How to Optimize the Sharpness of Your Photographic Prints: Part I - Your Eye and its Ability to Resolve Fine Detail

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Abstract: In the first of this series of two articles the ability of the human eye to resolve closely spaced details is discussed. We will also discuss what level of detail is needed in a negative to result in resolvable detail in a photographic print. In the second we will continue the discussion and also present useful charts that can be used in the field to make sensible, even optimal, f-stop selections to ensure maximum sharpness.

Introduction

Sharpness may or may not be desirable in a photographic print. Indeed, in the early part of the twentieth century non-sharp images were the norm. The advent of sharpness, championed by the f/64 group and its icons of photography changed things and broadened the notion of what was acceptable in a photograph. If one is interested in producing sharp detail in a photograph, one ultimately is led to the question, "How sharp is sharp enough?" The answer depends on many things and we will explore these over the course of these two articles.

To get at our question we will begin at the beginning. This first article will take us through a discussion of the ability of the human eye to resolve (or see as separate) two fine details that are close to each other. We will be able to quantify the limit of typical human ability to resolve fine detail by use of a concept known as the visual angle and compare this to the notion of 20/20 "normal" vision. In this article we will discuss limitations to sharp vision that are imposed by the anatomical structure of the eye and also by the behavior of light as understood by physics because each of these plays a critical role in the answer to our question. We will also explore the concept of resolution or sharpness in a negative and we will connect this to human ability to allow us to understand how sharp is sharp enough for a negative and a photographic print.

With that as background, we will in the second article go on to introduce information that will provide us with the means to obtain a clear answer to two practical questioins: (1) *Which f-stop will be the best* to ensure that a certain *range of distances* from the camera in a scene will be rendered in *optimally sharp focus*? And, (2) What *range of f-stop values* is available to us so that the selected range of distances in the scene will be *acceptably* in focus? This second question is a different question from the more often stated question of where in the scene should one set the focus position to allow for maximum depth of field. For that question, one sets the focus at the hyperfocal distance, H, and when one does that the depth of field is from a distance H/2 from the camera all the way to infinity. We could cover that topic as well, but that would take us off our main course.

What Your Eye Can See

The normal human eye is a remarkable device. It is composed of a roughly spherical enclosure with an iris behind the cornea that sets the diameter of the pupil that lets light into the eye, a lens to help focus the light, and a light sensitive region on the back of the eyeball, the retina. Small but discrete structures called rods and cones are the receptors of the light and are located in the retina. The rods and cones receive light, convert it into electrical signals, and send these signals on a complex pathway to the brain where they are interpreted. In the most important region of the retina there are only cones and this region produces the sharpest vision in bright light. In may be helpful to think about the eye as a familiar image capture device, i.e. a camera. The retina corresponds to the film, or better to a digital array that captures the image in a digital camera. The retina and the digital array both convert light to electrical signals and send them along to be processed. Film uses the light to create a latent image in silver halide that is later converted chemically to silver in the negative. The cornea and lens of a typical normal relaxed (i.e. focused at infinity and youthful) human eye together have an effective focal length of about 16.7 mm, which means that the normal relaxed eye has a strength of roughly 59.6 diopters. With the typical range of pupil diameters for a normal relaxed human eye controlled by the iris (roughly 1.5 mm to 8 mm), the f-stop range for the normal eye is roughly f /11 to about f /2.1, with some variation from person to person. At closest focus, the normal youthful human eye has a strength of roughly 68.2 diopters. As one ages, the normal middle-aged eye looses some of its strength and this can be corrected by adding the strength provided by reading glasses.

As remarkable as the eye is, it is not capable of seeing ever smaller details, i.e. it is not capable of perfect resolution. That is, if we place two black dots on a piece of white paper, the eye-brain combination will only sometimes resolve the dots, i.e. see them as separate dots. Whether the dots can be resolved or not depends primarily on *four* things, the distance between the dots, the distance between the plane of the paper that holds the dots and the eye, the level of the illumination, and the contrast between the dots and the surface they are located on. The first two of these factors determine what is known as the angle of view (figure 1) and although we won't dwell on symbolism, this angle is often symbolized by the Greek letter θ, with 2θ defined as shown in Figure 1.

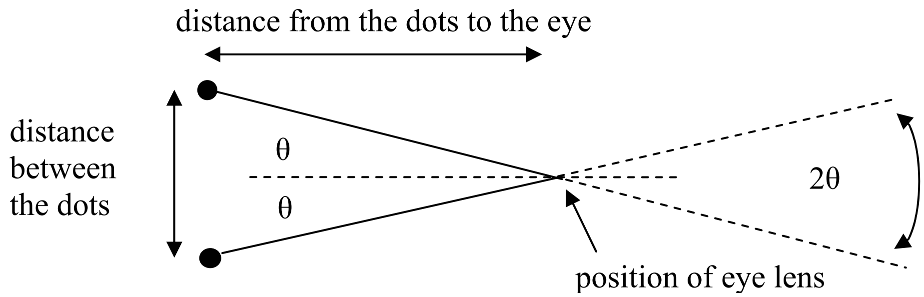

Figure 1: Definition of the angle of view as related to the distance between two black dots and the distance of those dots from the eye. We could just as well have used white lights in an otherwise dark environment.

Now, there is a smallest angle of view such that if the angle is any smaller, the eye is unable to distinguish the two dots as separate. This angle depends importantly on the contrast that is present, but to make the discussion more concise we will simply presume that the contrast is substantial. This minimum angle, called the minimum visual angle, $2\theta_M$, is often taken as the smallest angle at which two dots separated by an equally large white gap can be seen as separate dots (i.e. you can reasonably tell that there are two black dots). This minimum visual angle is defined and is shown in *greatly exaggerated size* in figure 2. This illustration will be in reasonable but not precise accord with a standard convention adopted in the physics of optics, as we shall see in due course.

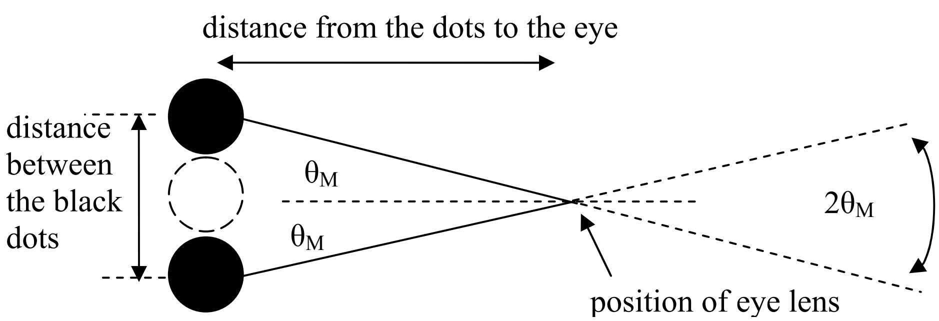

Figure 2: Definition of the minimum visual angle $2\theta_M$ as related to the distance between two dots and the distance of those dots from the eye.

As just noted, the normal human eye has a minimum visual angle; any smaller angle results in an inability to tell that the two dots are separate dots. Separate means that the dots are not perceived to be merged – there is observable non-black between them. When the dots are seen as separate, they are said to be *resolved*. This minimum angle is often called *normal acuity*. For a normal human eye, this angle is generally found under good conditions to be about $2\theta_M = 1/60$ of a degree. So, $\theta_M = 1/120$ degree. (Recall that 360 degrees make a full circle, so 1/60 of a degree is a very small angle. To help get a feel for this, note that the full moon in the sky creates a visual angle from edge to edge of about ½ degree.) In terms of figure 2, this means that if the distance from the dots to the eye is ten inches, then the black dots will be about 0.037 mm in size, separated by 0.037 mm (25.4 mm = 1 inch.) of white space. To get a somewhat different feel for this, if there were small lights attached to the north and south poles of a dark tennis ball, the visual angle between the two lights would be $2\theta_M = 1/60$ of a degree if the tennis ball were about 730 feet away from you.) We will see a bit later in terms of the anatomy of the eye, and separately from physics, where this ability to resolve objects no better than 1/60 of a degree originates.

While one can talk about the ability of an eye to resolve two dots, in photography contexts one instead often talks about the ability to resolve two thin parallel lines; i.e. the ability to tell there are two lines and not just one. This $2\theta_M = 1/60$ degree for the visual angle can be translated into the separation of two parallel lines if one knows the viewing distance. The normal closest viewing distance for reading for an adult is often taken to be 25 cm, or about 10 inches. So, with this normal closest viewing distance, a visual angle of $2\theta_M = 1/60$ degree corresponds to a separation of 0.0739 mm between the centers of two parallel black lines, each 0.037 mm wide that have equally wide white spaces between them. This separation between lines translates into 13.5 black lines (and the associated white spaces between them) per millimeter if there are many lines adjacent to each other. (Note that 1 millimeter is about 0.039 inches.) The picture to have in mind here is of 13.5 parallel lines separated by equally wide white spaces all in a distance of 1 mm. One such line and one associated white space is sometimes referred to as a *line pair* or a *cycle*.

With the numbers stated here, we have described what is generally taken to be the acuity of the typical human eye, an ability to resolve 60 cycles per degree of visual field. This number of lines per millimeter is the limit that can be resolved (i.e. seen as separate) by a normal eye when the viewing distance is ten inches. So, if you were shown a set of such black parallel lines on a printed page, ten inches from your eye, and you had very good vision, you could tell the lines to be separate so long as there were no more than roughly 13 or 14 of them separated by equal-width white spaces in each millimeter. Two per millimeter would be very easy for a normal eye to see as separate, 30 per millimeter would not be possible to see as separate lines. It is commonly stated that the typical eye can readily resolve 5 lines per millimeter at a viewing distance of 10 inches (see Figure 2), but if you have a good normal eye and try the experiment, it is likely that you may be able to do a bit better than 5 lines per millimeter and come closer to the observed limit of roughly 13 or 14. So, for our purposes, we will do better and take as a reasonably stringent standard 10 lines per millimeter. If we aim for this number in a final photographic print, we can be sure that most people who view the print from a distance of ten inches will regard the details in the print as sharp. (The eye-brain combination is rather remarkable and for various reasons can actually resolve lines better than simple dots. This is one reason why we are adopting 10 lines per mm rather than 5 lines per mm. But, there are also a variety of aberrations that can limit a given eye. We will not dwell on this at the moment and simply take 10 lines per millimeter as our standard, remembering that in fact some photographic papers may begin to loose their ability to separate details when those details exceed that density.)

As a check of your ability to see (at a distance), the equivalent of this many lines per millimeter when viewed from ten inches, examine Figure 3. Here lines have been printed on the page with a certain spacing. This spacing is calibrated to the horizontal bar in the figure to remove any magnification factor that may be present when the figure appears in print.

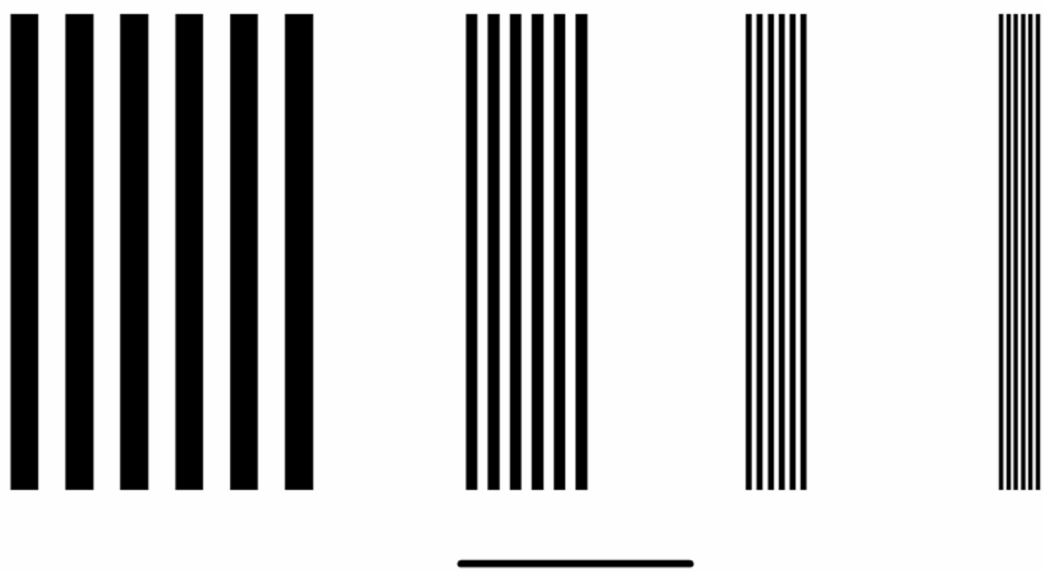

Figure 3: To see your ability to resolve details at a distance, first measure the horizontal bar at the base of the figure. If this measures x inches (e.g., 1.23 inches, or 0.8 inches), set this illustration in good light a distance of x times 10 feet from your eye (e.g., 12.3 feet, or 8 feet). As you scan across the figure, your ability to resolve details (from that appropriate distance) will be revealed as an equivalent number of lines per millimeter if viewed from ten inches. Here there are sets of parallel lines with spacing such that when viewed for the proper distance they are equivalent to 2, 5, 10 and 15 cycles per millimeter at a reading distance of ten inches. An equivalent test could be created for close vision, but the printed page would likely make this second case less successful, with lines merging on the printed page due to limitations of the printing process.

The Reasons Why Resolution is Limited

We now explore where this $2\theta_M = 1/60$ degree comes from in some detail. There are good anatomical and physics reasons for this angle. One has to do with the size and placement of the cones in the retina in your eye and the other has to do with physical effects that happen to light when it passes through an aperture.

A critical factor that determines the smallness of detail that one can see is the discrete nature of the structures in the eye that detect light. In the region of the retina that results in the sharpest vision, the cones that detect light and send signals on their way to the brain have a diameter of 2.3 micrometers and a typical separation of approximately 2.5 micrometers center-to-center. (For reference it may be helpful to remember that a typical human hair has a diameter in the range of 75 to 100 micrometers.) A scene in your visual field is focused on your retina. For one to perceive two tiny things in the visual field to be separate, the light from these two must fall predominantly on two of these cones but not on a cone between the two. Here we are ignoring the ability of the eye-brain combination to actually do bit better than this when detecting lines. Thus, there is a natural minimum visual angle, below which one will not perceive two items as separate. Knowing the overall geometry of the eye, with its retina located about 17 mm behind the optical center of the lens system, and understanding the need for a relatively non-stimulated cone between two stimulated cones, allows one to conclude from a bit of calculation that this minimum angle is in the vicinity of $2\theta_M = 0.0169$ degrees, very close to the observed standard of 1/60 degree (0.0167 degree). Ignoring any possible aberrations, the observed ability of a good eye to resolve images is consistent with the fundamental anatomy of the eye itself (as it must be!). The density of cones off the axis of sharp vision (i.e. slightly peripheral vision) is lower and this results in a resolution larger than 1/60 degree – so your vision in bright light is not as sharp when you are not looking directly at something.

The second factor comes from the fundamental behavior that happens with the passage of light through an aperture. When light passes through a small hole it spreads out a bit, a result of the wavelike nature of light and the behavior of waves. A reasonable analogy to have in mind is to imagine waves on the ocean that encounter a small (say thirty feet wide) short (say twenty feet long) opening that leads into a protected bay. The ocean waves enter the opening and when they reach the bay they spread out. Equivalently, there is a bit of spreading introduced into the light's path by the presence of a hole. The smaller the aperture, the worse this problem becomes. Such effects are called *diffraction* effects. So, the aperture formed by the iris in your eye that defines the pupil of your eye introduces a fundamental limit on the ability of your eye to resolve those lines or two adjacent dots printed on a page. This would be true even if there were no limitation due to the cones.

To get a feeling for this phenomenon, we consider Figure 4, which shows the pattern of the intensity of light that might be transmitted by a circular aperture to a screen behind it (e.g. your retina). If diffraction effects were not present, the intensity of the light would rise sharply behind the aperture and would define a white circle with a sharp edge (Figure 4, left). But, diffraction effects spread the light out and what appears behind the aperture is instead more like what is shown in figure 4, right. The circle on the screen has soft edges and indeed has secondary annular rings of dim light – all introduced by the fundamental behavior of light. For the purposes of illustration visibility here, we have enhanced the secondary annular rings a bit; they are actually quite dim. This is a fundamental limitation imposed by the nature of light itself. The scale of the diffraction effect depends on the size of the aperture; smaller apertures produce more spreading.

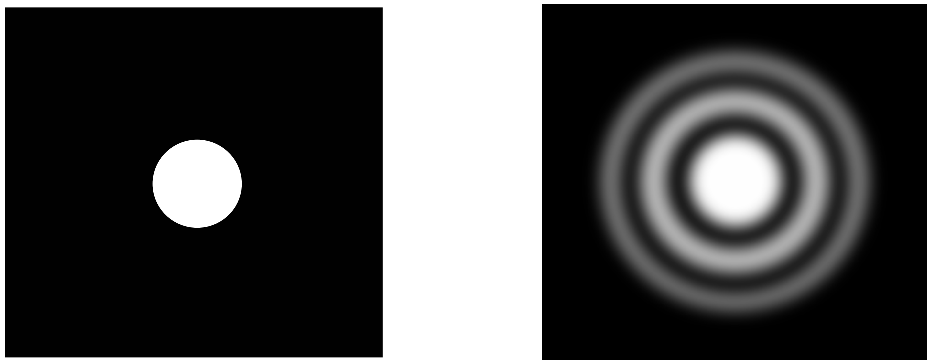

Figure 4: Here (left) is a white circle projected onto a dark background. If light did not have wavelike properties, we might expect that light projected through a round hole would look like this and produce a bright circle with sharp edges. In such a case, if we were to measure the intensity of light as we moved across the diameter of the circle, we would record no intensity until we reached the area with light, and then constant light across the diameter of the circle. Light behaves as a wave and as a result uniform light that passes through a round aperture does not produce a circle of uniform intensity. Instead, it produces a pattern of light (right) that is brightest in the center, with a gradient in intensity (dimming) as one approaches the edges. In fact, there are secondary dim fuzzy rings of light around the circle. Two of these are shown greatly enhanced here to make them more visible.

The minimum angle that defines two sources of light as being "just, or barely resolved" for any aperture is given by the rules of optics according to a commonly accepted criterion (called Rayleigh's criterion) as $\theta_R = 70\ \lambda/a$ (in units of degrees) where λ is the wavelength of light and "a" is the diameter of the aperture. Here this angle θ_R is defined to be a special value for the angle between the lines of sight from the aperture to the centers of the two sources (see figure 1, 2θ). Rayleigh's criterion is defined in terms of one of the patterns of light shown in figure 5. Specifically, Rayleigh's criterion is satisfied when the maximum in intensity from one light source falls on the first minimum in intensity of the adjacent light source. For such a visual angle, one could "just resolve the sources as being two, rather than just one. Now, this criterion is a bit arbitrary and there are other choices, but it is the commonly accepted convention. In Figure 5 we give a graphic illustration of this definition. We will see that the conventional definition for θ_R is reasonably consistent with our definition for $2\theta_M$ and we can compare the two.

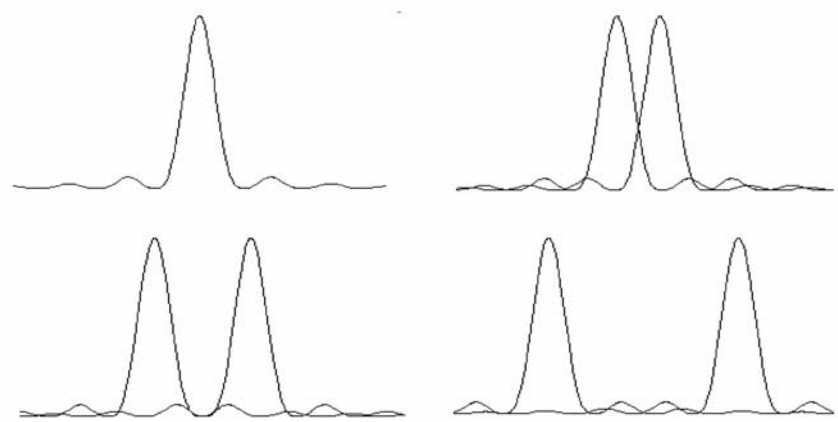

Figure 5. Here are shown approximate patterns of the intensity of light as transmitted through a circular aperture. In the upper left we show the pattern of light intensity as would be found for a single source of light, if you measured the intensity across the bulls eye pattern in Figure 4. On the upper right is shown the pattern of light from two sources that are at a visual angle that just satisfies the Rayleigh criterion – the maximum intensity of one source falls at the first minimum in intensity of the second source. On the lower right is a pattern from two sources that are better resolved, where there is a completely dark space between the two bright regions – the two first minimums in intensity overlap (a close analog to our Figure 2). Finally on the lower right is shown a case where the two sources are extremely well resolved.

The wavelength of light depends on color, but a reasonable approximation is to use about 560 nanometers (0.00056 mm) for the wavelength. The actual range of visible light is from about 400 nm (deep blue) to 700 nm (deep red). (For reference here, it may be helpful to remember that a typical human hair has a diameter of roughly 75,000 – 100,000 nanometers; so, about 140 wavelengths of light span the diameter of a typical human hair, if we take a diameter of 80,000 nm to be definite.) A human eye has a pupil diameter that changes depending on the amount of light incident on the eye. In bright light your pupil closes down; in dim light it opens. A good typical value for the diameter of the pupil of the eye in relatively bright light is about 3 mm. If we substitute these numbers into the rule $\theta_R = 70\ \lambda /a$, we find that $\theta_R = 0.01312$ degrees. Clearly if the pupil diameter changes a bit, so does this limiting angle; for a brighter light a 2 mm diameter pupil results in 0.0196 degree while for conditions of dim light an 8 mm diameter pupil results in 0.0049 degree. Given these numbers, we see that the standard of 1/60 degree (0.0167 degrees) is quite consistent with the limits imposed by diffraction that we just found. This is especially the case when we realize that for the two sources to be a bit better resolved than "barely resolved" the angle must be a bit bigger than θ_R, i.e., a bit closer to the situation in the lower left of Figure 5. So, the typically determined limiting viewing angle of the normal (unaided by glasses) human eye for resolution (ability to separate two details) of 1/60 degree (see Figure 2) is very consistent with the limitations imposed by the anatomy of the eye and also with the fundamental limitations imposed by physics. The eye has evolved to be an optimal device for seeing the wavelengths of light that we can see. Further evolution of the eye, to produce closer spacing of the cones, for example, would not be helpful since the fundamental behavior of light would make such closer spacing not very useful.

Incidentally, if you have been told that you have 20/20 vision, what you have been told is generally consistent with these ideas, but not precisely. We can explore this. 20/20 vision means that you can resolve capital letters that are 8.87 mm high at a distance of 20 feet. This level of resolution for the eye corresponds to a visual angle of about 5/60 of a degree for the top to bottom span in distance for the height of a capital letter, which is traditionally an E and found on a Snellen eye chart of the type you have probably seen many times; figure 6. So, 20/20 vision actually suggests something a bit different from the true resolution limit of a normal eye. This 5/60 of a degree implies that in the 20/20 designation you have 1/60 degree for the black bar at the top of the E, and another 1/60 degree for the white space, etc. (see figure 6). In fact, as we have said, the best human eyes can actually do better – we have noted that a good eye can actually see one full cycle (the black bar and the white space) in the visual angle of 1/60 degree. So, the typical good eye is better than 20/20, which is why a number of folks can see at the 20/10 level and it is only when your vision is worse than 20/20, e.g. 20/40 or 20/60, that you are told that you may need glasses. And, the choices we have made concerning resolution (that we will employ to good use in the next article) will ensure that our photographs will appear sharp, even to folks whose vision exceeds 20/20. Note that the usual 20/20 designation is limited to vision at this distance of 20 feet and says little about the ability of your eye to resolve detail from a much closer distance such as you might encounter when viewing a photograph because you may have difficulty focusing that close without glasses. A good vision test can also be done to find the *equivalent* of 20/20 for closer vision. Of course, bifocal glasses are glasses that help to bring vision closer to the equivalent to 20/20 for two different distances. Typically one of these is normal reading distance and the other is far-vision distance, or perhaps normal reading distance and computer screen distance.

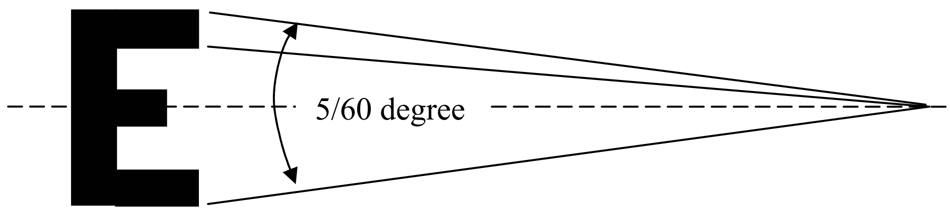

Figure 6. Schematic illustration of a typical eye test for the case when 20/20 vision is designated. The letter E is 8.87mm high and located 20 feet from the subject. The full span of the letter requires 5/60 degree, and 1/60 degree is the angle created by the spatial span of one arm of the letter. The line of sight is, of course, perpendicular to the letter, but we have shown the letter turned face-on here to make it visible.

Getting Detail into a Photographic Print

Now, clearly, your ability to discern small details when you examine a photograph, such as the blades of grass in a scene, will depend on your ability to see as separate (i.e. resolve) those details that are in the photograph. That is, the visual angle matters. Stand close to a photograph and the small details are apparent; stand further away and you loose the ability to see the small details that may be there in the print, even though you may have 20/20 vision at all distances, because the visual angle is smaller when you stand farther away. Your ability to see the small details is, of course, also determined by the ability of the photographer to properly render them there in the first place. Since this special angle of 1/60 degree is so important, we will need to keep it in mind.

What a photographer needs to capture in the way of sharpness in a negative will, in the end, be determined by the level of detail that he or she expects to be seen when the ultimate photographic print is viewed as it hangs on the wall. Clearly, the sharpness required in a *negative* will depend on the final enlargement that will be made to produce the print. View a negative from a distance of ten inches, and two objects in the negative will have a certain visual angle (or, angular separation). But, view a four times enlargement (say, a 4 x 5 negative is enlarged to a 16 x 20 print) and the angular separation of details will be four times as great for the *same* viewing distance. So, if you want that print to be such that you expect a viewer to observe it from ten inches (a bit too close for a 16 x 20 print, but people do sometimes stand close to look at details) and see all the detail they are physically able to see, then you need to assume that 1/60 of a degree is the visual angle that is relevant for the *print* at its given size when viewed from a distance of ten inches. You need not do better than this since the eye can't. But, in this case this means that we need a tighter constraint on the negative than on the larger final print.

For example, if the minimum separation of two details that are desired to be resolved on the 16 x 20 print when viewed from ten inches is 1/10 mm (and remember, some good normal eyes can do this), then the 4 x 5 negative (in this case a four times enlargement was done) must have those two details resolved to 1/40 mm. In the end, decisions in the field with regard to aperture and focus ultimately need to pay attention to the size of the final print you have in mind, and also to the expected viewing distance. Since you will make the final print, you have control of that, but since others will view the print, you can't control the distance from which they will do that. While the normal viewing distance for a typical print is generally considered to be a distance roughly equal to the diagonal of the print dimensions (since if a normal lens was used for the format of the film, this gives roughly the same perspective that the original camera position produced on the negative) some people like to get closer to a large print and so you have to maintain a stricter standard for the sharpness.

With this background established, and understanding how much sharpness is relevant in a negative, we will in the next article discuss the answers to our two questions: (1) Which f-stop will be the best to ensure that a certain *range of distances* from the camera in a scene will be rendered in *optimally sharp focus* and (2) What *range of f-stop values* is available to us so that the selected range of distances in the scene will be *acceptably* in focus? And, we will provide useful charts that will help make f-stop selections in the field.

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