10. PRESENT AND FUTURE

My intention in writing this book was to describe what we know of the anatomy and physiology of the visual pathway up to the striate cortex. The knowledge we have now is really only the beginning of an effort to understand the physiological basis of perception, a story whose next stages are just coming into view; we can see major mountain ranges in the middle distance, but the end is nowhere in sight.

The striate cortex is just the first of over a dozen separate visual areas, each of which maps the whole visual field. These areas collectively form the patchwork quilt that constitutes the occipital cortex and extends forward into the posterior temporal cortex and posterior parietal cortex. Beginning with the striate cortex, each area feeds into two or more areas higher in the hierarchy, and the connections are topographically organized so that any given area contains an orderly representation of the visual field, just as the striate cortex does. The ascending connections presumably take the visual information from one region to the next for further processing. For each'of these areas our problem is to find out how the information is processed—the same problem we faced earlier when we asked what the striate cortex does with the information it gets from the geniculate.

Although we have only recently come to realize how numerous these visual areas are, we are already building up knowledge about the connections and single-cell physiology of some of them. Just as area 17 is a mosaic of two sets of regions, blob and nonblob, so the next visual area, area 18 or visual area 2, is a mosaic of three sets. Unlike the blobs and interblobs, which formed islands in an ocean, the mosaic in area 18 takes the form of parallel stripes. In these subdivisions we find a striking segregation of function. In the set of thick stripes, most of the cells are highly sensitive to the relative horizontal positions of the stimuli in the two eyes, as described in Chapter 7; we therefore conclude that this thick-stripe subdivision is concerned at least in part with stereopsis. In the second set, the thin stripes, cells lack orientation selectivity and often show specific color responses. In the third set, the pale stripes, cells are orientation selective and most are end stopped. Thus the three sets of subdivisions that make up area 18 seem to be concerned with stereopsis, color, and form.

A similar division of labor occurs in the areas beyond area 18, but now entire areas seem to be given over to one or perhaps two visual functions. An area called MT (for middle temporal gyrus) is devoted to movement and stereopsis; one called V 4 (V for visual) seems to be concerned mainly with color. We can thus discern two processes that go hand in hand. The first is hierarchical. To solve the various problems in vision outlined in previous chapters—color, stereopsis, movement, form—information is operated upon in one area after the next, with progressive abstraction and increasing complexity of representation. The second process consists of a divergence of pathways. Apparently the problems require such different strategies and hardware that it becomes more efficient to handle them in entirely separate channels.

To throw a strike, a pitcher must project the ball over a plate about 1 foot wide, 60.5 feet away—a target that subtends an angle of about 1 degree, about twice the apparent size of the moon. To accomplish such a feat, with velocity and spin, requires excellent vision plus the ability to regulate the force and timing of over a hundred muscles. A batter to connect with the ball must judge its exact position less than a second after its release. The success or failure of either feat depends on visual circuits—all those discussed in this book and many at higher visual levels—and motor circuits involving motor cortex, cerebellum, brainstem, and spinal cord.

This surprising tendency for attributes such as form, color, and movement to be handled by separate structures in the brain immediately raises the question of how all the information is finally assembled, say for perceiving a bouncing red ball. It obviously must be assembled somewhere, if only at the motor nerves that subserve the action of catching. Where it's assembled, and how, we have no idea. This is where we are, in 1995, in the step-by-step analysis of the visual path. In terms of numbers of synapses (perhaps eight or ten) and complexity of transformations, it may seem a long way from the rods and cones in the retina to areas MT or visual area 2 in the cortex, but it is surely a far longer way from such processes as orientation tuning, end-stopping, disparity tuning, or color opponency to the recognition of any of the shapes that we perceive in our everyday life. We are far from understanding the perception of objects, even such comparatively simple ones as a circle, a triangle, or the letter A—indeed, we are far from even being able to come up with plausible hypotheses.

We should not be particularly surprised or disconcerted over our relative ignorance in the face of such mysteries. Those who work in the field of artificial intelligence (AI) cannot design a machine that begins to rival the brain at carrying out such special tasks as processing the written word, driving a car along a road, or distinguishing faces. They have, however, shown that the theoretical difficulties in accomplishing any of these tasks are formidable. It is not that the difficulties cannot be solved—the brain clearly has solved them— but rather that the methods the brain applies cannot be simple: in the lingo of AI, the problems are "nontrivial". So the brain solves nontrivial problems. The remarkable thing is that it solves not just two or three but thousands of them.

In the question period following a lecture, a sensory physiologist or psychologist soon gets used to being asked what the best guess is as to how objects are recognized. Do cells continue to become more and more specialized at more and more central levels, so that at some stage we can expect to find cells so specialized that they respond to one single person's face—say, one's grand-mother's? This notion, called the grandmother cell theory, is hard to entertain seriously. Would we expect to find separate cells for grandmother smiling, grandmother weeping, or grandmother sewing? Separate cells for the concept or definition of grandmother: one's mother's or father's mother? And if we did have grandmother cells, then what? Where would they project? The alternative is to suppose that a given object leads to the firing of a particular constellation of cells, any member of which could also belong to other constellations. Knowing as we do that destroying a small region of brain does not generally destroy specific memories, we have to suppose that the cells in a constellation are not localized to a single cortical area, but extend over many areas. Grandmother sewing then becomes a bigger constellation comprising grandmother-by-definition, grandmother's face, and sewing. It is admittedly not easy to think of a way to get at such ideas experimentally. To record from one cell alone and make sense of the results even in the striate cortex is not easy: it is hard even to imagine coming to terms with a cell that may be a member of a hundred constellations, each consisting of a thousand cells. Having tried to record from three cells simultaneously and understand what they all are doing in the animal's daily life, I can only admire the efforts of those who hope to build electrode arrays to record simultaneously from hundreds. But by now we should be used to seeing problems solved that only yesterday seemed insuperable.

Running counter to wooly ideas about constellations of cells is long-standing and still accumulating evidence for the existence of cortical regions specialized for face perception. Charles Gross's group at'Princeton has recorded from cells in the monkey, in a visual area of the temporal lobe, that seem to respond selectively to faces. And humans with strokes in one particular part of the inferior occipital lobe often lose the ability to recognize faces, even those of close relatives. Antonio Damasio, at the University of Iowa, has suggested that these patients have lost the ability to distinguish not just faces but a broader class of objects that includes faces. He describes a woman who could recognize neither faces nor individual cars. She could tell a car from a truck, but to find her own car in a parking lot she had to walk along reading off the license plate numbers, which suggests that her vision and her ability to read numbers were both intact.

Speculating can be fun, but when can we hope to have answers to some of these questions about perception? Some thirty-seven years have passed since Kuffler worked out the properties of retinal ganglion cells. In the interval the way we view both the complexity of the visual pathway and the range of problems posed by perception has radically changed. We realize that discoveries such as center-surround receptive fields and orientation selectivity represent merely two steps in unraveling a puzzle that contains hundreds of such steps. The brain has many tasks to perform, even in vision, and millions of years of evolution have produced solutions of great ingenuity. With hard work we may come to understand any small subset of these, but it seems unlikely that we will be able to tackle them all. It would be just as unrealistic to suppose that we could ever understand the intricate workings of each of the millions of proteins floating around in our bodies. Philosophically, however, it is important to have at least a few examples—of neural circuits or proteins—that we do understand well: our ability to unravel even a few of the processes responsible for life—or for perception, thought, or emotions—tells us that total understanding is in principle possible, that we do not need to appeal to mystical life forces—or to the mind.

Some may fear that such a materialistic outlook, which regards the brain as a kind of super machine, will take the magic out of life and deprive us of all spiritual values. This is about the same as fearing that a knowledge of human anatomy will prevent us from admiring the human form. Art students and medical students know that the opposite is true. The problem is with the words: if *machine* implies something with rivets and ratchets and gears, that does sound unromantic. But by *machine* I mean any object that does tasks in a way that is consonant with the laws of physics, an object that we can ultimately understand in the same way we understand a printing press. I believe the brain is such an object.

Do we need to worry about possible dire consequences of understanding the brain, analogous to the consequences of understanding the atom? Do we have to worry about the CIA reading or controlling our thoughts? I see no cause for loss of sleep, at least not for the next century or so. It should be obvious from all the preceding chapters of this book that reading or directing thoughts by neurophysiological means is about as feasible as a weekend trip to the Andromeda galaxy and back. But even if thought control turns out to be possible *in principle*, the prevention or cure of millions of schizophrenics should be easy by comparison. I would prefer to take the gamble, and continue to do research.

We may soon have to face a different kind of problem: that of reconciling some of our most cherished and deep-seated beliefs with new knowledge of the brain. In 1983, the Church of Rome formally indicated its acceptance of the physics and cosmology Gallileo had promulgated 350 years earlier. Today our courts, politicians, and publishers are struggling with the same problem in teaching school children the, facts about evolution and molecular biology. If mind and soul are to neurobiology what sky and heaven are to astronomy and The Creation is to biology, then a third revolution in thought may be in the offing. We should not, however, smugly regard these as struggles between scientific wisdom and religious ignorance. If humans tend to cherish certain beliefs, it is only reasonable to suppose that our brains have evolved so as to favor that tendency—for reasons concerned with survival. To dismantle old beliefs or myths and replace them with scientific modes of thought should not and probably cannot be done hastily or by decree. But it seems to me that we will, in the end, have to modify our beliefs to make room for facts that our brains have enabled us to establish by experiment and deduction: the world is round; it goes around the sun; living things evolve; life can be explained in terms of fantastically complex molecules; and thought may some day be explained in terms of fantastically complex sets of neural connections.

The potential gains in understanding the brain include more than the cure and prevention of neurologic and psychiatric diseases. They go well beyond that, to fields like education. In educating, we are trying to influence the brain: how could we fail to teach better, if we understood the thing we are trying to influence? Possible gains extend even to art, music, athletics, and social relationships. Everything we do depends on our brains.

Having said all this, I must admit that what most strongly motivates me, and I think most of my colleagues, is sheer curiosity over the workings of the most complicated structure known.