Telescope specifications ("Optics IV")

References:

Telescopes and Techniques, C. R. Kitchin, Springer publishing

Somewhat obnoxious animation, but maybe helpful: https://slideplayer.com/slide/8993523/

Telescope optics and viewing details: https://www.handprint.com/ASTRO/

Term	**Description or explanation.** **Equation.** **Desired range or ideal value.**
Seeing	*'Seeing'* describes how steady the atmosphere is. With poor seeing, stars appear twinkly without a telescope and look blurred through telescope. This is also called "scintillation"
Objective or primary	The objective lens or mirror is the optical element that the light from the object being viewed first encounters. It is also referred to as the "primary lens" or "primary mirror"
Objective diameter (D)	The diameter of the primary mirror or lens, D Range: Larger diameters provide ability to see fainter stars and have greater magnification and resolution if the seeing is good; however, they are more sensitive to atmospheric disturbance. Small objectives perform a bit better when seeing is poor (stars are twinkling). Also, small objectives result in smaller overall telescope size and lower weight telescopes – and less expensive, too. D = 8 inch is considered by many to be an "ideal" general purpose scope.
"Size" of telescope	"Size" almost always refers to the objective's diameter. A "*200mm refractor*" has a 200mm diameter objective lens.
Entrance pupil	The diameter of the objective (primary mirror or lens), D
Exit pupil (d_{exit})	The diameter of the collimated light leaving the eyepiece towards the eye. $d_{exit} = D/M$ where D is the objective diameter and M is the magnification. Range: 2mm to 5mm is best, but these are not hard limits.
Rich Field	"*Rich field*" refers to low magnification views that allow for many stars to be visible in the field of view at one time. Rich field telescopes are designed to have low magnification (short focal length).
Magnification (M)	Magnification is how much larger the image appears to the eye (measured as an angle). M = Focal length of primary optic / focal length of eyepiece. Also: $M = D/d_{exit}$ High magnification allows for better detail if seeing permits. Lower magnification allows "rich field" experience.
Apparent Field of View (AFOV)	The angular size of the sky that is apparent to the eye. It is a function of the eyepiece design only. Generally, the bigger the better. 70° AFOV provides a "window" into space and 100° is a much bigger window. Less than about 35° AFOV becomes a "pin-hole" view. The "cost" to larger AFOV is that additional lenses are required: increasing weight and slightly reduced light transmission. The other cost is financial. A respectable 45° eyepieces will typically cost around $50. 70° will cost at least $150 (but "the sky is the limit" on costs).
Field of view (FOV)	The angular size of the area of the sky visible in the telescope. FOV = AFOV/Magnification
f/#	The focal ratio, aka, f-number. f/5 or less (such as f/4) are "fast" telescopes. f/# = objective focal length/D There is no ideal. Too "fast" and image quality may suffer. Too "slow" and the scope may be too long. f/4 to f/15 are "typical"

Focal ratio

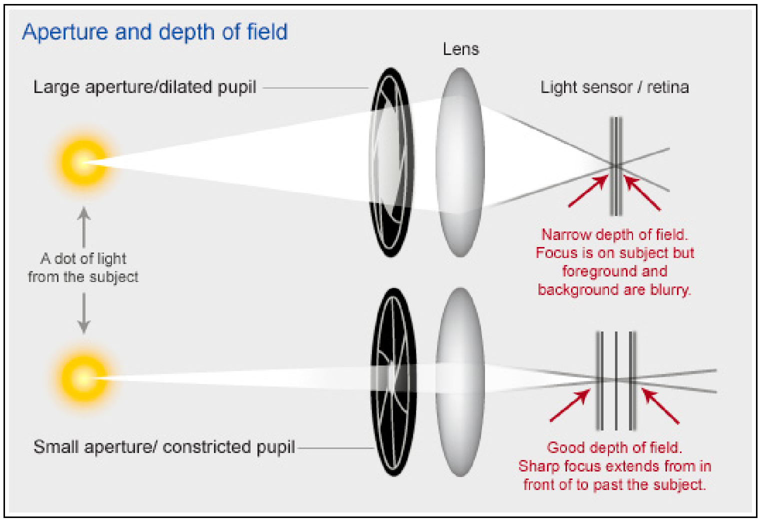
With all optics (cameras, telescopes, etc.) the focal length is the distance from the lens or mirror that an object on the optical axis at infinite distance is brought to a single focused point (as we described previously). The focal ratio is the ratio of focal length to the diameter of the primary lens or mirror. For example, assume a 50mm diameter lens has focal length of 400mm. That lens would have a focal ratio of 8 (400mm/50mm = 8). This is written as f/8. A focal ratio of 4.5 is written as f/4.5, etc. This is also referred to as "the f-number" (the f-number of an f/8 lens is f/8).

What is unique with camera optics (at least with Single Lens Reflex cameras (SLR)), is that the aperture of a lens is adjustable – it can be opened wide or stopped down to a narrow opening. This could be done with any lens including telescopes, but for astronomy stopping down the aperture generally serves no purpose.

https://houseofroseblog.com/how-to-use-your-camera-manual-mode-understanding-aperture/

Camera aperture has two effects: larger apertures allow more light to pass through, and therefore the camera shutter must be quickly opened and shut to prevent too much light from entering (which may saturate the image). Small apertures let less light through; and therefore, require slower camera shutter speeds. In the image above, f/1.8 would require relatively fast shutter speed and f/22 would require a relatively slow shutter speed (how fast and how slow would depend upon how bright the object is, etc.).

The other effect is on depth of field. Depth of field describes how "in focus" an object appears even if it is not at the precise focal location. Large apertures (such as f/1.8) have low depth of field and smaller apertures (such as f/22) have greater depth of field. The figure below demonstrates why:

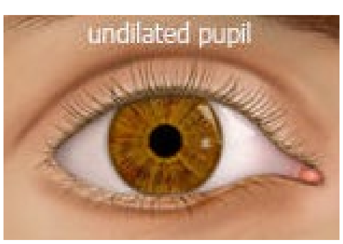


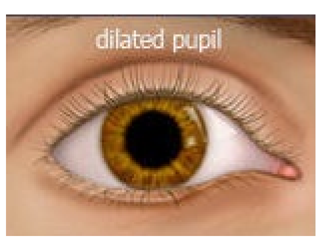
http://www.abc.net.au/science/articles/2010/07/29/2966484.htm

Image at left was taken with aperture of f/22 (small opening). Image at right is with the same lens at the same location but with a faster shutter speed and larger aperture (F/4.5). The objects in the background are in focus in the left image and out of focus in the image at the right.

Notice that the image size is in no way affected by aperture. Only the amount of light passing through the optics and the depth of field are affected.

Since with telescopes all objects are effectively at infinity, depth of field is not important in telescopes. However, your eye's depth of field is affected by your pupil size. In bright light, the iris contracts letting in less light (and avoiding saturating your retina). In dim light, it dilates to allow in more light. Under bright light conditions, the human eye has a focal ratio of about f/8.3 and under dim conditions about f/2 to f/3 (Ref: https://petapixel.com/2012/06/11/whats-the-f-number-of-the-human-eye/). Therefore, your depth of field is greater in bright light than in dark lighting.





JirehDesign.com

The phraseology from photography that describes shutter speeds in relation to aperture has carried over into telescopes. Telescopes with about f/5 or less (such as f/4) are referred to as “fast” telescopes. That’s because in photography, fast shutter speeds are needed with large apertures. Typical amateur telescopes are in the f/6 range with a common range of about f/4 to f/15. There are pros and cons to “fast” and “slow” focal ratios.

Pros and Cons

For “fast” telescopes (about f/5 or ‘faster’ such as f/4), precise shape of the lens or mirror becomes more critical. Small deviations from ideal paraboloid starts to affect the image quality. Even perfectly shaped optics with f/5 focal ratio will start to produce “coma” which means that stars not in the center of the image become elongated (look like “beans” rather than points of lights). The faster the focal ratio, the more noticeable coma becomes. This can be corrected with additional optics (coma correctors), but they cost $100 and up, add weight to the top of your telescope, and add more lenses to the optical path.

So why “fast”? Faster telescopes are shorter – more compact. “Slow” telescopes can become unmanageably long. For example, a Newtonian telescope with 8” mirror at f/10 would have a 80” focal length (over 6 feet). That’s a long amateur telescope – it would require a ladder for most people look through the eyepiece. However, Cassegrain designs are inherently compact. An 8” primary mirror at f/10 still has a 80” focal length, but due to the optics, the optical path can physically be fit into a telescope less than 20” in length. So if you want a long focal length telescope, a Cassegrain design may be a good choice (but they are expensive). The compactness is why very large professional scopes often are a Cassegrain design.

Besides these few (but important) pros and cons, what effect does focal ratio have on telescopes? Not much, but focal length does. The common way to describe a telescope is the size of the primary optic (mirror or lens) and the focal ratio. From those two parameters, you can calculate the focal length (as shown in the previous paragraph). Focal length directly impacts magnification.

Mel Bartels is pushing the boundaries creating very fast mirrors. His 25inch f/2.6 mirror has a focal length of only (25*2.6) 65 inches. That’s a very large mirror and no ladder is required! This represents the next major advancement in amateur telescope making for those interested in grinding their own mirrors! https://www.bbastrodesigns.com/25/25%20inch%20F2.6%20Telescope.html

Magnification

Magnification is measured in term of angular magnification. We view the world in terms of angles. An object appears larger if it angular size is increased. At 1X (no magnification) the moon appears to be about 0.5 degrees. At 100X, it appears to be about 50 degrees.

The image at the right has twice the magnification (2X) than the image at left. Magnification is described linearly (an increase in angular size), but the area is squared. In the image at the right, the height of the tree appears to be double the original, but area of the tree appears to be 4 times greater; $(2X)^2$.
The magnification that the telescope produces depends upon the focal length of the objective (lens or mirror) and the focal length of the eyepiece:

Magnification, $M = FL_{primary}/FL_{eyepiece}$

Where:
$FL_{primary}$ = focal length of primary optic
$FL_{eyepiece}$ = focal length of eyepiece

Common commercial eyepieces range in focal lengths from about 3mm to about 40mm. Eyepieces are the optical elements closest to your eye, and are easily swapped in and out of a telescope. Since there is no "ideal" magnification, most amateur astronomers will have a few different eyepieces so that they can change the magnification of their view.

Depending upon the primary optic size, amateur telescopes have focal lengths of about 20 inches to 60 inches; although longer and shorter focal lengths are not uncommon. Let's assume a focal length of 40 inches (40"=1000mm) and a 5mm eyepiece, the magnification would be: 1000mm/5mm = 200X. The same telescope with a 30mm eyepiece would have a magnification of: 1000mm/30mm = 33X. Notice, the diameter of the primary optic nor the focal ratio have any direct impact on magnification – only the focal length matters when calculating magnification.

Remember back, we mentioned that resolution improves with increased primary size. Under excellent conditions, high quality optics can deliver about 50X per inch of diameter. A 4 inch primary mirror's maximum effective magnification would be about 200X. However, the typical limit to magnification is not determined by the optics, but often by the Earth's atmosphere. Regardless of the telescope's design, on a night with very good seeing, about 200X to 300X is a reasonable upper limit for many telescopes. On exceptionally steady nights (exceptionally good seeing), 500X may be possible with large telescopes. On a night with poor seeing, even 60X may too high.

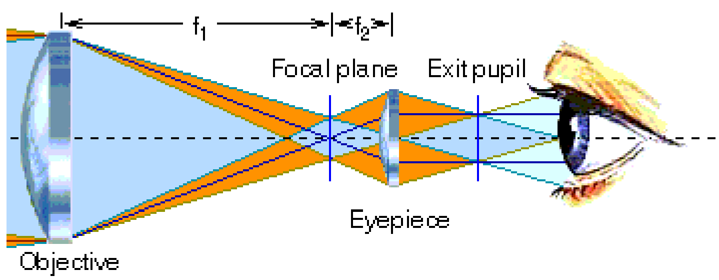
Another limit to magnification is tracking. If you are using a telescope that does not track the stars (move as the earth rotates), the object will not stay in the field of view for very long if you are using high magnification. It can be annoying to constantly be nudging the scope to keep the object in view.

Is there a lower limit to magnification? Sort of. At some point, the telescope becomes useless – just look up at the sky (that's a magnification of 1X). Exit pupil is an important parameter for determining lower limit effectiveness. So that's next.

Entrance Pupil and Exit Pupil

The "entrance pupil" in telescope is the diameter of the primary mirror or lens (objective optic). In an eye, the "entrance pupil" is the diameter of the eye's pupil. In other words, for an eye the entrance pupil = size of the pupil. Under bright light, the iris contracts making the pupil smaller (about 2-4mm). Under dim light, the iris dilates making the pupil larger. A fully "dark adapted" adult eye will have a pupil size of about 4-8mm. Maximum pupil size of a dark adapted eye will vary from person-to-person, and decreases with age.

The "exit pupil" in a telescope is the diameter of the light cone coming out of the eyepiece from a focused pinpoint object (http://www.astrosurf.com/luxorion/reports-epsuggestions3.htm):



The magnification is the ratio of the telescope's entrance pupil to the exit pupil:
Magnification, M=entrance pupil/exit pupil = D/d_{exit} (both typically expressed in millimeters).

As we have seen before, the magnification is also:
Magnification, M = focal length of primary optic / focal length of eyepiece = $FL_{primary}/FL_{eyepiece}$

Therefore, we can calculate the exit pupil: $d_{exit} = D/M$

Let's do an example to determine exit pupil of a telescope. Given: 10" diameter f/5 primary mirror (D=10"=250mm diameter), using a 25mm eyepiece (i.e. the eyepiece focal length is 25mm).

Primary's focal length = D * f-number = 250mm * 5 = 1250mm
Magnification, M = $FL_{primary}/FL_{eyepiece}$ = 1250mm/25mm = 50X (images are enlarged by a factor of 50)
Exit pupil: d_{exit} = D/M = 250mm/50 = 5mm

Since the exit pupil of the telescope is nearly the same as the eye's natural pupil size, this is an "appropriate" magnification. Let's do another example with the same telescope, but the astronomer wants greater magnification, so she decides to use a 5mm eyepiece.

Magnification, M = $FL_{primary}/FL_{eyepiece}$ = 1250mm/5mm = 250X
Exit pupil: d_{exit} = D/M = 250mm/250 = 1mm

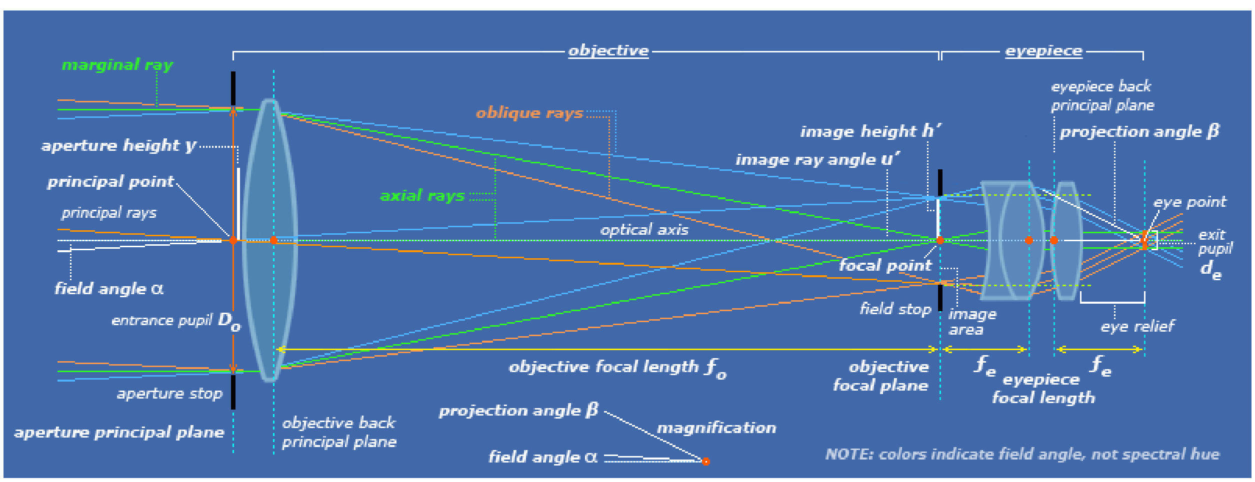
The exit pupil (1mm) is now much smaller than the normal entrance pupil of the human eye, so the eye is not well designed for this small spot. Your brain will now be able to see 'defects' in your eye such as floaters and blood vessels. This is not a problem, but it may reduce your viewing pleasure – but maybe not. If you do want to do lots of high magnification viewing, you should consider a large aperture telescope.

Let's do one more example. Now the astronomer wants to look at broad area of the sky, so she selects a 40mm eyepiece to produce low magnification.

Magnification, M = M = $FL_{primary}/FL_{eyepiece}$ = 1250mm/40mm = 31X
Exit pupil: d_{exit} = D/M = 250mm/31 = 8mm

The exit pupil (8mm) is now larger than the entrance pupil of most eyes – even fully dark adapted eyes. Some of the light coming through the telescope will not reach your retina – it will be blocked by your own eye's pupil. Bright stars will not be quite as bright, and dim nebula will be dimmer.

Conclusion: eyepiece focal length affects magnification and exit pupil. To get the most out of your telescope, the general advice is select eyepieces that provide an exit pupil of about 1 to 2mm or larger, but not much larger than about 5 or 6 mm. There is no harm in using eyepieces that provide exit pupils outside that range, but the view may be less than "optimum" – or not. Try it and see. Each eye/brain is different.

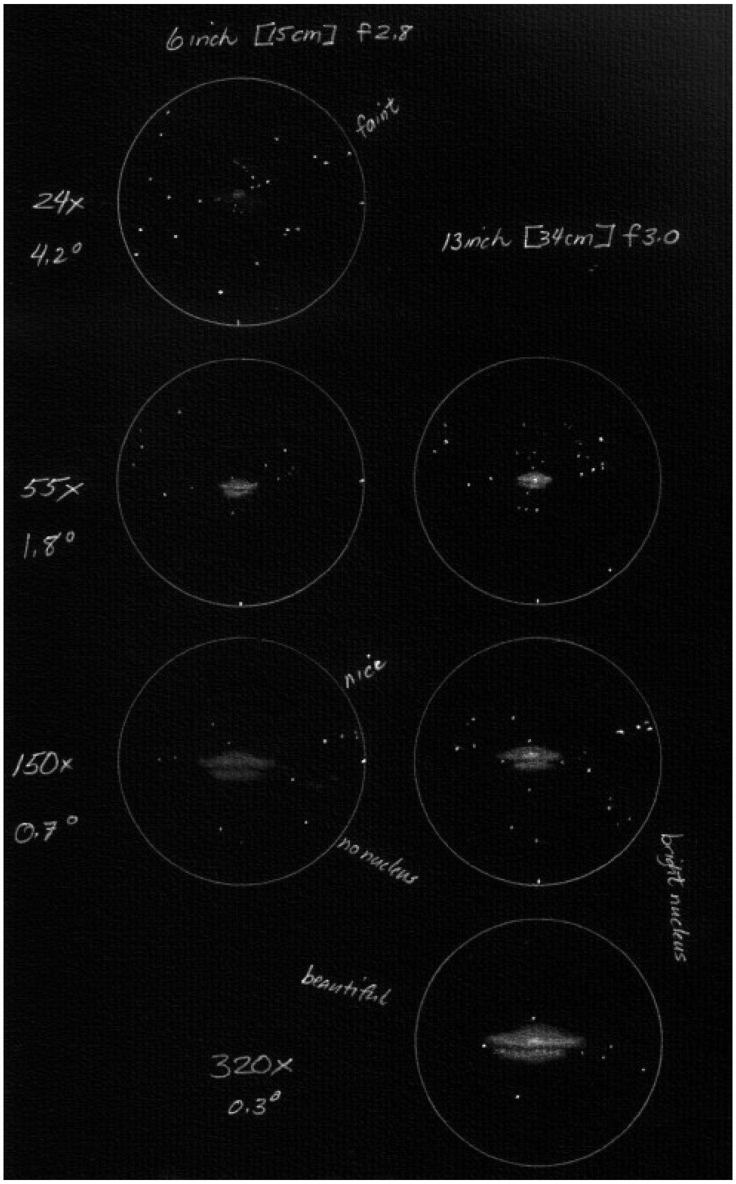


https://www.handprint.com/ASTRO/ae2.html

Telescope's job?
A telescope does two things: it gathers light and it magnifies the image. Only highly specialized telescope designed for incredibly high resolution can magnify a star sufficiently beyond a "point". Amateur and most professional grade telescopes can NOT magnify stars beyond being a point of light! However, when viewing stars (points of light) through a telescope or binoculars, larger apertures increases the brightness and the limiting magnitude. The limiting magnitude is the least bright star that you can see – and aperture affects that. For example, a 4" telescope has a limiting magnitude of about 13.4. A 12" scope increases that by 2 magnitudes to 15.4 – much dimmer stars are visible in a 12" telescope than a 4". The same result is not directly noticed when observing extended images such as galaxies and nebulae.

When telescopes or binoculars magnify an extended image, they spread the light out over a greater area. The net result is that the telescope cannot increase surface brightness of an extended object. So why can we see dim objects, such as galaxies and nebulae better with a larger telescope? Because faint objects that are larger are easier to see. Aperture size does matter, but not as much as one might think.

What is the net effect of increased aperture and increased magnification? Mel Bartels sketch below gives a good example by comparing the same extended object viewed through two different telescopes (6" and 13") but at similar magnifications. The larger telescope does gather more photons, but the eye can only take advantage of that if they are delivered to it. In other words, there is a complex interaction between the telescopes entrance pupil (size of the primary mirror), exit pupil, and your eye's pupil.



Lulay's additional notes. For Mel's sketches, here are the exit pupils (d_{exit} = D/M) for the sketches:

	mag	6" (15cm)	13" (34cm)
Exit pupils (mm)	24	**6.3**	
	55	**2.7**	**6.2**
	150	**1.0**	**2.3**
	320		**1.1**

Note: dilated human eye pupil is typically 5-7mm.

Photograph of the *Sombrero Galaxy* that Mel was sketching: 

For Mel's own comments: https://www.bbastrodesigns.com/Is%20Aperture%20King.html

What if the exit pupil is larger than my eye's pupil? It simply means that some of the light from the telescope is not entering your eye – this is NOT problematic! However, it does mean that some of the light is "wasted" and that you could use a smaller telescope to get the exact same surface brightness. Mel Bartels' eyes probably have dilated pupil size of 6 or 7mm. But let's pretend his eyes have changed since drawing these sketches, he now has very small eye-pupil of 2.7mm. What would change in his sketches? His sketch using the 6" telescope at 24X would be much fainter than it is above because his "new" eyes would only let in 2.7mm diameter of light (where as the exit pupil of the telescope eyepiece is 6.3mm). Since the all of the light from the 6" telescope at 55X (2.7 mm exit pupil) would enter his eyes with both his "old" eyes (6mm or 7mm pupil) and his "new" eyes (2.7mm pupil), there would no change to what he sees – his new sketch at 55X with the 6" telescope will look like the one above. However, if he were to look through his 13" telescope at 55X (exit pupil of 6.2mm), with his "new" eyes (2.7mm pupil) it would look **just like the 6" scope's** view – much dimmer than the sketch above with the 13" telescope! The light striking his retina would be the same at 55X for both telescopes.

Here is what *I think* is true regarding changes in magnification:

<u>Extended objects (nebulae, galaxies, etc.)</u>:

For ***low magnification*** ($d_{exit} > d_{eye\text{-}pupil}$) the surface brightness is not affected by changes magnification, but by definition the image size is. Larger appearing objects will activate more rods and cones in your eye, so the object becomes easier to see with higher magnification.

We know that when our eye's pupil size is decreased, less light is received by our retina making objects appear dimmer. At high magnification, where magnification results in the exit pupil being smaller than our own eye's pupil ($d_{exit} < d_{eye\text{-}pupil}$), the amount of light received by our retina is as if our own eye's pupil was decreased to the size of the exit pupil; resulting in a decreased perceived brightness. Therefore, for high magnification ($d_{exit} < d_{eye\text{-}pupil}$) the surface brightness *decreases* with further increased magnification (I think). However, because extended objects increase in apparent size they may become easier to see with higher magnification (assuming they remain bright enough to activate the rods and cones in your eye). Also working in our favor is that while the object's brightness decreases, so does the ambient sky-light; therefore, contrast remains constant. Note: a truly dark sky (no light pollution from natural or artificial sources) is about 21.8 mag $arcsec^{-2}$ (Wikipedia). It is an extended object and will be affected by a telescope the same way as any other extended object.

<u>Stars and Star-like objects (point sources of light)</u>:

For low magnification ($d_{exit} > d_{eye\text{-}pupil}$) the brightness of stars will increase with increased magnification up until $d_{exit} = d_{eye\text{-}pupil.}$ For greater magnification ($d_{exit} < d_{eye\text{-}pupil}$) brightness will remain unchanged with changes to magnification. Even though stars are points, they will appear larger as the Airy's disk will increases with greater magnification. However, you will never resolve any detail in a star no matter what magnification is used.

These changes will be subtle. The "take away" is that you should not hesitate to try different magnifications when looking at objects to determine what is best.

Conclusion:

Bigger aperture telescopes gather more light, but cannot increase the surface brightness (the amount of light in a given area). Larger images activate more rods/cones in your retina and make dim objects easier to see and therefore, may appear brighter.

When is more magnification not better? Other factors such as seeing conditions (steadiness of the atmosphere) and how fast an object moves through the eyepiece are often the two most significant factors limiting magnification. There are other limits including theoretical limits to optical resolution and the quality of the telescopes optics. And for large objects, lower magnification may produce a superior view. So when is more better? There is no general answer – try it and see. Each object is different, each person is different, each night is different.

When is less magnification better? If you want to see a larger area of the sky (such as a rich-field view with many stars visible at once), then low magnification is generally better. However, with low magnification, the exit pupil becomes larger and hence less of the light enters your eyes (effectively making the telescope behave as if it had smaller aperture). No harm in this, but less star-light is gathered to your eye if $d_{exit\text{-}pupil} > d_{eye\text{-}pupil}$