The influence of exit pupil diameter on visual acuity – a personal investigation

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An extended object and a point source test pattern were observed through a range of apertures simulating exit pupils of different sizes. Clarity of vision was found to vary as a function of 'exit pupil' size and the nature of the test object. Optimum definition was obtained with apertures of about 3mm for extended objects and a little less for point sources of moderate brightness. Bright point sources were more poorly resolved at all apertures because of glare. The results are indicative that low power instruments with exit pupils around 3mm and of relatively modest aperture, will yield superior definition than larger instruments of similar magnification. At higher powers small aperture instruments (within their diffraction limited capabilities) would also be expected to give better definition of bright double stars than larger instruments at comparable magnifications.

Introduction

'Every amateur astronomer should own a pair of binoculars.'[1] This is typical of the advice given to novice astronomers. Binoculars come in a variety of shapes and sizes but are generally specified in the familiar format Magnification × Aperture (mm) (e.g. 8×30). A selection of binoculars advertised in recent periodicals[2] is shown in Figure 1, which graphically demonstrates the wide range of magnifications and apertures available in instruments for astronomical and/or general purpose use.

A feature of binoculars often seen in advertisements is the diameter of their exit pupil (effectively the diameter of the beam of light emerging from the eyepiece.) Large exit pupils are associated with comfortable viewing and good performance in poor lighting.

For binoculars and telescopes in normal use the size of the exit pupil conforms to the familiar relationship:

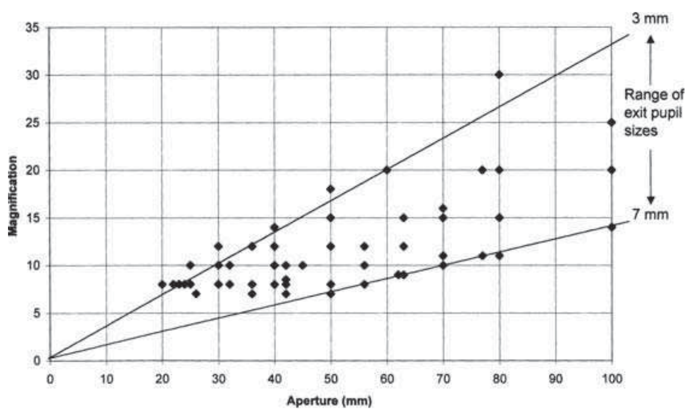

Figure 1. Specifications and related exit pupil sizes for a range of commercially available binoculars.

Magnification
= Clear diameter of objective / Diameter of exit pupil
= Focal length of objective / Focal length of eyepiece

A more complete discussion of this topic is found in standard texts such as Sidgwick.[3]

It can be seen from Figure 1 that most available binoculars have exit pupil diameters within the range of about 7mm to 3mm. With telescopes using moderate or high magnifications the diameter may be 1mm or less.

The diameter of the (entrance) pupil of the human eye varies with the degree of íllumination over the approximate range 2mm to 8mm.[4] (The larger end of this range is only normally available to those of wide-eyed youth under particularly dark conditions.) A large exit pupil therefore allows more of the natural aperture of the eye to be utilised under darker conditions and hence a brighter image on the retina (at least for extended objects) to be obtained.

The eye is not optically perfect, however, and can be subject to various optical aberrations. The spacing of the photoreceptor cells on the retina is consistent with a diffraction-limited performance (and a maximum resolution of about 1 minute of arc) at somewhat less than full aperture.[5] In common with most camera lenses[6] the eye improves with 'stopping down' to a certain extent below its maximum aperture.

The exit pupil of a binocular or telescope effectively acts as a limiting aperture stop to the dark-adapted eye and its size may therefore be expected to influence the observer's visual acuity. Conversely, in bright light the eye pupil may close and limit the light output from the eyepiece. This effectively stops down the instrument and with inferior optics may lead to an improved image, but this second scenario is not investigated here.

The idea of an optimum exit pupil size is not new and Dall suggested a value of about 3mm in an article concerning the structure and performance of the eye.[7] No specific experimental data were presented however.

Procedure

To eliminate instrumental effects a set of 'artificial exit pupils' was constructed by drilling holes of 1 to 7mm in diameter, at 1mm increments, in a thin aluminium strip. These could be placed one at a time in front of a dark adapted eye to view an extended object or point source test pattern. No other optical instrument was used.

The extended object was a copy of part of a photographic test chart consisting of light and dark bars with a spacing of 1.25mm. The bars are set out in blocks at different orientations (i.e. horizontal, vertical and diagonal) as a test for direction-dependent aberrations such as astigmatism. This was chosen to simulate observation of terrestrial or perhaps lunar features. It was illuminated with either a diffuse torch beam in a darkened room, to simulate twilight conditions, or with a spotlight in a day-lit room to approximate to 'cloudy-bright' daylight illumination.

The point sources consisted of an 'asterism' of three small pinholes in thin aluminium foil. The holes were placed at the apices of an equilateral triangle having 2mm sides. (This shape was chosen for consistency with the previous test chart so that direction-dependent aberrations could be detected whilst allowing a constant point source separation in each direction.) This was placed over the diffused output of a lamphouse. The intensity of the lamp was controlled by a variable transformer. A Weston Master III photographic light meter was used to calibrate the unfettered lamp output with respect to the filament current. This is shown in Figure 2.

Two conditions of illumination were employed with the 'asterism'. In the first the lamp brightness was held constant near its maximum level throughout. (Larger exit pupils would therefore produce brighter images.) In the second the lamp output was varied in inverse proportion to the area of the 'exit pupil' used (the current and corresponding apertures are also shown in Figure 2) so that image brightness would appear at least approximately constant throughout. The changing colour temperature of the lamp at different intensities would probably elicit a different response in the light meter and the observer's eye, so exact correspondence is unlikely.

When observing the test patterns a retractable tape measure was held in the hand and the free end fixed at the position of the test object. With one of the 'exit pupil' apertures over a dark adapted eye, the chart or 'asterism' was approached until all the elements of the pattern could be clearly seen. (The criterion 'clearly seen' was chosen as giving greater consistency in observation than the more debatable, and more stringent, 'just resolved'. This also implies a situation where detail is readily discernable to an experienced observer rather than after protracted observation). The distance from the chart to the eye, at this point, was measured with the tape. Similar measurements were made with each aperture in turn and the procedure repeated to give a total of 4 determinations for each aperture.

The corresponding angular separations of the elements of the test objects were calculated from their linear spacings and the distance from which they were first clearly seen. The mean value and 95% confidence about the mean were calculated for each 'exit pupil' for each of the test conditions.

Most observations were carried out in a darkened room with the eye given time to dark adapt. A red filtered torch was used to read scales and record results so as not to compromise dark adaptation.

As far as possible the test conditions, although limited, were designed to simulate typical observing conditions. It is appreciated that these can at best only approximate to actual conditions and the diverse nature of objects encountered.

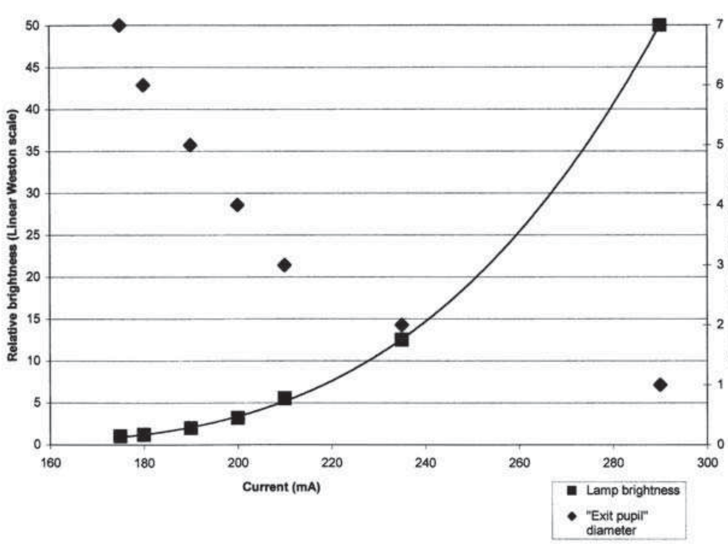

Figure 2. Calibration of changing lamp brightness.

Results

The results presented are those obtained with the author's eye alone. The resolution values are somewhat poorer than the previously quoted one minute of arc ideal. This, to a certain extent, reflects this individual's eyesight but also the less stringent 'clearly seen' observation criterion. The imposition of an external limiting stop, be it physical or an optically produced exit pupil, may also degrade the eye's performance if it is not co-incident with the eye's own entrance pupil or not symmetrically positioned around the optic axis. In any case it is generally accepted that under astronomical conditions of observation (which these tests were designed to simulate) the performance of the human eye particularly with point sources falls below the ideal.[8]

Figure 3 displays the angular separations at which the extended object test pattern could be

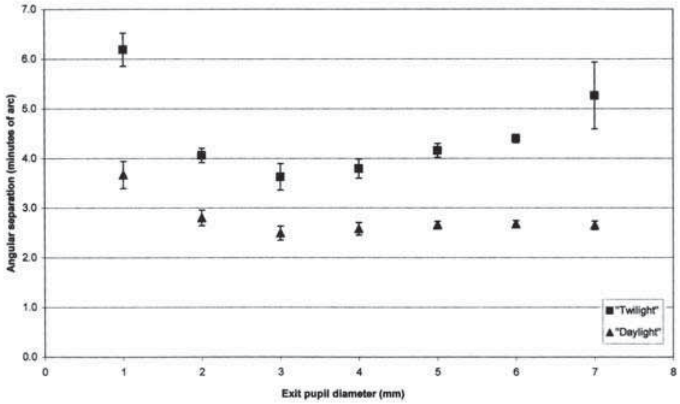

Figure 3. Angular separation at which the extended object test pattern could be clearly seen at each 'exit pupil' size, for 'twilight' and 'daylight' conditions.

clearly seen at each 'exit pupil' size. (The smaller the angle, the greater the clarity of vision.) Greatest resolution was obtained at an aperture of about 3mm. A significant decrease was evident at much larger or smaller apertures under twilight conditions. Under bright conditions the eye pupil did not open enough to fill the larger test apertures above about 4mm, so resolution remained practically constant for these. The test pattem was clearly less well seen under simulated twilight conditions than in daylight even at similar apertures. This was presumably a result of greater 'signal to noise ratio' under the stronger illumination.

Figure 4 shows the result for observations of the 'asterism'. The upper data series represents the situation where the perceived image brightness increased with the size of the 'exit pupil'. This is analogous to maintaining constant magnification but progressively increasing aperture (e.g. 10×30, 10×50, 10×70 etc. binoculars). The lower data series represents approximately constant image brightness irrespective of exit pupil size. This is analogous to changing the magnification at constant aperture (i.e. changing eyepieces on a single telescope).

Both series started at approximately similar brightness for the smallest aperture. This was visually similar in appearance to a bright star or planet seen with the unaided eye.

Under constant image brightness conditions, the trend in resolution is generally similar to that for the extended source but with best definition at slightly smaller apertures. In contrast, where image brightness was a function of exit pupil diameter, definition fell off steadily as exit pupil diameter increased. The increase in pupil diameter would have increased brightness by a factor of almost 50 for this data series at the largest aperture and the closer approach of the eye necessary to resolve the pattern would have increased this even further. Through the 7mm aperture the total difference in illumination between the two data series was something like 5 or 6 stellar magnitudes (comparable to the enhancement produced by large binoculars or a small amateur telescope over the naked eye view). The combination of the increased size of exit pupil and greater illumination is clearly deleterious to definition. No optimum aperture is apparent within the range considered with the smallest 'exit pupils' clearly advantageous to definition. An over-bright image will result in dazzle to the observer's eye and a spreading of the image on the retina (irradiation). This is a well documented effect which leads to difficulty in resolving bright double stars or those with somewhat unequal components.[9]

It is possible when observing bright point sources that the observer's iris would involuntarily close to less than the imposed exit pupil size. The results obtained are stíll a valid measure of the eye's response to such imposed conditions even though the full exit pupil is not used.

Note

The angular separations shown in the figures apply to those clearly resolved by the unaided eye. Where an optical system is used they must be divided by the magnification of that system to obtain the actual angular separations at the object itself. For example taking the 'twilight' data from Figure 3 with a 10×30 instrument (3mm exit pupil), my eyes should clearly see detail separated by 3.6/10 = 0.36' or 22" of arc. However, with a 10×70 instrument (7mm exit pupil) this would be 5.3/10 = 0.53' or 32" of arc. The smaller aperture instrument would consequently give the better definition.

Discussion

This observer is a little past the age of wide-eyed youth. My pupils will still open beyond 6mm under dark conditions but struggle to reach the 7mm of the test conditions. Increasingly, I suffer from far sightedness and a small degree of astigmatism. The use of spectacles very slightly improved the clarity of vision at the two largest test apertures but only results from my unaided 'master' eye are reported here. Clearly, these are subjective and no doubt many eagle-eyed observers will surpass these levels of resolution. Consequently they cannot be considered as definitive values and individuals may care to make their own determinations. An amalgamation of such results should determine more pre-

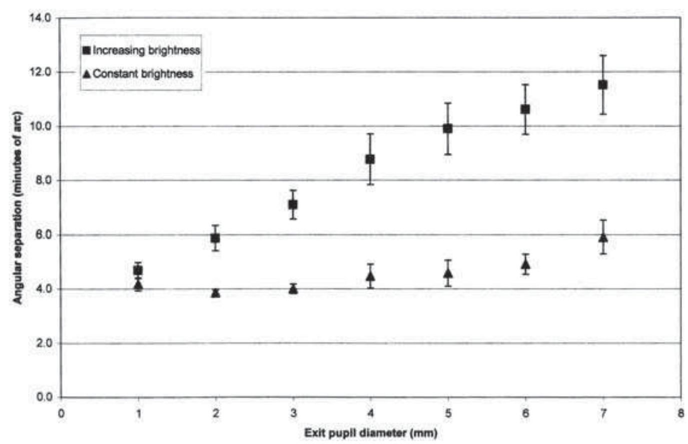

Figure 4. The point source test pattern observed with increasing brightness (upper series) and constant brightness (lower series). See text.

cisely what an 'average' observer might discern. This could perhaps be a project for a student or an interested society to undertake and include a more detailed investigation on the effect of varying the test conditions than is reported here.

Theoretically the maximum resolution (R) of a good quality (diffraction limited) instrument is determined by the diameter (D) of its objective. The well known Dawes limit R" = 116/D mm[10] is an empirical expression of this for equally bright double stars. High powers (and consequently small exit pupils <1mm) are normally applied to obtain this resolution. With low power instruments this limit may never be reached, then magnification and the visual acuity of the observer are the limiting factors not the aperture. When visual acuity is highest the image will be as well resolved as it can be at that magnification. Increasing power may push the resolution towards the Dawes limit but will be accompanied by the familiar 'softening' of the image as diffraction effects predominate. At larger exit pupils than optimum, visual acuity may suffer due to increasing eye aberrations. Of course in practical observational seeing conditions, sky brightness and transparency etc. impose further limitations beyond the control of the observer. However, small apertures are less affected by poor seeing and small exit pupils darken the sky background.

The results indicate that the size of an instrument's exit pupil should influence the perceived clarity of image regardless of its inherent optical quality. I use 8×50 binoculars[11] for astronomical and general use (exit pupil 6.3mm) whilst my wife uses a compact 9×25[12] largely for daytime use (exit pupil 2.7mm). Both are of good optical quality and yield comparably sharp images in bright daylight.

Under twilight or astronomical conditions the larger instrument unsurprisingly provides a substantially brighter image. Prominently lit terrestrial objects and bright stars, however, seem more clearly defined in the smaller instrument although faint detail is lost. This observation in fact prompted the investigation here described and is quite consistent with the results displayed in Figures 3 and 4 (i.e. optimum definition for extended objects at an exit pupil of about 3mm, increased aperture at constant magnification deleterious to definition of bright point sources).

Although primarily concerned with the large exit pupils found with low power instruments the arguments can also be applied to higher power telescopes. I have a 55mm refractor (Dawes limit about 2.1"), which clearly, if tightly, resolves the bright double star Castor at ×70 (exit pupil about 0.8mm). Extrapolating the results from the triangular 'asterism' test object to an actual binary star must be treated with some caution but considering Figure 4, the unaided eye might be expected to clearly resolve about 4.5' of arc under these conditions. This corresponds to 4.5'/70 = 3.9" at the object. A recent value for the separation of Castor is 4.0",[13] in good agreement with expectation. My 222mm Newtonian (Dawes limit about 0.52") would have an exit pupil of about 3.2mm at the same magnification and produce a considerably brighter image. Again consulting Figure 4 (upper series) the eye might be expected to resolve about 7' of arc which corresponds to about 6" at the object. This would make Castor a difficult object at this power. Indeed experience shows that a higher power (i.e. smaller exit pupil) and good seeing are required for clearly resolving Castor with this telescope despite its inherently superior resolving power.

Under conditions of indifferent seeing I sometimes use a 90mm off-axis aperture stop on the 222mm Newtonian (i.e. reducing aperture and exit pupil size). At powers of ×90 to ×180 this generally improves the images of bright stars (e.g. resolves Castor) but lunar and planetary images, although steadier, lose contrast. Again this is consistent with the results displayed in Figures 3 and 4 (small exit pupils and reduced illumination benefiting bright point sources but resulting in a loss of definition in extended objects).

It is suggestive that the often precocious performance of small refractors on bright double stars is, in part at least, a consequence of their small exit pupils and limited light grasp. Interestingly the range of image-stabilised binoculars much vaunted for astronomical use[14] employs magnifications and relatively small apertures which result in exit pupils around the 3mm mark. This would seem a more favourable combination for good stellar definition than larger aperture and lower magnification alternatives.

Conclusions

The results from simulated exit pupils indicate that, for this observer, the diameter of an instrument's exit pupil would influence the perceived definition of the image. This is a result of the changes in visual acuity as the aperture of the dark adapted eye is effectively controlled by the exit pupil size. At large apertures eye aberrations increase, at small apertures diffraction effects predominate.

For extended objects maximum definition was achieved for an exit pupil aperture of around 3mm and fell off markedly at much larger or smaller apertures. A higher light intensity improved definition at each aperture.

For simulated stars (point sources) high light intensity and large exit pupils were deleterious to good definition. Point sources of equivalent intensity to bright naked eye stars were best seen with an aperture of around 2mm; brighter sources were less clearly discerned, because of glare, but benefited from smaller apertures.

The above implies that for maximum visual clarity low power instruments such as binoculars should have an exit pupil of around 3mm to maximise visual acuity, and a relatively modest aperture (when maximum light grasp is not a prime requirement) to minimise glare. Specifications for suitable instruments may be gleaned from Figure 1.

Similarly small telescopes might be expected to outperform larger instruments, at comparable magnifications, when observing bright double stars within their diffraction limited capabilities.

These findings, although extrapolations from a simple 'kitchen table' experiment, are in agreement with general observing experience using binoculars and telescopes on stellar and extended objects.

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