Vernon B. Mountcastle

1918–2015

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
Michael Merzenich

NATIONAL ACADEMY OF SCIENCES

VERNON BENJAMIN **MOUNTCASTLE**

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By Michael Merzenich

Vernon Mountcastle was one of the world's most important and distinguished neuroscientists across the second half of the 20th Century. His experimental studies, scholarship and leadership played a central role in the neuroscience awakening that has marked these past decades of human history. Mountcastle's groundbreaking 1957 discovery that the brain's cerebral cortex is comprised of vertical columns of cooperating nerve cells, each processing column-specific information, revolutionized modern neuroscience. In parallel, beginning with exquisite studies of the coding of tactile sensation by specialized receptors in the skin of human and non-human primates, his team focused on the neurological coding bases of human tactile perception, perceptual magnitude, and discrimination. In the primary cerebral cortical areas most directly fed by inputs from body surfaces, his team elegantly showed that you could not account for tactile signal detection or the discrimination of tactile magnitudes or differences by neuronal activity. In a later brilliant series of studies conducted in awake, behaving primates, he showed, to the contrary, that 'higher' brain processes actively biased and controlled all dimensions of our perceiving, as a complex function of behavioral context.

After graduating from Roanoke College with a chemistry degree at the age of 19, Mountcastle was accepted for admission for medical training at Johns Hopkins. After completing his MD and a short residency, he volunteered for World War II service as a Navy surgeon. After three years of active duty he returned to Johns Hopkins, where he made key and enduring contributions to systems neuroscience research and scholarship, and to university and public service.

Vernon Benjamin Mountcastle, Jr., was born in Shelbyville, Kentucky, in 1918, the first son and the third of five children in his family. In a brief personal memoir (2009), he expressed the lifelong pride he took in his immigrant Scottish ancestry, in his American family roots that extended back to the earliest years of colonization in Virginia, and in the gallant participation of his grandfather and three great uncles as members of Jeb

Stewart's 3rd Virginia Calvary in the Civil War, even though his predecessors refused to own slaves. Vernon was a proud Virginia gentleman of the best sort, in manner, spirit and personal integrity, throughout his adult life.

When he entered active duty in the summer of 1943 at age 25, he must have been one of the youngest surgeons to receive his commission and be sent into action.

When Vernon was 3 years old his family moved to the western Virginia city of Roanoke, drawn there because of his father's work as a partner in a railroad construction firm. Vernon described a young life in a secure and loving home near the boundary between town and the beautiful Piedmont countryside, a life filled with outdoor adventures, sports, games, and a grounding in classical education. Advanced mentally beyond his age because of early benefits he attributed to his schoolteacher mother, Anna-Frances, Vernon enrolled at Roanoke College at the age of 16. Upon graduation in three years with a bachelor's degree in chemistry, he was accepted, to his considerable surprise, by the Johns Hopkins University School of Medicine in the then (for this Southern mountain boy) alien climes of Baltimore—beginning more than 60 years of his devotion and service to this preeminent American institution.

It was a special time in the history of the Hopkins School of Medicine, and young Vernon was bedazzled by it all. In his recounting of those formative experiences, one is struck by the intensity, the quality, and the personalization of mentorship in the education of a young medical doctor at this great institution.

During his third year in med school, America went to war. Vernon enlisted in a U.S. Navy medical service program that prepared him, via his internship and a brief general surgery apprenticeship, for military medical service. When he entered active duty in the summer of 1943 at age 25, he must have been one of the youngest surgeons to receive his commission and be sent into action. After landing at Oran on the North African coast and spending a short stint on a hospital staff treating wounded soldiers during the Tunisian campaign, he was transferred to a specially equipped LST (landing ship, tank) supporting the medical needs of the Naval Amphibious Force in Italy. He took justifiable pride in his tour of duty on the front lines of the invasions at Anzio and, later, Utah Beach in the D-Day landing on Normandy.

After D-Day Vernon expected to be sent to the Pacific for what seemed to be an almost certain, and certainly horrendously bloody, invasion of Japan's home islands. Instead, the war abruptly ended in August 1945, with the dropping of atomic bombs on Hiroshima and Nagasaki. Upon his return home, Vernon reestablished a connection with a childhood acquaintance, Nancy Clayton Pierpont, falling in love with and marrying this greatest individual in his life just three weeks after the end of the war. That proved to be three weeks too late in one respect, however, because to his great frustration he was retained in the navy specifically because he'd been unmarried at the end of the war.

Vernon was then surprised by being discharged a year later—and he immediately returned to the familiar landscape of Johns Hopkins and Baltimore with the goal of initiating his long-held plan to train as a neurosurgeon. When no residency position was available for him at Hopkins, however, he inquired at Duke University, where he was again too late in the selection process to be granted a position in the 1946 residency class. He then looked into the possibility of spending a holding year as a research fellow in the laboratory of the chairman of Hopkins's Physiology Department, the distinguished Dr. Philip Bard. "Yes," he was told. "In that event, we'll have a position open for you next year." Neurosurgery's loss was to turn out to be one of neuroscience's greatest gains—because over that year Vernon was infected by a neuroscience research virus that held him in its grip to the end of his life, creating one of the most productive and distinguished medical neuroscience careers in our history.

Research apprenticeship and early achievements

The Physiology Department at Hopkins was an ideal training environment for Vernon, who provided us with a description of one of his primary mentors, Dr. Bard.[1] Bard was

> *...tall and powerfully built, his features regularly formed in heavy granite, his eye a piercing, pale blue...[who]...possessed great charity for the opinions of others, and avoided disputation. [In] counsel [he was] wise, modest, and persuasive... [and] radiated an ambient spirit of good humor, friendliness, and a fond concern for those about him.*

Above all Bard was optimistic about Vernon's prospects for great achievement, and he repeatedly expressed this confidence to his young protégé.

At the same time, other brain-science-oriented members of Bard's young faculty—and especially the brilliant Jerzy Rose, a Polish-Jewish refugee rescued in 1939 along with

1 Philip Bard was elected to the National Academy of Sciences in 1944; with a highly distinguished record of achievement in neuroanatomical and somatosensory and auditory physiological sciences. Rose was elected 1972.

other young Jewish physician-scientists by Adolph Meyer's Johns Hopkins Psychiatry Department, and who was also just back from his own service in the Pacific war—counter-balanced Bard's open-handed approach. Rose had been trained in the European tradition as a neuroanatomist. To say that his scientific approach was conservative or that Rose held high standards for proof is to understate the reality. "Every scientific claim," went the mantra, "must endure." In this tradition the longer the span of future time during which experimental data holds up without modification or extension, the better the science. To Rose it was a mortal sin to state conclusions that extended a millimeter beyond the limits of demonstrated fact.

These American and European research traditions were deeply imbued with scholarship and demanded logical completeness and scientific integrity. Vernon integrated these perspectives into his own research. Working with Bard, he conducted a landmark early limbic-system study identifying brain structures contributing to rage (1948). With Rose and others he completed the first functional mapping of the thalamic areas representing physical body sensations and pain (1952a,b 1954, 1958), using then state-of-the-art microelectrode-implemented physiological recording methods.

When Vernon and his colleagues then extended these studies in the mid-1950s to the reconstruction of the detailed representation of the body in the cerebral cortex itself, they became the first to document its fundamental columnar organization—initially in the cat (1957a; also see 1957b), then later, with Tom Powell, in the monkey (1959a,b). Vernon and others have told the tale of this discovery, one of the most important in neuroscientific history. As he would write (2009, 1978a, 1997), the fact that all cells in a vertical column of cells had a special association and were engaged cooperatively in signal processing is self-evident to any careful observer. Introduce an electrode orthogonal to the surface into the somatosensory regions of the cerebral cortex and one sees that every recorded neuron responds to the same sources of inputs, identified by body location, mode, and dynamic stimulus-evoked responding. When a recording microelectrode is introduced obliquely, it detects a saltatory progression; every neuron had shared properties over a short distance; then there is a shift to a new population in which every neuron has a new set of shared properties; and so forth. In three dimensions, this process directly translated into a dense mosaic of functionally delineable, response-specific columns.

Vernon later argued a now broadly accepted proposition—that the several hundred million "cortical mini-columns," each comprising about 100 neurons, are the basic functional processing units of the cerebral cortex[2] (1959a,b, 1978a, 1997). Their discovery was certainly gratifying to Vernon, but not, initially, to his collaborators (Al Berman and Phil Davies), and especially not to a strongly contentious Jerzy Rose. Perhaps Rose's greatest problem with this finding was that at the time these functionally documented columns were anatomically invisible. By contrast, the *horizontal* layering of the cortex was *highly* visible. Distinctions in that layering had been a primary basis for the subdivision of the cortex into large functional zones. Under Rose's influence, Berman and Davies asked that their names not be included on a manuscript that Vernon had written describing this landmark discovery.

It is a true test of the integrity and quality of a careful individual when he or she gets the answer right, even while fact and reason *must* trump what most believe to be the well-established truth. We call such an event "discovery." Early in his career, and many times later, Vernon passed this test with flying colors.

Sensory-Perceptual Coding in Somestheses

In these early studies Vernon developed a core interest in trying to understand how sensation and perception could be accounted for by the temporal response patterns of neuronal discharges in the cerebral cortex. The focus of his interest was human perception, behavior, and consciousness. He had chosen to study this grand subject in the broad domain of somesthesis—the faculty of bodily perception and the sensory systems involved.

To gain a foothold for addressing these issues, Vernon initially pursued several lines of research and development that he believed to be prerequisite for generating useful answers. Initially working with a visiting German neuroscientist, Gerhard Werner, he began a long journey of documenting, in quantitative detail, the information delivered from "organized" cutaneous mechanoreceptors delivering fast receptor-specific inputs into the somatosensory nervous system (1965). From these landmark studies of inputs delivered from the skin to the spinal cord, Vernon undertook a parallel human:nonhuman primate (macaque monkey) study approach, in which the coding of sensory information from the skin of monkeys was correlated with a psychophysical documentation of sensation recorded using parametrically identical stimuli applied in humans (1967, 1968a, 1972). To Vernon's delight, elementary aspects of somatosensory receptor

2 See also Buxhoeveden, D. P., and M. F. Casanova. 2002. The minicolumn hypothesis in neuroscience. *Brain* 125:935-951.

responses evoked by stimulation of the surfaces of the hand in monkeys were almost perfectly paralleled by elementary attributes (detection, dynamics, response magnitude, texture judgment) of tactile perception in humans.

There had been a long history of largely qualitative studies of somatosensation, and researchers would go on to quantitatively define, for the ages, the cutaneous sensory interface contributions of the principal receptor types innervating the surfaces of our most important human tactile and haptic organ, the hand (1965, 1967, 1968a, 1972, 1975a). But Vernon and his colleagues' research enjoyed a quantitative advantage over all preceding studies of skin sensation, because they were able to use sophisticated mechanical stimulators. Engagement of skin surfaces with mechanically defined stimuli requires refined control of tactile probes or tactile surface displacements, forces, and movement dynamics. John Chubbuck, an engineer at Hopkins's Applied Physics Laboratory, played a key collaborative role in Vernon's research by developing devices that permitted the requisite quantitative stimulus control.

In 1960 Vernon's team was selected by the National Institutes of Health (NIH) to receive one of six of the world's first "mini-computers" (the 12-bit 2048-word LINC computer, designed by an MIT research team), which they deployed to control stimulus delivery and response recording. This was an unprecedented—indeed, revolutionary—technical advance, in an era in which physical stimulus control was largely qualitative, and neurological response data was largely collected using laborious film and galvanometer-record paper-trace methods. While this computer was, from a 21st Century perspective, laughably limited, it had important virtues in interface design, in being constructed to feed data to and receive data from a tape deck, and in being programmable in BASIC computer language. With rapid advances in both software and hardware, the laboratory evolved into one of most technically sophisticated neurophysiological research facilities in the world.

A practical problem that frustrated studies of the neural coding of sensation and perception was that the only practical animal models for such studies had to be deeply anesthetized throughout the course of study. After Vernon's team conducted many studies in the thalamus and cortex in such anesthetized preparations (1952a,b, 1954; 1957a,b, 1959a,b), an experimental series conducted in the early 1960s in the somatosensory thalamus in an unanesthetized monkey confirmed Vernon's long-held suspicion that there were dramatic differences in neuronal response dynamics in unanesthetized vs. anesthetized brains (1963a; also see 1963b,c). From that point forward it made little sense to him to study issues of the neurological representations of sensation and perception in an anesthetized brain.

All of these issues were addressed over a period of about a decade, and by the late 1960s Vernon's team was making powerful use of, first, a paralyzed unanesthetized animal, then a "waking monkey" preparation, in which Rhesus macaque monkeys were trained to tolerate head constraint while they worked on behavioral tasks that directly measured aspects of their tactile perception (1968b, 1969, 1975b). This "combined experiment" strategy most directly followed the model of an imaginative NIH researcher, Edward Evarts.

With this humane approach, Vernon and his colleagues directly recorded readings from neurons in the somatosensory cortex during behavioral training sessions, with animals voluntarily placing their hands to receive computer-controlled mechanical stimuli, such as indentations, forces, and dynamics. Using multi-site recording electrodes and state-of-the-art data acquisition methods, the team collected large datasets of isolated single neuron responses in each experimental study. Conducted to the highest level of proof, these studies have few if any equals in quantitative control in this formative epoch of integrative neuroscience.

From these experiments Vernon and his colleagues conducted foundation studies that shall stand far into the future as a basis for all research on the coding of cutaneous perception. They established the elementary contributions of specific cutaneous receptors and documented their spatiotemporal patterns of representation of all of the dimensions of skin sensation. They first described the sense of "flutter-vibration," by which two different organized receptor types in the skin contributed to different aspects of the neurological representations of vibratory frequency and by which four organized receptor types contributed to the representations of the features of felt objects or surfaces.

At the level of the primary somatosensory cortex, they showed that at low stimulus intensities, skin stimulation evoked positive neuronal discharges, but that the thresholds for vibration detection were associated with the higher stimulus level requisite for evocation of periodic neuronal discharge. In an era in which a commonly held view was that single neurons represented percepts, they showed that basic aspects of somatosensation were represented by distributed, cooperatively responding neuronal populations (1968b, 1969).

Two “negative results” established at a high level of proof were of great interest to integrative neuroscientists. First, there was no clear accounting, in the neuronal discharge patterns in the primary somatosensory (S1) cortex, for a liminal difference in stimulus frequency or intensity. Second, when an animal made a decision about the detection of a stimulus or a stimulus difference, responses of neurons in S1 were defined by the stimulus, and not by whether the animal correctly detected it (1968b, 1969). When stimuli were identical, so, too, were responses of behavioral “hits” or “misses.”

These “failures” were disappointing to Vernon. A primary goal of his team had been to define, quantitatively and for the first time, the coding bases for distinguishing elemental differences in stimuli at threshold and across all of their parametric continua. The fundamental coding bases of the granularity of perceptual continua and the qualia of perception remained elusive. Two overlapping events soon changed his outlook. First, Juhani Hyvärinen, a Finnish fellow who had contributed to primary somatosensory cortical studies, initiated studies when he returned home to Helsinki in more posterior cortical areas, and his findings stimulated Vernon to look beyond the primary somatosensory receiving area of the cortex for answers. Second, in the course of studies in which electrodes could be innocuously positioned into the cerebral cortex in the alert monkey, Vernon and his research team had developed the habit of introducing exploratory electrodes into surrounding areas in the parietal and temporal lobes and, by qualitative examination, saw neurons within them that appeared to respond as a function of complex behavioral contingencies or outcomes. There, in the more posterior parietal cortex, might be areas in which neuronal activities could account for behavioral circumstance and consequence.

Studies in the Posterior Parietal and Superior Temporal Cortex

Beginning in the mid-1970s Vernon’s team extended their studies of human perception to the more posterior areas of the parietal cortex, predicating their initial study designs on the documentation of striking neurobehavioral consequences of brain damage for body image representations and for corporeal and oculomotor movement control in this cortical zone (1975b). They demonstrated that neurons in posterior parietal cortical areas responded when an animal was attending to a task, but not when they were not, or responded when important sensory input contributed to a purposeful action, but not when action was purposeless (1975b, 1976, 1977a).The researchers extended their studies to show that visually evoked responses were also strongly modulated as a function of the animal’s behavioral engagement in the posterior parietal cortex (1976, 1977a, 1978b, 1981a) but not in the same behaviorally dependent way in the visual cortical area that projected most directly to them (1987a). They documented processes by which the brain monitored and controlled its active vision in ways that plausibly guided the control of motoric actions in immediate extra-personal space and that demonstrably guided eye movement to visual objects of behavioral interest (1977b, 1978c, 1981b, 1983, 1987b, 1987c, 1988). They described visual flow reception processes that appeared to account for the stabilization of the eyes with the head (or the visual scene) in motion. They showed, for the first time, that movement command and control were systematically "mapped" across visual (not somatic) axes. In sum, and with further conclusions arising from Mountcastle-descendant laboratories (see below) and from the findings of other scientists inspired by this work, over a period of a little more than a decade there emerged a broad first-level understanding of how the brain controls our actions in our immediate (within-reach) physical environmental sphere.

In a final experimental research chapter Vernon's team crossed the central sulcus—a groove in the surface of the brain that contributes to an increase in the brain's surface area—to more completely document how perceptual signals contributed to the ongoing, continuously adjustable flow of action. Among other findings they described neurons in the premotor cortex that responded in a manner signaling that the animal had correctly detected a perceptual difference, responding in a strikingly different way from when it did not (1990a,b, 1992). These responses preceded the animals' "reporting" their decisions by behavioral action. Here, finally, in the complex integration of connections fed from the more-primary areas and the top-down connections from anterior frontal attention, working memory, and executive control areas, Vernon and his colleagues had found the apparent neural origin of this long-sought aspect of perception.

The trajectory of Vernon's scientific life, from the acquisition of requisite details about sensory inputs to the encoding of real-life perceptions and perceptually driven actions in a wide-awake, behaving brain, comprised a passage of scientific fulfillment that he deeply appreciated. He had set out, in young life, to come to a level of understanding of these great issues related to human brain function. He found answers to his great questions.

A descendant legacy

Vernon was a truly extraordinary person. Everyone who met him holds him in sharp memory. His approach to scholarship and science provided us with an exemplary professional standard. His contributions to education and to science leadership have broadly impacted our research discipline. Young researchers, especially, would benefit from understanding the scientific approach of this outstanding man, as they consider their own strategies for addressing the great issues of their science. Vernon was always the commander in his laboratory, but he appreciated and later generously honored all his troops. This exceptional group of comrades in arms delighted him, both as colleagues and then forever after by their rich extensions of his core research and perspective. Ian Darian-Smith and especially Kenneth Johnson extended studies of the coding of textures, response magnitudes, and complex and dynamically moving tactual and haptic stimuli, reconstructed both for cutaneous receptors and in the primary somatosensory cortex of behaving monkeys. Bob LaMotte has conducted groundbreaking studies on human perception and haptics from a neuroscience-informed perspective. Juhani Hyvärinen and Hideo Sakata both conducted other studies addressing issues of neurobehavioral control in the posterior parietal cortex.

Gian Poggio applied a Mountcastelian approach in his studies of the coding of depth perception and other aspects of emergent visual perception in waking monkeys and initiated research on action-control representation in frontal motor cortical areas. Apostolos Georgopoulos completed a long series of studies that demonstrated the nature of population coding in motor cortex that accounts for key aspects of motor planning and control. Rodulfo Romo's research team focused on understanding how perceptual representations guide motor actions in real-life behaviors—and through this research has been recognized as a great scientific persona in his native Mexico. James Lynch, Michael Steinmetz, Brad Motter, Tom Yin, and Mark Molliver all contributed importantly to studies of the neural control of eye movements, of attention control—and, with landmark contributions by Roberto Caminiti and John Kalaska, to a new understanding of issues of vision- and hearing-guided corporeal and oculomotor action planning, command, and control. Richard Andersen extended and further validated our understanding of reference frames for movement control. After demonstrating that action-related signals in the posterior parietal cortex are the neural correlates of an animal's intentions, he applied these findings to advance the development of neural prosthetics. I was inspired to document aspects of stimulus coding and representation paralleling the Mountcastelian logical path in the auditory system—then to conduct studies in both the auditory and somatosensory systems (in parallel with studies conducted by another former student, Robert Dykes) demonstrating their lifelong plasticity.

Those studies revealed that the cortical mini-column was itself an emergent and continuously modifiable product of our dynamically revisable brain. Vernon respected every individual who worked with and for him. His greatest affection, perhaps, was preserved for Thomas Powell, the great Oxford anatomy professor; for Gian Poggio, whom he loved as a scientist and special friend; for Edward Perl, his first postdoctoral fellow, who played a major role in founding the Society for Neuroscience and was a seminal contributor to pain research; for Kenneth Johnson, a great experimental scientist who worked down the hall from Vernon for several decades; and for Apostolos Georgopoulos, whose work represented perhaps the strongest direct extension of Vernon's own scientific approach and perspective.

When Vernon wrote his own memoir, it is a measure of the man that he provided us with heartfelt tributes to the electronic, mechanical, anatomical, and office assistant professionals whom he always regarded—and treated—as first-string members of his world-class scientific team.

Contributions to scholarship and public service

Vernon succeeded Philip Bard as the Chairman of Physiology at Johns Hopkins in 1966. Over that same period, he also inherited from Bard the editorship of *Medical Physiology*—the most scholarly and widely distributed physiology textbook in this era. Taking on this daunting task with exceptional energy, he transformed this text by expanding its neuroscience sections (neuroscience was now elevated to a separate volume). Twenty-nine new chapters extended this highly scholarly treatment of physiology through more than 500 additional pages. Vernon's hand was apparent throughout this transformation, as the revised text embodied a special approach summarizing the state of our understanding of physiology as it applied to medicine in an era in which basic science had begun its explosive growth. In Vernon's words introducing the book

> *...mammalian physiology must deal with problems of the interactions between large populations of cells, organs and organ systems and, finally, the integrated function of an entire animal. Physiology ... must bridge the distance from cellular biology on the one hand to systems analysis on the other; each [level] is important, and any one is incomplete without the others.*

Given Vernon's lifelong interest in the historical origins of great ideas, *Medical Physiology* under his editorship also made a serious attempt to place then-contemporary science within the context of historical scientific progression.

The neuroscience-focused second volume included what could be argued to be the most scholarly, useful, and widely read reviews published up to that time on the physiology of somatosensation, pain, sleep, perception, the cerebral cortex, and the limbic system—the best chapters of which were written by Vernon, himself. As a fellow working in his laboratory when he was at work on this great project, I remember thousands of cards filling boxes on and around his desk, each card covered with detailed notes, each representing a scientific paper, with Vernon in his office late night after late night, trying to read every relevant paper about each complex subject at hand. When this great book was turned over to the publishers in this and in two subsequent editions, Vernon was arguably the most deeply and widely informed neuroscientist on Earth.

In parallel with these efforts he was building a world-class department that assumed responsibility for all instruction in physiological science at Johns Hopkins. He also contributed to Hopkins's neuroscience standing by promoting the elevation of a neurology division in the Department of Medicine to what would become a world-class neurology department and by persuading the university to reorganize Physiology to create a new Neuroscience Department. As a part of that reorganization, Vernon played a central role in the organization and administration of an integrative neuroscience arm in this new department, the Philip Bard Laboratories of Neurophysiology. In the early 1990s he helped establish another brain research center at Johns Hopkins' Homewood campus, the Zanvyl Krieger Mind/Brain Institute.

In 1970, at the age of 49, Vernon agreed to stand for election as the president of the new Society for Neuroscience. Vernon claimed to be surprised by his election; certainly no one else was. Once he was in harness, anyone who knew him knew that no one would work harder at organizing an inaugural Society for Neuroscience meeting that would get this big new idea off to a roaring start.

Through much of his career Vernon was somewhat reluctant to publish reviews summarizing his research perspective. A large proportion of reviews that he read in his sub-discipline were, in his eyes, less than completely satisfactory. Fortunately for the rest of us, he did write several lengthy treatises that stand as landmarks in our field and that broadly exposed the wider neuroscience community to his scientific perspective about the human brain. In *The Mindful Brain*, Vernon extended his "columnar" hypothesis, arguing in 1982 that it had now been demonstrated, to his conservative satisfaction, that the primary processing unit of the entire cerebral cortex is the cortical "mini-column" (1978a). He further postulated that the several hundred million mini-columns were aggregated into larger processing units ("columns")—acknowledging the description of this organization in the primary visual cortex while convincingly arguing that such organization applied all across the great cortical mantle. These…"modular elements [are] linked together in echeloned parallel and serial arrangements [in] distributed systems." In his conception, it was important to recognize that "…the complex function controlled or executed by [a] system is not localized in any one of its parts. The function …resides in the system as such." He argued that distributed systems "are by definition and observation both reentrant systems and linkages to inflow and outflow channels of the nervous system." And he asserted that "…phasic cycling of internally generated activity, accessing first primary sensory but then successively more general and abstract processing units… allow a continual updating of the perceptual image of self and self-in-the-world as well as a matching function between that perceptual image and impinging external events. This internal readout…[provides] an objective mechanism for conscious awareness [that is] not beyond the reach of scientific inquiry." From this time forward to the present day, the evidence that now-visible mini-columns are a universal cortical processing unit—and that all cortical functions are most accurately viewed as being a product of distributed, relational reentrant systems—has, again, been repeatedly affirmed.

Closer to the end of his scientific career, Vernon wrote two books that summarized a long list of conclusions that he thought had now been established in integrative neuroscience. In *Perceptual Neuroscience* he turned his attention to human perception, considering perception specifically from a physiological perspective (1998). There is no better starting point, for a scientist trying to understand the physiological coding and representation of perception than to read this now nearly 20-year-old volume.

In his second great summing up, Vernon focused on his favorite sensory implement, *The Sensory Hand* (2005). Almost everything relevant to our broad neurological understanding of the hand and its functions, from the beginning of time, is recorded in this wonderful treatment.

Vernon earned, and richly deserved, a litany of honors throughout his long career. He was elected to the U.S. National Academy of Sciences in 1966. He was awarded the Lashley Prize from the American Philosophical Society (1974); the Schmitt Prize and Medal from MIT (1975); the Sherrington Gold Medal from the Royal Society of Great Britain (1977); the Louisa Gross-Horwitz Prize (jointly with David Hubel and Torsten Wiesel) from Columbia University (1978); the Gerard Prize from the Society for Neuroscience (1980); the Albert Lasker Award for Basic Medical Research (1983); the U.S. National Medal of Science (1986); the Zotterman Medal from the Swedish Physiological Society (1990); the Fidia-Georgetown Medal and Prize from the American Association for the Advancement of Science (1990); the Australia Prize (1993); and the NAS Award in the Neurosciences (1998).

> I learned that it was not a matter of how many papers you published. What mattered was what was in them, and how long and how completely what was in them turned out to be enduring, and true.

Working with Vernon

Anyone who had the good fortune to work with Vernon could provide you with their own inspirational stories about that experience. My own list of Mountcastelian mantras is undoubtedly not identical to those of anyone else, but there must be strong overlap. In my memory, I learned that scholarship and science are inseparable, that laboratory science is a serious profession, and that we should not waste our (or our professor's) time with scientific blather. I learned that Vernon seemed to believe (or so he said) that I (and this was a great surprise to me) "was expected to be a better scientist than he was." I learned that the more zeroes behind the period and before the 1, the better. I learned that the use of animals in research was a solemn and very serious endeavor in which every possible strategy must be deployed to ensure humane treatment. I learned that every aspect of an experiment must be validated through careful calibration and rigorous process control, and that no one should ever have to do an experiment over. I learned that a laboratory was an orderly environment, where everything had its proper place. I learned that, in his view, the study of neurological coding or representation in an anesthetized—or later, in a behaviorally disengaged—animal could be expected to unnecessarily limit the value of your work. I learned that a scientist should be a continuous presence in his or her laboratory and be fully aware of every aspect of data collection and analysis, if the reporting of that data was to bear that scientist's name. I was told that a scientist had a responsibility to generate a logical framework to guide his or her scientific planning, and I could see, by example, that it was critical to work very hard to grow and elaborate that framework by mining *everything* known about the subject at hand. I learned that it was not a matter of how many papers you published. What mattered was what was in them, and how long and how completely what was in them turned out to be enduring, and true. I learned that more than one adjective or adverb in a sentence in a scientific manuscript was impermissible, and that no adjectives or adverbs was even better. I learned that it was a good thing to reason, sure—but to speculate, never. We all learned that it was very important to understand the difference. And I learned that all of our works have a history, and that the understanding of that history is often a rich source of enlightenment. It was obvious to all that Vernon loved his work. Those who knew him also understood how deeply he loved and appreciated his wife, Nancy, and his children and grandchildren. He loved sailing, horses, and tennis, where he was a fierce competitor.

With this memorium, all former colleagues, fellows and friends join together, to honor this very special scientist—and exemplary, vividly remembered human individual—Vernon Benjamin Mountcastle.

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