The Manifold Ways of Perception

H. Sebastian Seung and Daniel D. Lee

Two-and-a-half millennia ago, the Greek philosopher Heraclitus, observing that the world is in eternal flux, wrote that you can never step in the same river twice. If he were alive today and working as a psychologist, he might say that you can never see the same face twice. Indeed, faces can grow hair, acquire wrinkles, or be surgically enhanced. But facial images also vary from moment to moment, as you can demonstrate at home while watching television. Make a small aperture in a piece of paper, and place it over a face on the screen. The light coming through the aperture will vary with time, mostly as a result of changes in the location and orientation of the face.

The aperture might show a tooth at one instant, and a nostril at the next, crudely simulating the fluctuations in light incident on a single retinal photoreceptor cell. This illustrates that the signals carried from the eye to the brain by the million or so axons in the optic nerve are perpetually changing as we look at a face. Nevertheless, we are able to perceive that these changing signals are produced by the same object. This is the fundamental mystery of perception: How does the brain perceive constancy even though its raw sensory inputs are in flux? The mystery intrigues not only scientists but also engineers, who yearn to construct vision machines that equal the performance of humans at visual object recognition.

To precisely characterize the variability of images and other perceptual stimuli, it is essential to take a mathematical approach, which is just what Tenenbaum et al. (1) and Roweis and Saul (2) have done on pages 2319 and 2323 of this issue, respectively.

Manifolds in visual perception. The retinal image is a collection of signals from photoreceptor cells. If these numbers are taken to be coordinates in an abstract image space, then an image is represented by a point. Only three dimensions of the image space are depicted, but actually the dimensionality is equal to the number of photoreceptor cells. As the faces are rotated, they trace out nonlinear curves embedded in image space. If changes in scale, illumination, and other sources of continuous variability are also included, then the images would lie on low-dimensional manifolds, rather than the simple one-dimensional curves shown. To recognize faces, the brain must equate all images from the same manifold, but distinguish between images from different manifolds. How the brain represents image manifolds is as yet unknown. According to one hypothesis, they are stored in the brain as manifolds of stable neural-activity patterns.

H. S. Seung is at the Howard Hughes Medical Institute and Brain and Cognitive Sciences Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. D. D. Lee is at Bell Labs, Lucent Technologies, Murray Hill, NJ 07974, USA.
of neurons. Neurophysiologists have often found that the firing rate of each neuron in a population can be written as a smooth function of a small number of variables, such as the angular position of the eye (4) or direction of the head (5). This implies that the population activity is constrained to lie on a low-dimensional manifold.

What is the connection between such neural manifolds and the image manifolds we have just discussed? According to a well-known idea, memories are stored in brain dynamics as stable states, or dynamical attractors (6). Because the possible images of an object lie on a manifold, it has been hypothesized that a visual memory is stored as a manifold of stable states, or a continuous attractor (7). Recent studies of neural manifolds suggest that continuous attractors actually do exist in the brain (8, 9). Whether they are the basis of visual and other types of perception remains to be resolved. If the answer is affirmative, then manifolds will prove to be crucial for understanding how perception arises from the dynamics of neural networks in the brain.

References