Does the brain perform a Fourier analysis of the visual scene?

Norma Graham

The decomposition of a complex auditory sound into its constituent simple harmonic variations (pure tones) is an example of Fourier analysis. Does the brain do something like this to visual scenes, decomposing a visual pattern into some simpler representation to help ease the information-processing load? As Norma Graham explains below, the answer to this question is both yes and no. But, yes or no, the idea that the brain might do a Fourier analysis of the visual scene has been a powerful impetus to much exciting visual research in the last decade.

Fourier analysis

To discuss Fourier analysis as applied to visual patterns, I find it easiest to begin by considering one simple pattern, a *sinusoidal grating*. A sinusoidal grating is a pattern which looks like a set of blurry, alternating dark and light stripes (see Fig. 2a of the article by Murray Sherman[3]). The luminance in the direction perpendicular to the stripes varies sinusoidally, while the luminance in the direction parallel to the stripes is constant. The *spatial frequency* of a sinusoidal grating is the number of cycles of the sinusoid per unit distance, or, in other words, the number of dark-bar–light-bar pairs per unit distance. (The usual unit of distance is a degree of visual angle.) Spatial frequency and size of bar are inversely proportional to each other; a grating of high spatial frequency has narrow bars and a grating of low spatial frequency has wide bars.

The *mean luminance* of a grating is the average of the luminances at every point across the whole spatial extent of the grating. The *contrast* of a grating is a measure of the difference between the maximum luminance and minimum luminance usually taken to be one-half that difference divided by the mean luminance. (One of the attractions of sinusoidal gratings is that the mean luminance of a grating can easily be held constant, keeping the observer in a relatively constant state of light adaptation, while the contrast and spatial frequency are varied.)

Now consider any visual stimulus, the luminance of which varies along only one dimension. As follows from a theorem due to the eighteenth-century mathematician Fourier, *any* such stimulus can be constructed by superimposing sinusoidal gratings of different spatial frequencies, contrasts, and phases (positions). Further, there is only *one* set of sinusoidal gratings which can be superimposed to form a particular stimulus. Thus, any one-dimensional visual stimulus can be described as containing certain spatial frequencies. The amount and phase of each spatial frequency contained in a stimulus (the contrast and phase of the component sinusoidal grating of that spatial frequency) are given by the *Fourier transform* of the stimulus.

Analysis into spatial frequencies is not restricted to one-dimensional visual stimuli. Consider an ordinary black-and-white photograph as an example of a two-dimensional visual stimulus. Any such stimulus can be constructed by adding up sinusoidal gratings which differ in orientation as well as in contrast and frequency and phase. A picture of fine-grained sandpaper, for example, could be formed by adding up sinusoidal gratings of high spatial frequencies and many orientations. A picture of coarse-grained sandpaper could be formed by adding up sinusoidal gratings of low spatial frequencies and many orientations. The amount and phase of each spatial frequency at each orientation is given by a *two-dimensional Fourier transform*. Fourier transforms can be computed in higher dimensions as well (allowing for depth, colour, and time, for example), but in this article I will talk, for simplicity's sake, as if all visual patterns were two-dimensional.

To do a Fourier analysis of a visual pattern is to compute the Fourier transform of that pattern, that is, to compute how much of each spatial-frequency/orientation combination is present in the pattern and at what phase it is present. In terms of the component sinusoidal gratings from which the pattern could be formed, to compute a Fourier transform is to compute the contrast and phase of each of these component gratings. There are well-established mathematical procedures for doing this computation.

The brain does not perform a *strict* Fourier analysis of the visual scene

What would we mean if we said that the brain performed a Fourier analysis of the visual scene? We might mean, if we were speaking strictly, that there was a set of neurones that computed the Fourier transform of the visual pattern. The magnitude of the response of a particular neurone in the set would be *completely determined* by the amount (or by the phase) of a particular spatial-frequency/orientation combination present in the pattern. In other words, each neurone in the set would respond only to an *extremely narrow* range of spatial frequencies and orientations. Different neurones would respond to different spatial-frequency/orientation combinations so the set as a whole would compute an excellent approximation to a Fourier transform. (It is an approximation because there are only a finite number of neurones and the Fourier transform is a continuous function, but this kind of approximation has no practical consequences.)

There is *no* such set of neurones anywhere in the brain; at least, there is absolutely no evidence, either physiological or psychophysical, that such a set of neurones exists. The brain, therefore, does not perform a *strict* Fourier analysis of the visual scene.

The brain performs a *crude* Fourier analysis

Although there is no evidence that the brain performs a strict Fourier analysis, there is an accumulating mass of evidence that the brain performs operations with many of the characteristics of Fourier analyses, operations that could be called crude Fourier analyses. Let us look at the neurophysiological evidence first.

Neurophysiological evidence

For several decades, neurones in visual systems of all but the lowest animals have been known to be specialized. Different neurones require different stimuli for maximal response. Particularly important for the present discussion is the fact that neurones in the visual cortex of higher animals respond to gratings of certain spatial frequencies, but not to spatial frequencies that are much higher or lower. They also respond only to a restricted range of orientations. Some particularly interesting results have been obtained recently in primates by DeValois, DeValois, Albrecht, and Thorell[1] at the University of California at Berkeley, and by Movshon, Thompson, and Tolhurst[4] at Cambridge University.

Since different cells respond to different ranges of spatial frequency and orientation, one can obtain an approximate idea of how much of any spatial-frequency/orientation combination is present in a pattern by finding out which cells respond most to that pattern. Thus one can obtain a rough approximation to the Fourier transform of the pattern. The whole set of cells can be described, in short, as doing a crude Fourier analysis.

No magic is required for cells to do this crude Fourier analysis. They do not literally have to do the mathematical computations usually called Fourier analysis. Their selective sensitivity for certain narrow rangles of spatial frequency and orientation is an immediate consequency of their receptive-field organization. Roughly speaking, the sizes of the excitatory and inhibitory segments of a receptive field determine which spatial frequency the cell responds to maximally; the orientation of the receptive field determines which orientation the cell responds to maximally.

Psychophysical evidence

About 10 years ago, Campbell and Robson of Cambridge University, Pantle and Sekuler of Northwestern University, and Thomas of the University of California at Los Angeles, suggested that there were 'spatial-frequency channels' or 'size-detecting mechanisms' in the human visual system. A number of people have also suggested that there are orientation channels. These channels were hypothesized to be selectively sensitive to narrow ranges of spatial frequency and/or orientation. Although the channels investigated in psychophysical and perceptual experiments are far from established as being identical to the cortical neurones described above, it is a useful heuristic to assume tentatively that they are. In any case, these psychophysical channels could also be properly described as doing a crude Fourier analysis.

A very large amount of psychophysical evidence from the last decade supports the notion of these channels. I summarized this evidence in a recent chapter[2]. Here I will just briefly mention the main lines of evidence. In *summation experiments*, the visibility of a compound pattern containing several sinusoidal grating components is compared with the visibility of each component alone. If all of the components affected the same channel, the compound should be much more visible than any component. In fact, however, the compound is not much more visible. The visual system acts as if the components were being processed by separate channels and therefore could not help each other out.

In *adaptation and masking* experiments, the visibility of test patterns is measured either after the observer has inspected a supra-threshold adapting pattern, or while he is inspecting a masking pattern. The visibility of the test pattern should be affected by the adapting or masking pattern if the patterns are processed by the same channel, but not otherwise. In fact, when the test and adapting (or masking) patterns contain similar spatial frequencies and orientations, the visibility of the test pattern is affected; but when the test and adapting (or masking) patterns contain very different spatial frequencies or orientations, the visibility of the test pattern is *not* affected.

These summation, adaptation, and masking experiments, as well as many others, provide evidence that channels selectively sensitive to spatial frequency and orientation do exist. In short, they provide evidence that the visual system does do a crude Fourier analysis.

The brain performs a crude Fourier analysis. So what?

We are a long way from understanding exactly what the neurones and psychophysical channels described above are good for, that is, what their function is in visual perception, but people are beginning to have ideas. One interesting possibility is that channels/neurones sensitive to low spatial frequencies may be responsible for the global processing of visual scenes (the breaking-up of the scene into objects perhaps) and the channels/neurones sensitive to high spatial frequencies may be responsible for the local processing (the scrutiny of fine details, the recognition of particular patterns). Another possibility is that all of the channels/neurones may be active in detecting texture gradients or in doing effortless texture discrimination.

Whether these particular possibilities are correct or not, there is no doubt that the idea of the brain's performing a crude Fourier analysis of visual patterns continues to stimulate much exciting experimental and theoretical work in neurophysiology, psychophysics, and perception.

Reading list

1. DeValois, R., Albrecht, D. G. and Thorell, L. (1977) In: H. Spekreijse and L. H. van der Tweel (eds), *Spatial Contrast*, North-Holland, Amsterdam, pp. 60–63.
2. Graham, N. (1979) In: M. Kubovy and J. Pomerantz (eds), *Perceptual Organization*, Lawrence Erlbaum Associates, Hillsdale, NJ.
3. Sherman, S. M. (1979) *Trends NeuroSci.* 2, 192–195.
4. Movshon, A. J., Thompson, I. D. and Tolhurst, D. J. (1978) *J. Physiol. (London)*, 283, 53–120.

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