Chapter 6

Spatial Vision

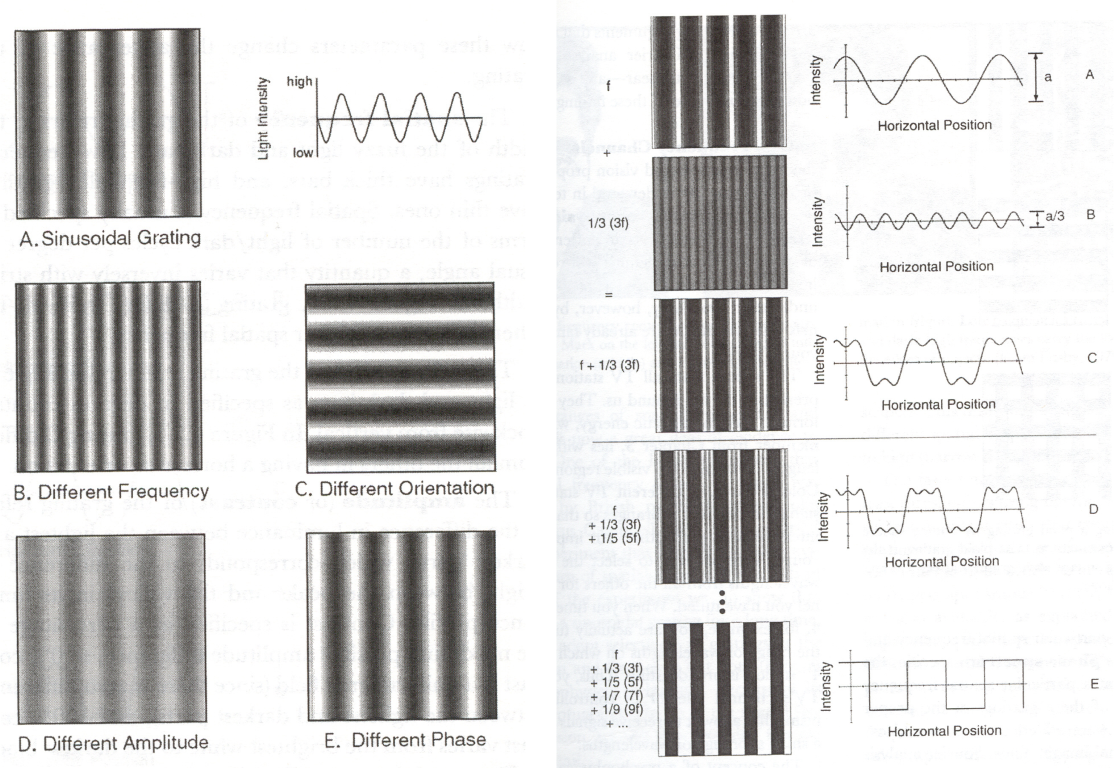

Figure 6.1: Left: Gratings of different frequency, amplitude, phase and orientation. Right: Fourier transform of a square grating.

In this chapter, we will deal with how our eye detects image components and features. We have discussed this to some extent while discussing the visual cortex and the cells sensitive to edges in the visual cortex. Till now, we have looked at feature detection theory. Now we will read another theory called the spatial frequency theory. Note that unlike the field of color vision, in the field of spatial vision, the physiological and the psychophysical studies have not come to an convergence yet. The spatial frequency theory is predominantly a psychophysical theory and is very convincing. In this chapter we will study primarily luminance sensitivity. Little work has been done in the direction of color spatial frequency. However, we will touch upon it a little and see the open problems existing in that area.

Figure 6.2: Left: An Image. Middle: The image with its high frequency components removed. Right: The same image with the lower frequency components removed.

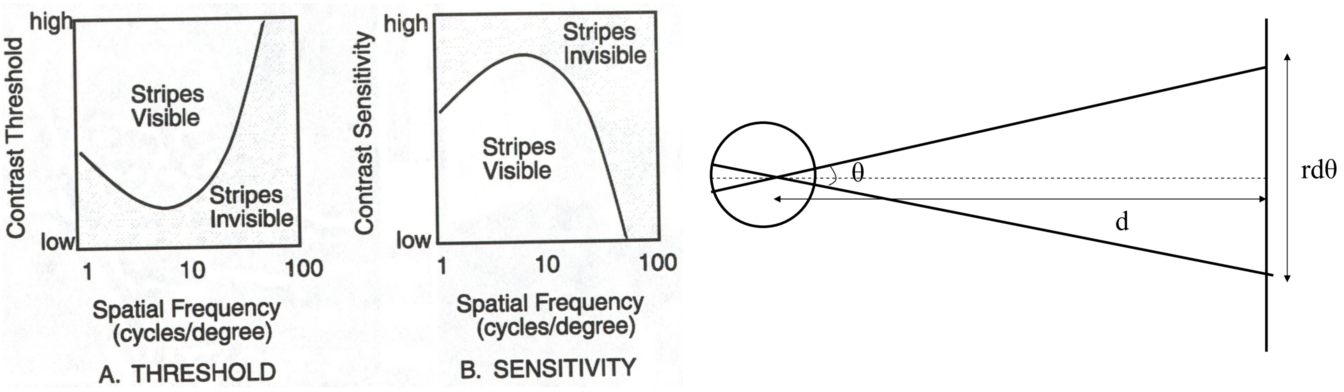

Figure 6.3: Left: The Spatial Contrast Threshold Function: Middle: The Spatial Contrast Sensitivity Function. Right: The number of cycles in one degree of angle subtended on the eye.

6.1 Spatial Luminance Vision

To study this, we first need to know what is spatial frequency. Fourier discovered that a set of sine waves, each of different frequencies, form a set of basis functions to define any signal in any dimension. To explain this in a single dimension, any one dimensional signal can be represented as a linear combination of a a set of sine waves of different frequencies with varying amplitude and phase. The amplitudes defines the coefficients of the basis functions. In the two dimensional case, these sine waves forming the basis functions are not only of different frequencies, but also of different orientations.

An image where the luminance varies as a sign wave is called a *grating*. Figure 6.1 shows gratings differing in their frequency, orientation, phase and amplitude. Note that the amplitude of the gratings provide the sense of contrast. Higher amplitude gives higher contrast.

An image $I(x,y)$ defined by a two dimensional array of luminance values can be transformed by *fourier analysis* to produce an *amplitude* and *phase* image of same dimensions denoted by $A(x,y)$ and $P(x,y)$ respectively. The origin of this image is at the center as opposed to the origin of $I(x,y)$ being in the lower left corner. $A(x,y)$ and $P(x,y)$ defines the amplitude and the phase of the basis sine wave with frequency $\sqrt(x^2+y^2)$ and orientation $tan^{-1}\frac{y}{x}$ in the analysis of I. Inversely, the images $A(x,y)$ and $P(x,y)$ can be combined by process of *fourier synthesis* to get back $I(x,y)$. A and P together define the *frequency spectrum* of an image.

To illustrate, which spatial frequency contributes of what aspects of an image, here is an example in Figure

6.2. The image on the left is first transformed using fourier transform. Then its higher frequency components are removed. This modified spectrum is then inverted back to create the middle image. Note that all the details are lost. Thus high frequency parts of the image are the edges and the details. Similarly another image is generated by inverting the spectrum with its lower frequency components eliminated. This generated the image on the right which has retained all the sharp features.

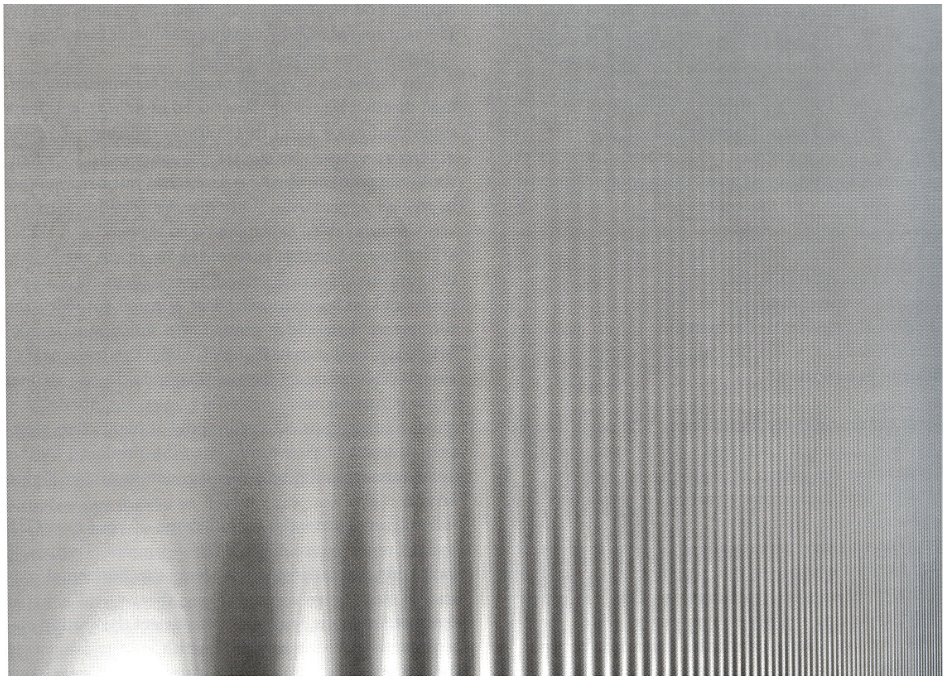

Figure 6.4: Testing the contrast sensitivity function. X direction has varying frequency and Y direction have varying contrast. Your contrast sensitivity is given by the bow shaped curve that separates the pattern and the gray region you see.

6.1.1 Contrast Sensitivity Function (CSF)

In this section we will study spatial, temporal and spatio-temporal contrast sensitivity functions.

Spatial CSF

An effort was first made to measure our sensitivity to the different spatial frequencies. The following experiment was done for this purpose. Say, particular frequency sinusoidal grating was viewed by subjects. Note that the amplitude of the gratings defines its contrast. The subjects had the control the change this amplitude or contrast. They were asked to detect the contrast at which this grating pattern was barely detectable from an uniform gray field. The same experiment was carried at different frequencies. Thus, the contrast threshold i.e. the minimum contrast required to detect a sinusoidal grating, was detected for all frequencies. This plot of contrast threshold versus spatial frequency is what we call the spatial contrast threshold function, as shown in Figure 6.3. The reciprocal of this function, which is a plot of contrast sensitivity to spatial frequency, is called the spatial *contrast sensitivity function (CSF)*. Note the bow shaped structure which indicates it lesser sensitivity towards both high and low frequencies. The peak is at about $4-5$ cycles per degree. This shows that the CSF acts like a band pass filter blocking very low and very high frequencies.

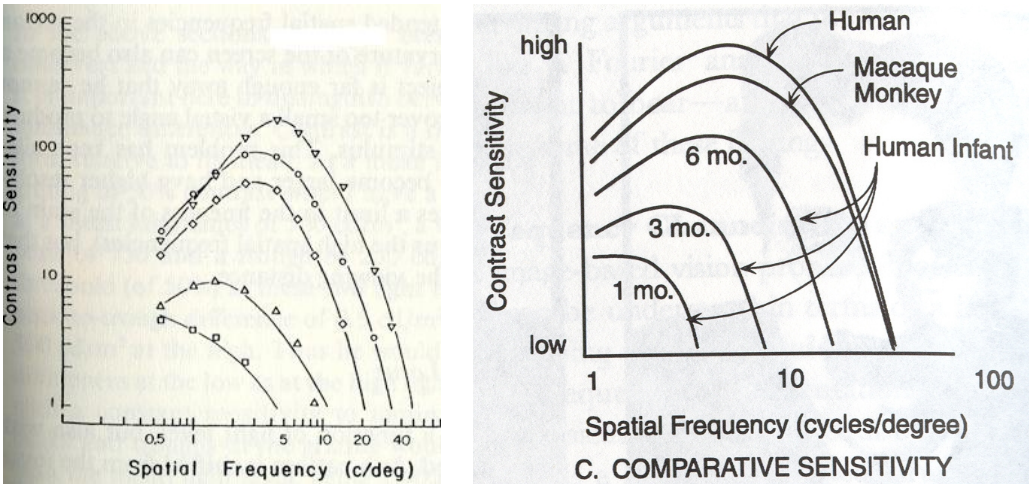

Figure 6.5: Left: Variation in CSF with varying luminance. Right: Development of contrast sensitivity.

One important point to note here is that the spatial frequency is expressed in $cycles/degree$. This is number of cycles of the sinusoidal grating subtended in one degree of the eye. Let the distance of the observer from the screen where the gratings be presented by d inches. Let the resolution of the screen be r pixels per inches. And let one cycle of the sinusoidal grating be s pixels wide. From this we can find out the number of cycles of the gratings that is subtended per degree of the eye, as shown in Figure 6.3. We need to find the number of pixels that a $\theta = 1$ degree subtends on the eye. Since the size of the eye is negligible compared to d, the distance on screen that is imaged for this θ is given by $d\theta$. The number of pixels in that region of the screen is given by $dr\theta$. If s pixels from one cycle of the sinusoid, the number of cycles subtended per degree of the eye is given by $\frac{dr\theta}{s}$. θ needs to be represented in radians which makes the equation

$$cycles\ per\ degree\ of\ eye = \frac{dr\pi}{180s}$$

Figure 6.4 is a great image to verify the shape of the CSF. This is a luminance image where spatial frequency is varied in the X axis and contrast in the Y axis. As you move from bottom to top of the image, notice that different frequencies are getting detected at different levels. And the overall bow shaped that separates the region with the pattern from the gray region you see is actually the CSF.

Note that till now we have been talking about the contrast that gives the amplitude of the sine wave. However the mean of the sine wave gives how bright the grating is. This gives the luminance of the grating. Luminance does play a role in our CSF. Contrast sensitivity generally increases for higher luminance. The curve we were seeing so far was for photopic conditions. Figure 6.5 shows how the CSF changes as the luminance decreases. Note that with the decrease in luminance sensitivity to higher frequency reduces. This is the reason we cannot see details in dark. Also the region of peak sensitivity shifts from 5 cycles per degree to 2 cycles per degree. For extremely low luminance, the sensitivity just decreases monotonically with frequency.

The next question is, do we have such a CSF throughout our lives. As it turns out, CSF of infants show a lot less sensitivity especially in the high frequency region. That is the reason we find that till a certain age infants cannot recognize people. They cannot see the high frequency details which are probably what differs most from one face to another. In the same curve, we show that the CSF of monkey and macaque are very close to the humans.

Another interesting aspect in the development of CSF in species is they are usually adapted for the kind of regular activities a species is going to be involved in. For example, for a falcon which has to locate a small prey (like a rat) on the ground from great heights, sensitivity to higher frequencies are critical for survival. On the other

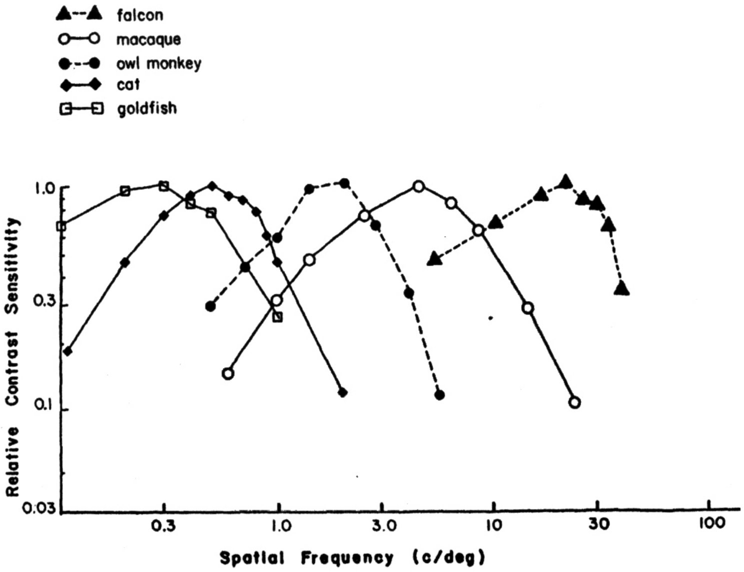

Figure 6.6: CSF of different species adapted by evolution to aid them best in the critical functions of survival.

hand, for a cat whose prey will probably be very close to it, sensitivity to much lower frequencies are required. Figure 6.6 shows the CSF of different kinds of animals.

Temporal CSF

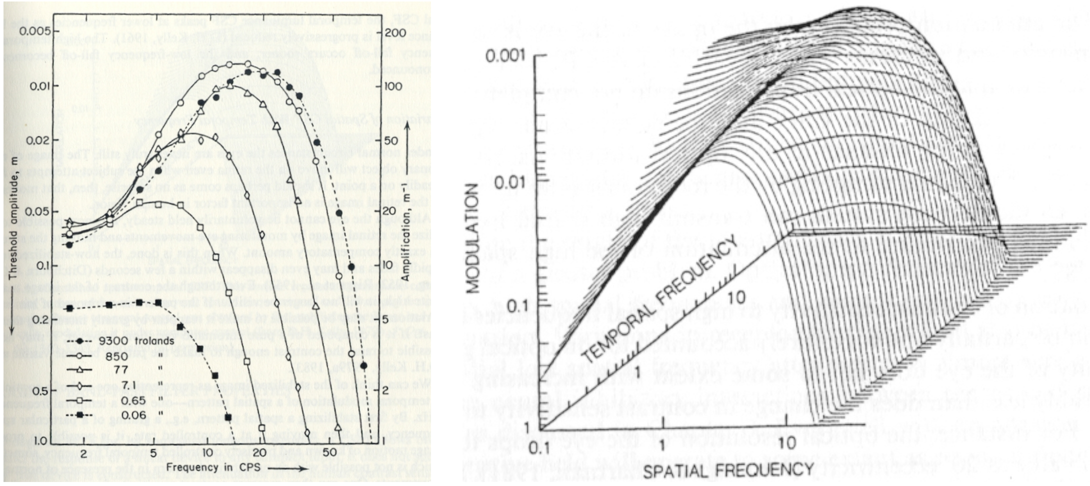

Figure 6.7: Left: Varying temporal CSF with varying luminance. Right: Spatio-Temporal CSF.

Till now, we have just examined the CSF for spatial variation. But we are also sensitive to temporal variation. To measure our temporal CSF, the following experiment was done. A sequence of images were presented each of which was a flat gray color. But this gray color changed in a sinusoidal fashion over time. And the number of cycles of the sinusoid gave the cycles per second that forms one of the axis of the temporal CSF. The contrast of this function was adjusted to find the contrast at which the flicker was barely detectable. This was done for different frequencies to create the temporal CSF. Figure 6.7 shows the results for different luminance levels of such temporal gratings. Note that here also the sensitivity decreases with the reducing luminance levels.

Spatio-Temporal CSF

The next obvious thing to do would be to test this when grating has both spatial and temporal variation. The result for that is shown in the 3D plot in Figure 6.7. Note that the sensitivity to higher frequency reduces with higher temporal frequency. At high temporal frequency, the CSF acts more like a low pass filter rather than a band pass filter.

Now, this insensitivity to low frequency has lot of advantages. Our most important tasks that helps us to decide between danger and other critical situation is the reflectance properties of the objects in the world. The eye's job is to find it. Note that the spatial and temporal change in the illumination is always low frequency. Thus, this low frequency helps us to ignore the effects of illumination and find the real reflectance of the objects. Second, the afterimages formed in the eye are often very low frequency. The insensitivity in this region also prevents these images from interfering with our regular vision.

6.2 Spatial Channels

The most important aspect of spatial vision is the idea of spatial channels, both in frequency and orientation.

6.2.1 Frequency Channels

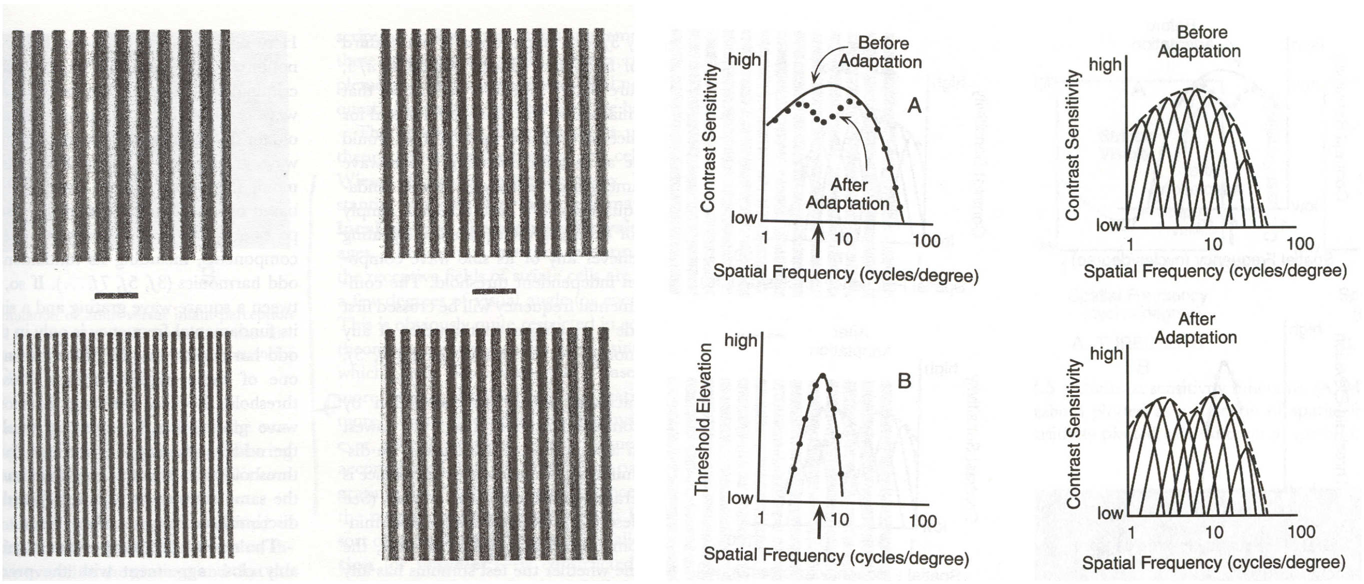

Figure 6.8: Left: Spatial Frequency Aftereffects. Right: Effects of adapting to a particular frequency on CSF

The spatial frequency theory says that we have different channel (set of cells) in our visual system that response to different ranges of frequencies. The response are overlapping and together creates the spatial CSF that we saw before. The path breaking experiment that revealed this was through selective adaptation. First, it was shown that just like color afterimages due to chromatic adaptation, we can also have afterimages due to frequency adaptation. Figure 6.8 shows the experiment to see it for yourself. First, make sure that the two gratings on the right hand side have exactly same frequency. For the gratings on the left, the lower one has higher frequency than the top one. Now adapt your eye to this left grating by moving it back and forth across the line in the middle of the top and bottom grating. After adapting likewise for 30 or more seconds, move your eye to the right pattern. Note that the top pattern appears to have higher frequency than the bottom. These effects can be explained as usual by adaptation.

A more convincing experiment showed that if the humans are adapted to a particular frequency, a lower sensitivity to range of frequency centering it is observed after adaptation. This is shown in the CSFs before and after adaptation shown in Figure 6.8. Note that subtracting the CSF after adaptation from the one before adaptation, gives us the sensitivity of the cells which adapted to this range of frequencies. Thus, adapting to different frequency levels helps us to find the sensitivity of different sets of cells that are responding to each range. And surprisingly enough, the envelop of all these make the spatial CSF as shown in Figure 6.8.

Once this model was proposed it was used to predict response and match it with reality. One such test is to find the contrast threshold for square gratings. It was predicted that if our eye uses different frequency channel, the square grating will be detectable only when one of the component sine waves (by fourier transform) is detectable. The component frequencies of the sine gratings in the square grating was deciphered and the minimum contrast threshold amongst all these frequencies were found. Next the contrast threshold of the square wave was tested by experiment and was found to match the predicted one at all cases. Note intuitively it seems that the square wave having higher slope would be detectable at a lower threshold which is not true.

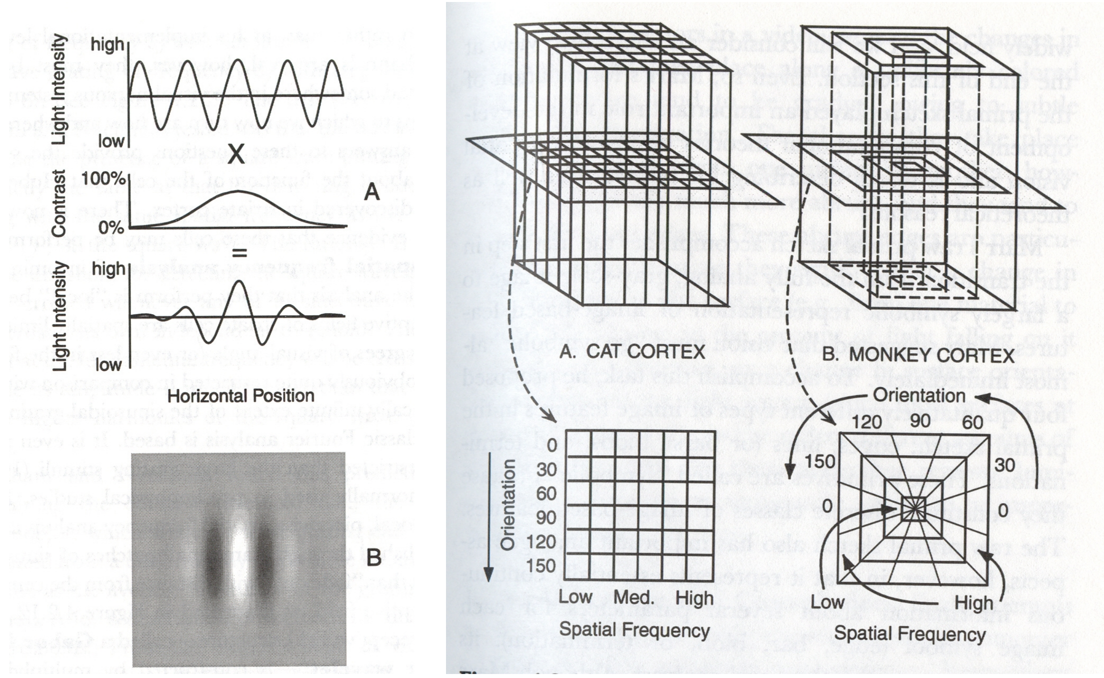

Figure 6.9: Left: Garbor Functions. Right: Models of cortical hypercolumn architecture in cats and monkeys. One arranged in cartesian coordinate and the other in radial coordinates.

The problem that physiologists has with this theory stems from the fact that fourier analysis is usually used for signals that extend infinitely in space. But this is not true for the receptive field of the eye. However, a local piecewise spatial frequency analysis can be accomplished through many small patches of sine gratings that fade out with distance from the center. This sort of receptive field structure can be simulated by a sine wave multiplied by a gaussian - called a Garbor function (or wavelet). This is shown in Figure 6.9. Note that we have seen that many cells in the visual cortex show exactly this kind of response with a secondary lobe adjacent to the primary one.

6.2.2 Orientation Channels

Similarly, orientation channels have also been identified. Figure 6.10 shows the orientation after effects. Like before, the right gratings have identical orientation. The left gratings have different orientation. Adapt your eye to the left gratings by moving them back and forth on the line between the left gratings. After adapting your eye for 30 second, move your eye to right gratings and notice the opposite orientation aftereffects in the right gratings. Here also, orientation sensitivity was measured before and after to show the change in the OSF (orientation sensitivity function).

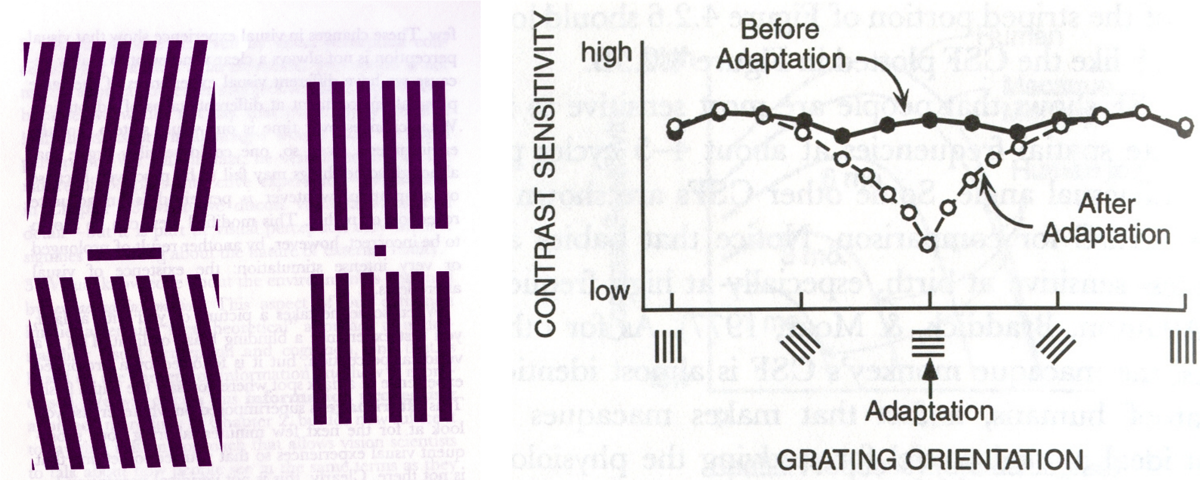

Figure 6.10: Left: Aftereffects of orientation adaptation. Right: OSF before and after adaptation.

Physiological evidence of such cells with spatial frequency and orientation tunings is coming up in recent studies. Also, it has been found that these cells are arranged in a very organized manner, at least in cats and monkeys. Figure 6.9 shows that they are arranged in a cartesian fashion in cats and radial fashion in monkeys.

6.3 Spatial Chrominance Vision

It is difficult to define chromatic contrast. This is mainly because we will need a definition that involves both hue and saturation. Color gratings can be designed to vary dominant wavelength sinusoidally. The different hues thus generated in the grating can be equated in terms of luminance so that the grating is strictly varying in chrominance. Also, it is difficult to generate all the different hues precisely. However, the amplitude of this gratings is what is difficult to define. One way may be to draw a straight line joining the two dominant wavelengths and defining the 100% contrast be defined as the maximum length of this line in the real color space of chromaticity diagram. However, physical reproduction of this kind of gratings would be almost impossible.

A more common way to generate chromatic gratings is to take identical frequency luminance gratings of two different hues. These two gratings are out-of-phase. They are then added up to create the chrominance grating. Notice that this grating will have same luminance everywhere since it is the addition of two out of phase luminance gratings. And since the colors generated are given by the proportions of luminance, the dominant wavelength of the colors will vary sinusoidally.

The CSF for such red-green (602, 526nm) and blue-yellow (470, 577nm) gratings are shown in Figure 6.11. This shows that we are slightly more sensitive to red-green gratings than to blue-yellow gratings. This may be due to the reduced blue sensitivity. But, more importantly, notice the difference of this CSF from the luminance CSF in Figure 6.5. First, the chromatic CSF behaves more like a low-pass filter than a band pass filter. Also, note that

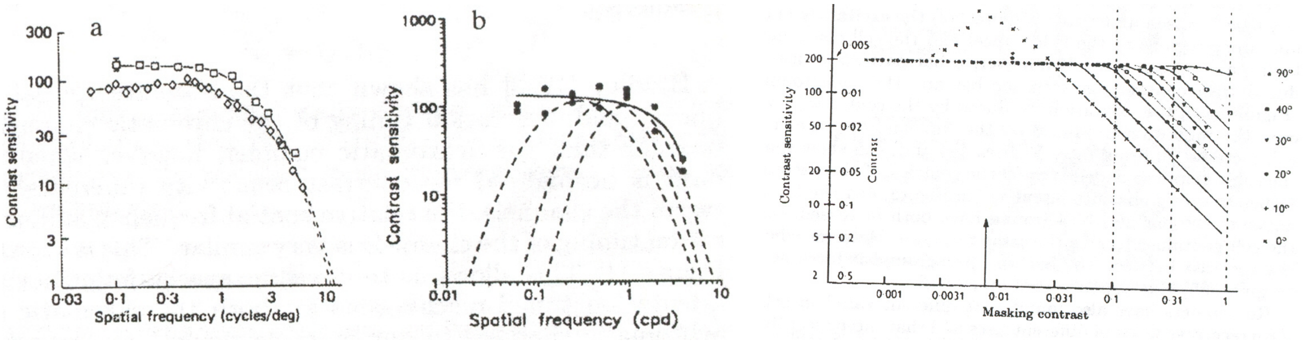

Figure 6.11: Left: Chromatic CSF for red-green (shown by squares) and blue-yellow gratings (shown by diamonds). This also shows the different spatial channels of chromatic contrast sensitivity function. Right: This shows the effect of visual masking in pattern orientation.

in general the chromatic sensitivity is lower than the luminance sensitivity. This means that we humans are more sensitive to luminance variation than to chrominance variation. In addition, the cut-off frequency of the low pass filter is 11 cycles per degree as opposed to 30 cycles per degree. This indicates that we have a lower chrominance acuity than luminance acuity i.e. we are not very sensitive to high resolution chrominance details.

6.4 Visual Masking

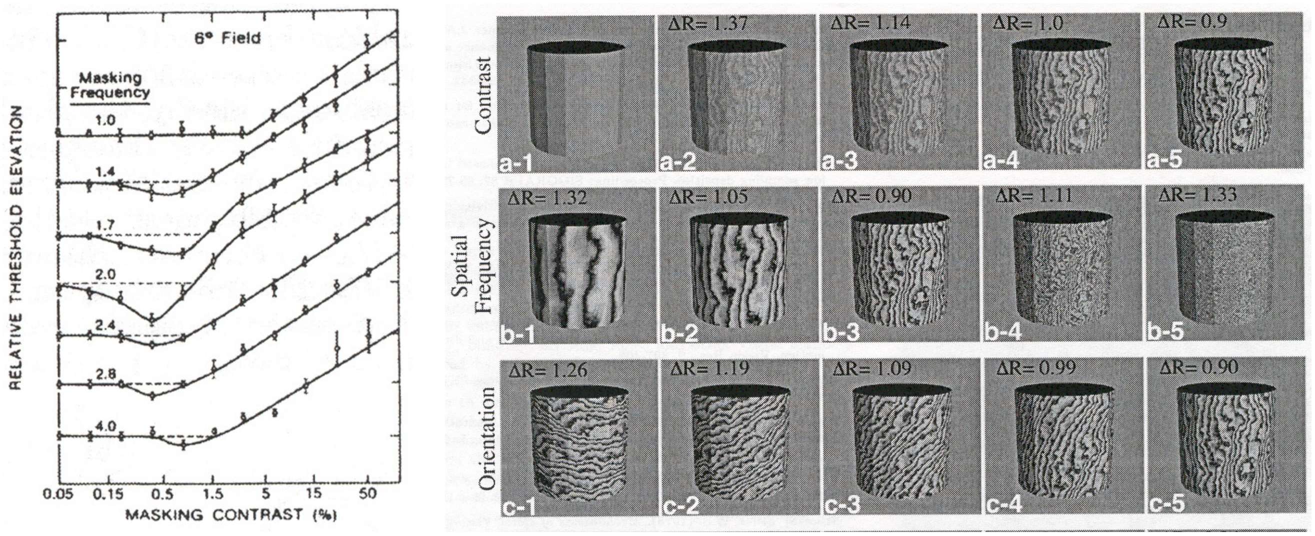

Figure 6.12: Left: Visual Masking of different frequencies. This shows that nearby frequencies mask each other. Right: Visual masking demonstrated for different contrast, frequency and orientation.

Next, we are going to describe a very interesting phenomenon called the visual masking. Till now, we have been dealing with sinusoidal gratings of one frequency. However, in real life the images that we see has all the different frequencies superimposed on each other, as is evident from the fourier analysis of an image. So, it is important to analyze how the sensitivity to different spatial frequency and orientation changes in the presence of other spatial frequencies of different orientation.

For this, the following experiment was conducted. A test luminance grating was presented over a background luminance grating. The contrast sensitivity of the test grating was measured by changing the properties of the background grating. This showed how the test grating behaved in the presence of the background grating. The background grating was called the masking grating.

First, the effect of orientation masking was measured. A vertical grating was used as the test grating. The orientation of the masking grating was changed from vertical to horizontal. The sensitivity of the test grating with changing contrast of the masking grating was measured for each of these orientations. The results are illustrated in Figure 6.11. Note that for high contrast masking grating, the sensitivity to the test grating decreases. However, this reduction in sensitivity is maximum when the masking and the test grating have similar orientation and goes down as the difference in the orientation increases. Thus, similar orientations can mask each other. Also note that there is a region for low contrast similar masking orientation, where the sensitivity to the test grating actually increases. This is called facilitation.

Similar experiment was carried out to find the effects of frequency masking. The results are shown in Figure 6.12. However, here threshold is plotted instead of sensitivity. The test grating was of 2 cycles per degree. The masking grating was varied from $1 - 4$ cycles per degree. Note that the threshold for detecting the test grating decreased (sensitivity increased) for lower contrast, however with higher contrast the threshold increased very fast (sensitivity decreased) creating the masking effect. Also note that this masking effect is maximum for the masking grating of 2 cycles per degree and decreases as the difference in the frequency between the test and the masking grating increases.

The effect of these visual masking is illustrated in Figure 6.12. The figure show a coarsely tesselated cylinder covered by texture. Note that since the cylinder is coarsely tesselated, vertical artifacts as visible. The first row shows the effect of applying a texture and changing its contrast. Initially, when the contrast of the texture is low, the tesselation becomes more evident with texturing. This stage is that of facilitation. As the contrast is increased, the tesselations slowly disappear as visual masking takes place. The second row shows how visual masking happens with texture frequency similar to the tesselation frequency. Initially, the tesselation is visible with low frequency texture. The frequency of the texture is invisible in the second image. With further increase in frequency, the tesselation becomes visible again. Finally, the third row shows the effect of orientation masking. Starting with horizontal frequency, as the texture orientation becomes closer and closer to vertical, the tesselation artifacts become less and less visible, becoming least visible with vertical orientation.