Artificial pupils and Maxwellian view

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When control of the pupil size is required, the simplest method is to use a physical artificial pupil or aperture that is placed in the spectacle plane. In some clinical applications (e.g., the potential acuity meter) an optical artificial pupil is imaged in the plane of the natural pupil by a Maxwellian view optical system. We compared visual performance with physical and Maxwellian artificial pupils by measuring the effects of the pupil diameter (0.5–5 mm in range) and defocus (5-D myopia to 4-D hyperopia) on minimum angles of resolution (MAR's) and on angular blur disk diameters. For pupil diameters down to ~2.0 mm there were no meaningful differences between the visual resolution that is obtained with the physical and the Maxwellian pupils. At the smallest diameter (0.5 mm) the physical artificial pupils caused the MAR to increase because of the diffraction limitation on resolution, and defocus no longer affected MAR. With the small Maxwellian pupils vision did not become diffraction-limited so that maximum resolution could still be obtained. MAR was still affected by defocus. The angular blur disk diameters measured with the smaller Maxwellian pupils were slightly but significantly larger than those found with physical artificial pupils. For physical artificial pupils, field-of-view restrictions may result from vignetting with the eye pupil. Thus small physical artificial pupils can act as pinholes causing resolution to become impaired but insensitive to defocus. Also vignetting by the eye pupil can restrict the field of view. Small optical artificial pupils from Maxwellian viewing do not impair resolution, and the resolution may remain sensitive to defocus. The eye pupil does not cause any field restriction, although, if small, it may filter higher spatial frequencies out of the retinal image.

Key words: Pupils, Maxwellian view, resolution, visual acuity, defocus, minimum angle of resolution, angular blur disk diameter.

Introduction

The simplest method for controlling the pupil size in vision research and in clinical applications is to center an aperture of the required size in front of the eye. Such an aperture is usually placed in the spectacle plane.[1] If optical instruments are used in manipulating the visual image, optical methods of controlling the pupil size can be used.

One optical method is to use the exit pupil of a Keplerian telescope (or microscope) system as the artificial pupil. The size and shape of the artificial pupil are determined by the aperture stop of the optical system, and its image becomes the exit pupil of the system. This image is an optical artificial pupil, and it is usually made to be coincident with the pupil of the eye. In such systems all the light entering the aperture stop is imaged through the optical pupil.

Examples of such systems are the ocular-focus stimulator of Crane and Cornsweet[2] and the telemicroscopic system used by van Meeteren and Dunnewold[3] to image a remote grating target through an 0.8-mm optical pupil.

Another optical method of presenting visual stimuli has become known as the Maxwellian view. In the Maxwellian view the exit pupil of the optical system is an image of the effective light source. Schor et al.[4] used a Maxwellian system to induce a small exit pupil (~0.75 mm) (Ref. 5) to increase the depth of focus of the eye sufficiently to open the accommodative loop.

Maxwellian View

In the original Maxwellian view optical system, the source and the exit pupil were slits, but small circular sources are more common today.[6] Such optical systems are used widely in vision research where uniformly illuminated fields of light need to be generated from sources of relatively low power.[7] Experiments that utilize monochromatic or narrow chromatic bandpass light often use the Maxwellian view to achieve luminances in a photopic range without requiring high-intensity lamps (such as the xenon arc), which

would be needed if the stimulus were to be projected onto a screen and viewed directly. Maxwellian view optical systems are also used where a point of entry into the eye is to be controlled, such as in the studies of the Stiles–Crawford effects.[8,9] They are also used in some interferometers for measuring visual acuity (see Ref. 10).

In the Maxwellian view system light is usually captured by a collimating lens that is positioned close to the light source. This light can then be manipulated optically without losses resulting from the inverse square law before being channeled into the eye passing through an image of the light source that is formed in the plane of the observer's eye pupil. This image of the light source is the exit pupil of the Maxwellian view system.

If the Maxwellian exit pupil lies entirely within the observer's eye pupil, by geometrical optics theory the observer's eye pupil would be effectively replaced with an optical pupil having the size and shape of the Maxwellian exit pupil located in the plane of the observer's eye pupil. For a Maxwellian viewing system geometrical optics theory can be inadequate because it ignores physical optics properties that can be quite important to image quality.

Westheimer's[7] analyses for Maxwellian viewing systems show that when the source of illumination is small and monochromatic, the image quality is independent of the exit pupil size and dependent only on the size of the eye-pupil aperture. In such conditions the illumination is essentially coherent. Since the source of illumination is made large and if it is not monochromatic, the illumination becomes only partially coherent or incoherent. Westheimer calculates that incoherent imagery occurs for Maxwellian exit pupils when diameters are greater than ~2.2 mm and that a diameter of less than ~0.06 mm is required for coherent imaging properties.

The coherence of light affects imaging properties in Maxwellian viewing systems when the eye pupil or the ocular media act as spatial filters to limit the range of the spatial frequencies within the Fourier spectrum of the image.[7] When unstructured fields are used as targets, such effects would be seen only as changes in the clarity or the nature of the edge of the field. However, when spatially structured targets, such as acuity targets or other stimuli with fine detail, are presented in a Maxwellian viewing system, the use of coherent light affects the retinal images of the targets themselves.

With coherent light in a Maxwellian system, a Fourier transform of the target amplitude function (i.e., the Fraunhofer diffraction pattern that is produced by light passing through the target) is formed in the plane of the entrance pupil of the eye. The higher-spatial-frequency information is represented in the more peripheral regions of this diffraction image. It is possible for the eye pupil to act as a low-pass filter by blocking the more peripheral parts of the diffraction image. Bradley et al.[11] calculate that the width of the diffraction image should be at least

1.2 mm to create a 30-cycle/deg retinal image for light of 700-nm wavelength. An eye-pupil size of ~2.5 mm would be required to ensure the passing of all potentially visible spatial frequencies.

Physical Artificial Pupils

Physical artificial pupils are apertures that, by virtue of their placement in front of the eye, take over the light-limiting functions of the eye pupil. Small physical artificial pupils have a low-pass filtering effect because of diffraction restricting the range of spatial frequencies in the image so that the image quality can be significantly reduced. Small optical artificial pupils from Maxwellian viewing systems do not lead to the constraint of the diffraction image that formed in the pupil plane, and thus they do not have the same low-pass filtering effect.

The purpose of this study was to measure differences in visual performance with Maxwellian and physical artificial pupils as a function of pupil size. Smith[12] argues that the angular blur disk diameter is better than the object vergence for quantifying defocus because the effects of defocus are so strongly dependent on pupil size,[1] and the angular blur disk diameter reflects both the defocus and the pupil size. Both visual acuity and depth of focus should be related to the angular blur disk diameter, and, since blur disk diameters are so closely related to pupil size, we measured both the minimum angles of resolution (MAR) and the angular blur disk diameters (ABDD's) for the various pupil sizes and for both types of artificial pupil in both clear and defocused conditions.

Methods

The apparatus is shown schematically in Fig. 1. A pair of +10-D achromatic lenses (Melles Griot 01LAL017) mounted on an optical bench were separated by 60 cm. For the Maxwellian viewing system an incandescent lamp illuminated a translucent diffusing screen that was immediately behind and in contact with aperture A_M, which was positioned in the primary focal plane of the first lens (L_1). An image A_M' was formed in the secondary focal plane of the second lens (L_2) and was equal in size to aperture A_M. The observer's eye was positioned so that the eye pupil was in the same plane and centered on the image A_M'. This creates a telecentric Badal optometer,[13] since the secondary focal point is at the entrance pupil of the eye. The position of the targets for the visual resolution and the blur disk diameter measurements was varied over a range of ~5–15 cm from the second lens. Such a system allows the vergence of light from the target incident on the eye to be varied over a range of approximately +5 to −5 D while angular magnification remains constant.

The conversion from Maxwellian viewing to normal viewing through the physical artificial pupil was achieved by placing a large white externally illuminated screen, which was 50 cm in front of lens L_2, and inserting the physical artificial pupils (A_r) 15 mm before the focal plane of lens (L_2). A filter holder (with
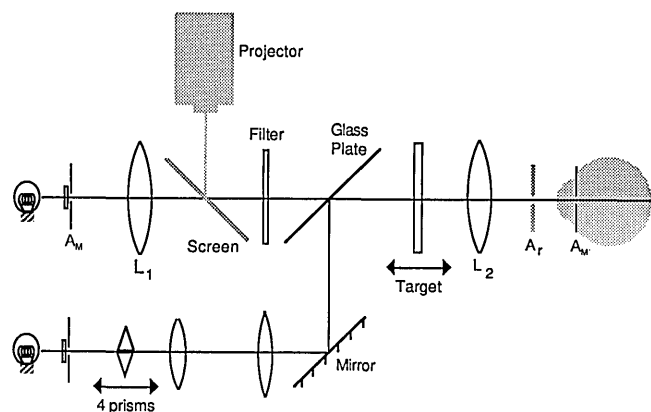
Fig. 1. Schematic view of the apparatus. A_M is the Maxwellian aperture stop with a translucent diffuser behind. L_1 and L_2 are identical +10-D lenses. An image A_M' is the Maxwellian exit pupil that is formed in the plane of the dilated eye pupil. For viewing with physical artificial pupils the projector illuminates a white screen that is placed behind the target, and the pupil apertures (A_r) are positioned 15 mm in front of the eye pupil. The targets may be moved longitudinally to vary the vergence of light incident on the eye. The neutral-density filters control retinal illuminance. The secondary alignment control system has an illuminated pinhole, a translatable quad prism and relay lenses, and mirrors that form four images that are focused on the iris of the subject.

an aperture of 45 mm × 39 mm) that was situated 40 cm from lens L_2 limited the effective area of the background screen. For all conditions the retinal illuminance was set at 30 Td (as for a test target luminance of 160 cd/m^2 as seen through a 0.5-mm pupil) by using appropriate neutral density filter combinations. Thus for both Maxwellian viewing and viewing through the physical artificial pupil the subjects saw a 22-deg circular field containing the target and its background, which was uniformly illuminated and kept free of discernible texture and unaffected by target position.

Targets for the measurement of the minimum angle of resolution were either a transparent Rochester Institute of Technology alphanumeric test object (RP-1-71) or reduced-size transparent Bailey–Lovie charts.[14] Both charts gave comparable visual acuity scores. Resolution threshold sizes of 50% were found by using probit analysis with appropriate correction for guessing that is associated with the five (Rochester Institute of Technology) or ten (Bailey–Lovie) alternatives in the forced choice procedures.

The target for the measurement of the perceived blur disk diameters (ABDD's) produced by defocus was a pair of retroilluminated apertures (diameters of ~150 μm) of variable separation. This target was placed in the same planes as the acuity targets, and the separation of the sources was adjusted by the subject until the two blur disks that were perceived by the subject appeared to just touch. At least five measurements were made for each viewing condition. This technique is similar to that introduced by Smith[12] and used by Chan et al.[15]

All measurements were made with the subject's eye pupil dilated, and accommodation was paralyzed for the emmetropic and hyperopic defocus conditions. The subject's head and eye position were maintained by using a bite bar, and a secondary optical system was used to detect transverse displacement of the eye pupil. In this secondary system a quadruple prism was used to create four exit pupils symmetrically disposed around the primary Maxwellian exit pupil. The longitudinal movement of prisms caused radial displacement of these secondary exit pupils, which were focused on the observer's iris close to the margin of the dilated pupil. The light source for this system was green, and any movement from alignment by the observer's eye caused a green border to become visible at the edge of the field. This indicated the presence and direction of misalignment. For these experiments the exit pupil of the stimulus system was coincident with the center of the observer's eye pupil. For both subjects it was determined that the primary achromatic (or visual axis) passed within 0.25 mm of the center of the eye pupil.

In the first experimental sessions myopic defocus levels (target vergence at the eye pupil > 0.0 D) were used, and emmetropic (target vergence = 0.0 D) and hyperopic defocus (target vergence < 0.0 D) were presented in subsequent sessions. Within sessions defocus levels were presented randomly, and, within defocus levels, pupil size changes were in random sequence. The defocus levels covered a range of 5-D myopia to 4-D hyperopia in 1-D steps, and these were referenced to the subject's refractive error determined by finding the most remote target position that allowed maximum resolution when a viewing through a physical artificial pupil of 3-mm diameter. At each pupil size MAR was measured before ABDD measurements were taken. For each condition the order of the artificial pupil type (physical or Maxwellian) was chosen randomly. For the myopic defocus levels 1% tropicamide was used for mydriasis. The observer's far point was measured before and after each pupil size change, and the position of targets with respect to the second 10-D lens L_2 was adjusted if the changes in the refractive error were > 0.1 D. For the emmetropic and hyperopic conditions 1% cyclopentolate was used for mydriasis and cycloplegia.

Results

Blur Disk Size

The relationships between the ABDD's and defocus for the two pupil types and the various pupil diameters are shown for subject RJJ in Fig. 2. The results for the second subject showed closely similar patterns. On each graph of Fig. 2 a dashed curve shows the relationship between the blur disk size and the defocus that is predicted by applying simple geometric optics theory to the Gullstrand 1 Exact Model Eye[16] for both types of artificial pupil for each of the eight diameters. When the defocus simulates myopia the predicted blur disk diameters for Maxwellian view pupils are slightly larger than for those with physical artificial pupils, and the converse is true for simulated hyperopic defocus. The dashed curves on these
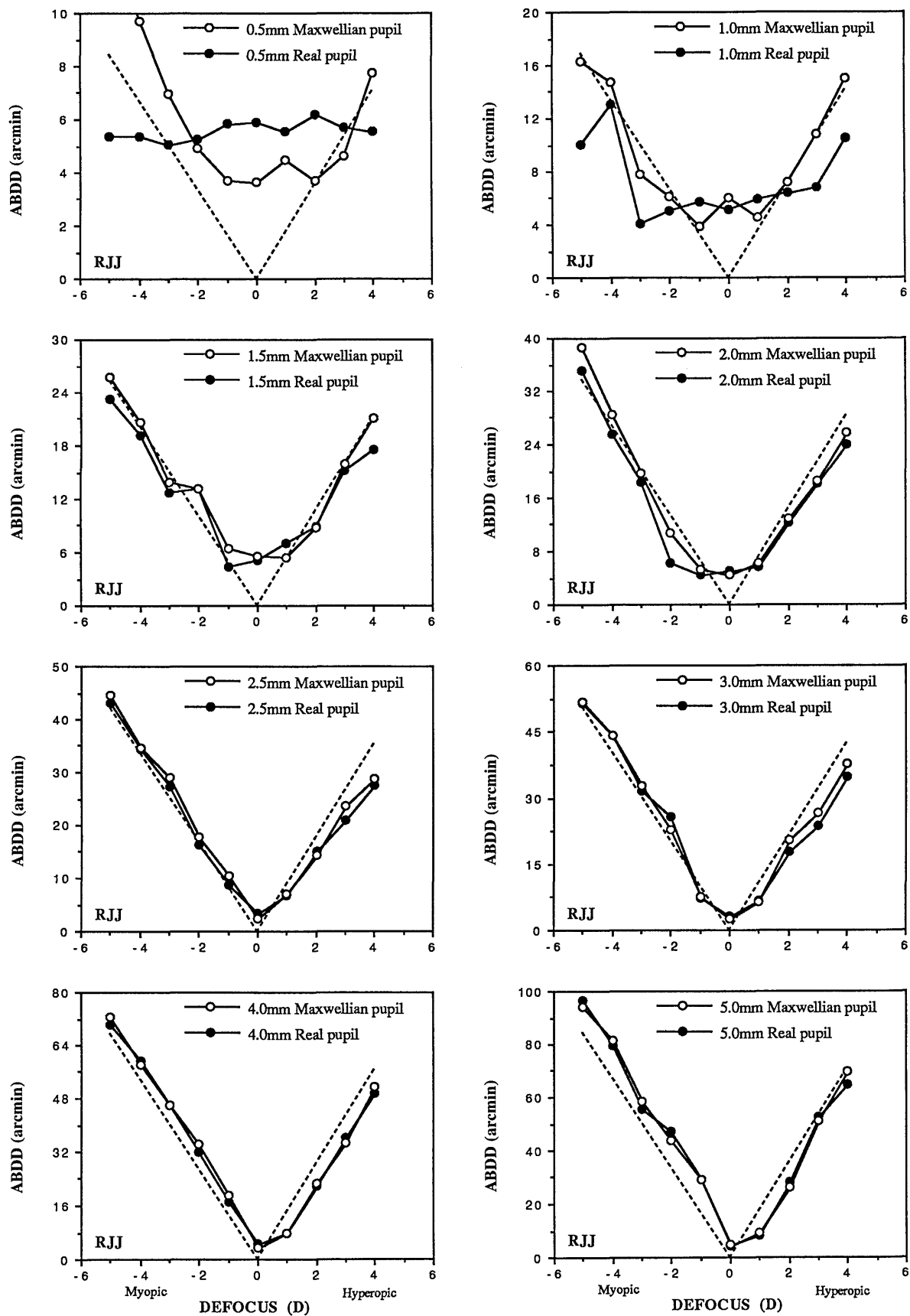
Fig. 2. Relationships between ABDD and defocus for viewing with both Maxwellian artificial pupils and physical artificial pupils. Pupil sizes are 0.5–5.0 mm for subject RJJ. Dashed curves show ABDD–defocus relationships predicted by applying geometrical optics blur disk theory to Gullstrand's 1 Exact Eye.

graphs represent the average of the predicted blur disk diameters for the two pupil types. The measured blur disk diameters were expected to show certain deviations from geometrical predictions, the most obvious being that the measured blur disk size should not become zero at zero defocus because of the limitations that are imposed by the anatomy and physiology of the retina and the imperfect optical imaging properties of the eye.

For pupil diameters of 2 mm or more there was a consistent tendency for the measured ABDD's to be larger than predicted for myopic defocus and smaller for simulated hyperopia. This could be explained by the positive spherical aberration, which enlarges blur disks in myopia and reduces them in hyperopia. For all pupil diameters the minimum ABDD was ~4 or 5 arcmin.

The technique for measuring ABDD's is a psychophysical measure that reflects the angular diameter of the point-spread function of the eye. For conditions that provide the best quality retinal image, the ABDD was ~4.5 arcmin, which was slightly smaller than the 5.2 arcmin that was found by Chan et al.[15] Campbell and Gubisch[17] measured the luminance profile of the projection of a retinal image of a point source. Their results suggest that the minimal ABDD's were between 2 and 5 arcmin, depending on how much of the tail of the luminance profile is included in the blur disk. It may be that psychophysical measures of ABDD, such as those that are used in this study, overestimate the point spread function since the images take on a starlike appearance that makes the edge of the disk more difficult to locate.

For the smallest pupil size (0.5 mm) the ABDD's for physical pupils were virtually unaffected by defocus, while the ABDD's in Maxwellian viewing were still substantially affected by the higher magnitudes of defocus. At the four smallest pupil sizes the ABDD's tended to be larger for the Maxwellian pupil than for physical pupils, especially at higher defocus levels.

A four-factor analysis of variance (pupil type, pupil size, defocus, and subject) confirmed that the pupil size and defocus have statistically significant effects on the ABDD's. There were no significant differences between the two subjects, but there were significant interactions between pupil type and pupil size, pupil type and defocus, and pupil size and defocus.

Visual Resolution

The effects of defocus on the threshold minimum angles of resolution (MAR's) for the two types of viewing system and the eight pupil sizes are shown on logarithmic scales in Fig. 3. This figure presents the results for one subject (RJJ), and the results for the second subject showed quite similar patterns. On each graph of Fig. 3 is a dashed curve that indicates the expected relationship between logMAR and defocus, which would be obtained if there were a constant ratio between ABDD's and the MAR's that are mea-

sured in the same viewing conditions. The shape of these expected curves is determined by the predictions of ABDD for the Gullstrand 1 Exact Eye. The vertical placement of the curves depends on the chosen ratio of ABDD to MAR. The ABDD/MAR ratio represented here is 4.6:1, and this value was found by averaging the ABDD/MAR ratios across all defocus levels for both pupil types and all pupil sizes.

For pupil sizes of 2 mm and larger there was little difference between the visual acuities that are obtained with the two types of artificial pupil, although both tended to provide better acuities than those represented by the expected curves, especially at the moderate levels of defocus.

With the smallest physical artificial pupil (0.5 mm) the visual resolution was essentially unaffected by defocus even though the acuity that was obtained was significantly less than the best acuities that could be obtained at zero defocus with the larger pupil sizes. For Maxwellian viewing with 0.5-mm pupils excellent visual acuity could be obtained at zero defocus but acuity declined substantially with increasing defocus. This result is not predicted by geometrical optics theory relating to blur disk diameters. For pupil sizes of 2 mm or less there was a consistent tendency for Maxwellian viewing to give slightly poorer visual resolution than that obtained by viewing through physical artificial pupils of the same size and at equivalent levels of defocus.

When pupil sizes were 2 mm and larger, there was little difference between results for the physical and Maxwellian artificial pupils. Increasing defocus produced an increase in MAR, and this effect became more pronounced with increasing pupil size.

Relationships Between Resolution and Blur Disk Diameter

Geometrical optics theory predicts direct proportionality between the resolution limit and the size of the blur patch on the retina. Assuming that there is direct proportionality between the resolution limit and our psychophysical measure of MAR and between the extent of the retinal image and our measure of ABDD, there should be a direct proportionality between the measures of MAR and ABDD. A previous study[18] found a direct proportionality between MAR for Landolt rings and ABDD as measured with the dual-fiber optic apparatus of Chan et al.[15] Their average ABDD/MAR ratio was 3.8:1, but the range of individual proportionality constants was 3.3–4.3.

Figure 4 shows the relationship between MAR and ABDD for Maxwellian and physical artificial pupils at four of the different pupil sizes for subject RJJ. The second subject showed a similar pattern of results. On each graph is a reference line, MAR = ABDD/4.6, since 4.6 was the average ABDD/MAR ratio for all conditions for this subject. On these reference lines is marked the ABDD's that are predicted for the various defocus levels for the Gullstrand 1 Exact Model Eye. For the second subject the average ABDD/MAR ratio was 4.3.
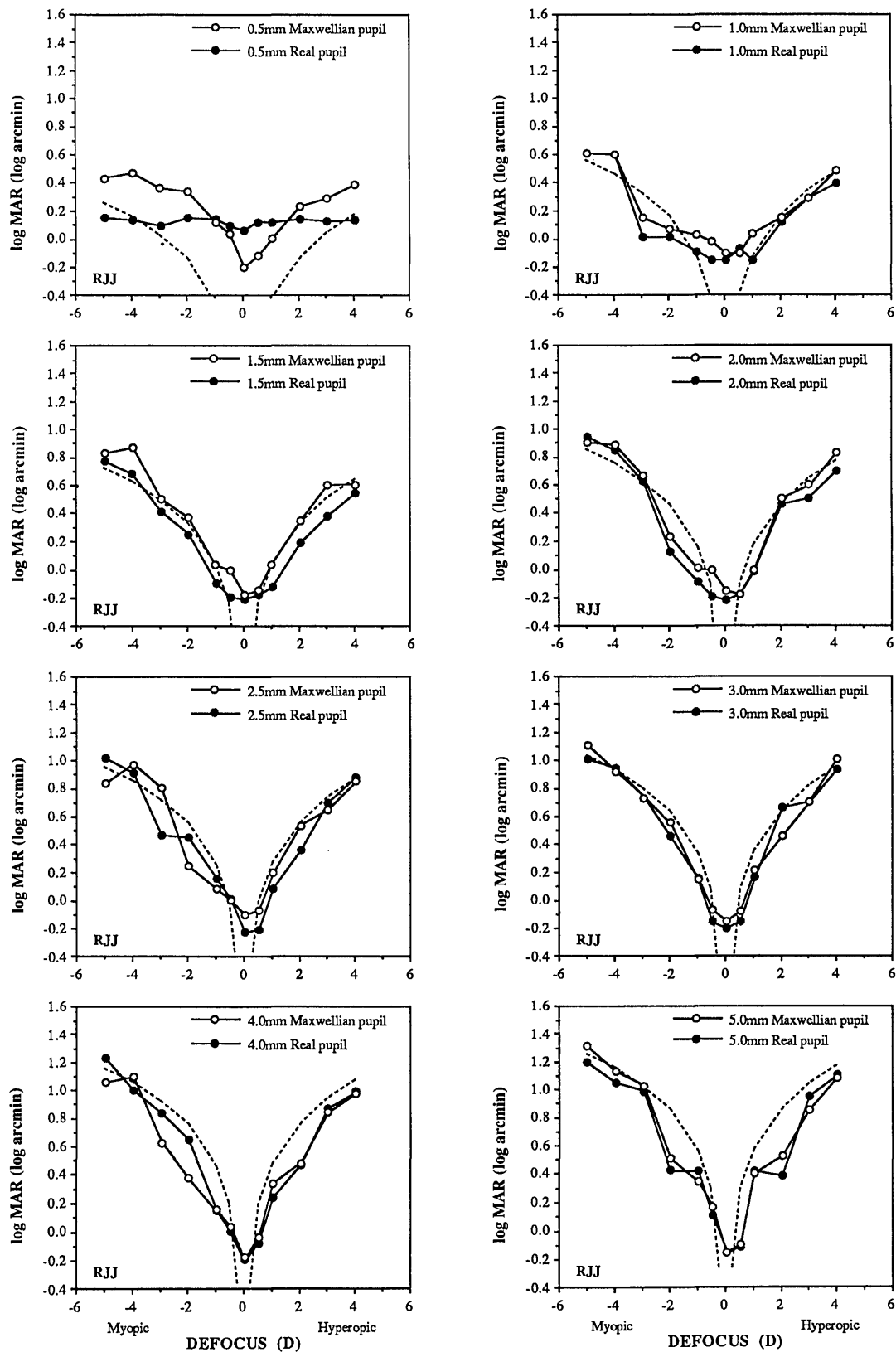
Fig. 3. Relationships between resolution thresholds (logMAR) and defocus for viewing with Maxwellian pupils and with physical artificial pupils. Pupil sizes are 0.5–5.0 mm for subject RJJ. Dashed curves show the predicted relationship between logMAR and defocus. The shape of this curve is determined by theoretical predictions of blur disk size, and the vertical placement of the curves assumes an ABDD:MAR ratio of 4.6:1.
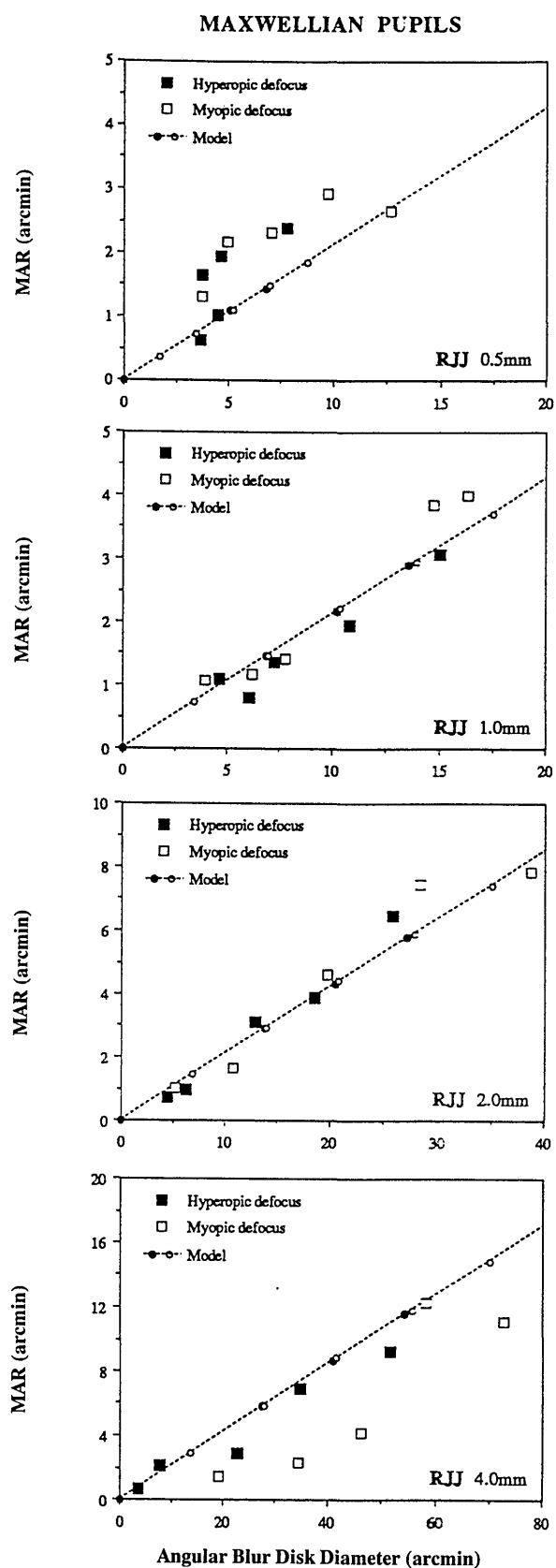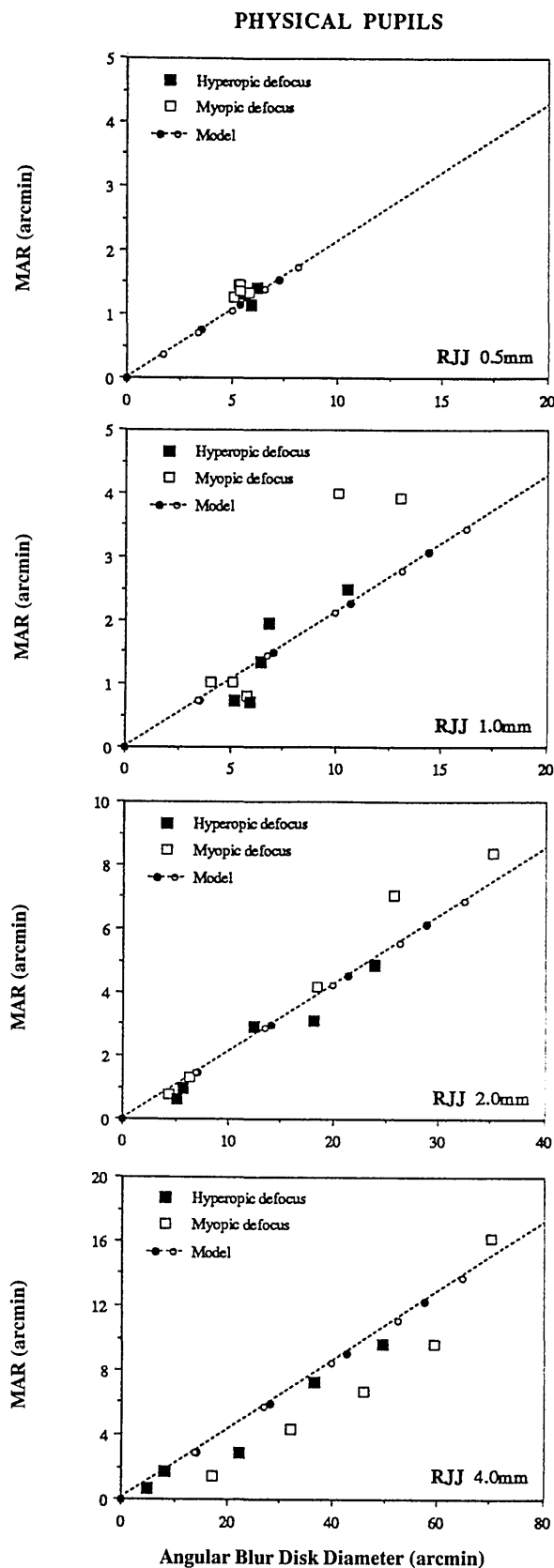
PHYSICAL PUPILS

MAXWELLIAN PUPILS

Fig. 4.   Relationships between MAR and ABDD at four different pupil sizes for viewing with Maxwellian pupils and with physical artificial pupils. Open symbols indicate values obtained with myopic defocus, and solid symbols represent hyperopic defocus. In each case the dashed line represents the average ABDD:MAR ratio of 4.6:1 determined from data for all conditions for subject RJJ. The predicted blur disk diameters are shown on this line.

From Fig. 4 it can be seen that for the smallest physical artificial pupil (0.5 mm), the points are tightly clustered since both MAR and ABDD were virtually unaffected by defocus. MAR values were all in the range of 1.0–1.5 arcmin, and the ABDD values ranged between 5 and 7 arcmin. For Maxwellian viewing with the 0.5-mm optical pupil, better acuity (MAR of ~0.5 arc min) could be obtained, but there was a much wider range of MAR and ABDD values. The resolution in defocused conditions was found to be poorer than might be expected from the associated ABDD.

For the 1-mm physical artificial pupil the blur disk diameters were smaller than predicted by geometrical optics, and the MAR values were commensurately smaller except for the two highest levels of myopic defocus when the resolution was poorer than expected from the measured ABDD values. For the 1.0- and 2.0-mm Maxwellian view pupils and for viewing with the 2-mm physical artificial pupil, the measured blur disk sizes were close to the geometrical predictions. The consistent ABDD:MAR ratio was ~4.6 for most points, but there was a tendency for this ratio to be higher for the high levels of myopic defocus.

At the larger pupil diameters (the data for the 4-mm pupils are shown in Fig. 4) there were virtually no differences between the results for the Maxwellian and the physical artificial pupils. For both pupil types at the larger diameters there was a consistent pattern of ABDD's being larger for myopic defocus than for equivalent magnitudes of hyperopic defocus. Subject RJJ showed a clear trend for the visual acuity to be better than predicted from the measured ABDD values and the ABDD/MAR ratio of 4.6.

Discussion

The results of these experiments show that physical and Maxwellian pupils are essentially equivalent for presenting resolution targets only if the pupil size is 2 mm or larger. For smaller pupil diameters there are significant differences between the two types of artificial pupil. At a diameter of 0.5 mm the physical artificial pupil causes vision to become diffraction-limited so that visual acuity becomes reduced. The resolution remains independent of defocus at least over the range of 5-D myopia to 4-D hyperopia.

Even at the smallest pupil size Maxwellian viewing does not cause a comparable diffraction limitation on resolution. Maximum resolution can still be obtained, and also MAR and ABDD remain dependent on the magnitude of defocus. Thus Maxwellian view systems do not create the same pinhole effect that is shown by the physical artificial pupils. This can have clinical relevance in clinical instruments such as the potential acuity meter, which uses the Maxwellian view. This instrument presents an acuity chart to the patient's eye through a 0.15-mm Maxwellian pupil. This instrument requires a focus adjustment to correct ametropia to maintain clarity of the target, and the need for this feature is predictable from the results of our experiment. Bradley et al.[11] have shown that defocus affects the acuities that are measured with the potential acuity meter.

For smaller pupil diameters (<2 mm) the Maxwellian pupils produce slightly larger ABDD's than the corresponding physical artificial pupils do, and, for the smallest Maxwellian pupils the ABDD's remain dependent on defocus. Westheimer[19] presents a mathematical treatment of blur disk formation in coherently illuminated Maxwellian view systems and shows that retinal image blur disks are affected by the target defocus. Subjects in our experiment observed that, for smaller pupil diameters at larger magnitudes of target defocus, Maxwellian viewing created blur disks that had indistinct margins, and some ringing was evident. For the physical artificial pupils of the same size, the blur disks appeared to have sharp borders. The reduction in visual acuity with increasing defocus for the smallest Maxwellian viewing pupils was disproportionately larger than the increased ABDD's. We attribute this to defocus, which produces phase distortions that degrade the spatial fidelity of the retinal image and so reduce resolution but that have less effect on the appearance of the blur disk.

The progression of the differences between Maxwellian and physical artificial pupils that occur when diameters are <2 mm is expected because of the coherence properties of light becoming more important to image quality when pupil diameters become smaller. When detailed targets are viewed with a Maxwellian pupil size of 0.5 mm, light may be considered to be essentially coherent, and the plane of the Maxwellian pupil contains the spatial transform of the target being viewed. This diffraction image of a Maxwellian view system occupies an area that is significantly larger than its exit pupil, and provided this diffraction image is not blocked by the eye pupil or media opacities, high-spatial-frequency information may be conveyed to the retinal image. In contrast small physical artificial pupils act to limit resolution by filtering some higher-spatial-frequency content from the image.

Blur disk diameters and resolution performance are essentially identical and for viewing with physical and optical artificial pupils when pupil sizes are 2.0 mm or greater. There are, however, significant deviations from the geometrically based predictions of ABDD and MAR. First, blur disk sizes were found to be larger than predicted for myopic defocus and smaller for simulated hyperopia. These effects could be attributed to positive spherical aberration of the eye. Second, when pupil sizes are larger the visual acuity in defocused conditions was better than that predicted from the blur disk size. This may be a result of the Stiles–Crawford effect, which Westheimer[19] suggests is probably equivalent to an apodizing filter with a radially symmetric gradient of density being placed over the eye pupil. The Stiles–Crawford effect should cause the blur disks to have effectively a more

gradually tapered profile, which was neither observed nor accounted for in our measurements of ABDD but which could be responsible for acuity improvements that are disproportionate to the perceived blur disk diameter.

Retinal illuminance differences could possibly contribute to the perceived ABDD. It is conceivable that systematic errors in the control of retinal illuminance may have contributed to the trend for ABDD's to be larger for Maxwellian viewing when pupil diameters were 2 mm or less. We therefore conducted an experiment measuring relationships between ABDD and defocus over a 4-log unit range of retinal illuminances for a full range of pupil sizes, and for this experiment we used a third subject. Over this range (0.003–30 trolands) retinal illuminance had little effect on measured ABDD's, and no systematic changes were observed. During the main experiments there were no noticeable variations in target luminance observed by our subjects, and we conclude that if there were errors in controlling retinal illuminance they were small and did not contribute to any systematic trends in our results.

Fields of View

When physical artificial pupils are located just in front of the eye, the artificial pupil and the eye pupil may create vignetting effects that restrict the field of view. For example, calculations show that a 1-mm artificial pupil located 12 mm before a 5-mm eye pupil will cause vignetting to begin at 19 deg, and for an eye pupil of 8 mm vignetting commences when the field size is 32.5 deg (see Table I). To ensure wide fields of view when using physical artificial pupils, the artificial pupil aperture should be close to the eye, and the eye pupil should be dilated.

Maxwellian viewing is free from such vignetting problems, and the field of view is limited by the Maxwellian lens with only a small influence from the size of the Maxwellian pupil. The proximity of the Maxwellian exit pupil to the eye pupil can affect the resolution.[20] When the illumination from a Maxwellian view system can be considered coherent, the eye pupil may act as a spatial filter removing potentially visible spatial frequencies if the eye-pupil diameter is < 2.4 mm or if the Maxwellian exit pupil is decentered so that it comes too close to the edge of the eye pupil. For Maxwellian view systems in which high spatial frequencies should be passed, the size and position of the eye pupil should be controlled so that it does not occlude part of the diffraction image that is formed in the plane of the eye pupil.

Conclusions

We set out to determine the extent to which physical and Maxwellian artificial pupils could be considered to be equivalent. Provided that the pupil diameters are 2 mm or greater, both physical and Maxwellian artificial pupils provide essentially equivalent visual resolution and angular blur disk diameters over a wide range of defocus values. When physical artificial pupils of 2 mm or larger are used, the eye pupil should be dilated to avoid undue limitations of the field of view. At large pupil diameters spherical aberration of the eye may have different effects for myopic and hyperopic defocus, and the Stiles–Crawford effect may serve to enhance visual acuity.

For small pupil sizes physical artificial pupils can act as pinholes. A 0.5-mm physical artificial pupil causes vision to become diffraction-limited so that visual acuity is reduced even for in-focus imagery, and with such pupils the resolution remains unaffected by defocus. When the smaller optical artificial pupils are used in appropriately arranged Maxwellian viewing conditions, the visual resolution is always excellent for in-focus vision, but the resolution is still affected by defocus.

Applegate *et al.* independently conceived and planned a similar experiment investigating relation-

Table I. Fields of View with Physical Artificial Pupils[a]

		Field Stop Eye, Pupil (mm)					
		3.0		5.0		8.0	
		Aperture Stop, Artificial Pupil (mm)					
Angular Fields of View[b]		1	2	1	2	1	2
Field—full illumination	(Vignetting begins)	9.5	4.8	18.9	14.3	32.5	28.1
Field—half illumination	(Half-vignetting)	14.3	14.3	23.5	23.5	36.9	36.9
Absolute field	(Vignetting complete)	18.9	23.5	28.1	32.5	41.1	45.2
Widths of Fields of View[c]							
Field—full illumination	(Vignetting begins)	1.6	0.6	3.2	2.3	5.7	4.8
Field—half illumination	(Half-vignetting)	2.5	2.5	4.2	4.2	6.7	6.7
Absolute field	(Vignetting complete)	3.4	4.4	5.1	6.0	7.6	8.5

[a]Field sizes in degrees.

[b]Widths in centimeters at 10 cm from eye pupil.

ships between visual acuity and the diameter of physical and Maxwellian pupils. They reported their results in R. A. Applegate, A. Bradley, and L. N. Thibos, "Visual acuity and pupil size in Maxwellian and free view systems with and without refractive error," in Noninvasive Assessment of the Visual System, Vol. 1 of OSA 1992 Technical Digest Series (Optical Society of America, Washington D.C., 1992), pp. 170–174.

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