result of pupil constriction (Boxer-Wachler B.S. *et al.*, 1999). This effect may well be related to the non-uniform scatter over the pupil with its outermost regions contributing more scatter, a region that does not contribute to light scatter when the pupil is small (Edgar *et al.*, 1995). Due to the tendency for laser surgery to increase both forward light scatter towards the retina, as well as irregular aberrations particularly under dilated pupil conditions, there is a need for a 'pupil-sparing' aberration test. The Mesoptometer has been employed in Germany to assess patients post-PRK (Kriegerowski *et al.*, 1997) but this test suffers from the use of a point glare source on which patients tend to inadvertently fixate. The 'pass' criteria under these conditions is excessively difficult to achieve and is probably irrelevant to aviation. It should also be remembered that when viewing an object, visually degrading intraocular scatter originates from all points within the visual field, some of which are much closer to the fovea than the designated glare source and therefore can contribute more scatter. In other words, scatter originating from within the retinal image of the object of regard, often causes more visual degradation than scatter from a peripheral glare source.

2.1 **Visual Task Analysis**

Detailed visual task analysis within a modern flight deck was undertaken to establish the relevant test parameters, such as minimum target size, light level, effective visual field, range of stimulus contrasts, etc. Target size measurements indicated that the smallest alphanumeric characters that are considered important subtended between 12 and 18 minutes of arc at the eye (for an average working distance of 80cm). Assuming a standard character format in which each limb is one fifth of the overall target size, the minimum angle of resolution required to discriminate the graphics ranged between 2.5 and 3.6 minutes of arc – approximately 3 times the maximum nominal, high contrast visual acuity of the eye. These target sizes, combined with the very high contrast levels generated on flight deck displays ($\delta L/L >$ 200%) under both photopic and mesopic light levels (see Fig.i), mean that observation of the instrumentation is one of the most visible tasks on the flight deck. Careful design has ensured that all targets within a single screen are at least resolvable, although not necessarily interpretable, when the pilot's point of regard is the centre of the screen. Analogue instruments in older aircraft employ much lower contrasts and other targets within the visual scene tend to be of significantly lower contrast. Further tasks such as scanning for air traffic, searching for the runway and reading airport maps, can also involve lower contrast targets. Consideration of only high contrast display information is not therefore justified. Since the information on adjacent screens cannot be resolved because of the large loss in visual acuity with eccentricity, the functional visual field of interest on a single screen only covers an area of 5° either side of the visual axis, when the displays are viewed from approximately 80 cm, a typical eye to instrument distance. In order to examine information from another display screen, the eye has to alter fixation.

Fig.i Modern display arrangement in the Airbus 320 flight deck

Photopic test measurements utilised a background light level of 12 cd m^{-2}. Although lower than the average daylight luminance within the flight deck, 12 cd m^{-2} falls well within the photopic range and causes less pupil constriction than would occur with average daylight luminance levels, making the test more sensitive to aberrations and light scatter that relate to pupil size. At night, the background light levels within the flight deck were approximately 0.05 cd m^{-2} although the high contrast instrumentation graphics ensured that the fovea remained photopic and hence good colour discrimination is retained. This luminance value falls within the mesopic range in which both rod and cone receptors determine visual function. Testing under mesopic conditions can provide valuable information since the low retinal illuminance results in large pupil dilation, which is likely to exacerbate the effect of light scatter and aberrations. In addition, the predominance of the rod function and the loss of the Stiles-Crawford effect[2] at such low light levels, further increase the influence of scattered light and aberrations.

2.2 General Test Parameters

The Contrast Acuity Assessment (CAA) test is based on the gap orientation discrimination threshold measurement developed during the initial City University study, which was identified as sensitive in our preliminary studies. Visual function was assessed over a field of ±5°, corresponding to the functional visual field. The stimulus was presented randomly at the following eccentricities in the visual field: –5°, –2.5°, –1.25°, 0°, +1.25°, +2.5°, +5° along the horizontal meridian (see Fig.ii). A central fixation target was surrounded by 4 oblique guides to aid central fixation by reducing the tendency to saccade[3] to the test target. The duration of the stimulus was 120ms so as to ensure its offset preceded the onset of any saccadic eye movement, which has usually a longer latency (Barbur *et al.*, 1988). In each of the experiments discussed below, the stimulus locations were presented in a random order and a four-alternative, forced-choice procedure was used to determine threshold for the variable in question, (i.e. upper left, upper right, lower left, lower right). The subject was required to press one of four buttons to indicate the position of the gap in the ring. A correct answer resulted in a reduction stimulus size or contrast. If the gap could not be resolved, a guess was made and a button pressed. Since two sequential correct answers were required before the computer reduced the size or contrast of the stimulus, the chance probability of correct responses was 1/16.

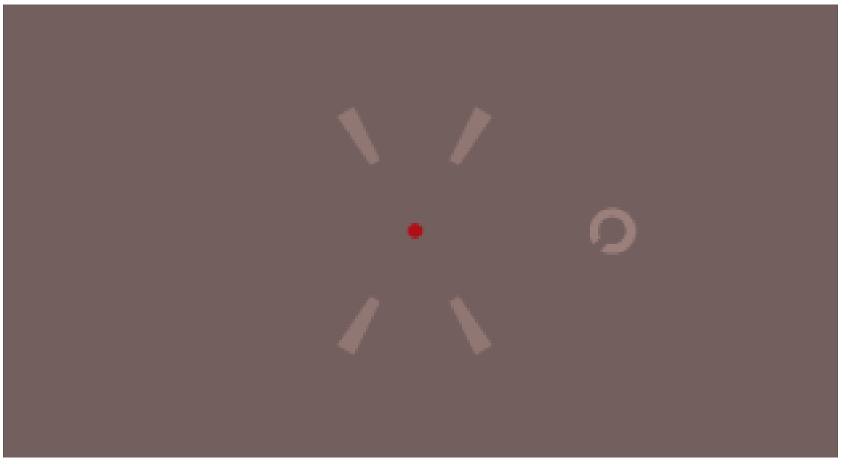


Fig.ii Screen dump of stimulus configuration employed in the CAA test. The picture shows the stimulus at +2.5°. eccentricity, together with central fixation target and guides

[2] Note: The Stiles-Crawford effect describes the optimisation of light rays on the visual axis and the reduced effectivity of off-axis light rays and scattered light due to the orientation of retinal cone receptors. Rod receptors which are predominately in use under low illumination, do not demonstrate the same orientational properties and are therefore more susceptible to scattered light.

[3] Note: A saccade is a rapid eye movement made in order to establish fixation on a particular object.

3 EXPERIMENTAL PROCEDURE

For all tests, subjects underwent an examination of their ocular health to exclude those with any abnormality. A refraction was undertaken to ensure that the eye under test was fully corrected. Only normals that could be corrected to 6/6 acuity or better were considered. The stimulus display was turned on and allowed to warm up for a minimum of 15 minutes prior to the test. In preparation for mesopic testing, the subject was required to wear a light-proof patch over the selected eye for a minimum of 15 minutes. Mesopic light levels were achieved by viewing the display through a spectrally calibrated neutral density filter[4] (a nominal optical density of 2). The display was viewed through a booth so as to ensure that the only light that reached the subject's eye had passed through the filter. The spectral absorption of the filter was taken into account to ensure that no colour distortion occurred in the mesopic range.

4 TARGET SIZE / CONTRAST SELECTION EXPERIMENT

In order to assess contrast visual acuity over the whole of the pilot's functional visual field, regarded as ±5° either side of the visual axis, the size of the target needed to be scaled with eccentricity. It was felt important to consider targets adjacent to the fixation point because pilots do use paracentral vision for obtaining flight information. Each individual display screen employs a range of target sizes over a certain area such that much of the displayed information can be resolved from a single fixation, therefore increasing the speed at which visual information can be obtained. Because contrast acuity appears to be the most sensitive test for detecting a reduction in visual performance following surgery, it was felt that the target size should be adjusted with increasing eccentricity (rather than increasing contrast). This would ensure that the contrast threshold values remained relatively low for the size of stimuli used and were therefore more likely to detect the influence of increased scatter and/or aberrations. It was also felt that target size scaling would mimic the pilot's visual tasks most accurately. What was needed was a task which was sensitive to changes in performance post-surgery, and had some relevance to the task of flying an aircraft. The CAA test parameters are based on a study of modern aircraft flight deck design, although these parameters may also apply to other visual tasks.

It was necessary to determine the choice of target size and how this size should be scaled with eccentricity so as to take into account the decrease in the resolution of the retina with increased eccentricity. The relationship between target size and eccentricity is known to be highly contrast dependent. A high contrast target would mimic the contrast of the graphics displays employed in modern flight deck design, and would yield a small angle of resolution (i.e., the high contrast acuity limit). Such small spatial detail would undoubtedly not be resolved when viewed at lower contrast and may not even be representative of what is considered to be important in the flight deck. More importantly, Snellen acuity measurements for high contrast targets are known to be largely insensitive to the presence of scattered light. A very low contrast, on the other hand, would be more sensitive to image degradation but the target size required under such conditions would be significantly greater than the minimum critical target size employed in aviation. Such large stimuli sizes would also reduce sensitivity to image degradation.

[4] Note: The quantity of light transmitted through a neutral density filter is reduced evenly across the visible spectrum, hence affecting the luminance but not the colour.

To aid selection of the most suitable target size for use in such experiments, three subjects completed a gap discrimination test in which the size of the target was varied systematically for a number of different contrast levels. The test took the same format as that described in section 2.2 with the stimulus size as the variable. The 7 stimulus locations were presented in a random order and a four-alternative, forced-choice procedure was used to determine size threshold, (i.e. upper left, upper right, lower left, lower right). The subject was required to press one of four buttons to indicate the position of the gap in the ring. A correct answer resulted in a reduction stimulus size. If the gap could not be resolved, a guess was made and a button pressed. Two incorrect answers in succession resulted in an increase in stimulus size. The size threshold was measured by averaging 4 out of 6 reversals[5] with the first 2 results ignored. Under photopic conditions, the stimulus size was increased or decreased by 2 minutes of arc reducing to 0.5 minutes of arc for the last 4 measurements of threshold. Under mesopic conditions, the stimulus size increased or decreased by 5 minutes of arc reducing to 1 minute of arc for the last 4 measurements. The measurement of size threshold was repeated three times for each of a series of different target contrasts (δL/L: 6, 12, 24, 48, 96, 192, 364%), at both photopic and mesopic light levels. For each condition, the smallest resolvable gap size was measured at each chosen eccentricity within the visual field.

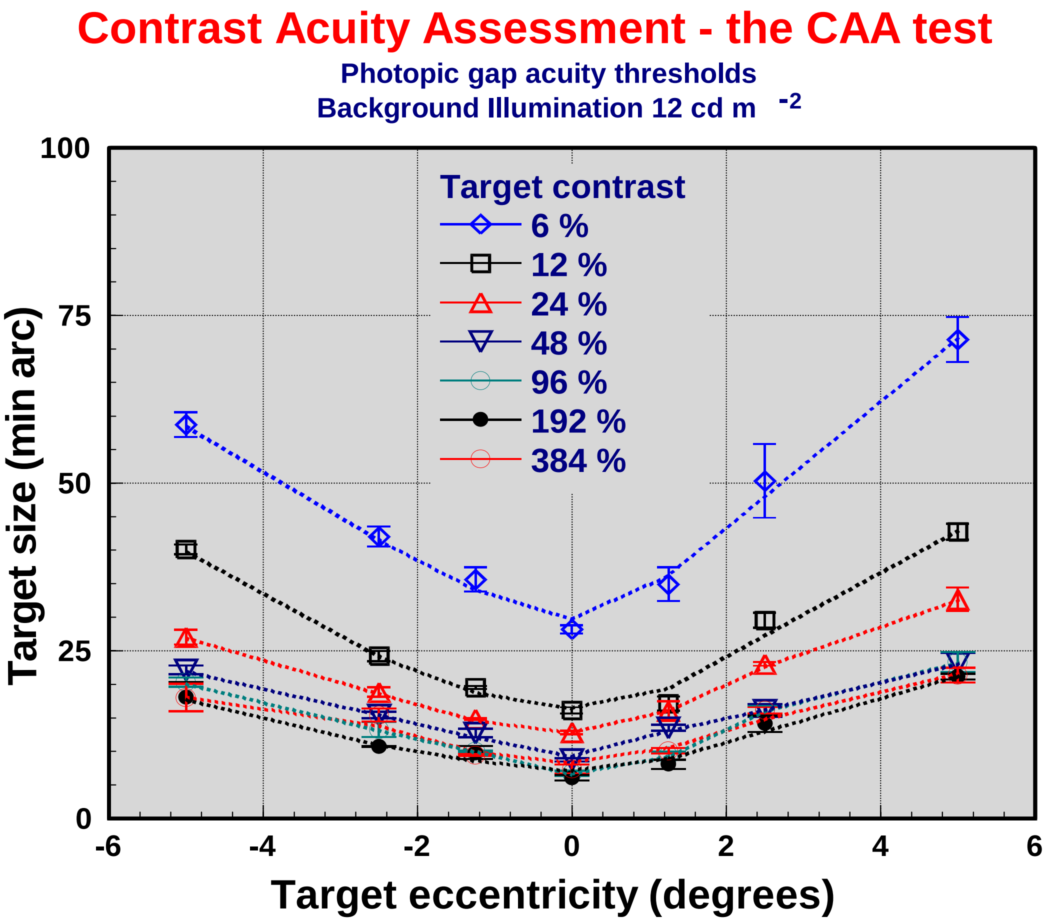


Fig.iii Photopic measurements of gap acuity averaged for 3 normal subjects at each of 7 contrast level

[5] Note: During these experiments, a change in subjective response initiates a 'reversal' in the direction that the target parameter is being adjusted, e.g. if target size is reduced, a point is reached at which the target is no longer visible, requiring the size to be increased.

The results of Fig.iii show that the minimum resolvable target size is highly dependent on target contrast, in the low contrast range. These size thresholds also increase with eccentricity. All three subjects found the 6% and 12% contrast runs more difficult, resulting in a slightly larger standard deviation for these contrast levels.

How can we use these data to select the optimum target size for use in our proposed contrast acuity tests? The smallest alphanumeric characters that are considered important on flight deck displays subtend a visual angle in the range 12 to 18 min arc. The results of Fig.iii show that the 24% contrast data corresponds well to this range of target sizes. Higher contrast levels do not yield significantly lower size thresholds, but are known to be less affected by increased scatter in the eye. In view of these arguments, the 24% contrast test yields the most appropriate target size for use in contrast acuity measurements over a range of eccentricities.

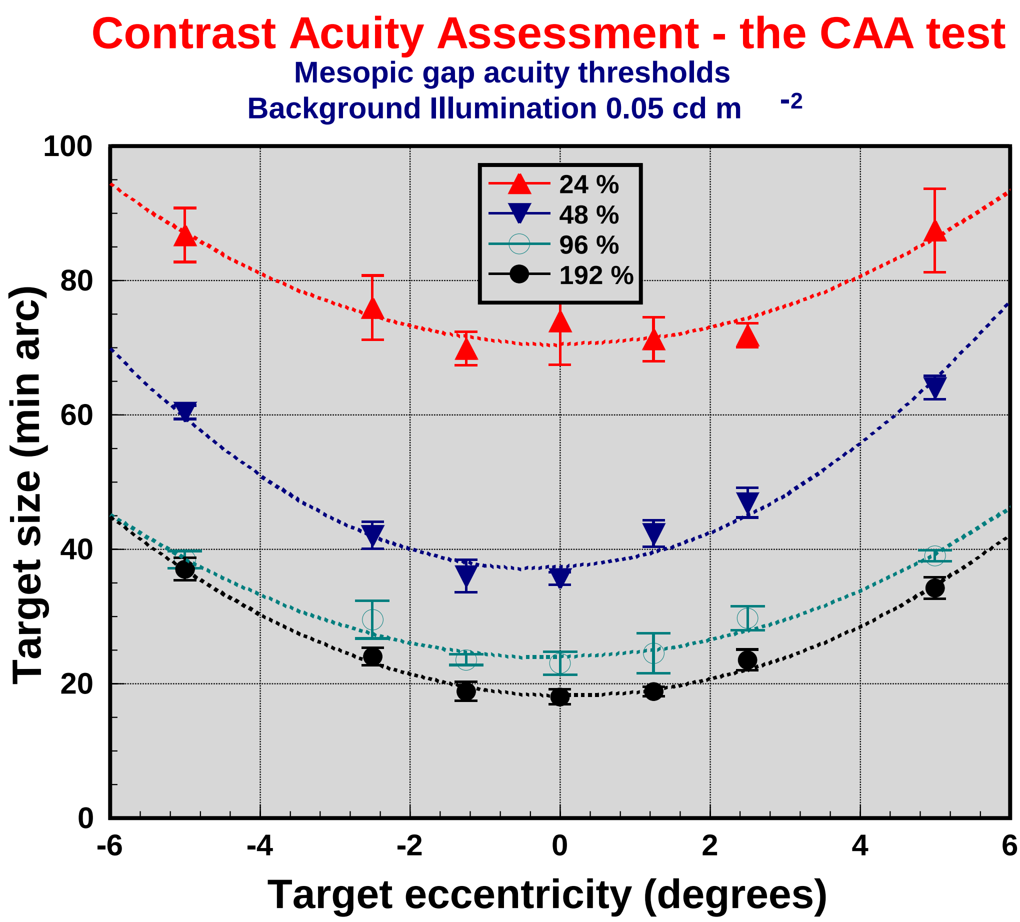


Fig.iv Contrast acuity thresholds for gap orientation discrimination measured at mesopic levels of light adaptation. The data show averaged results for 3 normal subjects at each of 7 contrast levels

In addition, 24% contrast is low enough to yield detectable changes as a result of scattered light and aberrations. At this contrast level, the size threshold test yields a foveal measurement that matches closely the minimum target size that a pilot needs to resolve easily in order to interpret with no ambiguity the alphanumeric information presented on flight deck displays.

The mesopic data in Fig.iv show a similar pattern to the photopic data in that the minimum resolvable target size increases significantly with eccentricity. Completing the test at 24% contrast was difficult and could not be completed by one subject and the test was almost unachievable for 6% and 12% contrast for all three subjects. The results show the massive loss of visual acuity when rod vision is involved with targets in the low contrast range being virtually unresolvable. The 48% contrast was selected for establishing the size scaling data in the mesopic range since this was the lowest contrast level at which the task could be easily performed and yields gap acuity thresholds of 10 min arc (as expected for mesopic vision). This contrast is also more sensitive to image degradation than the 96% or 192% contrast levels.

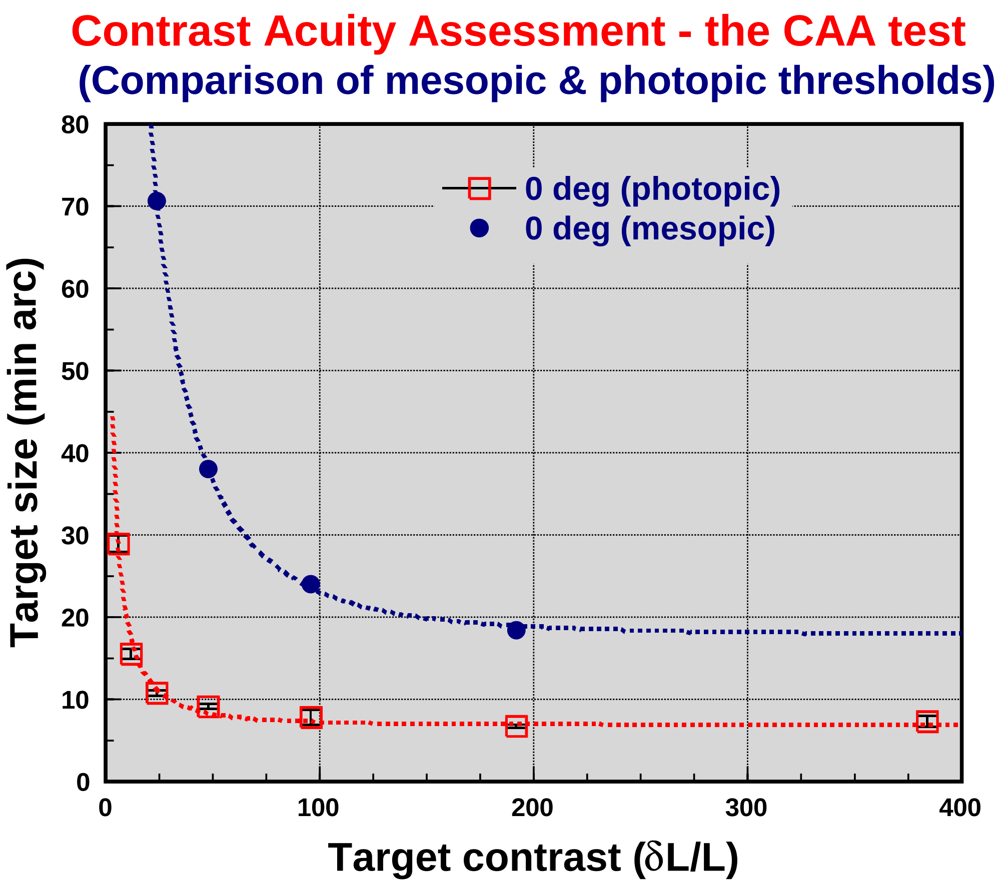


Fig.v Comparison of photopic and mesopic conditions. Foveal data showing how target size thresholds for gap orientation discrimination vary with target contrast. Mean data are shown for three normal subjects

Fig.v illustrates foveal size threshold measurements for 24% contrast (photopic light level) and 48% contrast (mesopic light level), and provides further justification for the choice of contrast levels for use in the CAA test. In order to remain sensitive to the reduction in image contrast produced by the presence of scattered light and irregular aberrations, the target contrast must be located on the steep portion of the curve, where any reduction in image contrast will translate into a large change in target size (i.e., visual acuity). For the photopic data, the 24% contrast level is located close to this part on the curve. For the mesopic light level, the 48% contrast level is likewise located on the steep portion of its curve.

5 SIZE SCALING EXPERIMENT

Having selected 24% and 48% contrast values for the photopic and mesopic light levels respectively, size-scaling data were measured for the 3 subjects. Fig.vi depicts the results for a single subject.

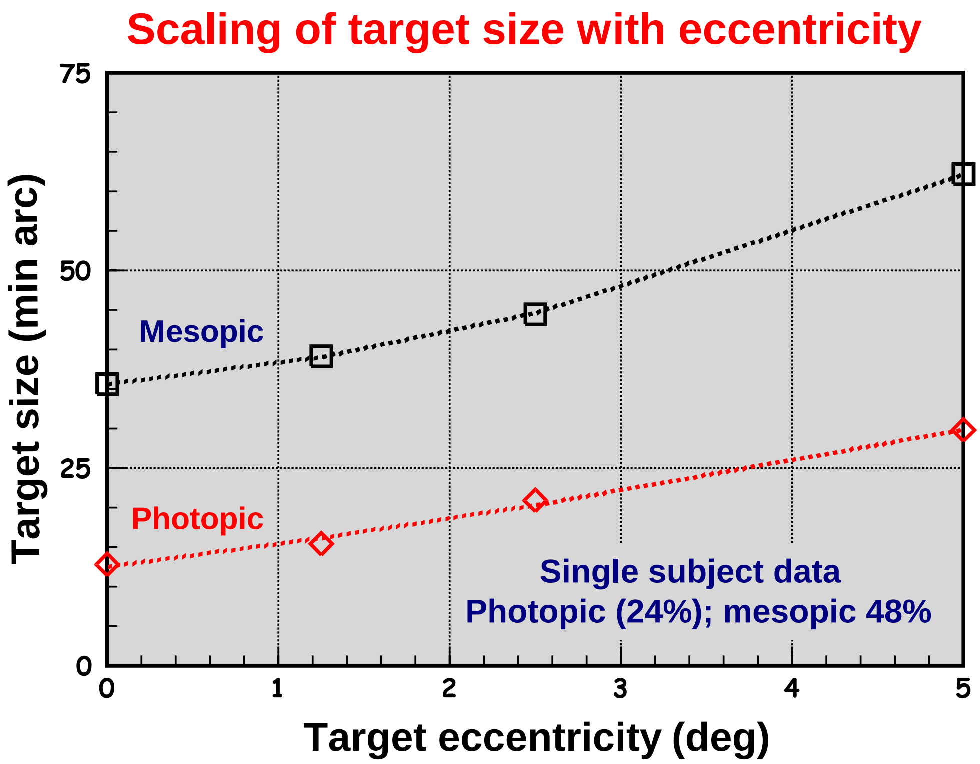


Fig.vi Size scaling data for a single subject at photopic and mesopic light levels. The target contrast was 24% (photopic) and 48% (mesopic)

The scaling of the overall target size and the gap size with location in the visual field, so as to reflect the expected retinal loss of visual acuity with eccentricity was taken for a number of reasons. By measuring contrast acuity thresholds for the smallest resolvable target size at each eccentricity (established with contrast levels of 24% or 48%), the 'standard observer' is expected to require precisely 24% and 48% contrast, independent of target eccentricity. The loss of retinal visual acuity with eccentricity has therefore been eliminated. A simple zero gradient, straight-line relationship is expected for both photopic and mesopic measurements. The results are therefore easy to interpret. Normal subjects will resolve the targets at contrasts close to that achieved by the 'standard observer' as shown in Fig.'s viii and ix. Data below or above the expected 'normal' line indicate better or worse performance, respectively.

In order to define a 'standard normal observer' for size scaling data that is representative of what can be expected of the normal population, target size thresholds were measured in a group of 62 normal subjects under both photopic (24% contrast, 12 cd m^{-2} background) and mesopic (48% contrast, 0.05 cd m^{-2} background) conditions. Each subject performed 3 repeats of each condition and the results are shown in Fig.vii. On examination of this data there was no significant difference between the size thresholds in the temporal and nasal fields therefore the results were averaged. The graph shows a wide inter-subject variability, particularly for the mesopic data, which increases with increasing target eccentricity. A small increase in minimum resolvable target size can be seen at the fovea for the mesopic data, indicating the predominance of rod receptor function under low illumination and the absence of rods in the foveal region. The average age of the normal subjects was 30.9 years.

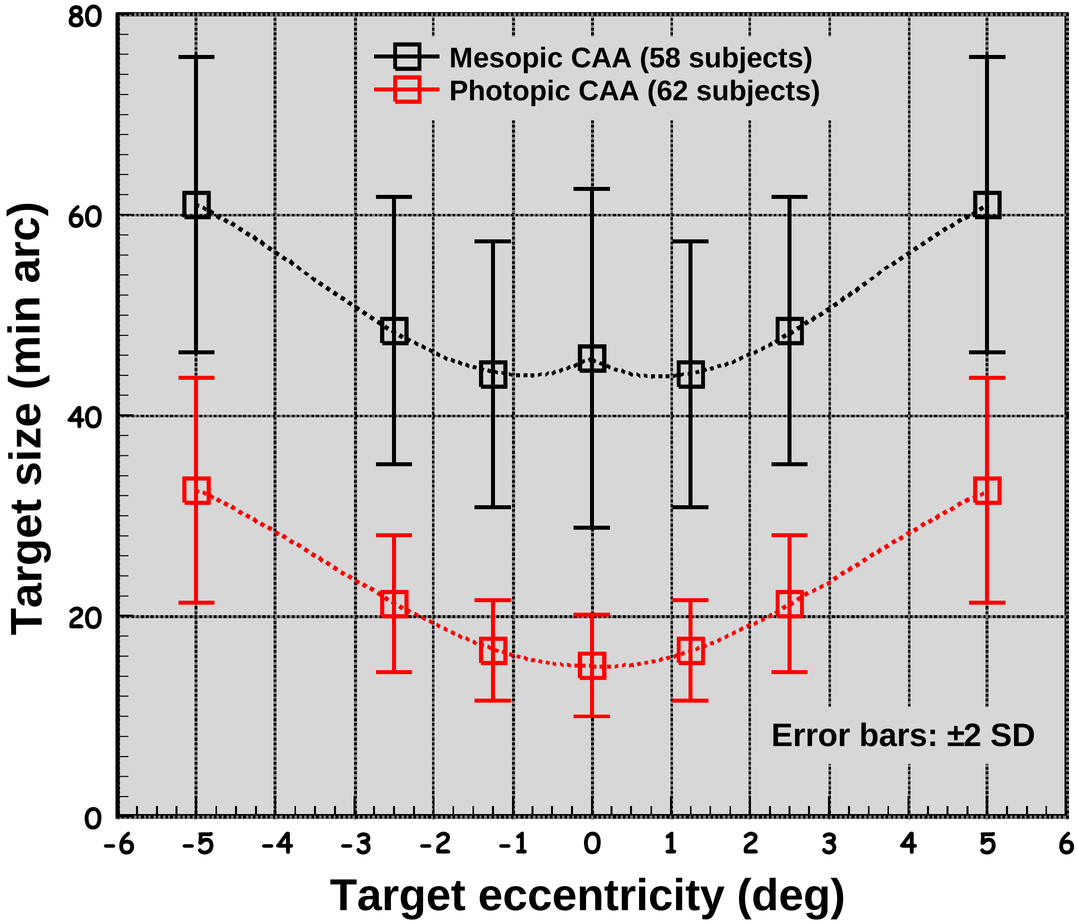
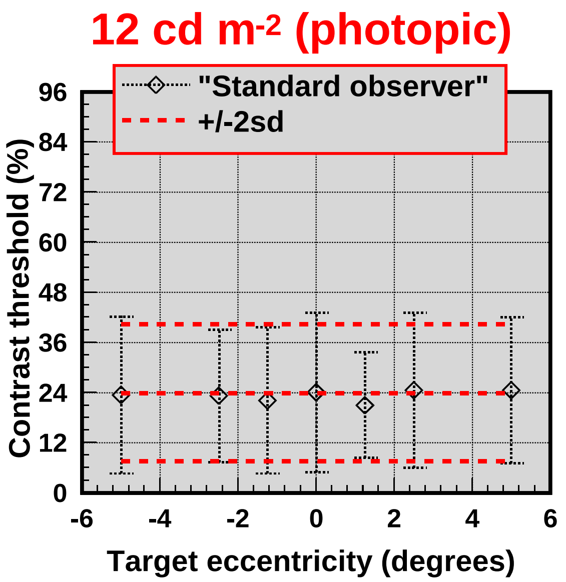


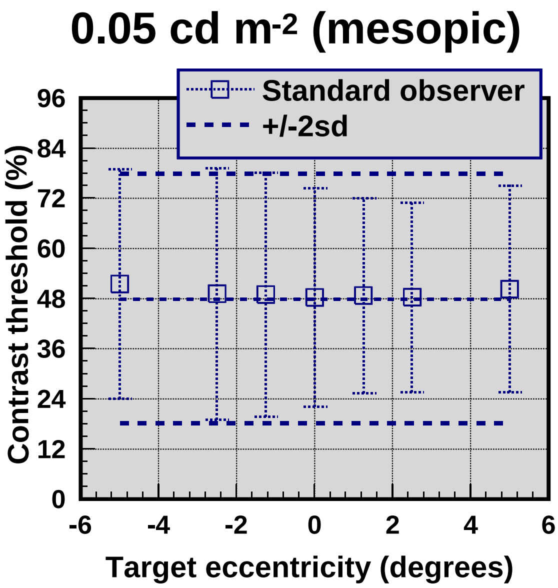
Fig.vii Target size thresholds for gap orientation discrimination as a function of eccentricity measured in the photopic (24% contrast) and the mesopic (48% contrast) range as shown in figures iii and iv. In this case, the data are the averaged results obtained in 62 normal subjects and show the expected change in visual acuity with eccentricity for the 'standard normal observer'

6 CONTRAST ACUITY ASSESSMENT TEST (CAA TEST)

The size scaling data of Fig.vii were employed in the CAA test. The process was reversed and subjects were required to measure threshold contrast for gap orientation discrimination for targets scaled for size with eccentricity according to the curves in Fig.vii. Contrast threshold measurements were repeated three times at each light level for a group of 64 normal subjects. Out of the 62 subjects that participated in the size scaling experiment, 61% were available for the CAA test. The remaining 39% were new recruits who met the control criteria. The results are expected to yield mean contrast acuity thresholds of 24% (photopic) and 48% (mesopic) at each eccentricity.

At both light levels, the average contrast values clustered around the contrast level expected for the 'standard observer', i.e. 24% under photopic conditions and 48% under mesopic conditions, (see Fig.'s viii and ix). The 2 standard deviation limits were determined by calculating the difference between the contrast value obtained and the contrast value expected for the 'standard observer'.





Figures viii and ix show that contrast threshold remains constant over the 10° field because the target is progressively increased in size (scaled) as determined for the 'standard observer' in section 5

7 EXAMINATION OF A SMALL SAMPLE OF REFRACTIVE SURGERY PATIENTS USING THE CAA TEST

A group of refractive surgery subjects were recruited which included 6 subjects who were symptomatic, reporting symptoms such as starbursts and poor visual quality, particularly at night. A proportion of subjects were also available for photopic and mesopic contrast sensitivity measurements. These measurements were carried out on the P_SCAN system (Barbur *et al.*, 1987) using the computerised City University Contrast Sensitivity test. A sinusoidal grating[6] was generated in the centre of the visual display covering a diameter of 5 deg. The uniform grey background had a luminance of either 12 cd m^{-2} or 0.05 cd m^{-2} (with the neutral density filter), and the stimulus was presented as a short flash of 250ms duration. The subject was required to fixate the centre of the screen and respond by pressing a 'yes' or 'no' button to indicate the presence or absence of grating bars. All 11 spatial frequencies, between 1.2 and 24 cycles per degree, were presented in a random order and the contrast of the grating was increased and decreased in response to the subject indicating no detection or detection of the grating pattern respectively. These measurements were carried out to provide additional information on the visual performance of the subjects investigated.

[6] Note: Sinusoidal grating: A variation in luminance across the field of view that takes the form of a sine wave. This gives the impression of a series of regular black and white bars with indistinct edges. The grating is described in terms of its spatial frequency, i.e. the number of cycles per degree where one cycle is measured from the centre of one light band to the centre of the next light band, in other words from peak to peak.

8 PRELIMINARY RESULTS IN NORMAL AND SYMPTOMATIC PATIENTS

Seven PRK and seven LASIK subjects were examined to validate the test and assess possible experimental difficulties. These data are presented in Appendix 1. These were not unbiased subgroups since they included a larger than average proportion of symptomatic subjects who were keen to be involved in the study to find out more about the cause of their symptoms. The subject numbers were also small and therefore insufficient to draw general conclusions about visual performance after refractive surgery or to establish the percentage of outliers in the normal and refractive surgery groups. Consequently, the results may not be representative of the normal refractive surgery groups and each subject must therefore be considered on an individual basis. However, two general trends were identified which are demonstrated below by 4 representative examples.

8.1 Corneal refractive surgery patients with good visual performance indicated by the CAA test

Subject KC, PRK, Asymptomatic
Age 37.
Pre-operative refraction: –2.00/–0.25x180. Treated 6 years ago, zone size 6mm, mean photopic pupil diameter 6.2mm, mesopic pupil diameter was not assess but is likely to increase by 1–2mm, cornea clear. Refraction on day of testing: +0.50/–0.25x180, giving 6/4

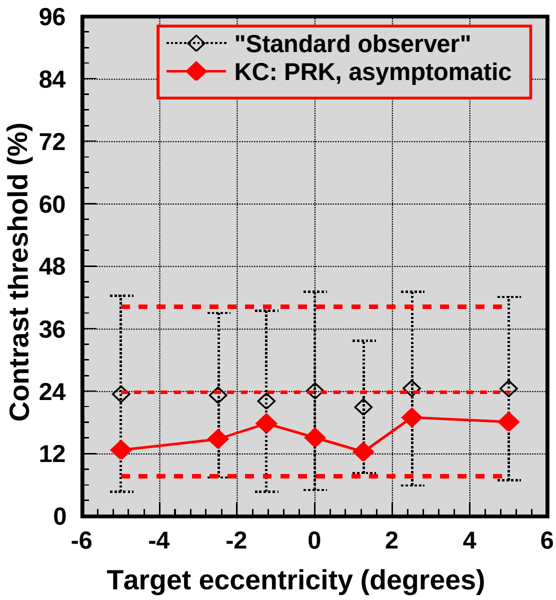


Fig.x Photopic contrast acuity results for asymptomatic subject KC. All data points fall within the normal range of ±2sd.

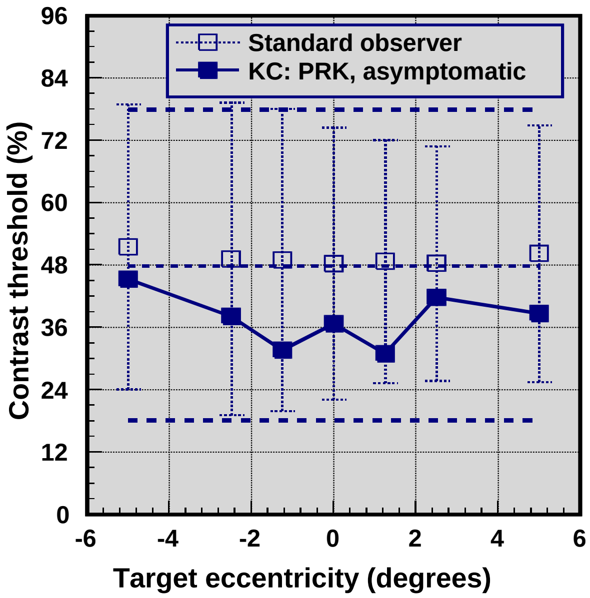


Fig.xi Mesopic contrast acuity results for asymptomatic subject KC, again showing that all data points fall within the normal range of ±2sd.

Subject KC was asymptomatic and had exceptional best-corrected visual acuity (6/4). Her contrast acuity thresholds were better than the 'standard observer' at both photopic and mesopic light levels (Fig.'s x and xi). Subject KC therefore fell within the normal range ±2sd at both light levels.

Subject IB, LASIK, Asymptomatic
Age 38. Pre-operative refraction: –8.25/–0.25x170
Treated 2 years and 7 months ago with a zone of 5x7mm.
Mean photopic pupil diameter 4.2mm, mesopic pupil diameter likely to increase by 1–2mm.
Refraction on day of testing: plano giving 6/5, cornea clear.

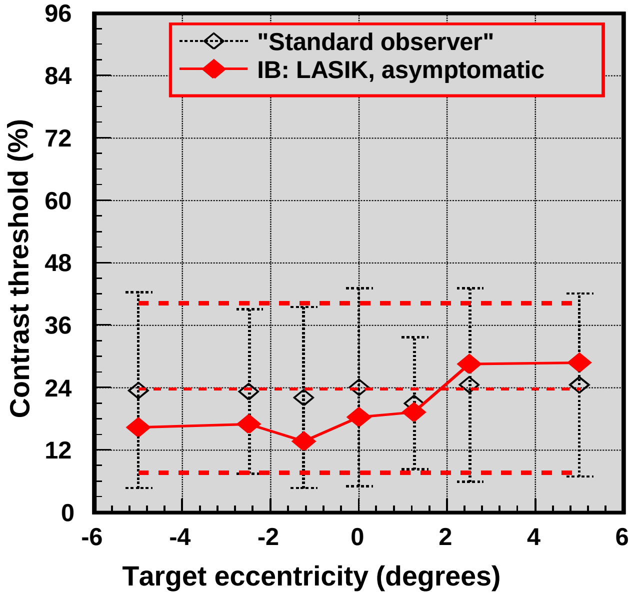


Fig.xii Photopic contrast acuity thresholds for asymptomatic subject IB with all data points falling within the normal range of ±2sd.

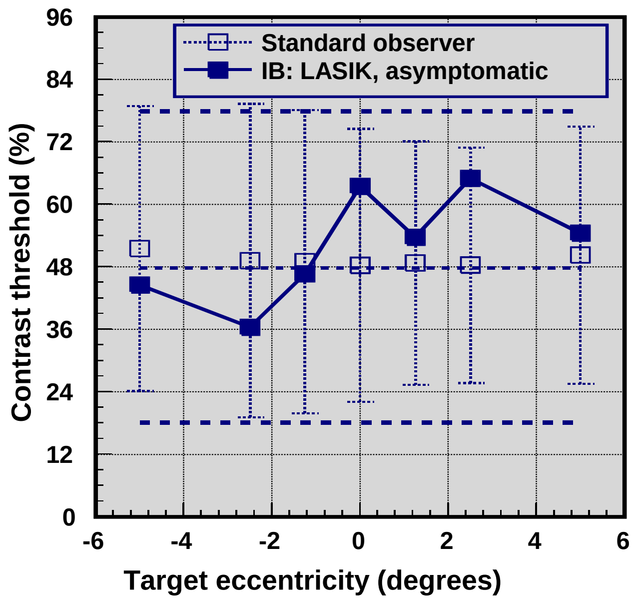


Fig.xiii Mesopic contrast acuity thresholds for asymptomatic subject IB, again showing all data points within the normal range ±2sd.

Subject IB exhibited contrast acuity thresholds that clustered around the ‘standard observer’ at both photopic and mesopic light levels (Fig.’s xii and xiii), indicating good visual performance.

8.2 **Corneal refractive surgery patients with poor visual performance indicated by the CAA test**

Subject KMcK, LASIK, Poor vision, especially at night and halos around lights
Age 35. Pre-operative refraction: –6.50DS. Treated 1 year ago, zone size 6mm, mean photopic pupil diameter 6.50mm, mean mesopic pupil diameter 7.35mm. Refraction on day of testing: +0.50/–0.25x60 giving $6/9^{+2}$, cornea clear but slightly irregular topography.

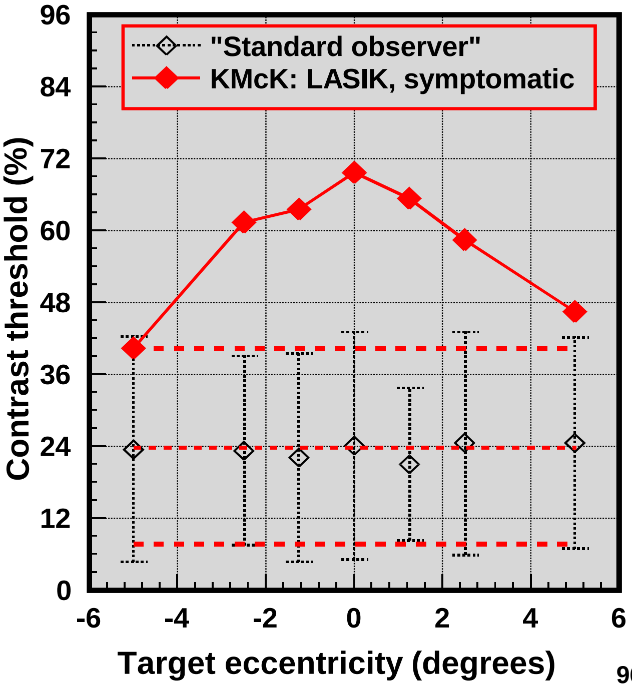


Fig.xiv Photopic contrast acuity thresholds for symptomatic subject KMcK. All data points fall outside the normal range (±2sd) with the deviation from the 'standard observer' peaking foveally. This pattern of visual loss is highly indicative of scattered light and/or aberrations as the cause of retinal image degradation.

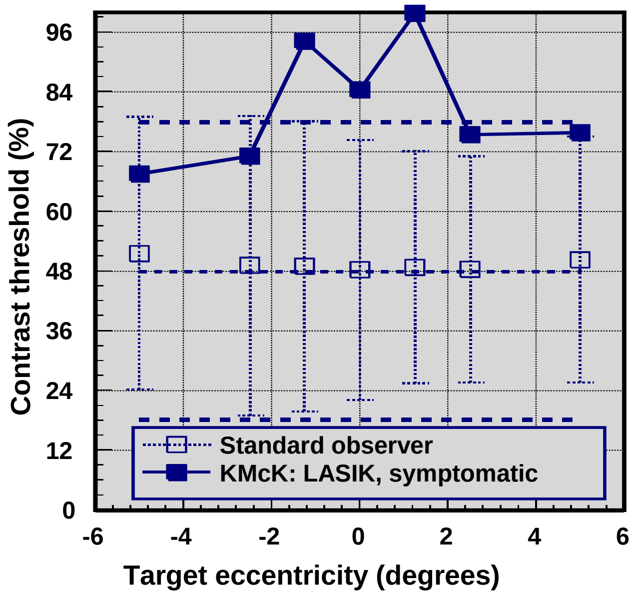


Fig.xv Mesopic contrast acuity results for symptomatic LASIK subject KMcK. Data points within the central 1.25° fall outside the normal range (±2sd) in a similar pattern to the visual loss at photopic light levels.

Subject KMcK demonstrated a significant reduction in visual performance compared to the 'standard observer'. At photopic light levels the loss was greatest centrally (Fig.xiv) as would be expected in the presence of intraocular scatter and/or aberrations. The central targets employed by the test were the smallest and generally the lowest in contrast and are therefore more susceptible to degradation. The mesopic contrast thresholds were also elevated (Fig.xv) particularly close to the centre of the field. This reduction in visual performance is most likely related to the presence of irregular aberrations caused by an irregular ablated area and a significant mismatch between the pupil and the ablation zone at both light levels.

Subject LS, PRK, night vision not as clear since surgery
Age 35. Pre-operative refraction: –3.75DS
Treated 7 years ago, zone size 6.5mm, mean photopic pupil diameter 5.8mm.
Mesopic pupil diameter likely to be 1–2mm larger.
Refraction on day of testing: –1.00DS giving 6/5, cornea clear.

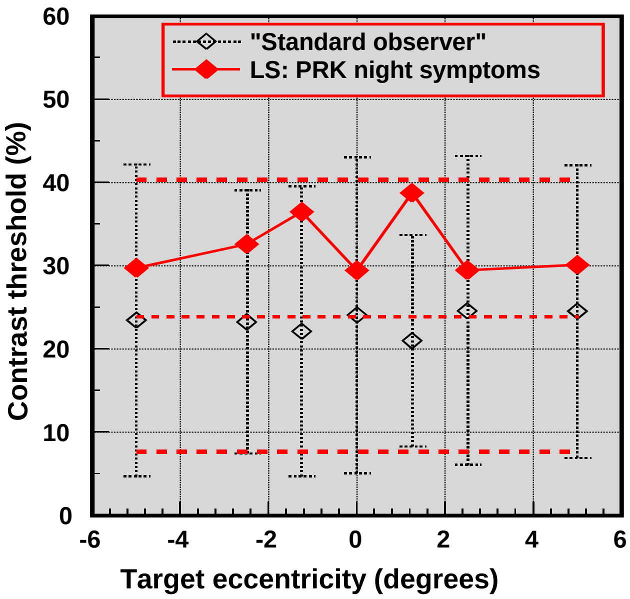
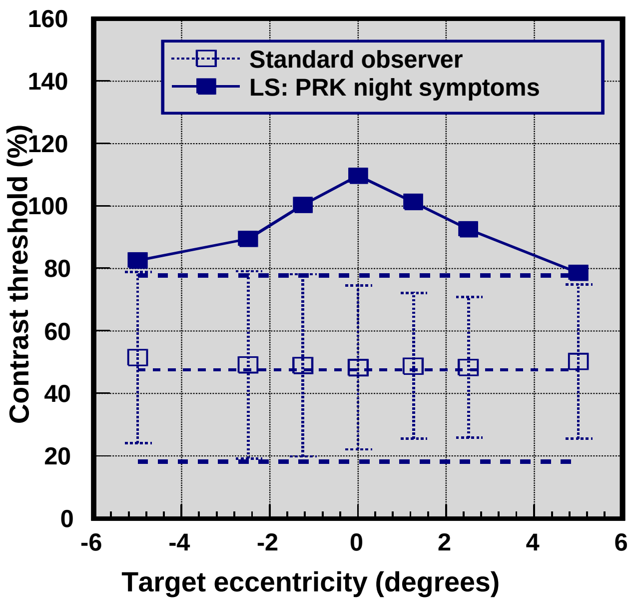


Fig.xvi Photopic contrast acuity results for symptomatic PRK subject LS. The data indicate a level of visual performance below the 'standard observer', however all data points fall within the normal range ±2sd.

Fig.xvii Mesopic contrast acuity thresholds for symptomatic PRK subject LS. All data points fell outside the normal range (±2sd). The greatest disparity between the data and the 'standard observer' occurred foveally, similar to the pattern of visual loss seen in subject KMcK. This indicates the presence of significant scatter and/or aberrations under mesopic conditions, related to the increase in pupil diameter.



Subject LS was asymptomatic under daylight conditions, exhibited a normal visual acuity of 6/5 and photopic contrast thresholds within the normal range (Fig. xvi). Under mesopic conditions, when pupil diameters tend to enlarge, LS suffered an increase in contrast thresholds, particularly within the central 2.5° (Fig.xvii). This strongly implicates an increase in either intraocular light scatter and/or irregular aberrations, both of which are known to have a more detrimental effect on the smaller targets found centrally. It is well known that both scattered light and aberrations increase at larger pupil sizes. In addition, the absorption efficiency of the aberrated, off-axis rays is increased due to the significant reduction in the Stiles-Crawford effect in the mesopic range. To summarise, this subject was identified as having poor visual performance because although she performed within the normal range at the photopic light level she had difficulty with the CAA test at the mesopic light level.

9 DISCUSSION

The data from a total of fourteen refractive surgery subjects are presented in Appendix 1. This was not a random sample since a high proportion of symptomatic patients volunteered for the study. Consequently, the results from this group are not fully representative of the LASIK and PRK refractive surgery groups. An estimate of the percentage of refractive surgery patients who fall outside the normal range requires an unbiased and much larger sample size.

The results show examples of the 2 most commonly encountered outcomes of the CAA test. The majority of asymptomatic subjects produced similar contrast thresholds, clustering around the straight-line data of the 'standard observer' at both light levels (see Fig.'s x, xi, xii, xiii).

In the majority of subjects who performed poorly on the CAA test, the pattern of visual loss took the same form as subjects KMcK and LS; the contrast acuity thresholds tended to peak centrally, indicating greater image degradation over the central ±2.5° (see Fig.'s xiv, xv, xvi, xvii). The corresponding contrast sensitivity data tended to show a reduction in sensitivity at low and medium spatial frequencies[7] (see Appendix 1). These results suggest that the prime cause of reduced visual performance was either an increase in intraocular light scatter and/or an increase in irregular aberrations following surgery. Both would similarly affect the retinal image by causing a reduction in image contrast, which would be of greater significance for the smaller, central targets due to the loss of critical image contours. The results of previous work for the CAA suggested that light scatter was not a major factor after the first 3–4 months post-surgery, however, small angle scatter cannot be measured easily and may cause a reduction in visual performance when smaller size targets are involved. Nevertheless, an increase in irregular aberrations[8] is the most likely reason for the observed reduction in visual performance in these subjects. A number of studies have reported an increase in irregular aberrations under dilated pupil conditions, following corneal refractive surgery (Martinez *et al.*, 1996; Seiler *et al.*, 2000). This is because the paraxial light rays that pass through the mid-peripheral

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[7] Note: Spatial frequency refers to the width of the bars in a sinusoidal grating. The units of spatial frequency are cycles per degree where a cycle is measured on the luminance profile from one peak to the next and the angle in degrees refers to the angle subtended by the target at the eye.

[8] Note: Aberrations occur when light passes through an optical surface that differs from the ideal, such as the cornea or lens. Regular aberrations can be quantified mathematically and have been clearly defined. Irregular aberrations are often seen after refractive surgery but can not easily be categorised.

cornea contribute to the retinal image when the pupil is dilated. Oliver et al. (Oliver *et al.*, 1997) reported a general trend towards increasing irregular aberrations, most similar to spherical aberration[9] and coma[10] at 1 year post-surgery, although a few eyes demonstrated a decrease in such aberrations.

Three asymptomatic subjects performed poorly at one or both light levels, stressing the need to perform a suitable visual assessment of all post-refractive surgery patients regardless of their lack of symptoms. Such assessment is critical when attempting to determine the suitability of an individual to safely complete a vision critical task but is also useful in properly determining the success of a particular procedure.

One subject (LS) performed poorly on the test at the mesopic light level only (see Fig.xvii) emphasising the importance of examining refractive surgery patients under both photopic and mesopic conditions. Visual degradation may only be revealed when the conditions allow full pupil dilation such that the pupil diameter exceeds the ablated zone.

10 CONCLUSIONS

Having established the range of results within the normal population, the Contrast Acuity Assessment (CAA) test provides a quick and easy tool for examining ocular function in a range of subjects. By plotting the results for a particular subject against the established normal data, it is immediately obvious where the results fall compared to the normal range at both photopic and mesopic light levels. Whether a subject suffers from increased intraocular light scatter, increased irregular aberrations or compromised retinal function, the outcome is the same – a higher than average target contrast is required in order to resolve the gap at a particular eccentricity.

The CAA test can be used to identify those refractive surgery subjects that suffer a significant degradation in visual performance, even when they are not symptomatic. These subjects could undergo further investigation to determine the cause of the visual degradation, by measuring intraocular scatter, contrast sensitivity, whole eye aberrations and retinal function, for example.

[9] Note: Spherical aberration is a form of regular aberration in which the light rays passing through the mid-periphery of the cornea and pupil (off-axis rays) are refracted more or less than the on-axis rays. They focus in front or behind the retinal image respectively and result in image degradation.

[10] Note: Coma is a regular aberration in which light rays passing obliquely through the optical system are deviated to form a comet-shaped image on the retina. This results in retinal image degradation.

Appendix 1

Asymptomatic Subjects
Subject CM, PRK, Asymptomatic
Age 42, Pre-operative refractive error: –2.00D. Treated 13 months ago, zone of 6.5mm, mean photopic pupil diameter 4.4mm. Refraction on day of testing: +0.50D, giving 6/5, cornea clear.

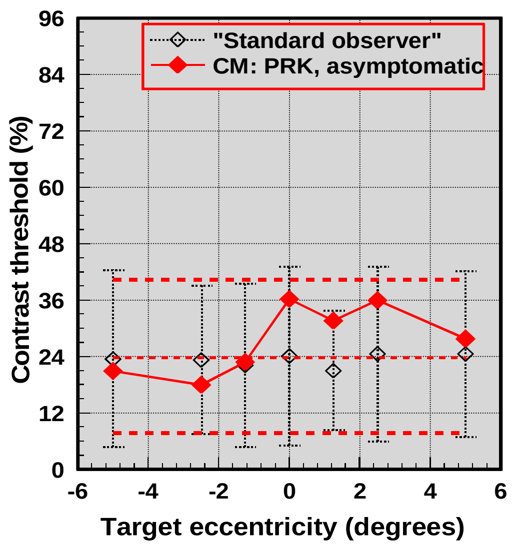


Fig.1 Photopic contrast acuity results for asymptomatic subject CM. All data points fall within the normal range ±2sd

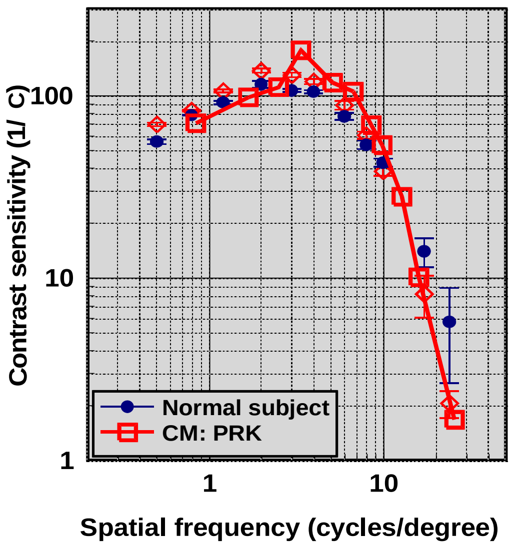


Fig.2 Photopic contrast sensitivity results for subject CM, indicating normal contrast sensitivity.

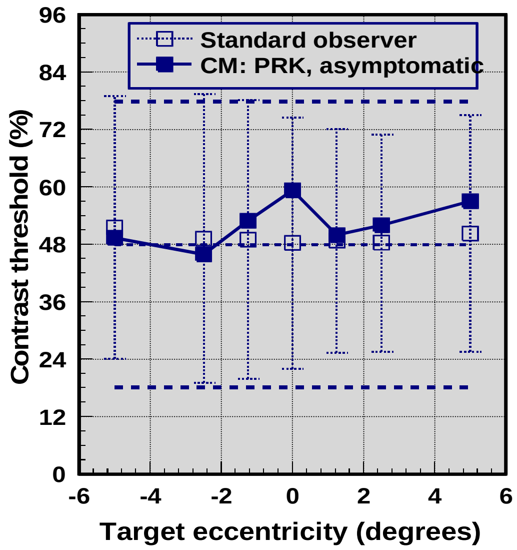


Fig.3 Mesopic contrast acuity results for asymptomatic subject CM. All data points fall within the normal range ±2sd.

Subject CM performed well in the CAA test at both photopic and mesopic light levels with all data points falling within the normal range ±2sd (Fig. 1 and 3). This is as expected for an asymptomatic patient. Normal visual function was confirmed by the agreement between the photopic contrast acuity and normal contrast sensitivity data (Fig.2.) No mesopic contrast sensitivity data was available for this subject.

Subject DO, PRK, Asymptomatic

Age 40, Pre-operative refractive error: –0.50/–1.75x180
Treated 25 days ago, zone size unknown, mean pupil diameter unknown.
Refraction on day of testing: +1.00/–0.75x170 giving 6/5^{-3} corneal haze grade 1.

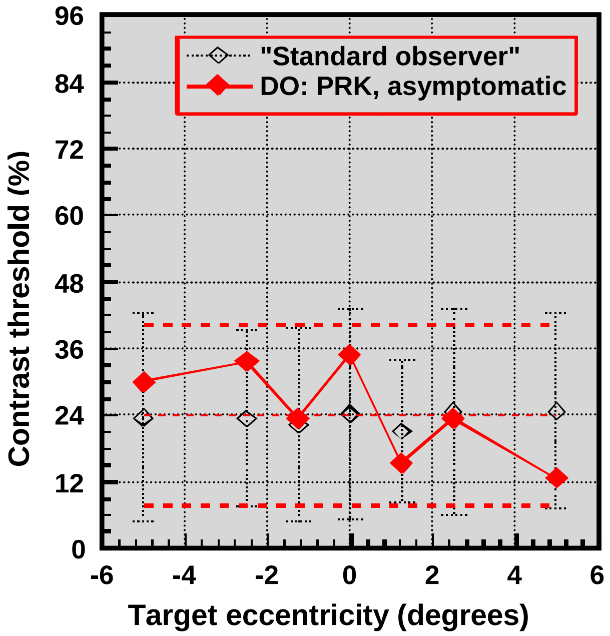


Fig.4 Photopic contrast acuity results for asymptomatic subject DO. All data points fall within the normal range ±2sd.

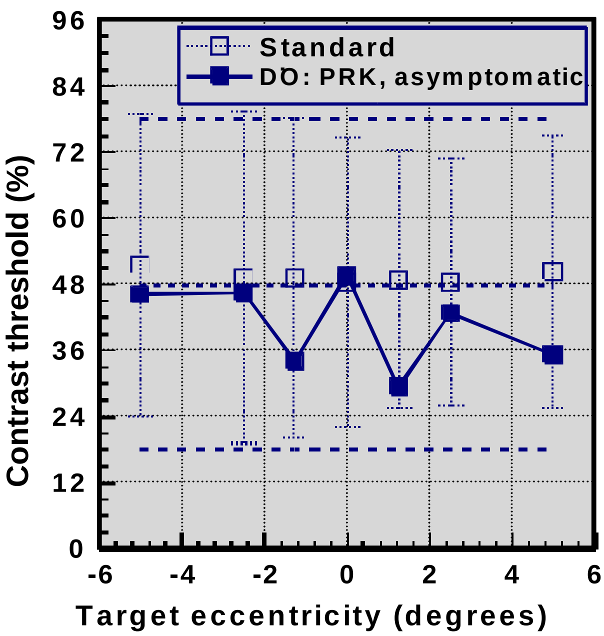


Fig.5 Mesopic contrast acuity results for asymptomatic subject DO. All data points fall within the normal range ±2sd.

Examination of Fig. 4 and 5 indicate that the contrast acuity results were within normal limits at both light levels ±2sd. This was despite the presence of grade 1 corneal haze related to her short follow-up time. The data reflect the asymptomatic status of the patient. No contrast sensitivity data was available for this subject.

Subject JQ, LASIK, Asymptomatic

Age 35, pre-operative refraction: –5.00/–0.75x5, treated 1 year 5 months ago with 6.5mm zone, mean photopic pupil diameter 6.6mm. Refraction on day of testing: +0.25/–0.25x10, 6/5, cornea clear.

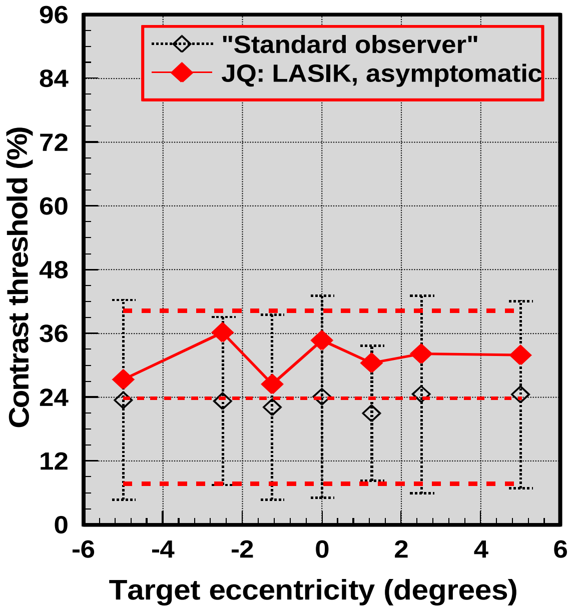
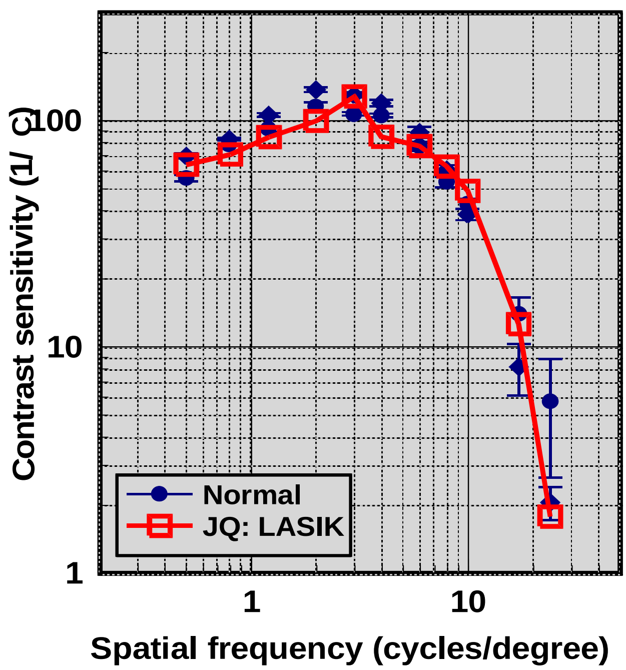


Fig.6 Photopic contrast acuity thresholds for asymptomatic subject JQ. All data points fall within the normal range ±2sd.

Fig.7 Photopic contrast sensitivity data for asymptomatic subject JQ indicating a normal contrast sensitivity function.



Subject JQ was asymptomatic and demonstrated photopic contrast acuity thresholds within the normal range (Fig. 6) concurrent with his best-corrected acuity of 6/5 and a normal photopic contrast sensitivity function (Fig. 7).

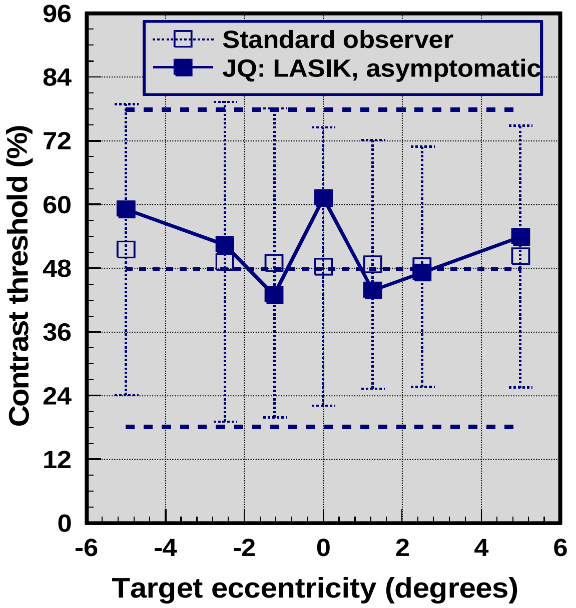
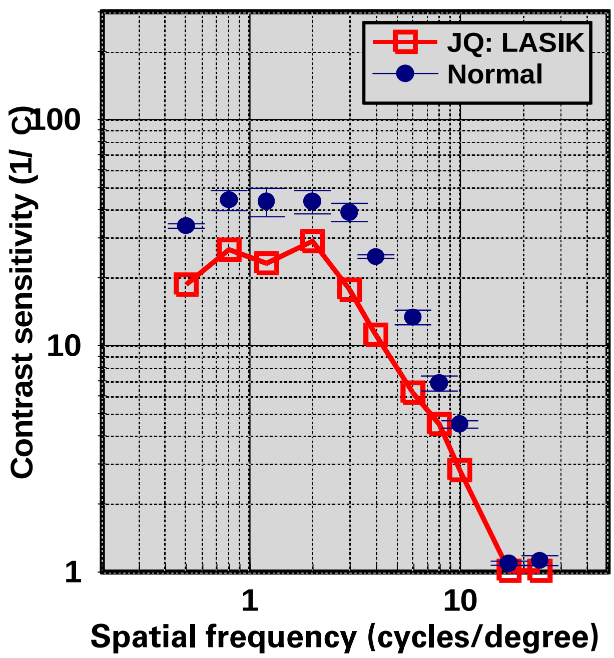


Fig.8 Mesopic contrast acuity thresholds for asymptomatic subject JQ illustrating the clustering of data points around the 'standard observer'.

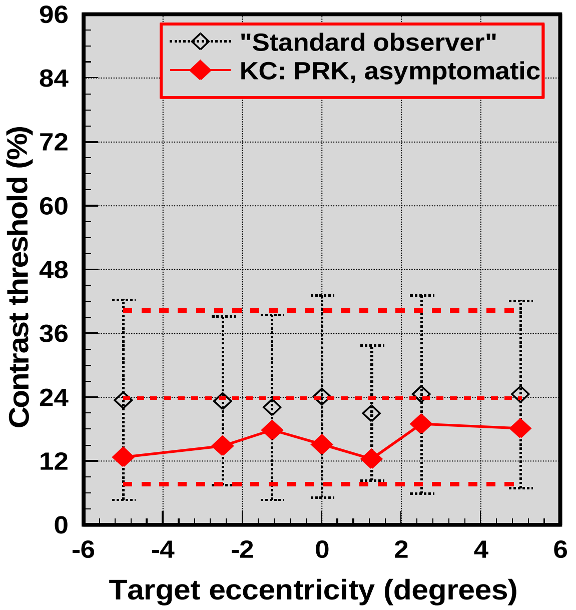
Fig.9 Mesopic contrast sensitivity function for subject JQ indicating a slight loss at low and medium spatial frequencies



At mesopic light levels, the contrast acuity thresholds were also within the normal range (Fig. 8) indicating that subject JC performed well at both light levels. However, the mesopic contrast sensitivity data indicated a slight loss of sensitivity at low and medium spatial frequencies (Fig. 9). This is likely to be related to a mis-match between the pupil and treatment zone since the pupil under mesopic conditions will be greater than the 6.6mm diameter measured under photopic conditions. The discrepancy between the contrast sensitivity data and contrast acuity data at the mesopic level demonstrates why an assessment of contrast sensitivity may not always be the best method to examine visual performance. It shows the importance of designing an assessment method attuned to the specific task involved.

Subject KC, PRK, Asymptomatic

Age 37, Pre-operative refraction: –2.00/–0.25x180. Treated 6 years ago, zone size 6mm, mean photopic pupil diameter 6.2mm. Refraction on day of testing: +0.50/–0.25x180, giving 6/4, cornea clear.



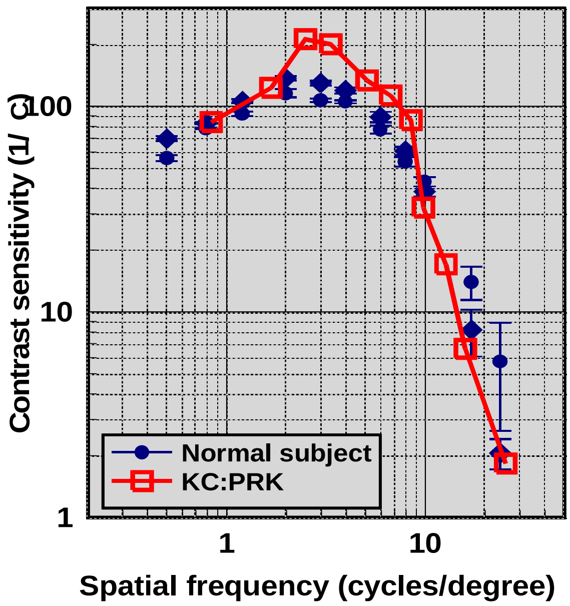


Fig.10 Photopic contrast acuity data for asymptomatic subject KC. This subject performed better than the 'standard observer' across the field.

Fig.11 Photopic contrast sensitivity data for PRK subject KC demonstrating a normal function at this light level.

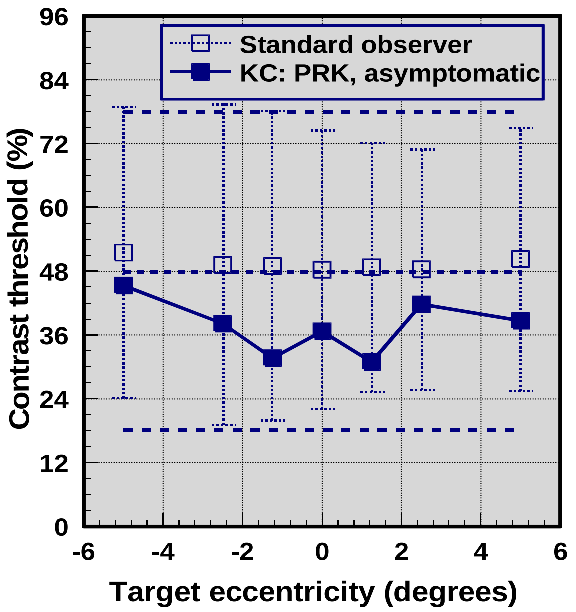
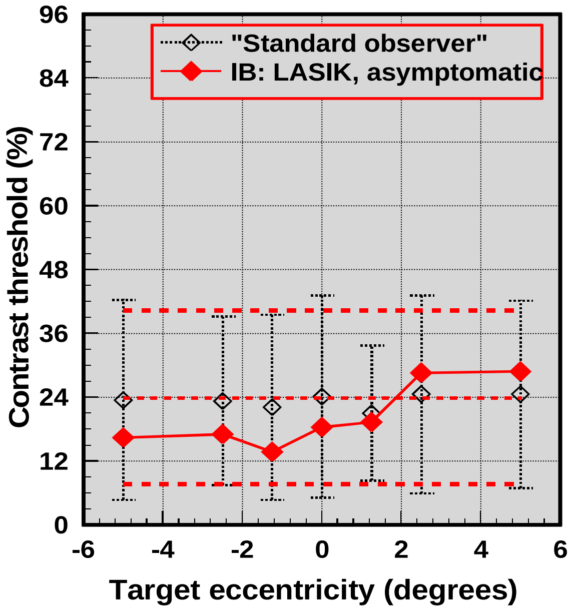


Fig.12 Mesopic contrast acuity data for asymptomatic subject KC. As for the photopic results, this subject performs better than the 'standard observer' across the field with all points falling within the normal range ±2sd.

Subject KC was asymptomatic and had exceptional best-corrected visual acuity (6/4). Her contrast acuity thresholds were better than the standard observer at both light levels (Fig.10 & 12). These findings correspond to her photopic contrast sensitivity function (Fig. 11). No mesopic contrast sensitivity data was available for this subject.

Subject IB, LASIK, Asymptomatic

Age 38, Pre-operative refraction: –8.25/–0.25x170. Treated 2 years and 7 months ago with a zone of 5x7mm, mean photopic pupil diameter 4.2mm. Refraction on day of testing: Plano giving 6/5, cornea clear.



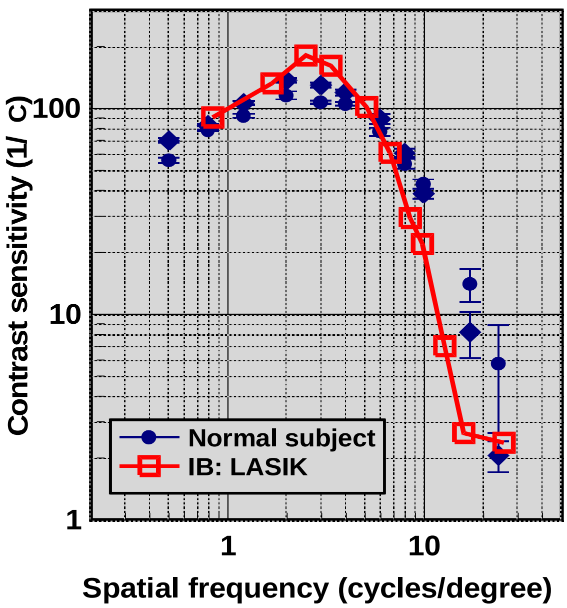


Fig.13 Photopic contrast acuity threshold for asymptomatic LASIK subject IB. All points fall within the normal range ±2sd.

Fig.14 Photopic contrast sensitivity data for subject IB, indicating normal sensitivity.

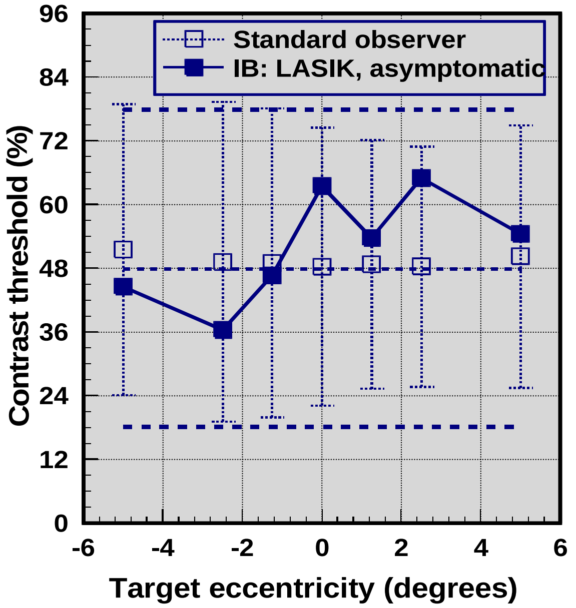


Fig.15 Mesopic contrast acuity results for asymptomatic LASIK subject IB. As for the photopic results, all data points fall within the normal range ±2sd.

Fig.13 & 15 indicate that the contrast acuity thresholds for subject IB were within the normal range and constitute good performance on the CAA test. Normal visual performance was confirmed by the agreement between the photopic contrast acuity data and the photopic contrast sensitivity result, (Fig.14). No mesopic contrast sensitivity data was available for this subject.

Symptomatic Subjects

Subject GA, PRK, mild glare at night

Age 35, Pre-operative refraction: –5.25/–0.25x180. Treated 6 years ago, zone size 5.5mm, mean photopic pupil diameter 6.3mm. Refraction on day of testing: –0.50DS giving 6/6, cornea clear.

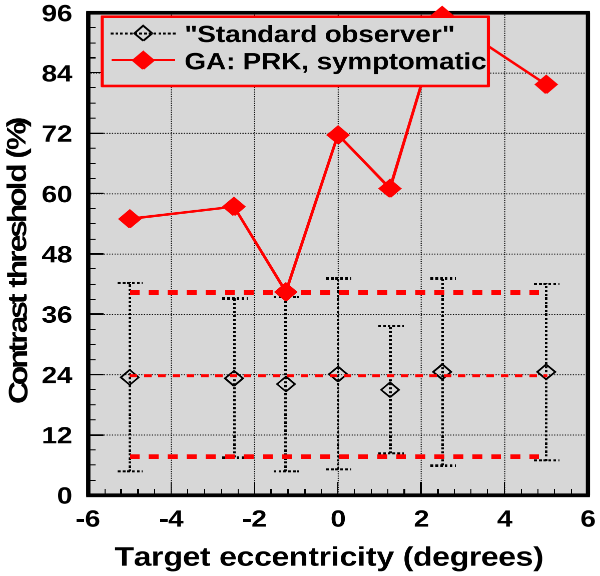


Fig.16 Photopic contrast acuity data for symptomatic subject GA. All points fall outside the normal range indicating poor performance at this light level.

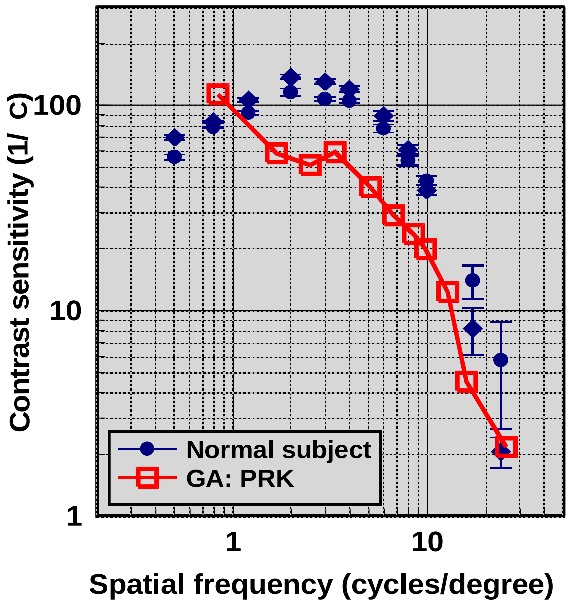


Fig.17 Photopic contrast sensitivity data for subject GA, indicating a loss of sensitivity at medium and high spatial frequencies.

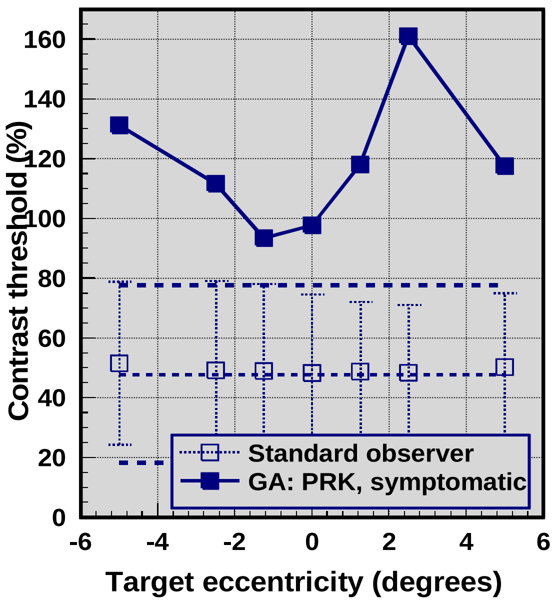


Fig.18 Mesopic contrast acuity data for symptomatic subject GA. All points fall outside the normal range indicating poor performance on the CAA test at this light level.

The contrast acuity thresholds at both photopic and mesopic levels (Fig.16 & 18) were rather irregular and consistently fell outside the limits for the standard observer ±2sd. This corresponds to the measured reduction in photopic contrast sensitivity (Fig.17) although the subject was not aware of a reduction in visual performance at this light level. The patient reported poor night vision relating to the elevated contrast thresholds under mesopic conditions but mesopic contrast sensitivity data was not available. The reduction in vision is likely to be related to the presence of extreme irregular aberrations caused by the pupil being larger than the treatment zone at both light levels. This could also explain the significant variability across the field. However, the asymmetry of the contrast acuity results means that abnormal retinal function can not be ruled out.

Subject GC, LASIK, slightly reduced night vision

Age 44, Pre-operative refractive error: –4.00/–1.00x20. Treated 7 months ago, zone 6mm, mean pupil diameter unknown. Refraction on day of testing: +0.50/–0.25x130, giving 6/6, cornea clear.

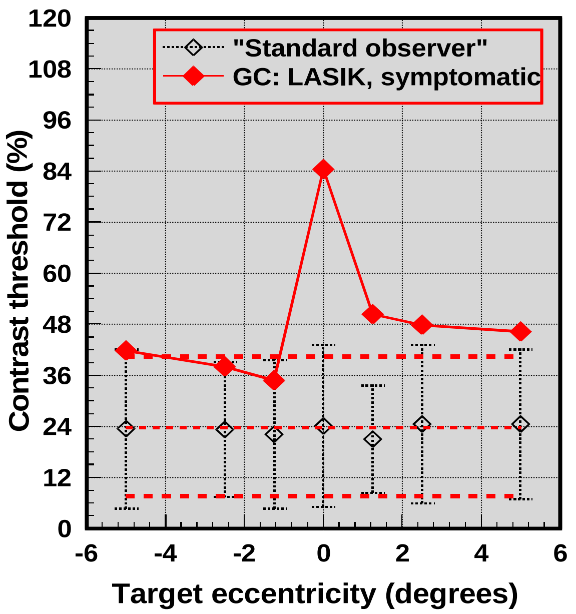
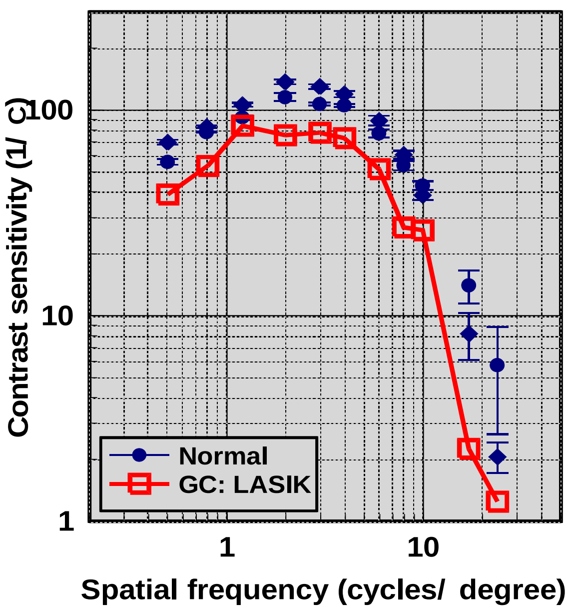


Fig.19 Photopic contrast acuity results for symptomatic subject GC. The majority of points fall just outside the normal range indicating poor performance for the CAA test under photopic conditions. A large increase in contrast threshold is seen foveally suggesting the presence of scattered light and/or aberrations.

Fig.20 Photopic contrast sensitivity results for subject GC showing a very slight reduction in sensitivity across the range of spatial frequencies.



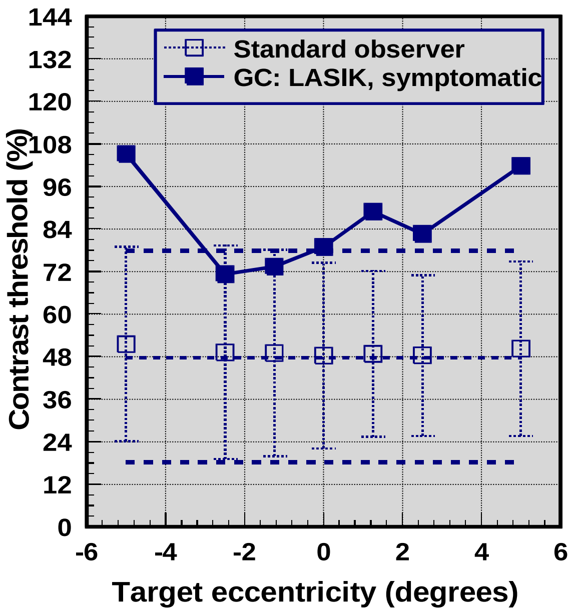


Fig.21 Mesopic contrast acuity data for symptomatic subject GC. The majority of points fall outside the normal range indicating poor performance for the CAA test at this light level. The greatest discrepancy between subject GC and the 'standard observer' occurs towards the edge of the field suggesting that retinal factors play a part in the outcome.

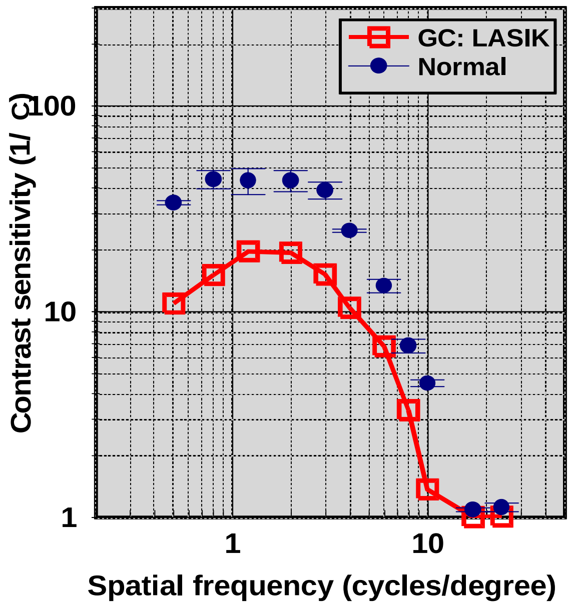
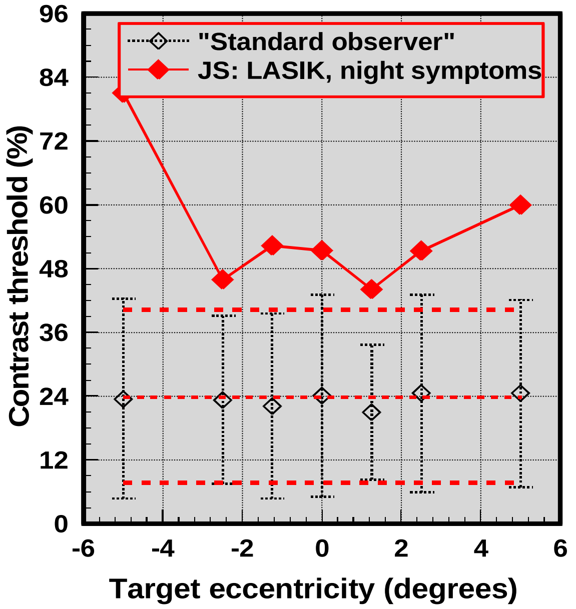


Fig.22 Mesopic contrast sensitivity data for subject GC, indicating a significant loss of sensitivity, particularly at low and mid spatial frequencies.

Subject GC reported only mild difficulty seeing under low illumination and felt that he had adapted over time such that he was rarely aware of the visual loss. His best-corrected visual acuity was average, (6/6), but the photopic contrast acuity thresholds suggested a slight loss of visual performance, particularly at the fovea (Fig.19). This loss corresponded to a very slight depression in the photopic contrast sensitivity function across the range of spatial frequencies (Fig.20). Under mesopic conditions the visual loss was more significant as expected from his symptoms with the loss was greatest beyond 2.5°. The mesopic contrast acuity thresholds fell outside the normal range (±2sd) for all but a few central eccentricities (Fig.21), and the mesopic contrast sensitivity function indicated a significant loss of sensitivity, particularly at low and medium spatial frequencies (Fig. 22). The pattern of loss under mesopic conditions is not characteristic of the visual loss produced by scatter and aberrations as seen under photopic conditions, (Fig.19). The poorer performance in the paracentral field could be explained by a non-standard rod receptor distribution. Rods begin to predominate at this eccentricity and if their pacing was slightly greater than average, the size scaling produced for the 'standard observer' would be incorrect. If this was the case, the subject would require a larger stimulus in order to resolve the target at the 48% contrast level or for the standard scaled size, a higher contrast would be required as indicated in Fig.21.

Subject JS, LASIK, slight halo and poor contrast at night

Age 45, Pre-operative refraction: –4.50DS. Treated 11 months ago, zone size 6mm, mean photopic pupil diameter 7mm. Refraction on day of testing: –0.25DS giving $6/6^{-1}$, cornea clear.



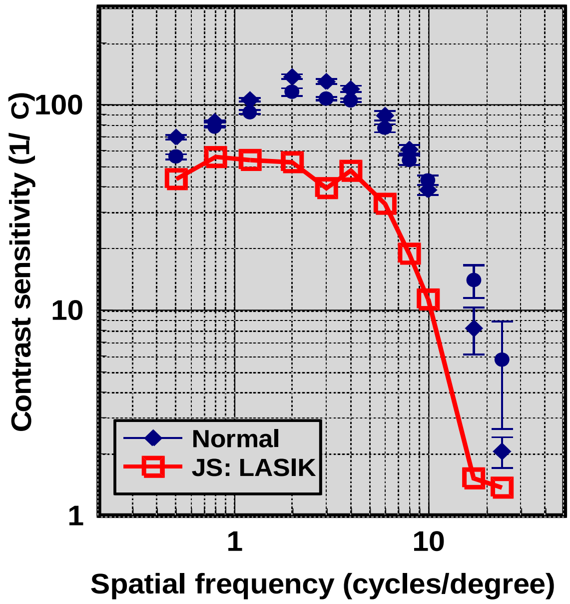
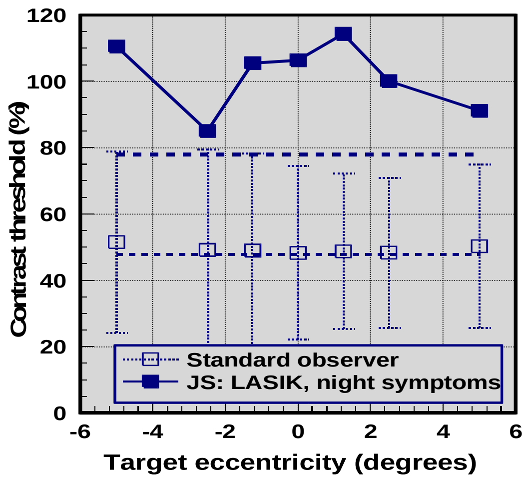


Fig.23 Photopic contrast acuity data for symptomatic subject JS. All data points fall outside the normal range (±2sd), particularly at 5°. These data indicate poor performance for the CAA test under photopic conditions

Fig.24 Photopic contrast sensitivity data for subject JS indicating a slight reduction in sensitivity across the range of spatial frequencies.



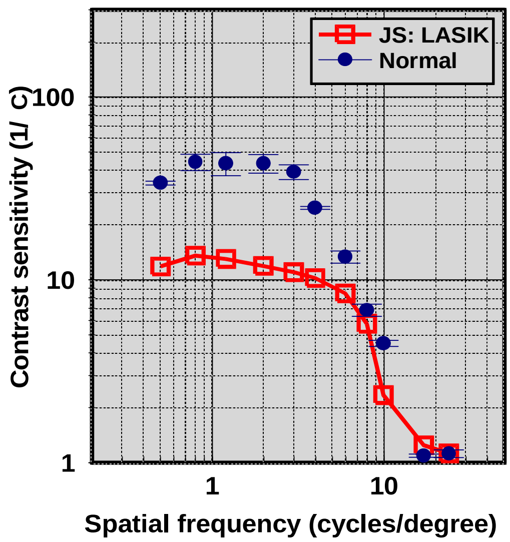
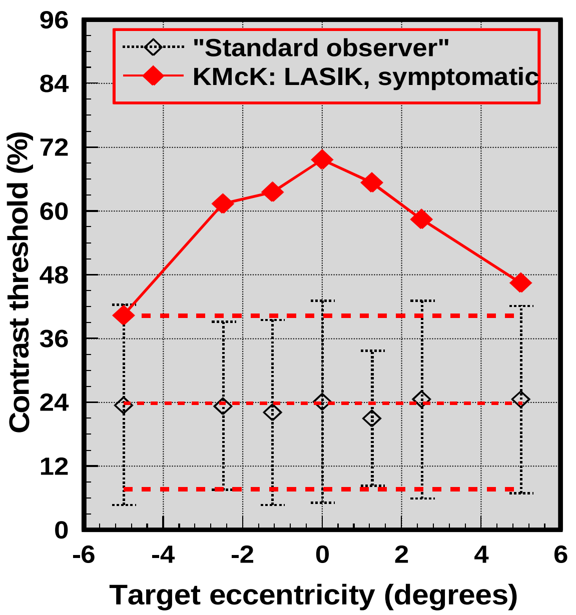


Fig.25 Mesopic contrast acuity data for symptomatic subject JS. All data points fall outside the normal range ±2sd, indicating poor performance at this light level.

Fig.26 Mesopic contrast sensitivity data for subject JS demonstrating a loss of sensitivity particularly at low and mid spatial frequencies.

Subject JS complained of poor vision and a slight halo around lights at night. He was asymptomatic under daylight conditions. The data indicate a loss of visual performance at both light levels but particularly under mesopic conditions in agreement with his symptoms. The photopic contrast thresholds were particularly elevated beyond 2.5°, (Fig.23) suggesting the possibility of a larger than average cone receptor spacing beyond the central retina. The photopic contrast sensitivity function was also slightly depressed (Fig.24). The elevated mesopic contrast thresholds (Fig.25) relate to the more significantly reduced mesopic contrast sensitivity, particularly at low and medium spatial frequencies (Fig.26). It is not surprising that the patient achieved $6/6^{-1}$ high contrast acuity since the contrast sensitivity was normal at high spatial frequencies.

Subject KMcK, LASIK, Poor vision, especially at night and halos around lights
Age 35, Pre-operative refraction: –6.50DS. Treated 1 year ago, zone size 6mm, mean photopic pupil diameter 6.50mm. Mean mesopic pupil diameter 7.35mm. Refraction on day of testing: +0.50/–0.25x60 giving $6/9^{+2}$, cornea clear but slightly irregular topography.



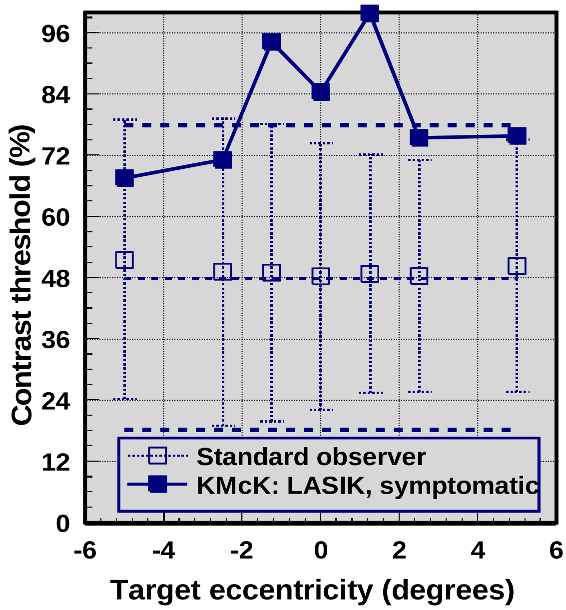


Fig.27 Photopic contrast acuity thresholds for symptomatic subject KMcK. All data points fell outside the normal range ±2sd indicating a poor visual performance at this light level. The degree of discrepancy between the data and the 'standard observer' was greatest for more central targets, implicating scattered light and/or aberrations.

Fig.28 Mesopic contrast acuity data for symptomatic subject KMcK. The central three data points fell outside the normal range ±2sd in a similar pattern to the photopic data

Subject KMcK demonstrated a significant reduction in visual performance compared to the standard observer. At photopic light levels the loss was greatest centrally (Fig.27), as would be expected in the presence of intraocular scatter and/or aberrations. The central targets employed by the test were the smallest and generally the lowest in contrast and are therefore more susceptible to degradation. The central peak also corresponds to a below average level of best-corrected visual acuity ($6/9^{+2}$). The mesopic contrast thresholds were also elevated (Fig.28) particularly close to the centre of the field. This reduction in visual performance is most likely related to the presence of irregular aberrations caused by an irregular ablated area and a significant mis-match between the pupil and the ablation zone at both light levels. No contrast sensitivity data was available for this subject.

Subject LS, PRK, night driving not as clear since surgery

Age 35, Pre-operative refraction: –3.75DS. Treated 7 years ago, zone size 6.5mm, mean photopic pupil diameter 5.8mm. Refraction on day of testing: –1.00DS giving 6/5, cornea clear

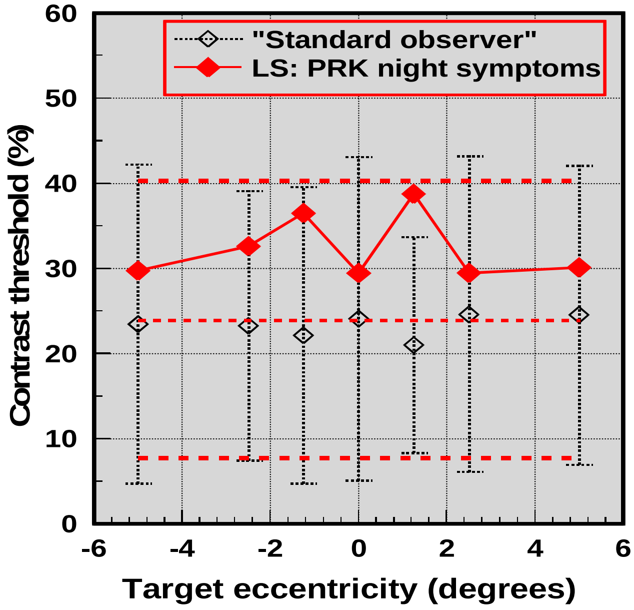


Fig.29 Photopic contrast acuity data for symptomatic subject LS. All data points fall within the normal range under photopic conditions.

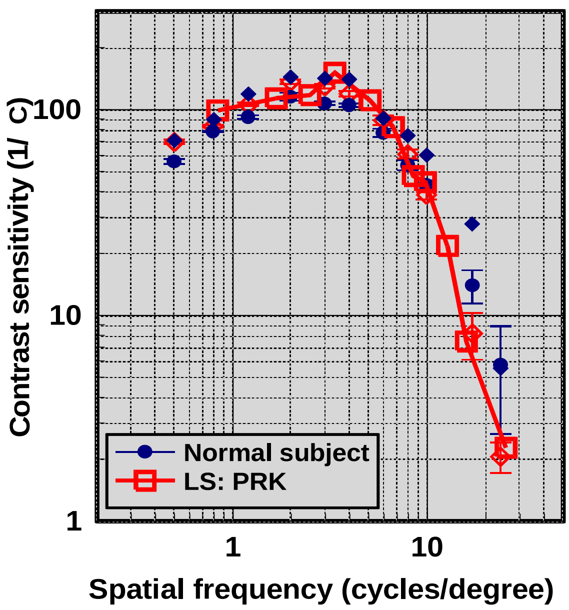


Fig.30 Photopic contrast sensitivity data for subject LS indicating a normal function under photopic conditions

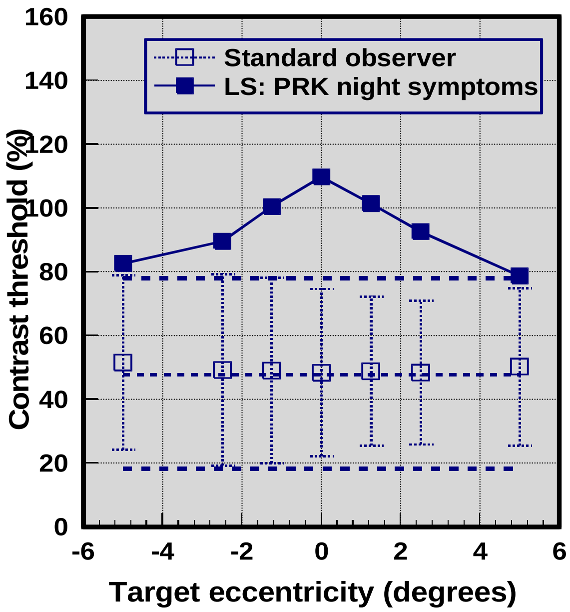


Fig.32 Mesopic contrast acuity data for symptomatic subject LS. All data points fall outside the normal range indicating poor performance at this light level. This greatest discrepancy from the 'standard observer' occurred foveally.

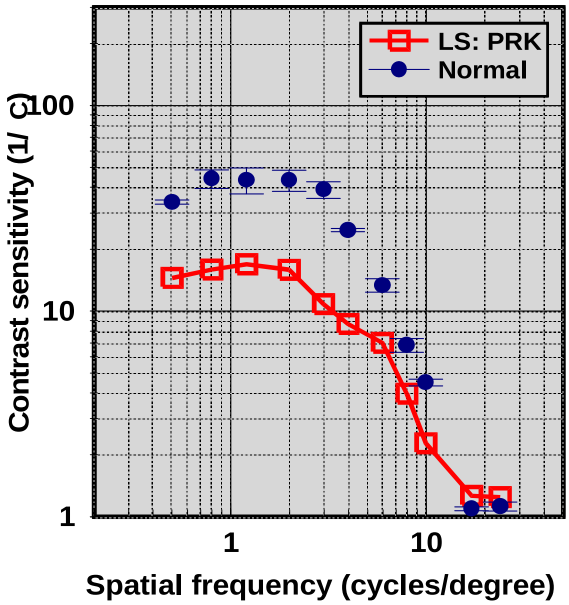


Fig.33 Mesopic contrast sensitivity data for subject LS showing a significant loss of sensitivity at low and mid spatial frequencies

Subject LS was asymptomatic under daylight conditions, exhibited a normal visual acuity of 6/5 and a normal contrast sensitivity function, (Fig.31.) Contrast acuity thresholds were within the normal range ±2sd at this light level (Fig.30.) Under mesopic conditions, when pupil diameters become larger, LS suffered an increase in contrast thresholds, particularly within the central 2.5° (Fig.32.) Her mesopic contrast sensitivity was also compromised, particularly at low and mid spatial frequencies (Fig.33.) This pattern of contrast threshold loss strongly implicates an increase in either intraocular light scatter and/or irregular aberrations, both of which are known to have a more detrimental effect on the smaller targets used centrally. It is well known that both scattered light and aberrations increase at larger pupil sizes. In addition, the absorption efficiency of the aberrated, off-axis rays is increased due to the significant reduction in the Stiles-Crawford effect in the mesopic range. To summarise, this subject performed poorly for the CAA test because although she performed within the normal range at the photopic light level she performed poorly at the mesopic light level.

Subject PL, LASIK, poor vision, especially at night and glare

Age 43, Pre-operative refraction: –8.00/–1.25x70. Treated 4 years ago (including one retreatment), zone size 4.8mm, mean photopic pupil diameter 4.1mm. Refraction on day of testing: –0.25DS, giving 6/9^{+3}, cornea clear but topography indicates irregularity.

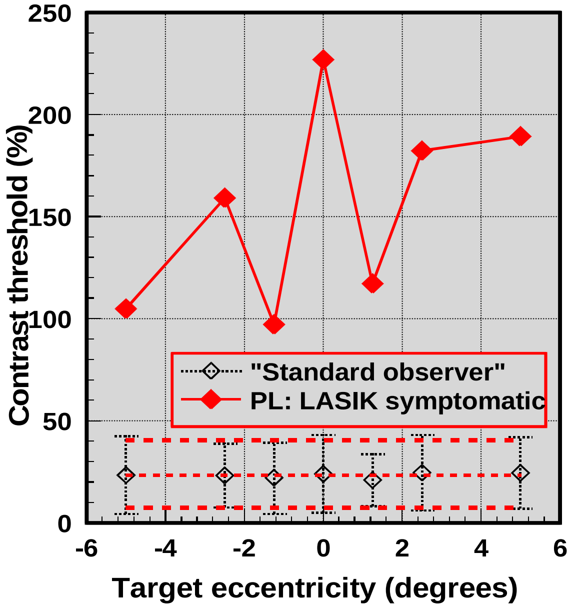


Fig.34 Photopic contrast acuity data for symptomatic subject PL. All data points fell outside the normal range indicating very poor visual performance at this light level. The greatest discrepancy occurred foveally although the data showed significant variability across the 5° field examined.

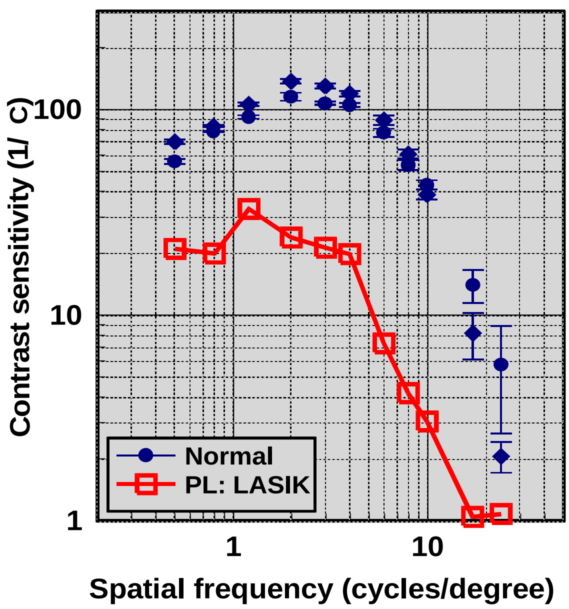


Fig.35 Photopic contrast sensitivity data for subject PL. A significant loss of sensitivity is seen across the full range of spatial frequencies in agreement with the compromised contrast threshold data.

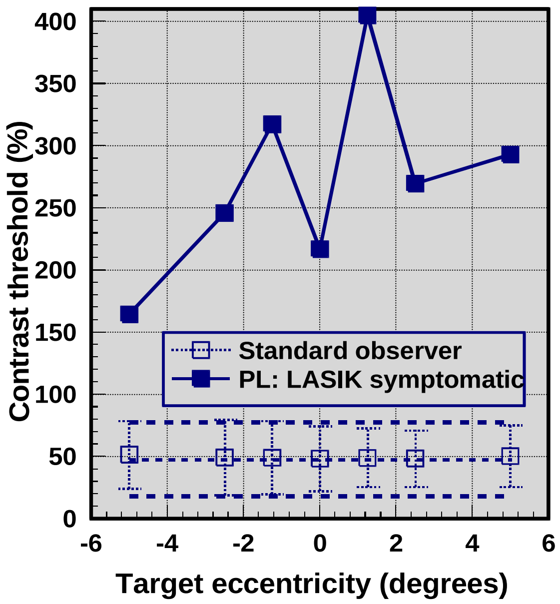


Fig.36 Mesopic contrast acuity data for symptomatic subject PL. All data points fall significantly outside the normal range indicating poor visual performance at this light level. A substantial degree of variability is seen across the central 5° field.

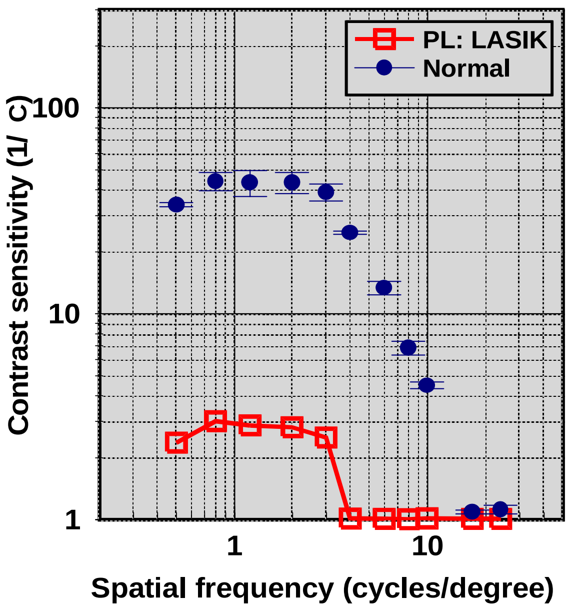


Fig.37 Mesopic contrast sensitivity data for subject PL indicating severely compromised visual performance across the whole range of spatial frequencies

Subject PL had undergone LASIK surgery to the same eye on two separate occasions. The first treatment had resulted in residual myopia and a degree of corneal irregularity. The second treatment improved his visual acuity by removing the spherical error but some irregularity was still visible on the corneal topography plot and within the retinoscopy reflex. PL complained of poor quality vision under all lighting conditions but particularly at night. He felt that he had adapted to an extent and now noticed it less. His best-corrected visual acuity was slightly below average ($6/9^{+3}$) and his contrast thresholds and corresponding contrast sensitivity functions were severely compromised at both light levels. The pattern of contrast threshold loss appeared to be similar under photopic and mesopic conditions (Fig.'s 34 and 36). Contrast sensitivity loss occurred across the range of spatial frequencies (Fig.'s 35 and 37). The extreme reduction in visual performance exhibited by subject PL is most likely to be caused by a significant increase in irregular aberrations, relating to notable corneal irregularity within the treatment zone. In such cases, the variability of the contrast threshold results can be seen to increase significantly.

Asymptomatic subjects with poor results

Subject PB, PRK, Asymptomatic

Age 42, Pre-operative refraction: –6.25/–0.75x18. Treated 6 years ago, zone size 6.5mm, mean pupil diameter 4.6mm. Refraction on day of testing: –0.50/–0.25x150 giving $6/5^{-1}$, cornea clear

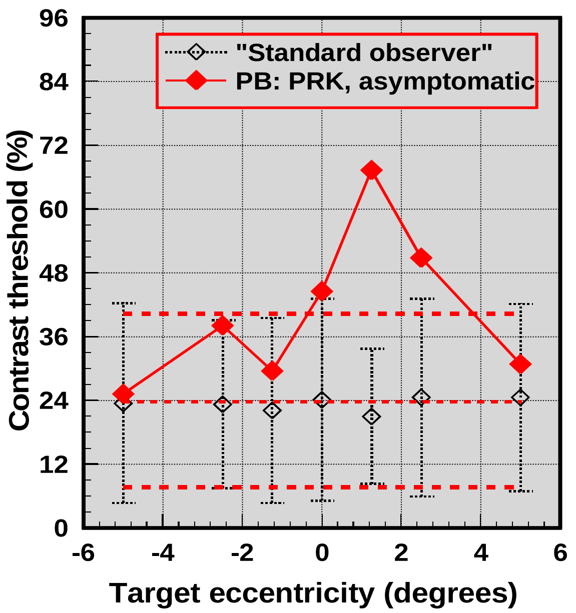


Fig.38 Photopic contrast sensitivity data for subject PB. Three data points fall outside the normal range but do not coincide with the centre of the field.

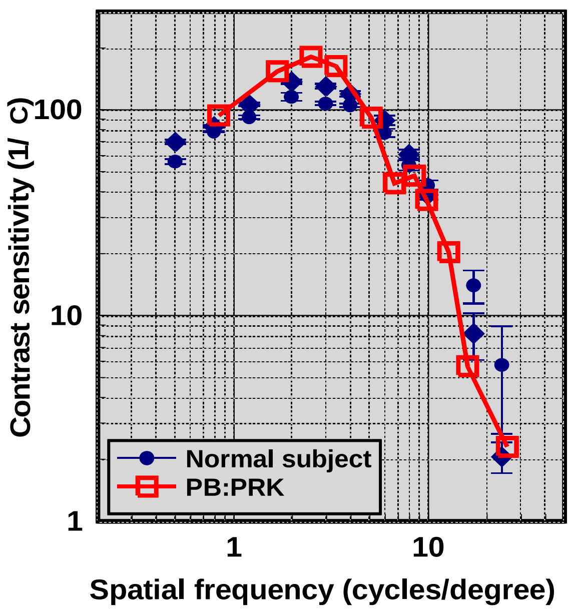


Fig.39 Photopic contrast sensitivity data for subject PB indicating normal sensitivity under photopic conditions

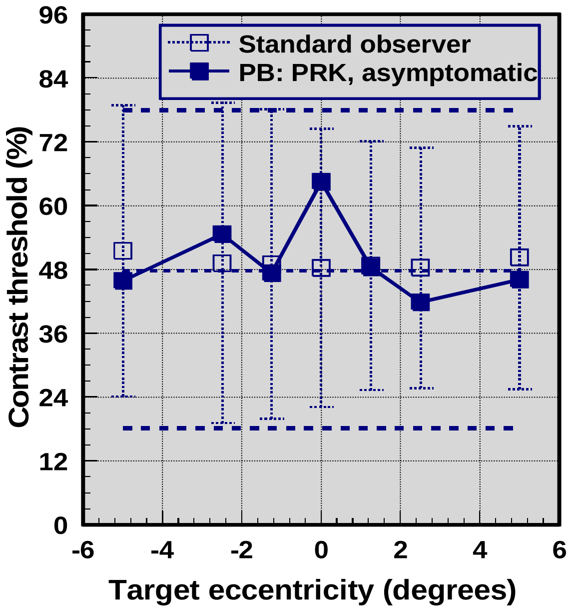


Fig.40 Mesopic contrast acuity data for subject PB showing the clustering of data points around the 'standard observer'. These data indicate good visual performance under mesopic conditions

Subject PB demonstrated better than average best-corrected visual acuity ($6/5^{-1}$) and a normal photopic contrast sensitivity function (Fig. 39). However, 3 data points within the photopic contrast acuity results were outside the normal range (Fig.38). This is likely to be an artefact and the asymmetry of the data and the lack of correspondence to either the contrast sensitivity findings or the mesopic contrast acuity data suggest that the cause was a loss of concentration during the test. A repeat measurement would be needed to determine the significance of this result and whether further investigation was required. Mesopic contrast acuity thresholds were normal (Fig.40) but mesopic contrast sensitivity data was not available for this subject.

Subject SL, LASIK, Asymptomatic

Age 28, Pre-operative refraction: –2.25/–0.25x140. Treated 8 months ago, zone size 6mm, mean pupil diameter unknown. Refraction on day of testing: –0.50DS giving 6/6^{-3}, cornea clear, retinoscopy reflex slightly irregular.

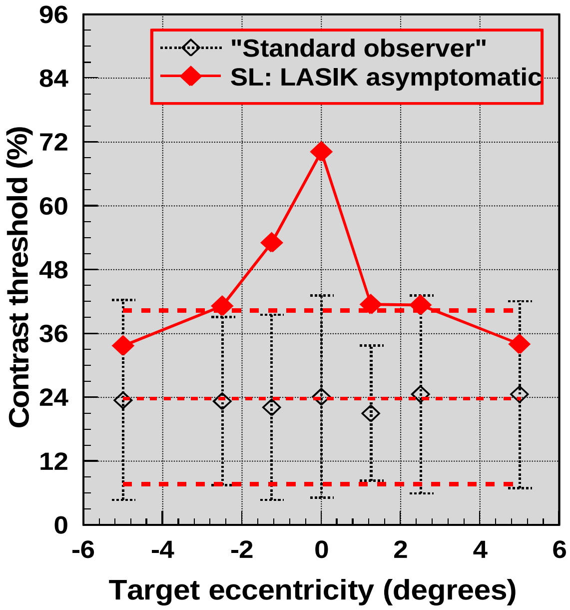


Fig.41 Photopic contrast acuity data for subject SL. The central five data points fall outside the normal range with the greatest discrepancy occurring foveally. This is the characteristic pattern of loss produced by increased scatter and/or aberrations and indicates poor visual performance at this light level.

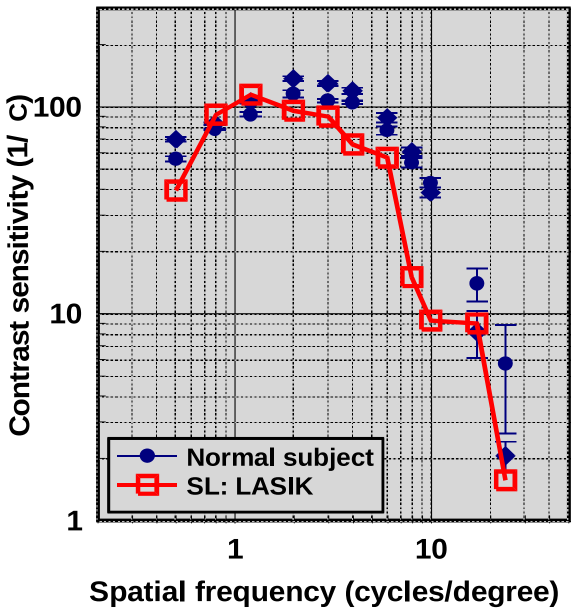


Fig.42 Photopic contrast sensitivity data for subject SL indicating a slight reduction in sensitivity at mid spatial frequencies

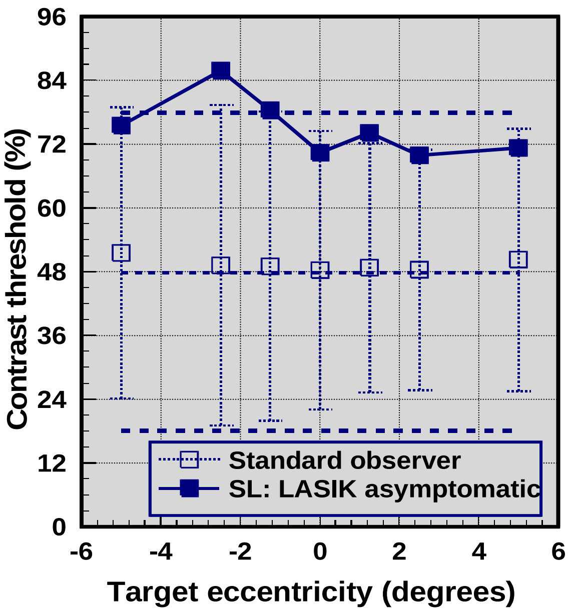


Fig.43 Mesopic contrast acuity data for subject SL. All but one data point fall just within the normal range ±2sd, indicating acceptable visual performance for the CAA test at this light level

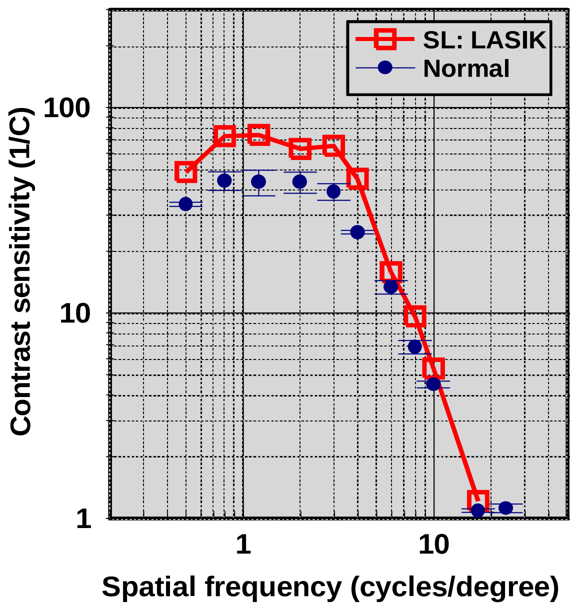


Fig.44 Mesopic contrast sensitivity data for subject SL indicating a slight increase in sensitivity at low and mid spatial frequencies, compared to the normal observer

Subject SL exhibited a best-corrected acuity of $6/6^{-3}$ and reported no symptoms. Her photopic contrast acuity thresholds fell outside the normal range over the central 2.5° (Fig. 41) suggesting the presence of raised intraocular scatter and/or irregular aberrations, which cause more significant degradation to the image of the smallest objects, such as those used centrally in the CAA test. The corresponding contrast sensitivity curve implied a very slight loss of sensitivity at medium spatial frequencies (Fig.42). Under mesopic conditions, the contrast acuity thresholds fell just within the normal range for all but one point (Fig.43), analogous with a normal mesopic contrast sensitivity function (Fig.44). Considered in conjunction with the irregular retinoscopy reflex, these findings suggest that the slight loss of visual performance was linked to surgically induced irregular aberrations within the ablated zone. In the case of subject SL, the mesopic contrast thresholds were slightly worse than the average yet the contrast sensitivity data was better than average. These results demonstrate why the measurement of contrast sensitivity may not always provide the best assessment of visual performance in relation to a particular visual task. The lack of symptoms can be explained by the scarcity of near threshold objects under photopic conditions; very few subjects have reported symptoms under photopic conditions despite often significantly compromised visual performance.

Subject SR, PRK, asymptomatic although has had no reason to drive since moving to London Age 29, Pre-operative refraction: –1.75/–1.00x20. Treated 5 years ago, zone size unknown, mean pupil diameter 5.9mm. Refraction on day of testing: +0.50/–0.25x165 giving 6/6, cornea clear.

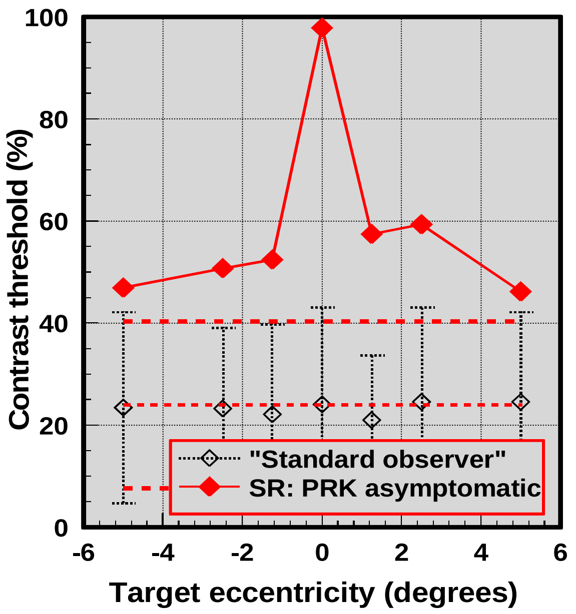
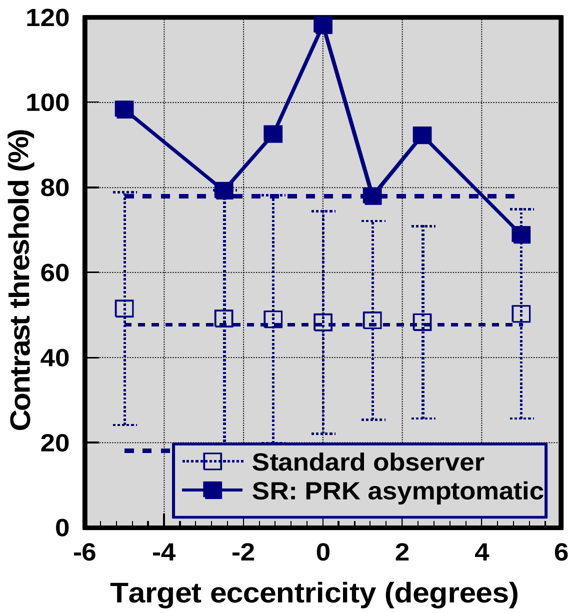


Fig.45 Photopic contrast acuity data for subject SR. All data points fall outside the normal range indicating poor visual performance at this light level. The greatest discrepancy occurs centrally implicating scatter and/or aberrations as the cause for the retinal image degradation

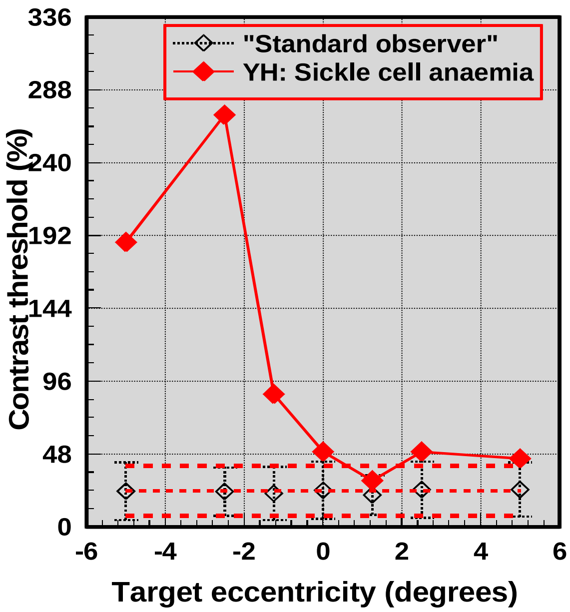
Fig.46 Mesopic contrast acuity data for subject SR. Virtually all data points lie outside the normal range indicating poor visual performance at this light level. Again, the greatest discrepancy occurs foveally



Subject SR had an average best-corrected acuity of 6/6 and reported no symptoms. However, her contrast acuity thresholds are irregular and fall outside the normal range at both photopic and mesopic light levels (Fig.'s 45 and 46). The general pattern for both photopic and mesopic testing is an increase in threshold within the central 1–2° field, suggesting the presence of irregular aberrations and/or scattered light. Her average pupil size was relatively large and since she was treated 5 years previously, she may have had a small ablation zone in comparison to the pupil diameter. In addition, the investigator noticed that subject SR did not appear to be very discerning with regard to her vision and was not a particularly good observer. This may explain why the subject was asymptomatic despite having a relatively significant reduction in visual performance at both light levels. She also did not drive, one of the more vision critical tasks undertaken by many people.

Retinal Function
In addition to the refractive surgery subjects, a non-surgery subject with retinal disease was examined to demonstrate that the test could be used to detect any deficit in visual performance, whether due to poor quality optics or retinal function.

Subject YH, age 39, Sickle Cell Anaemia No retinal signs although patient had been told there was peripheral retinal thinning. Right eye: plano, vision 6/5. Complained of poor night vision.



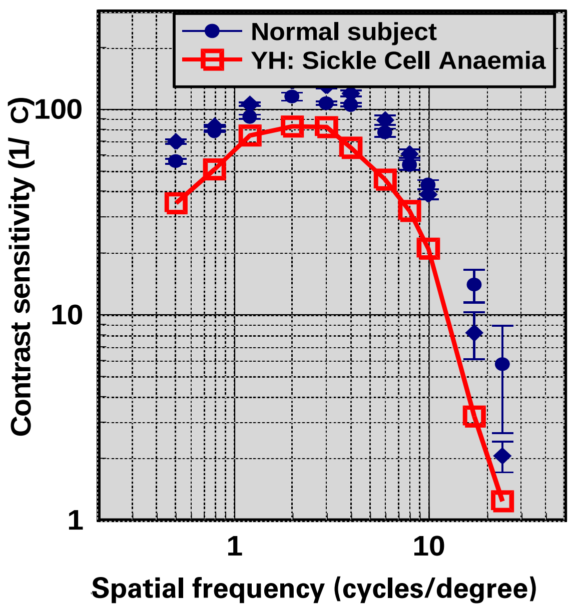


Fig.47 Photopic contrast acuity data for subject YH. All data points in the nasal visual field fall outside the normal range, suggesting significantly compromised temporal retinal function

Fig.48 Photopic contrast sensitivity data for subject YH indicating a slight loss of sensitivity across the whole range of spatial frequencies

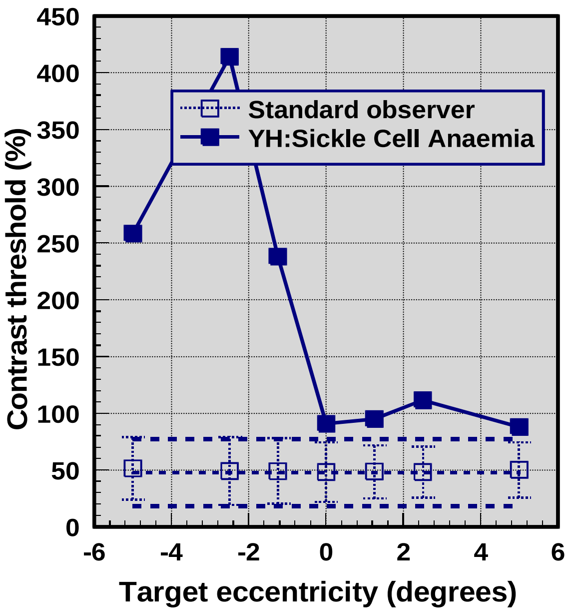


Fig.49 Mesopic contrast acuity data for subject YH. A similar pattern of visual loss is seen with all data points falling outside the normal range and the greatest discrepancy occurring in the nasal visual field

Sickle cell anaemia results in obstruction of small blood vessels, causing ischaemia of the surrounding tissue. This leads to a localised reduction in receptor and ganglion cell density and therefore a reduction in visual performance. Early signs include peripheral arterial occlusion and new vessel growth. Despite there being no visible retinal signs, YH demonstrated a severe reduction in visual performance in the nasal field of the right eye, as evident from the increase in contrast acuity thresholds at both photopic and mesopic light levels (Fig.'s 47 and 49). The photopic contrast sensitivity indicated a very mild loss of sensitivity across the whole range of spatial frequencies (Fig.48). This suggests that the visual loss was retinal rather than optical in origin.

Appendix Summary

Of the 14 subjects examined, 6 were symptomatic and 8 were not. The most common symptom was poor quality night vision but symptoms under photopic conditions were rare. Visual degradation is less noticeable under daylight conditions since visual tasks do not tend to be close to threshold.

Asymptomatic Subjects
The majority of asymptomatic subjects produce contrast thresholds similar to the straight-line data of the 'standard observer' at both light levels. Two of the 8 asymptomatic subjects produced photopic contrast acuity data that fell outside the normal range (±2sd), although their mesopic data was normal. One subject performed poorly at both light levels.

Symptomatic Subjects
Five out of 6 symptomatic subjects exhibit contrast acuity thresholds outside the normal range (±2sd), at both light levels. The 6^{th} subject (LS) performed poorly at the mesopic light level only when her pupil was more likely to exceed the ablated zone diameter.

Those subjects with a significant loss of visual function (e.g. subject PL), the contrast thresholds show significantly greater variability.

Two subjects, (GC and JS) demonstrated an increase in contrast thresholds that took a different form to that seen in the majority of symptomatic subjects. The greatest increase in threshold occurred beyond 2.5° possibly implicating retinal receptor spacing. A subject with a greater than average rod and/or cone spacing would require a larger or higher contrast in order to resolve the stimulus. This is particularly the case under mesopic conditions, as seen for subject GC, where the rod receptors begin to predominate beyond 2.5°.

Glossary of Terms

Aberrations: a deviation in power of the optical components of the eye, (either individually or in combination), from the ideal system that would produce a perfect point image on the retina. Low order aberrations include spherical defocus and astigmatism, both of which can be corrected with spectacles. Higher order aberrations include spherical aberration and coma, which are found to a degree in all eyes and can not be corrected with spectacles. Spherical aberration results in light rays that pass through the peripheral pupil focussing at a point either in front (positive) or behind (negative) the focal point of the axial and paraxial rays. Coma results in peripheral rays focussing at a point laterally displaced from the focal point of the paraxial rays, due to alterations in refractive power of the eye across the pupil. Aberrations have the effect of reducing retinal image contrast and hence visual performance. Both spherical aberration and coma increase with increasing pupil size. The aberrations induced by refractive surgery are best described as irregular aberrations but some studies tend to refer to them as being most similar to spherical aberration and coma.

Best Corrected Visual Acuity (BCVA): the vision obtained when any residual refractive error is corrected. Loss of 2 or more lines of BCVA is considered significant following refractive surgery.

CAA: Civil Aviation Authority and Contrast Acuity Assessment

Contrast Sensitivity: the lowest contrast at which a particular spatial frequency can be resolved. The peak of the average contrast sensitivity function falls between 2 and 5 cycles per degree.

Contrast Threshold: the contrast at which a stimulus can be detected or discriminated 50% of the time.

Illuminance: the quantity of light reaching a surface measured in lux. Retinal illuminance (intensity of light reaching the retina) is also dependent on pupil size.

Intraocular light scatter: the scattering of light by particles within the ocular media. Light scattered towards the retina reduces the contrast of the retinal image and hence reduces visual performance.

Laser Assisted In-Situ Keratomileusis (LASIK): a thin flap of corneal tissue is cut using a microkeratome and reflected back. The underlying stroma is ablated using an excimer laser to treat refractive error and the flap is repositioned.

LogMAR: logarithm of the minimum angle of resolution

Luminance: the quantity of light emitted by a source/surface per unit area, (dependent on the light incident on the surface and the reflective properties of the surface). Luminance is measured in candelas per metre squared (cd/m^2)

Mesopic range: range of low light levels over which both the cones and rods function. The limits of the mesopic range vary between individuals.

Myopia (short-sight): the optics of the eye are too strong for the axial length of the eyeball, resulting in the image focussing in front of the retina and therefore leading to a blurred retinal image. Distance vision is blurred but near vision generally remains good within a particular range.

Outlier: a subject whose data falls outside agreed limits. In the case of this study and the previous work undertaken for the CAA, the limit was set at more than 1.5x the interquartile range above the upper quartile, due to the non-normal distribution of the data.

Photopic range: in use under the majority of lighting conditions. Cone function predominates allowing good visual acuity and colour discrimination.

Photorefractive Keratectomy (PRK): following removal of the corneal epithelium, the underlying stroma is ablated using an excimer laser to reshape the surface to treat refractive error. The epithelium regrows across the treated zone within 5–7 days.

Stiles-Crawford Effect: rays of light entering the eye obliquely are less effective as stimuli than those entering the pupil centrally. This effect has been explained by the orientation of the cone receptors towards the centre of the pupil giving the cones directional sensitivity. This results in cones being less sensitive to scattered light since they do not detect light rays approaching from an oblique angle. Rod receptors exhibit no such effect and therefore are more susceptible to scattered light.

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