"MILES WITHIN MILLIMETERS" AND OTHER AWE-INSPIRING FACTS ABOUT OUR "MORTARBOARD" HUMAN CORTEX

by Robert B. Glassman

Abstract. Consideration of the amazing organized intricacy of human cortical anatomy entails a deeper appreciation of nature that is fully consistent with a mature religious spirit. A brain seems at first glance to be a mere lump of grayish claylike stuff, but facts of basic neuroanatomy compel us to consider that this particular kind of stuff may really contain all the richly tangible and richly ghostly inner essences of emotion, thought, and behavior. Humans are the "college graduates" of evolution. The human cortex is 3,400 times the volume of, yet only slightly thicker (about 3 millimeters) than, that of the mouse. This remarkable sheet is as thin as a graduation-day "mortarboard" cap, but its 2,600 square centimeter area is four times as large (about 20 x 20 inches if a square; both metric and English units used deliberately). Zooming in, there are about 50 billion cortical neurons; though named after "pyramids," they are more like tiny "magic trees," with branches and roots so long and fine that there are 1 or 2 *miles* of these electrically scintillating fibers within each cubic millimeter of cortex. Cortical neurons communicate intimately: viewed from above, beneath a single square millimeter 100,000 nerve cells intertwine; each such neuron makes 5,000 or more connections with others. These and many additional amazing facts about brain tissue, together with some conjectures about dense connectedness in the mathematics of graph theory, help to bear out the groundwork prepared by such pioneers as Ralph Wendell Burhoe that the spirit and knowledge of science might rejoin that of religion. If it takes enchanted matter to contain consciousness, this is a kind of enchantment that science may well be able to penetrate for eventual thoroughgoing understanding. Inevitable by-products will be greater reverence for nature and greater awe at the mystery of nature's origin.[1]

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. . . the human body is a population of highly differentiated but faithfully cooperating cells [one or two orders of magnitude] more numerous than the human population of the world. Each cell's operations are so delicately subservient to the general welfare of the total organism that you by and large find yourself to be a quite wonderfully one, single, integrated being.

The neocortex makes possible symbolic abstractions, including language and linguistic logic, and their projection in dynamic models of self and its world in dreams and linguistic symbols, motivated and fed by input from the "instincts" and "feelings" of the lower two brain levels as well as by input from the sensory modalities commonly "cross-referenced" and integrated to produce our conscious awareness of "things" and of our feeling-tones (hopes and fears) about them. These dynamic models of the world and self in the brain are the stuff out of which are formed not only common sense but also such things as religious myth, philosophy, theology, and science.

—Ralph Wendell Burhoe[2]

Since the time of Edmund A. Burke (1729–1797), the sublime has been contrasted with the beautiful. He identified the sublime with the vast, the terrible, and the obscure . . . and the beautiful with the smooth, the small, and the delicate. . . . According to Kant, "the contemplation of [the sublime] brings with it the idea of infinity." It is "that which is beyond all comprehension great." The meaning of the sublime . . . was not adequately described in those theories. . . . The perception of beauty may be the beginning of the experience of the sublime. The sublime is that which we see and are unable to convey. It is the silent allusion of things to a meaning greater than themselves [but it] is not necessarily related to the vast and the overwhelming in size. It may be sensed . . . in every drop of water. . . . Every snowflake in the winter may arouse in us the sense of wonder that is our response to the sublime.

—A. J. Heschel[3]

And, it must be added, every neuron.

Science and Religion: From Cordial Nods to Intimate Associations

At best, religion and science ought to go well beyond dignified, distant mutual nods of respect at each other's legitimacy. While that mutual respect is an important outcome of the life's work of Ralph Wendell Burhoe (see Breed 1992), it is time to continue exploring more deeply the possibility that these two traditions of thought might really *mix*, and do so in a way that is not merely mutually critical but achieves the kind of symbiosis that Burhoe hoped for (Glassman 1998). This paper attempts such a compounding of the fundamentally religious question of whether the human mind can fit within matter with some old and new exciting fundamental knowledge about the structure of brain matter.

Teaching about the Brain. This attempt is made within a framework of suggesting content that is both attention-getting and scientifically significant for an introductory discussion in teaching neuroscience to undergraduates or lay persons. While fully materialistic in its close-up discussion of the parts of the brain—at the scales of individual neurons, populations of neurons, and the singular overall shape of the cerebral cortex—the exposition that follows suggests that these specifics of nature's richness point clearly toward the readiness with which our human minds transcend the part structure of our brains.

The present discussion is designed to help secularists of any academic denomination to better understand that the amazing yet comprehensible matter inside our heads composes a sufficient substrate of mind for human selves and for our reaching toward meanings that are larger than our individual selves.

As important, while continuing fully within a biological evolutionary context, the discussion should help people immersed in strong religious frameworks to see an important way in which materialistic facts of neuroscience may be fully consistent with powerful encouragements in the literature of the Bible to appreciate the sacredness of matter—perhaps the most movingly significant examples of the Judeo-Christian tradition in Genesis 1 and John 1. We are knowledge-rich, embodied "reflections" of a potential that exists in the universe, "read out" by natural selection (Glassman 1977), a process whose long duration challenges the horizons of human intuition and ability to analyze. It would not be a bad thing for contemporary scientists to accept, on a literary level, the early Enlightenment idea that science is revelatory, a thought offered famously by Alexander Pope ([1730/1882] 1967) in his *Epitaph Intended for Sir Isaac Newton*:

> Nature and Nature's laws lay hid in night
> God said, Let Newton be! And all was light.

Contemporary scientific knowledge of the architecture of the cerebral cortex is breathtaking. The more we learn about it, the more the brain seems worthy of the disguised message painted by Michelangelo in his *Creation of Adam* fresco, as explained by Frank Lynn Meshberger (1990)[4]: The mantle surrounding the depicted God is undeniably a picture of a brain, and, as Meshberger argues, the pictured touch of God's finger must be to give Adam not his body, which is already fully formed in this image, but the spark of human intellect.

Although scientists often make quasi-religious exhortations about transcendent significances of their scientific findings, scientists usually draw back from outright theism, partly because of an aversion to a common perception of clergy as virtually claiming to have seen God's face and partly because of scientists' own excessively literalistic misconception of religion (see, e.g., Gilkey 2001). Ralph Burhoe argued persistently that glimpses of transcendent meaning are both in the "culturetype" of our religious and other historical traditions and in science's continuing new discoveries about our physical and biological foundations (see Burhoe 1981).

This paper also, by example, attempts to help move portions of neuroscience and portions of the religion-and-neuroscience dialogue beyond the largely idolatrous methodology of merely seeking neural localizations of psychological functions that concern various aspects of religiosity. To feel religiously triumphant and scientifically legitimized at such localizing discoveries is excessive and reveals misconceptions of both good religion and good science. Highly publicized newer methods of brain imaging yield the same sort of partial information about the locations in brain tissue of aspects of psychological functions, as did the much older lesion method (Glassman 1978). Sometimes "imaging" provides important new knowledge, but sometimes it merely locates critical functional dependencies with less resolution than does the venerable lesion method. In any case, locating a small part of the brain that is critically involved in a particular psychological function can be only a small aspect of understanding the way brain underlies mind.[5]

The present paper's main concern is not in locating a function but in the awesome wealth of possibilities of interactions, or of process, that the cortex provides by virtue of its particular patterns of dense internal connectedness and a peculiarity of its gross anatomical shape.

Amazing Facts. "Amazing facts" are attention-getting and thought-provoking, and a good way to open the semester in a first class meeting. In thus inspiring our students, we also inspire ourselves. Neuroscience professors know well the basic anatomical properties of the cerebral cortex, and yet those very facts remain largely unappreciated by us, not to mention by our students. The study of the anatomy of our wet insides has often become too cut-and-dried, too "liturgical." Considering the basic properties of the cortex more deeply can lead to new understanding of the nature of mind—and to awe. And by teaching these issues well, we may lead more members of the general public to value the significance of our work for their lives. Both they and we may then find more room in which to rejoin the spirit of science with the parts that remain youthfully vigorous and flexible within its older progenitor, religion.[6]

Amazing Life, Mind, and Brain. My source of interest in the study of psychology and the study of the brain begins in a complete fascination with the existence of life. I am amazed that among all the life on Earth I find myself. Each of us is incredibly tiny, compared to the size of the earth and the size of the sky—yet here we are.

Even before there were scientists, people were struck by the marvel of existence. Indeed, some sort of puzzled, excited self-awareness may have been the thing that first defined us as human, perhaps as recently as a few tens of thousands of years ago (Eccles 1984, 115–18). We might now renew that childlike attitude of wonder; indeed, the findings of brain science about the intricacies of organization of wholes and parts in nature, at scales from the microscopic to the very large, make it hard to resist being possessed by an attitude that was called "radical amazement" in the writings of twentieth-century Jewish theologian Abraham Heschel (1955). He must also have used that term during his walks on Riverside Drive in Manhattan with Christian theologian Reinhold Niebuhr (U. Niebuhr 1985).

Are we merely clinging to an archaic, childlike, or childish custom when we allow the science of the brain to be joined by a zest for religious issues?

The Spirit of Science and the Spirit of Religion

In his introduction to the 1996 printing of Niebuhr's 1941 treatise *The Nature and Destiny of Man*, Robin Lovin observed that while social scientists found this synthesis, as well as Niebuhr's 1932 *Moral Man and Immoral Society*, to be brilliant, they were quite bemused by Niebuhr's insistence on mixing his perceptive social commentaries with God-talk. Heschel's work never had as broad an impact on social science as did his friend Niebuhr's; this is probably less because of Heschel's Jewishness than his single-sided uncompromising theism. Yet for a scientist who for whatever reason slips past the "danger" signs, reading Heschel's poetic theistic writings—with their persistent, varied, beautiful exhortations to perceiving transcendent significance at even the mundane facts of human existence—makes it hard to resist being lifted up from a "merely in the parts" nuts, bolts, and gears attitude about the great subtleties of the living systems of human nature. Science has thus far revealed only some of that richness; it contains the promise of further revelation.

To be sure, it is necessary to remain alert. A serious risk with religion is that it often feeds an attitude of passive awe in the presence of authority figures' authoritative declarations. Religion's vague notions of the extranatural may enervate our creative and incisive questioning about nature (Glassman 1996, 160). And the violent events of September 2001 in New York and Washington, D.C., reminded us also of the shadow of religion that sometimes emerges as extremes of pressure toward group-marking, obedience to authority, and self-sacrificial altruism.

Then again, there already exists considerable, narrowing authority worship in spiritless valleys of the broad scientific enterprise. University scientists may be as blind to dogmatic components of their teaching and to many of its moral imports as certain clergy are to some of their own arthritic dogmas. But in its best moments, religion pairs its important knowledge traditions with a spirited constructive attitude. That spirit might well help lift us out of the darker valleys of both religion and science and to new peaks of discovery. It can help us to assume a spirited attitude toward the amazing facts of nature and toward good things to come that those facts hint at.

Burhoe: Reacquainting the Zestful Spirits of Science and Religion

Ralph Wendell Burhoe dedicated a career that spanned the second half of the twentieth century to overcoming the hackneyed illusion that science and religion were pervasively and necessarily incompatible. His methods of bringing together important ideas in the fields of science and theology included the fostering of friendships among interested leaders in those fields, and he helped to institutionalize the connectedness between the academies of science and theology by founding societies and scholarly journals. While Burhoe succeeded well in his struggle to open the door between these areas of study (Breed 1992), the scientific knowledge that has accumulated by the beginning of the twenty-first century suggests ways to advance further, beyond the acknowledgment of sources of mutual relevance to science and religion, to a deeper set of interchanges. The specific route of such communication as developed in this paper concerns the fine structure of our cerebral cortex.

The door Burhoe opened is one that many people will not readily pass through. If Heschel's exhortation to "radical amazement" remains suspect in your mind as a seductive temptation held out by a fundamentally dogmatic religious establishment, do at least face the fact that there are secular exclamations that say very much the same thing. Whatever the details of your life are right now—even if things have recently been bumpy—pause for a moment to indulge in a safer form of deviant self-expression: Remind yourself that the basic fact of your existence is very *cool!* It is a cliche, yet true, that the sweetness of just breathing and seeing and hearing ordinary things is sometimes not appreciated until the end of one's life appears at the horizon. But a traditional prime function of religion has been to help us capture a good attitude toward life, with all its length and particulars, to orient us across the concrete and abstract spaces in which we live. Religion and science both concern "what is really cool." Let us pursue this rhetorical indulgence a bit further.

A Song of Nature. Psalm 8 is a wonderful, concise exercise of the life-orienting function of religion. For present purposes let us consider this psalm's God-talk merely to be a metaphorical way of expressing abstract ideas that are not easy to express. The following is a somewhat brazen attempt to secularly update Psalm 8, while relaxing the formality of its language and adding a limited degree of postmodern focus on the individual. I hope the humorous parts of this passing effort do not detract from but rather sharpen our attention toward possible meanings of this ancient poetry.

My gosh; gosh almighty!
How excellent is the coherence of nature
that I experience all around me.

The vastness of the universe is incredible;
what can possibly account for all of this?
Children are born and grow, and then
some of the new things they begin to say
Reinvigorate us, and help us to reorganize
and transcend accumulated confusions.
And—when subtler exercises of freedom fail—
to silence meanness.

When I look up at the expanse of sky
Wondering how a primordial natural process
just happened to play itself through to
The moon, and to those trillions of stars,
and to the enigmatic dark matter of the galaxies,
I wonder why beings as tiny as we are
came to be illuminated with consciousness,
Each one of us at the center of the universe,
as if it had unfolded just for him or her.

We have evolved almost godlike qualities
in our human intelligence and freedom.
We attempt honorable and glorious achievements.
Evolution has bestowed upon us a power to control things
And to lead them where we will.

Sheep, oxen, horses, pigs, dogs and cats,
camels, llamas, goats, laboratory rats,
And their wild cousins, from which these obedient servants
were domesticated,
The birds of the air, the fish of the sea,
The chaotic dynamics of the immense ocean
and of the exotic creatures of its great deep.

My gosh; gosh almighty!
How very cool is this opportunity for each of us
to discover and create meaning,
while hoping that it all comes together with goodness.

Having just played lightly with profound matters, it is useful to add a pedantic qualification: In mid-twentieth-century America, while Heschel was discussing "radical amazement," the adjective *cool* was used mainly by hippies and teenagers. Today this term has achieved much wider usage, and we know now that the "coolness" of the free and creative human mind comprises much of what Heschel and other theologians were talking about in celebrating existence. They can hardly have suspected then how cool is the fine architecture of the brain that underlies the mind, which has the intellectual and emotional capacity to be radically amazed.

New Inspirations from Traditional Methods. Today, at the dawn of the new millennium, we have available a great many more findings of science and many more highly developed methods than a half century ago. Yet some of the newer findings that best help to illuminate what we are arise from diligent work with optical microscopes, a very traditional form of discovery that requires long hours of patient study. Anyone who has spent a long, quiet Sunday afternoon alone in the laboratory with a microscope, a set of slides, and the sun shining in through the window must suspect that such refreshing acts of knowledge-seeking have kinship with meditation. Today, the appreciation of the beauties of nature that emerges with such work has been enhanced by newer techniques of preparing and staining tissues as well as by finer optical equipment. That such innovations have complete continuity with techniques of microscopy that go back centuries to the earliest days of the scientific revolution seems especially significant. The public's attention has recently been captured by the flashiness of new and extremely expensive technologies of brain imaging, using highly computerized systems involving magnetism and radiation, that correlate activity fluctuations in broad brain regions with specific behaviors. Such resource-intensive research activity is carried out mainly in the research university cathedrals of science. In the meantime, it is the more traditional neuroanatomical methods, in combination with all the findings and ideas they have cumulated, that are enabling us truly to peer deeply and with much higher resolution into the awesome, fine structure of brain matter.

Pursuing Burhoe's Program. Burhoe, a quintessentially gentlemanly Protestant with New England roots, though not readily given to "hip" modes of expression, conversed easily with those of us who do try to add color to words because of our desire to communicate with undergraduates (some of the "babes and sucklings" referred to in the King James version of Psalm 8, out of whose mouths we hope will come strong ideas) or simply because of our own excited hope, with such stylistic resonance with the present, to be part of the flow and thrust of our rapidly changing scientific and technological times. We shared this zest with Burhoe, who particularly appreciated the remarkable "coolness" of the two main living information mechanisms with whose evolution has emerged our humanity: our genes and our brains. Both of these informational mechanisms have long interacted dynamically with culture, changing it and being changed by it. The human brain is the more individualistic partner of this pair of living substrates of human culture. While genetic evolution takes generations and eons, individuals' brains record and create knowledge on the shorter time scales of our individual lifetimes. The human brain is the home and the launching platform of all the human knowledge that can move freely, and sometimes with grace, among our individual selves. Somehow, though long neglected by academic psychology, our consciousness is intimately part of that process.

How can it be that this spark of awareness is sitting in your chair, in your body? What is a human mind, really?[7]

Can Thoughts and Feelings Reside in Tangible Material?

As you see, I cannot get over the strange and wonderful association between mind and matter—mind and brain. Thought and feeling seem to be volatile, ethereal, and ghostly (don't they?), or liquid and flowing, or something like that. For all we know, it's possible that mind is really made out of wispy stuff. Thoughts may begin as spirits floating someplace in hyperspace before they waft into your head by some sort of supernatural electromagnetic osmosis. (If I'm in an ebullient mood, as I always hope to be during a lecture, at this point I mysteriously gesture with waving hands, wiggling fingers, and narrowed eyes while humming music from *Twilight Zone* or *The X-Files* or some other popular piece appropriately evocative of mystery.) [8]

The subjective side of our mental lives, or consciousness, so obvious to each individual, remains a deep enigma. Although religionists have long addressed the "inwardness" that is the salient fact of existence for each of us, beginning early in the twentieth century "positivistic" philosophy of science helped to spread a kind of conjunctivitis of the mind's eye across psychology and across much of the rest of social science and biology. Too many scientists then shied away from looking within themselves. However, today, with the radical amazement that is encouraged by advancing knowledge, scientists again hope to shed light on the enigma of inwardness by committing to the idea that one's mind—in every little tiny bit of itself—is completely embedded in the stuff of one's brain.

Why Not Sooner? Less Complete Science Still Had the Vagueness of Belief in Magic. During the seventeenth century in the West, our learning curve about the remarkable physical properties of matter reached an inflection point, from which it has since accelerated acceleratingly. The Enlightenment of the eighteenth century and the growth of physics, chemistry, and biology during the nineteenth century put religionists on the defensive.

This was not because we then knew too much about the physical properties of matter, but because a little new knowledge was a dangerous thing! Many among scientists, including Darwin, saw themselves as appreciating the amazing works of God, but that perspective did not generally ring true as a main thrust in the history of science and technology, because here, in our own new knowledge, were alternative explanations of natural phenomena, together with the headiness of a growing power to manipulate things.

Immature Images of Power. In large part, those earlier explanations and uses of power were childish. Perhaps their net philosophical effects on us were motivated by unconscious, primitive metaphors regarding the nature of power. Such archetypal lenses may have arisen first from general familiarity with monarchical and aristocratic forms of government and later from the ubiquity of other varieties of governmental hierarchy or industrial economic hierarchy. Power suggests peremptoriness. A wave of the hand, a word—and orders must be followed.

Early scientists achieved such peremptoriness in their own newly powerful interactions with matter. Rub certain substances on fur and you can cause sparks; systematize that process with rotating belts, Leyden jars, and the like and you can create a spark that has quite a wallop (Nollet [1746] 1948; Roller and Roller 1967). Touch such electrical charges to a frog's leg and it twitches—it is galvanized to action. By the late eighteenth century, it seemed on the edge of plausibility that the fictional Victor Frankenstein might use techniques of science and medical technology to go so far as to give life to matter. But that story, like most later science fiction, contains much hand-waving in its explanations (Rabkin 1998), hardly more than the fabled magic power of words with which Frankenstein's well-meaning mythical hubristic predecessor of an earlier century had supposedly given life to "the golem."

The Courage to Understand. With immature knowledge, science is little more than magic. It becomes something greater than magic when, with creativity and critical systematization, we achieve organized conceptions of wholes and parts at many scales and when that knowledge grows in intricacy and intimacy. Along the way, such growing knowledge again opens the window to awe, to radical amazement at the marvelous richness of nature.

Think about the field of chemistry before and after the discovery of the periodic table of the elements. Think about biology before and after each of the following: the theory of evolution and the discoveries of the living cell, of cellular membranes and organelles, and then of the molecular structure of their components. Thus, matter is endlessly fascinating. There is no end to the new knowledge that embeds in or encompasses and reorganizes the old. There is nothing "merely" about lawful processes discovered through science. Awe is something that can grow in knowledge of nature rather than in giving way to the image of peremptory power that lies in mysterious "stuff" or domineering people.

Mind as a Complex Wave

We begin to see our way out of the difficulty that often seems to be presented by the idea that mind is in the brain: a brain looks like stuff. You can pick a brain up and hold it. But thoughts and emotions do not feel like stuff. Philosophers, psychologists, and neuroscientists have long puzzled over this, going back even thousands of years to Plato and the metaphysicians who preceded him. Perhaps one way to begin to reconcile the "phenomenological difference" (a fancy way of saying the "feel-difference") between mind and brain-matter is to think about thoughts metaphorically as being like waves in the water. Water is the matter, the material, without which there would be no waves. The wave itself is dynamic; we talk about it as a thing, but it is a thing that is really an event or a process. You can point to a wave, but not unless there is some supple material like water there as its substrate.

This may be more than a mere analogy. The billions of large and small electrical waves occurring in the brain at any given time may compose the actual physical side of our thoughts and feelings. As yet, all our knowledge of these waves has not come together in a nearly adequate understanding of their larger-scale organization. What can we do next? Let us pursue this way of thinking toward the greater intricacy and intimacy that is available in current scientific knowledge. Up very close and focused, what *is* brain matter?

Your Nexus of Self. You are your brain, but also, in many senses, you are your body, your family, the culture in which you live, even things that you own and that have become intimate extensions of your body in skilled behaviors (your tennis racket? your car? your computer? your inline skates?) and your place in friendships and other social structures.

At the center is your warm brain, humming away electrically and chemically, with vigorous support of nutrients carried by your bloodstream and by the cerebrospinal fluid in the middle of your brain and bathing its outside. Inside, the brain's parts communicate by scintillating with billions of tiny invisible electrical "sparks" and billions of tiny pulsations of dozens of different chemical transmitters in every second. And this is happening at this very moment, inside you.

Brain Structure: A Primer

When you know more about the architecture of the intricately patterned brain you may come to believe that it really is a kind of thing that can contain the mind. It is an incredibly complex and beautiful structure of tiny parts and fine interconnections, all packed densely together. Most of the human brain—about 90 percent—is in the part called the cortex. Most of your thinking, feeling, and planning are thus laid out within a thin sheet!

The human brain weighs about 3 pounds. Its volume is about a quart and a half, or about 1,400 milliliters. If that amount is hard to picture, wrap your hands around either side of your head, and then move them forward while holding that distance. Then move them together about three-quarters of an inch to allow for your skin, hair, and the thickness of your skull. That's how big your brain is. (Indeed, the human skull is not all that thick. It gets some of its strength from its curvature in somewhat the same way as does a Roman arch or an eggshell. Your skull is firm and rigid unless it gets bonked too hard. (So be nice to your head and wear a helmet when bicycling!)

But there is a sense in which we're all flatheads. The mass of human brain is not really as globelike as it seems. It's mainly a sheet. As humans evolved, most of the brain expansion took place at the very top, or front end. About 90 percent of the human brain is at the highest level, or cerebral cortex. And cerebral cortex is really a thin sheet.

"How thin is it?" you ask. Only about 2 to 3 millimeters. After subtracting out for the noncortical brain tissue and the spaces filled with cerebrospinal fluid, the total volume of the cortex is spread out over about 2,600 square centimeters (Mountcastle 1997, 701). If it were neatly flat instead of crumpled up in your round skull, and if the cortical sheet happened to have a square perimeter, its area would encompass a square measuring about 20 inches by 20 inches.

This 90 percent of the human brain might well be called our "mortarboard cortex." Actually, 20 x 20 inches is about twice the linear size (thus about four times the area) of a graduation mortarboard, which is normally a little less than 10 x 10 inches. Figure 1 illustrates what a cortex-sized graduation mortarboard would look like and thus humorously dramatizes the idea that natural selection's life-and-death "didactic" inscriptions in our human genes have made us the "college graduates of evolution."

Why aren't our heads actually flat, like a mortarboard? If they were, it might make it more convenient to think scientifically about the brain, instead of piecing things together as brain scientists have done over the centuries by studying the cortical sheet in its labyrinthine crumpledness.

Does a living neuron sheet constitute a good "page" on which to "write" thoughts? Professors, elicit responses from students. You might, with droll teacherly demeanor, raise the issue of how peculiar we would look with thin flat heads. And yet, if it were adaptive to *be* that way, we probably would have evolved the aesthetic tastes to enjoy *looking* that way.

There are other possible factors. A big flat head would be cumbersome. We would have to tilt our heads carefully to pass through narrow doorways. Getting past a closing elevator or subway door would require special care! But those doorway problems would likely be mitigated by an enhanced acuity for judging distance, the same sort of depth acuity that a hammerhead shark presumably benefits from with the greatly enlarged interocular distance that a wide head enables.[9]

Large surface/volume ratio would create vulnerability to ambient temperature changes. Knit wool caps would be especially necessary on cold winter days; they would be heavy and expensive, but their larger surface would allow for more interesting designs. On warm summer days, on the other hand, one would simply tilt one's head at an appropriate angle to the sun's rays; this would suffice so long as the ambient air temperature was sufficiently below 98.6 degrees Fahrenheit.

Head size at birth, pelvic size, and the human compromise between level of brain maturity and gestation time are additional problems. We are now among the most immature of organisms at birth, reserving most of the growth of brain volume for the first several years of life, after we have safely negotiated mother's birth canal. With a mature head size as broad as 20 x 20 inches, we might have to be born in an even more immature state, perhaps requiring human beings to evolve as did marsupials. Alternatively, head shape might gradually change during development after birth. That

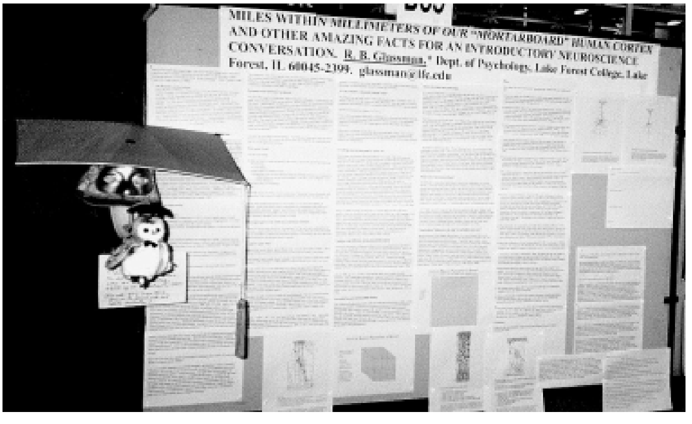

Fig. 1. Fanciful illustration of the main dimensions of the human cortex. Its area is 2,600 square millimeters (or a 20-inch square) and its thickness is about 3 millimeters. Although the area and thickness are accurately portrayed, this model, of course, takes a liberty in its square shape. That shape is used to illustrate the point that because our intelligence and hypersociality permit knowledge to leap from brain to brain by nongenetic modes of information transmission, human beings are the "college graduates of biological evolution." The life-sized Mardi Gras mask helps to set the scale for viewing this scene, which was photographed at the New Orleans Convention Center, at the (year) 2000 annual meeting of the Society for Neuroscience ("session," or group of posters, on "Teaching of Neuroscience").

would likely have led early developmental psychologists to theories of mind that related cognitive maturity to the shapes of parts of the brain.

An "internal" benefit of our extant rounded head shape is that its foldings might reduce the necessary length of some cortico-cortical connections, thereby allowing shortcuts within a gyrus (the ridge between two grooves of the convoluted brain). This possibility may have important implications if mathematical graph theory is relevant to understanding the cortex, as suggested below.

Will the sheetlike character of the cortex turn out to be a "mere" by-product of developmental and evolutionary factors? For example, might it be due to the opportunism of natural selection and its lack of foresight, and might it merely be due to the tendency of evolutionary accidents to "freeze" forms? (Might comparative studies across species, beyond the mammals that are discussed here, help answer this particular question?)

Illuminating and surprising answers may come from the students in our classrooms. Even with such well-known phenomena, we're on the edge of knowledge where learning and problem solving can transport us. As scientists, we very much need to think more about this simple, midlevel (between gross and microscopic), neuroanatomical fact of the sheetlikeness of the cortex. Is a sheet of this kind of tissue, indeed, just the sort of "neural papyrus" that is the most adaptive form on which the business of mind can be written out in the language of the brain? Does the language of mind/brain want a sheet? Could that sheet be the proverbial *tabula rasa*? Ah, but ethologists, evolutionary psychologists, and neuroscientists now know that the *tabula* is far from completely *rasa*. It contains ample hints and sources of preparedness for particular forms of learning and memory.

But again: Is there some reason why such hints and sources are stored especially well when embedded in a slightly thickened sheet? Do ideas associate and reassociate with each other and with the traces of new experiences in a particularly effective way when a sheet is their venue? Alternatively, does the laminate shape inexorably *limit* connectedness in an important way? Without such a limit, would the interplay of our mental associations be so free and unbridled as to lead all attempts at thought to a disorganized cacophony? Why in this three-dimensional world is most of our brain only a tiny 2 or 3 millimeters more than two-dimensional?

Enough about the brain from a distance. What does this tissue look like up close?

Constancy and Difference among Mammalian Species. Among the properties of human cerebral cortex are qualitative and quantitative ones that, remarkably, remain constant across mammalian species. Above all, through order-of-magnitude variations in overall brain volume across species—e.g., the brain of a human is 3,400 times as large as that of a mouse—mammalian cortex remains 1 to 3 millimeters thick (Abeles 1991, 3).

Indeed, the internal structure of the cortical sheet has long been known to be made up of layers within the main sheet. There are approximately six layers of neurons. However, there is also a strong "vertical" organization across those layers (Braitenberg and Schüz 1998; White 1989, 8–12, 20–29) that unifies them into a single sheetlike structure. This organization pervasively comprises units that neuroscientists call "columnar modules," which span the thin vertical dimension of cerebral cortex. These columns of neurons "only vary from 300 to 600 μm [microns, or thousandths of a millimeter] in diameter, even between species whose brains differ by a factor of 10^3," not only in sensory and motor cortex but also in association cortex (Eccles 1984; Mountcastle 1997, 702).

Fineness and Density. One of the most interesting points made by V. Braitenberg and A. Schüz in their detailed, quantitative examination of cortical architecture (1998) concerns the exceedingly dense spatial overlap of the neuropil (the aggregate of neuronal fibers) of individual pyramidal neurons in the cortex. Much of our knowledge of cortical microanatomy comes from the beautifully detailed patterns revealed by Golgi stains, which select one individual neuron from the mass of others with which its fibers intermesh and show it in all its anatomical detail (Rosenzweig, Breedlove, and Leiman 2002, 28–29). Cajal's famous sketches, done over a hundred years ago (Figure 2), remain quite similar to what some of the best recent neuroanatomical scholarship has revealed (Mountcastle 1998).

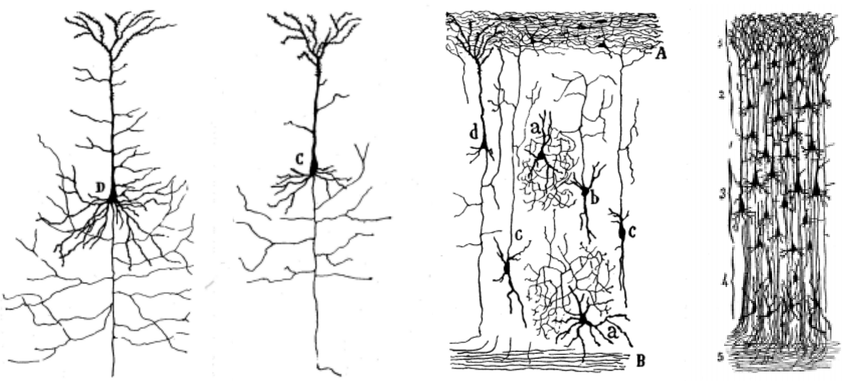

Fig. 2. These venerable sketches, by the great nineteenth century neuroanatomist Santiago Ramón y Cajal, illustrate both the remarkable complexity of a single cortical pyramidal neuron and the overall complexity and density of connections among cortical nerve cells. Our awe at cortical architecture continues to increase in step with increasing contemporary knowledge, such as that reviewed by Braitenberg and Schüz in their 1998 book. These drawings are from Figures 12, 13, and 10 (in that order) from Chapter 3, "The Cerebral Cortex," of Ramón y Cajal [1894] 1990, and are used with permission.

Miles within Millimeters. However, when we look at a picture of a cortical neuron in isolation, it is easy to forget that a pyramidal neuron that has been selectively stained by the Golgi method is but one of thousands that overlap within the same single cubic millimeter of brain. The upshot of the fact that each neuron has so many branches is that in all mammalian species a cubic millimeter of cortex contains about 456 meters of dendrites and 1 to 2 kilometers of axons (Braitenberg and Schüz 1998; also see Abeles 1991, who estimates 400 meters of dendrites and 3.2 kilometers of axon!). In other words, each cubic millimeter of your cortex contains 1 or 2 *miles* of neural connecting fibers. What circuits!

Your Brain Can Encircle the Earth. Let us stay with this amazing fact for a moment. The estimated 2,600 square centimeter cortical area equals 260,000 square millimeters. If we estimate an average cortical thickness of 2.5 millimeters, then there are 650,000 cubic millimeters of cortex. Because each of these cubic millimeters has 1 to 2 miles of neuronal fibers, your cortex as a whole must be wired with about a million miles of connecting lines. That's enough to wrap around the earth about forty times.

These amazing facts about brain tissue inspire the same awe as do the astronomical figures of astronomy—for example, there are 100 billion stars in our Milky Way galaxy (see Morrison et al. 1982 for a vivid depiction of this and other aspects of the vast range of sizes in nature). So the complex brain is a miniature, dense universe, with multiple, complex, interconnected tiny parts, all squeezed into a space the size of your head. Billions of dynamic electrochemical "waves" course across it every second. It seems more plausible, with these facts, that the thinking, feeling human mind is really in the human brain.

When numbers get very large, intuition falters. Thus, it is difficult to judge what are the implications of cortical density for connectedness among neurons. Although each pyramidal neuron synapses on about 4,000 others in the mouse (Braitenberg and Schüz 1998, 96), and as many as 24,000 to 80,000 in humans (p. 190), there is only about one chance in a thousand that a randomly chosen dendritic spine belongs to a given one of the pyramidal neurons whose basal dendrites are in that region. Such sparse direct connectivity of neurons might imply largely uncoupled, tiny "cliques," in the graph-theoretical sense (explained below), if local connectivity (called "B-type," or "basal-dendrite-type" by Braitenberg and Schüz) were highly specific; however, that does not seem to be the case. Rather, local connectedness among pyramidal neurons looks as if it is highly unspecific, so that Braitenberg and Schüz characterize the distribution of spines on cortical dendrites as looking as if "it rained synapses on the axon" (p. 51). They further note that "dendritic clouds of different neurons strongly overlap with each other and . . . axonal clouds permeate each other even more intimately" (p. 182).

Braitenberg and Schüz (1998) suggest that synapses of a cortical neuron that convey feedback onto itself are no more populous than that neuron's synapses onto any other pyramidal neuron in the local cluster. Therefore, these copious return branches seem a likely substrate for intimate associativity among the pyramidal neurons in a cluster. This kind of connectedness turns out to have important implications, as suggested by an area of mathematics known as graph theory, which is the systematic study of connections of things (Clark and Holton 1991; Diestel 2000). In brief, it seems to mean that small variations in brain activity might cause the whole cortex—or large areas of it—to unify around some overall pattern of activity, while other small variations could break up larger patterns and cause them to "flutter apart" (Watts and Strogatz 1998; Hayes 2000). The introductory book *Small Worlds,* by D. J. Watts (1999), which in many parts is quite readable by nonmathematicians, explains the implications for many areas of science of very basic ideas about connections among extremely large numbers of objects. When such hypothesized connections are considered to have the lifelike characteristic of being partly orderly and partly disorderly, there emerge some fascinating effects in the patterns of the whole.

Amazing Facts: A List

Here again are some of the previously mentioned "amazing facts" listed with some additional ones.

- There are about 10^5=100,000 neurons under every square millimeter of cortex in general, across mammalian species (research of Bok and of Rockel, cited by Braitenberg and Schüz 1998, 25–27).
- Neuropil occupies about 83 percent of the cortical volume. Of this, about 34 percent is axon and 35 percent is dendrite (recall that dendrites are generally thicker, while axons are thinner and longer), with another 14 percent comprising dendritic spines. The remaining volume is 11 percent glia (non-neural cells for structural support and other, incompletely known functions) and 6 percent extracellular space (Braitenberg and Schüz 1998, 37–40).
- Each single cortical pyramidal neuron is usually estimated to have about 10^4 = 10,000 inputs to its dendritic tree (e.g., Douglas and Martin 1998, 464). Because about three-quarters of all cortical synapses are from one pyramidal neuron to another (Braitenberg and Schüz 1998, 77), this implies about the same number of axon terminal outputs as there are inputs. One estimate for monkey motor cortex is that there are even more synapses than this, fully 60,000 synapses per neuron, and there are an estimated average 24,000 to 80,000 synapses per neuron in humans (Braitenberg and Schüz 1998, 37–38, 190).

- The human cortex may be as large as 4,153 square centimeters in area. This is derived from the figures of M. A. Hofman (1988), of 1,167 cubic centimeter cortical volume and average thickness of 0.281 millimeters.
- The cortex has levels of organization between the individual neuron and the large functional region. Cortical neuron clusters composing feature-analyzing modules comprise approximately 1 square millimeter of cortical area (as seen from above) (Mountcastle 1997). An alternative figure of 4 square millimeters might be used in considering the entire local set of feature analyzers that pertains to a unitary small area of the visual field (Bear, Connors, and Paradiso 2001, 264–65).
- Because a square centimeter comprises 100 square millimeters, the above empirically based estimates suggest 4,153 x 100 = 415,300 feature-analyzing modules in the human cerebral cortex. With its population of 10^5 neurons, each having 10^4 inputs and 10^4 outputs, each module therefore (disregarding overlaps) has an overall fanout ("fanning out," divergence of connecting lines), and overall fanin ("fanning in," convergence), of $10^5 \times 10^4 = 10^9$, or 1 billion, connections inward and outward. What are the most relevant dimensions of mind to consider in conjunction with such basic estimates of brain capacity? The overall span of an individual's knowledge? The "resolution of thought"? Redundancy and reliability of behavioral functions (Glassman 1987)?
- Parenthetically, the parameters used in these estimates imply an overall human cortical neuronal count of 40 billion, which is about halfway between the typical textbook estimate of 100 billion (Rosenzweig, Breedlove, and Leiman 2002; Bear, Connors, and Paradiso 2001) and the lower estimate of 10 billion, which Braitenberg and Schüz (1998) use at some points of their presentation.
- Each cubic millimeter of cortex contains about 9×10^8 (or just under a billion = $10 \times 10^8 = 10^9$) synapses; this density does not vary much from mouse to human. Synapses are spaced on dendritic membrane at about 1 micron from each other (Braitenberg and Schüz 1998; White 1989). As the total length of axons in the cortex is longer than the total length of dendrites, the average distance between synaptic contacts made by an axon via branches along its length and terminal arborizations is about 5 microns.
- Intracortical connections (that is, connections *among* regions of the cortex, as opposed to connections between the cortex and other parts of the brain or spinal cord) take up about 98.6 percent of the cortical white matter (Abeles 1991, 35). Axons are sent into the white mat-

ter by 80 percent of cortical neurons. Only up to 20 percent of synapses are from extracortical afferents in the primary sensory cortex, but this figure is much lower in other cortical areas (White 1986, cited by Braitenberg and Schüz 1998, 43). Thus, by far most of the brain's billions of communications every second occur fully within the cortex, so most of the life of the mind is an inner life.

- The synaptic space is about 20 to 50 nanometers (millionths of a millimeter); synaptic vesicles are 50 nanometers in diameter.
- There are thousands of channels in a square centimeter of neural membrane; when a channel opens, ions pass through it at a rate of over 1 million per second (Rosenzweig, Breedlove, and Leiman 2002, 79–80).
- The speed of nerve impulses varies from about 1 meter/second in slower axons to about 100 meters/second in faster ones, with the very fastest axons conducting at about 200 miles an hour. Though this is only about one-third the speed of sound in air (Rosenzweig, Breedlove, and Leiman 2002, 62–63), the modest distances of millimeters and centimeters over which neurons in the brain communicate make that velocity an adequate foundation for the speed of thought.

Conclusion

We human beings strive toward meaningful lives, yet this is a frequently uncertain experience, demanding something more than moment-to-moment judgment. In contending with individual freedom, each of us, again and again, looks for ways and moments to cognitively and emotionally grasp as much as we can. This is where religion and theology step in. Theologians have explained the extremely contingent, historical nature of human life as each of us exercises human freedom (e.g., Ashbrook and Albright 1997; Barbour 1997; Burhoe 1975; Hefner 1993; Niebuhr 1943). In this way, theology seeks the largest conceivable framework for understanding how we self-reflectively depict our moments and tell our stories, the main business of the humanities. The humanities, including theology, deal eagerly with flowing change, particularity, and incompleteness, even as they sometimes seek constancies behind the flow.

In contrast, in the sciences each single opus is an attempt to pin down a small or large constant, or "eternal truth," by the strengths of human observation and logic pulled within the confines of an "objective study." Yet, in whatever way we look scientifically at human beings, including scientists themselves, we see partialness.

Modern psychological science, for example, has amply shown how patchy and prone to fallible leaps of assumption is the apparatus of consciousness with which we negotiate the world. A fascinating set of examples in studies concerning long-term memory is in the compendium on memory in natural contexts edited by U. Neisser and I. Hyman (2000). Knowledge of short-term memory, or working memory, the conscious "doorway to growth" that each of us is constantly passing through as we move through the present from past to future, presents an equal enigma: Working-memory capacity is limited in the most extreme degree. We can bear in mind only a few simple, independent items at one time. And yet we sometimes manage with this marvelous and limited cognitive capacity to lead meaningful lives spanning broad reaches of space and time (Glassman 1999a, b; 2000a).

In biological science, at the level of neuroanatomy and neurophysiology, the remarkable properties of the cortex lead us to marvel at both immensity and finitude. This paper has considered, on the one hand, the vastness of numbers of elements and connections among them and, on the other hand, the extreme thinness of the sheetlike cortex. These properties pose exciting challenges for further theory and empirical investigation that may have unusual significance for theology.

For example, the basic facts of cortical microscopic and gross anatomy strongly suggest great potential in theoretically considering, in terms of plane topology and graph theory, possible patterns of cortical activation that hypothetically represent cognitive items in working memory (Glassman 2000b; forthcoming). Whether those particular conjectures about the underlying plan of the cortex are correct or not, the deeper message here is that we can envision real possibilities of scientifically exploring dynamic activity patterns that occur at the middle time/space scale at which the mind and brain of an individual are one and the same. In so doing we also touch the matter of how our social brain reaches both toward other brains and toward higher things. Research should proceed not merely by means of apologetics restricted to localist thinking about which parts of the brain seem most to subserve particular aspects of religiosity but by trying to look directly at the most essential qualities of our minds as they engage in every kind of thought, emotion, and behavioral action. We are fully justified in using the word *enthusiasm* about studying the brain, while recalling the etymological derivation of that word.

NOTES

1. Slightly revised form of abstract published in *Society for Neuroscience Abstracts* (2000), vol. 26, part 1, p. 46, #21.74.

2. The first quotation is from "Natural Selection and God," chap. 4 of Burhoe 1981. The excerpt, from p. 100 of this article, is from a section of the chapter entitled "Natural selection in a community of brains." The second quotation is from "The Human Prospect and the 'Lord of History'" (Burhoe 1975), p. 306, and is Ralph Burhoe's extrapolation from Paul MacLean's theory of the "triune brain."

3. The excerpt is from Heschel [1955] 1983, 38.

4. I thank Dr. Robert Luther, in 1990 my wife's supervisor at Abbott Laboratories, for bringing this excellent paper to our attention. See Ashbrook and Albright 1997 for further discussion of Meshberger's remarkable perception.

5 . Similar scientific logic applies to the experimental use of the lesion method with lab animals and to systematic clinical naturalistic observation in the neurology of human brain trauma. Experimentally, a specific region of brain tissue is removed (with the experimental animal under general anesthesia, and using other humane precautions and scientific structuring, for example, with control and experimental groups and statistical analyses, and good animal care) in order to see what effect this has on a particular set of measured behaviors. In clinical settings, by comparing patients and categorized groups of patients, attempts are made to correlate localized brain damage from trauma, stroke, or illness with particular behavioral symptoms. There has sometimes been confusion even among neuroscientists about exactly what is learned and what remains uncertain with the lesion method, by comparison with other methods such as electrical or chemical brain stimulation, recording localized electrical activity, assaying localized chemical effects in synapses, and others. There are more logical similarities among these methods than has sometimes been thought in regard to the ways in which they allow us to discover how aspects of psychological functions are localized in the brain (Glassman 1978). See the general neuroscience textbooks by Bear, Connors, and Paradiso (2001) and Rosenzweig, Leiman, and Breedlove (2002) for reviews of contemporary neuroscience methods.

6. This presentation alternates in voice between teaching undergraduates and more concise communication with colleagues.

7. Here, as frequently in other "inspirational science," there may be a certain implication of pantheism. Indeed, experienced scientists who reach into this arena of seeking broader meanings may not realize the degree to which they do something akin to mystical traditions in theology. Attendant philosophical issues have been dealt with well by theologians. For example, in volume 1, *Human Nature,* of his two-volume classic *The Nature and Destiny of Man* (1941), theologian Reinhold Niebuhr perceptively reviews the philosophical history and examines the social-functional implications of searches for higher meaning that emphasize immanence, or divine qualities in the material world, as compared with those that emphasize transcendence, or sources of meaning above and beyond those evident in day-to-day worldly affairs. I addressed these matters in "Symbioses Can Transcend Particularisms: A Memoir of Friendship with Ralph Wendell Burhoe" (Glassman 1998). Three excellent recent books with a broad span across these issues are Ian Barbour's *Religion and Science* (1997), Philip Hefner's *The Human Factor: Evolution, Culture, and Religion* (1993), and James Ashbrook and Carol Albright's *The Humanizing Brain* (1997).

8. I try to be a well-behaved materialist in this presentation, albeit with some parsimoniously measured mystical indulgences. The risks of promiscuous mysticism include a loss of motivation for scientific reasoning in favor of a lazy form of theism; hence my gentle mocking of that attitude. Nevertheless, fine neuroscientists and philosophers have sometimes challenged the putative comprehensiveness of neural materialism. For example, consider Eccles's "radical dualist-interactionist theory of brain and the self-conscious mind," the coda of this highly accomplished neurophysiologist's Gifford Lectures on life, mind, and brain (1984, 226).

9. Note the additional teaching opportunities here and at other points. For example, intelligent beings with wide flat heads would likely design different sorts of doorways—unless structural and cost/benefit factors in housing construction forced compromises. Although some critics of evotutionary theory argue that it is all too easy to come up with plausible evolutionary stories about what is, or what might be, these are good exercises inthe logic of natural selection. We can only see through the glass darkly, but we should learn to try to do so.

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