SPATIAL FILTERING: INTRODUCTION TO CONTRAST SENSITIVITY

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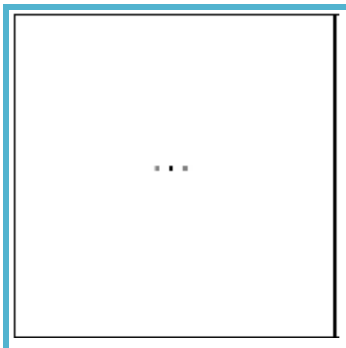
THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Spatial filtering
- Contrast sensitivity

REVIEW

Q. What information is contained in the spatial frequency spectrum (Fourier transform) of an image?

A. _____



0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	**0.5**	0.0	0.0	**1.0**	0.0	0.0	**0.5**	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 14-1: *Gray-scale plot of the data contained in the spatial frequency spectrum of an image, with a sample of the numbers from the center of the data array*

REVIEW (CONT.)

Q. What do the low spatial frequencies contribute to an image?

A. _____

Q. What do the high spatial frequencies contribute to an image?

A. _____

Q. What is spatial filtering?

A. _____

Q. What would an image look like if the high spatial frequencies were filtered out?

A. _____

0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	**0.4**	0.0	0.0	0.0
0.0	0.0	0.0	0.0	**0.5**	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	**0.5**	0.0	1.0	0.0	**0.5**	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	**0.5**	0.0	0.0	0.0	0.0
0.0	0.0	0.0	**0.4**	0.0	0.0	0.0	0.0	0.0

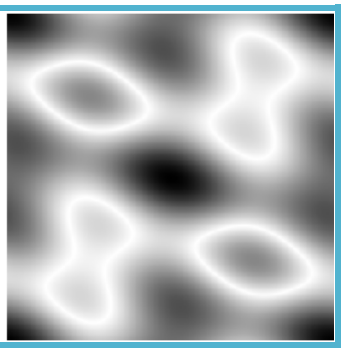


Figure 14-2: *Starting with the spatial frequency spectrum (middle value shown on left), we can compute its inverse Fourier transform to create the image on the right*

For any image you can compute its Fourier transform, which gives you the spatial frequency spectrum of the image. The two data sets, the spatial image and its spatial frequency spectrum, are a pair that is linked together by the mathematical process of Fourier transformation. Figure 14.3 shows an example of a spatial image and its spatial frequency spectrum.

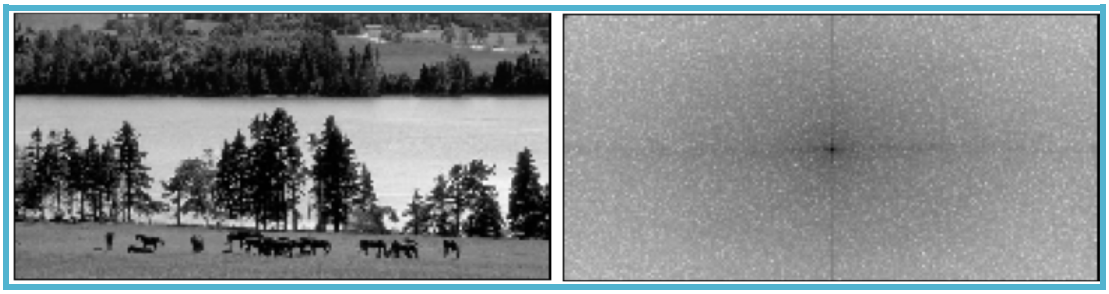


Figure 14-3: *Example of a spatial image (L) and a gray-scale plot of its spatial frequency spectrum* ***(R)***

REVIEW (CONT.)

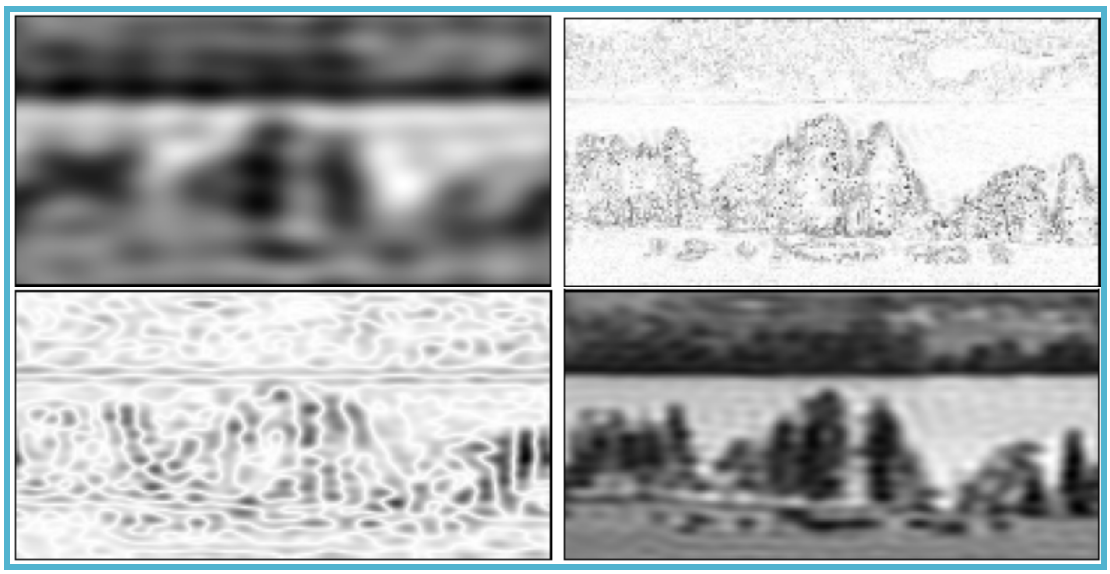


Figure 14-4: *Starting with the spatial frequency spectrum (middle value shown on left), we can compute its inverse Fourier transform to create the image on the right*

Figure 14.4 shows four images that are spatially filtered versions of the image shown in Figure 14.3.

Q. Can you identify the type of filtering that was performed on each image?

SPATIAL FILTERING

One application of Fourier transformation and spatial filtering is illustrated in Figure 14.5, below. The left image shows a raw Shack-Hartmann data image. A Shack-Hartmann aberrometer projects a tiny beam of light into the eye and then measures the light reflected out. The beam reflected out of the eye passes through an array of microscopic plus lenses that break the broad beam up into many smaller beams. Light from each beam is focused to a spot, so the raw data image looks like a circular array of spots on a black background. In order to compute the optical aberrations of the eye, we must analyze the location of each of the spots. The analysis, therefore, requires that we locate the position of each spot, but some, especially those near the edge are fainter and hard to see.

Q. Based on what you have already learned, why do the dots near the edge of the pupil appear dimmer?

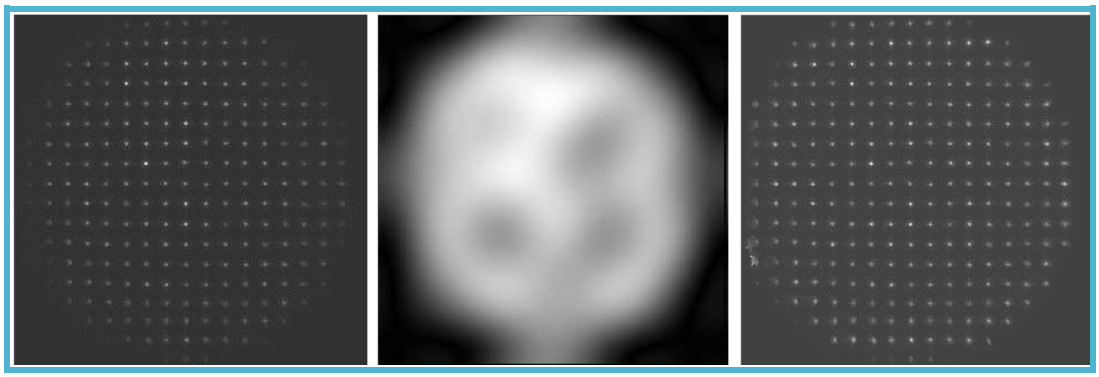


Figure 14-5: *Raw data (left) was divided by the low-pass-filtered version of the same image (middle) to even out the brightness of the dots. The result (right) shows more uniform dot brightness*

In order to improve Shack-Hartmann analysis across the whole pupil, the peripheral dots need to be brightened. To do so, the following steps were performed:

- Fourier analyzed the raw data image (left image, Fig. 14-5)
- Low-pass filtered the spectrum (threw away everything except the lowest spatial frequencies)
- Computed the inverse Fourier transform. This gave the overall, gradual variation in image brightness that caused some dots in the original image to be dimmer than others
- Divided the values in the original image (left) by the low-pass filtered image (middle) to produce the corrected image (right). Notice that the brightness of the dots is more uniform. That simplified analysis of the location of dots in the peripheral pupil

CONTRAST SENSITIVITY

The retinal image is produced by the eye's optical system (cornea and lens), but it is only the first part of the visual process. From the retina to the brain, the retinal image is transformed into electrical signals that are processed neurologically. Note that vision depends on two processes:

- Optical imaging
- Neural image processing

CONTRAST SENSITIVITY (CONT.)

The MTF characterizes the first part of the system – the optics.

Describe the meaning of the MTF.

A. _____

Q. Describe what the plot of the MTF would look like.

A. _____

When we subjectively test a person's vision, we are testing the end product of both the optical imaging and neural image processing. As with the testing of optics, the best way to evaluate visual performance is to see how well the person sees sine-wave gratings across a range of spatial frequencies.

This can be tested in the following way:

- Select one spatial frequency, for example, 1 cycle per degree (c/d)
- Vary the contrast to determine the **contrast threshold** at which the subject can barely see the stripes. Michelson contrast is used, so the contrast threshold will have some value between 1.0 and 0
- Compute the inverse of contrast threshold to get the **contrast sensitivity**. When the threshold is low, sensitivity is high. This indicates that, for the spatial frequency used, the person's vision is good, because the person can see the stripes, even when they have low contrast
- Repeat at other spatial frequencies. The **cut-off frequency** for the normal human eye is usually about 40-60 c/d
- Plot sensitivity (y-axis) as a function of spatial frequency (x-axis). **This is the contrast sensitivity function (CSF)**

Figure 14-6: *The CSF is determined by first measuring contrast threshold as a function of spatial frequency, then taking its inverse*

Although there are similarities between the MTF and CSF, there are several important differences:

- The MTF describes optical performance; the CSF includes the combined effect of optics and neural processing for the whole visual system. In other words, the MTF describes optics; the CSF describes vision
- The MTF can be used to describe any optical system; for example, the MTF of a camera lens. The CSF is used for the visual system
- The MTF plots how well an optical system transfers contrast, or image contrast, at different spatial frequencies. The CSF plots how well the visual system sees contrast at different spatial frequencies

CONTRAST SENSITIVITY (CONT.)

BASIC FEATURES OF THE HUMAN CSF

Schwartz, 2004 Fig. 7-8 shows a typical human CSF. Note that it is plotted on log-log axes. Also note the axis labels. The normal contrast sensitivity function has the following features:

- A slight decrease in sensitivity at the lowest spatial frequencies. Note that this is different from the MTF
- Peak sensitivity at about 4 c/d
- A decline to zero at high spatial frequencies. The frequency at which it drops to zero is the highest spatial frequency that the eye can resolve, and is known as the **cut-off frequency**, or the spatial resolution limit
- For a person with good vision, the high frequency cut-off is at about 40-60 c/d

As with the MTF, there are advantages to using sine-wave gratings to measure contrast sensitivity. However, you can also measure contrast sensitivity using square-wave gratings or letters. To do so, you first select a grating (or letter) of one particular size (one spatial frequency) and vary the contrast to determine the threshold. Re-measure the contrast threshold with test patterns having a range of sizes; for example, big stripes and small stripes or large letters and small letters. The inverse of the contrast threshold is contrast sensitivity. Plotting sensitivity as a function of spatial frequency yields the CSF (Fig.14-6).

One advantage of using sine-wave gratings when measuring contrast sensitivity is that it contains only a single spatial frequency.

If square wave gratings or letters are used to measure contrast sensitivity, the target will contain multiple spatial frequencies (Fig.14-7). Figure 7-5 in Schwartz illustrates the spatial frequency components of a square wave grating, and it shows that the square wave is made up of many spatial frequencies: **a fundamental frequency** and higher harmonics that are odd multiples (3, 5, 7 …) of the fundamental.

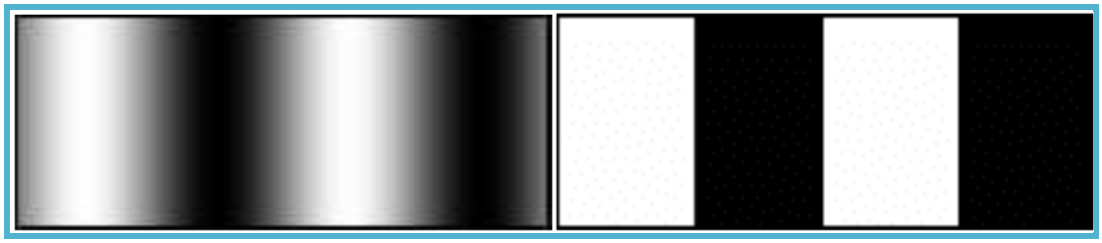


Figure 14-7: *Two kinds of grating patterns; both contain two cycles. The left pattern is made of a vertically oriented sine-wave grating. The right pattern also has two cycles, but it is based on a square-wave function*

SELECTED READING/REFERENCES

- Schwartz SH. **Visual Perception - A Clinical Orientation, 3rd Edition**. Appleton & Lange, Stamford, Connecticut, 2004