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REVIEW

Theodore H. Bullock: pioneer of integrative and comparative neurobiology

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Abstract Theodore H. Bullock (1905–2005) was a pioneer of integrative and comparative neurobiology and one of the founders of neuroethology. His work—distinguished by the tremendous number of different research themes and animal taxa studied—provided the basis for a comprehensive analysis of brain evolution. Among his major achievements are: one of the first physiological analyses of rhythmic central pattern generators; the first simultaneous recording from both the presynaptic and postsynaptic region of a chemical synapse; the demonstration of intercellular communication through graded potentials; and the discovery of two novel sensory organs formed by infrared receptors in pit vipers and electroreceptors in electric fish. He was also one of the first who applied computational tools to the analysis of complex neural signals and to perform a comparative analysis of cognitive events. His two-volume treatise "Structure and function in the nervous system of invertebrates" (with G. Adrian Horridge) remains the most comprehensive, authoritative review of this topic ever written. In addition to his research merits, his legacy is particularly based on his cosmopolitan way of thinking and acting, his large, worldwide school of students, and his committed advocacy for comparative and systems-oriented neurobiology.

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Introduction

Truth is bound to prevail in spite of us
Theodore H. Bullock

On 20 December 2005, Theodore ("Ted") Holmes Bullock passed away at the age of 90. Like no one else, he had influenced the development of comparative and integrative neurobiology in the twentieth century. There is hardly any major taxonomic group of animals he did not study during his lifetime. Similarly, his research interests were remarkably diverse, including, among others, the study of physiological processes at chemical and electrical synapses, the anatomy and physiology of sense organs, the analysis of electrical brain activity associated with cognitive events, and the mathematical modeling of neurophysiological activity. Despite this diversity, he pursued a rigorous scientific approach, aiming at a detailed and comprehensive analysis of a phenomenon under investigation. Possibly even more important, he inspired numerous students and co-workers all over the world to identify new research directions and to establish their own field of study—an attitude that will leave its stamp on generations of scientists to come.

The following review of Ted Bullock's life and major scientific achievements is based on analysis of his own publications and the comprehensive collection of documents from his laboratory, deposited in the Archives of the Scripps Institution of Oceanography, University of California at San Diego; interviews with his children and several of his former friends, colleagues, and students; as well as our own recollection of numerous meetings and conversations with him. In addition to a discussion of some of his major accomplishments, we have placed particular emphasis on a reflection and illustration of his unique approach—to both science and people.

Childhood, education, and early career

Ted was born in Nanking, China, on 16 May 1915, the second of four children of his Presbyterian missionary parents, Amasa Archibald Bullock and Ruth Beckwith Bullock (Fig. 1). His father had studied at the University of California, Berkeley, The University of Chicago, and Columbia University. Among other activities, Archibald Bullock established in China University programs in chemistry and agriculture, and directed schools. The family returned to the United States in 1928, one year after the outbreak of the Chinese Civil War. These first 13 years of Ted's life, with the immersion in Chinese society, seemed to have had a lasting influence on his respect towards other cultures and his lifelong feelings of being "a citizen of the world first, of the United States second" (Bullock 1996, p. 112).

Back in the States, Ted attended Garfield Junior High School in Berkeley, and Pasadena Junior College. After graduating from the latter with an associate-in-art degree in 1932, he transferred to the University of California, Berkeley for his junior and senior years, and majored in zoology in 1936. He stayed at Berkeley and did his Ph.D. thesis research under the guidance of Sol Felty Light (known to most people as S.F. Light) on the anatomy and physiology of the nervous system of enteropneusts, one of the two classes of acorn worms (phylum Hemichordata). Figure 2 shows Ted Bullock during that time in Berkeley.

Fig. 2 Ted Bullock in 1940. (Photographer unknown; courtesy Scripps Institution of Oceanography Archives)

Perhaps not only the research associated with the thesis topic, but also the person behind his mentor, drew Ted Bullock to Light. Like Bullock in his early years, Light (1886–1947) had spent many years abroad, teaching in Japan, China, and on the Philippines. Although, in contrast to Bullock, Light seemed to be a rather reserved man, his attitude towards people included a number of traits that later could easily have been attributed to Ted. In a letter included in a tribute of Park College, Parkville (Missouri), from which Light had graduated in 1908, Ted Bullock (then representing the University of California at Los Angeles) and Richard M. Eakin (representing the University of California at Berkeley) wrote on 4 April 1958:

> *In all his friends and students, whether intimates or not, he inspired something more than respect—a personal confidence and an attachment to the man. He will be remembered for his modesty, extending to an underestimation of self, for exacting criticism in*

Fig. 1 *Left* Baby Ted Bullock at the age of three months, with his father Amasa Archibald Bullock, in Kuling (China). This town, a mountain resort on the Yangtze river in Kiangsi province, was particularly popular among foreigners living in China in the first few decades of the twentieth century. *Right* Ted Bullock (second from right) with his mother, Ruth Beckwith, and his siblings (from left to right) Burlingane, Donald, and Beatrice. (Photographers unknown; courtesy Scripps Institution of Oceanography Archives.)

the use of words and ideas, which drove him now to caution and again to very forward positions, for a sincere interest in human relations, and for a strong appreciation of natural beauty.

After receiving his Ph.D. in 1940, Bullock was awarded a Sterling Fellowship to work in zoology as a postdoc under John Spangler Nicholas at Yale University. One year later, now as recipient of a Rockefeller Fellowship, he joined the laboratory of Harold Saxton Burr in the Medical School of Yale. Shortly thereafter, in early 1942, he was recruited into a research project commissioned by the Office of Scientific Research and Development (an agency of the US federal government created to coordinate scientific research for military purposes during World War II) and led by Louis Goodman and Alfred Gilman in Yale's new Department of Pharmacology. The group was assigned the task to study the effects of nitrogen mustard gas and to develop antidotes against this chemical warfare agent (ironically, although nitrogen mustard has never been used in the battlefield, this work led to a major scientific breakthrough—the development of chemotherapy, as nitrogen mustard was the first agent found to be effective in producing remission of some forms of cancer).

In 1942, after two postdoctoral years, Ted Bullock was appointed Instructor in Neuroanatomy in the Yale School of Medicine. In 1944, he left Yale to accept a position as Assistant Professor of Anatomy at the University of Missouri School of Medicine, Columbia. During the latter tenure, he taught courses in neuroanatomy, topographic and applied anatomy, and elementary anatomy. The teaching appointments in anatomy at Yale and Missouri, although not his "niche", as he later put it, saved him from being drafted during World War II.

Before commencing his first postdoc position at Yale University, Ted Bullock began a tradition to spend the summer months at the Marine Biology Laboratory at Woods Hole on Cape Cod. Often, he was accompanied by his wife Martha Runquist (whom he married in 1937) and later by their children Christine (born 1946) and Stephen (born 1949). These visits enabled him to meet numerous other scientists (Fig. 3) and to initiate a number of collaborations. The summers at Woods Hole appear also to have been formative and influential on his lifelong interest in applying a wide range of techniques to a large, albeit carefully selected, number of species to address biologically important questions. As he put it (Bullock 1996, p. 119):

Besides meeting a wide cross section of people in zoology, physiology, anatomy, and related fields, the opportunities to learn new techniques, especially electrophysiological ones, and to apply them to simple invertebrate preparations, were golden. I became imprinted on comparative physiology and on the importance of combining anatomy and physiology, on the value of simple systems, and on the diversity of integrative mechanisms in the nervous system.

Controversy about the role of acetylcholine in the conduction of nerve impulses

During the summers at Woods Hole, Ted Bullock initiated an extensive collaboration with David Nachmansohn (then a visiting investigator at Yale) on the role of acetylcholine in conduction of nerve impulses, which culminated in three joint papers published in the Journal of Neurophysiology (Bullock et al. 1946a, b, 1947). This project, which later he

Fig. 3 Meeting with eminent scholars at the Marine Biology Laboratory at Woods Hole. The photograph was taken by Ted Bullock in 1949 and shows (from left to right) Saul Korey, David Nachmansohn, Dean Burk, Albert Szent-Györgyi, Otto Warburg, Otto Meyerhof, Carl Neuberg, and George Wald. (Photograph by Theodore H. Bullock; courtesy Scripps Institution of Oceanography Archives)

would call a "bizarre" one (Bullock 1996, p. 118), followed up the previous work of Nachmansohn and his collaborators. In 1939, Nachmansohn and Egar Lederer had purified acetylcholine esterase (the enzyme that hydrolyses acetylcholine) from the electric organ of the *Torpedo* ray (Nachmansohn and Lederer 1939). One year later, Nachmansohn, together with Wilhelm Feldberg and Alfred Fessard, reported in a brief communication in the Proceedings of the Physiological Society (Feldberg et al. 1940) that the electric organ of *Torpedo marmorata* contains acetylcholine, and that injection of acetylcholine into the perfused electric organ causes electric discharges similar to the ones observed in the intact fish. The authors used these results as evidence to demonstrate that the "nerves supplying (the electric) organ...act by liberation of acetylcholine". According to their hypothesis, acetylcholine exerts only an intracellular, but not an intercellular, role, and transmission at the neuromuscular junction is purely electrical.

Over the following years, a number of laboratories discovered that not only the region of synaptic clefts, but also axons may contain high concentrations of acetylcholine esterase. Extending these studies, Ted Bullock, in collaboration with David Nachmansohn, Harry Grundfest, and Mortimer Rothenberg, identified acetylcholine esterase in a variety of nervous tissues, and in a number of vertebrate and invertebrate species, including planarians and tubularians (Bullock et al. 1947). Using inhibitors of acetylcholine esterase, such as diisopropyl fluorophosphate, they further showed that blocking of the enzyme correlates with the abolition of action potentials in conducting fibers. Based on these findings, they proposed that "the acetylcholine system plays an essential role on the conducting mechanism of all types of nerve and of muscle" (Bullock et al. 1947, p. 11) and "that the physico-chemical mechanism of conduction along axons does not differ fundamentally from transmission across synapse" (Bullock et al. 1946a, p. 9).

Nachmansohn used the results of these and other investigations to propose a general model of the role of acetylcholine as the central factor that produces permeability changes in the axon, thus mediating the conduction of action potentials. He further suggested that the release of acetylcholine at the neuromuscular junction is rather incidental to its primary action—the initiation of electrical transmission across the synaptic gap. This model was presented in detail in his controversial book "Chemical and molecular basis of nerve activity" (Nachmansohn 1959)—despite the fact that by the late 1950s alternative models had been accepted by the majority of scientists. The most important alternative model included the proposal by Alan Lloyd Hodgkin and Andrew Fielding Huxley to explain the generation and conduction of action potentials based on electric field effects, in combination with local changes in the concentrations of sodium and potassium ions (Hodgkin and Huxley 1952). Similarly important, in 1954 José del Castillo and Bernard Katz had shown that synaptic transmission at the neuromuscular junction is mediated by the release of quantal units of acetylcholine (del Castillo and Katz 1954).

After receiving a copy of Nachmansohn's book, Ted Bullock sent him a letter dated 23 October 1959, signaling some disagreement in scientific matters, yet loyal to his friend and mentor:

> *It was extremely kind of you to send me a copy of your valuable new book. Thank you very much. I prize this highly, and all the more for your personal inscription. It brings to mind many pleasant and valued memories of early days of collaboration with you. I learned more than you realize from this experience, and it has made its permanent stamp. I am still a strongly inclined Nachmansohnian and arise on many occasions to defend the true gospel. I am sure you will not be disappointed or surprised if in some small details I drift off the path from time to time since, in the long run, truth is bound to prevail in spite of us! The one point in which I have not deviated a hair is my warm regard and friendship, as well as high esteem for you as an individual and scientist.*

Two decades at the University of California, Los Angeles

In May 1944, the Department of Zoology of the University of California, Los Angeles (UCLA) informed Ted Bullock that plans were underway to expand its staff, particularly in the field of invertebrate zoology, and that his name had been suggested by S.F. Light as a possible candidate for new faculty. In a reply letter dated 12 May 1944, Bullock indicated his interest

> *...I will always be interested in opportunities at the University of California, Los Angeles. The institution and the region have many special attractions for me.*

One-and-a-half year later, Ted Bullock received the next letter, dated 23 November 1945; in it, following a unanimous decision by the faculty, UCLA offered him an appointment as Assistant Professor of Zoology.

Transmission at the squid giant synapse

The following two decades at UCLA were marked by an enormous scientific productivity and a rapid sequence of landmark discoveries made by Bullock and his associates. One of the areas in which Bullock and his laboratory at UCLA made a significant contribution to our understanding of important physiological processes was that of synaptic transmission. In the late 1940s, it was still unclear whether transmission between neurons in the central nervous system was mediated by an electrical mechanism, as demonstrated previously in case of conduction along axons, or whether this transmission was achieved through chemical signaling, as shown for the neuromuscular junction (for an historical account, see Bennett 1985). The former hypothesis was favored by most neurophysiologists, whereas, the majority of neuropharmacologists saw more evidence in support of the latter. Moreover, detailed information about the physiological events occurring in the presynaptic terminal and on the postsynaptic side was rather limited at that time.

One major obstacle in obtaining more information on synaptic transmission was the lack of good model systems. Such systems had to be not only accessible to physiological recordings, but also sufficiently simple to provide unambiguous answers. Based on earlier work by the British neurophysiologist John Zachary Young, Bullock started, around 1946, to make extensive use of such a favorable system—the giant synapse—which is located between the second- and third-order nerve fibers in the stellate ganglion of the squid (Fig. 4) (Bullock 1946, 1948). This synapse is remarkably large and consists of a single junction, which makes analysis much easier than in the case of many units in parallel. Stimulation of the preganglionic nerve causes contraction of the mantle after transmission across the synapse.

In the mid-1950s, Susumu Hagiwara (a visiting scholar from Japan who became his closest collaborator over the following years; Fig. 5) joined Ted to work on a project using the squid giant synapse. Soon thereafter, they were the first to succeed in making simultaneous recordings from both the presynaptic and postsynaptic fibers close to the junction (Bullock and Hagiwara 1957). Based on results

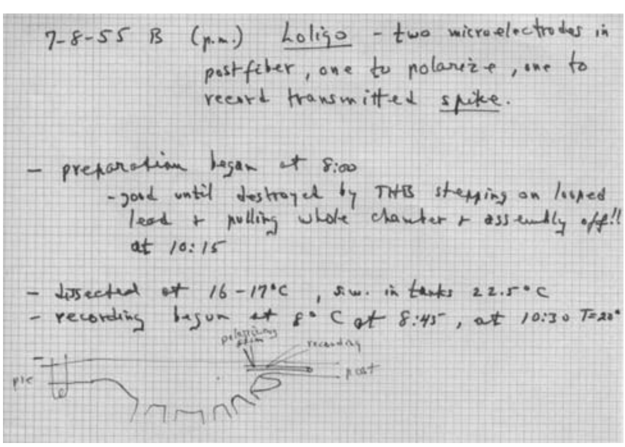

Fig. 4 Laboratory notes taken by Ted Bullock of an experiment using the squid giant synapse. (Courtesy Scripps Institution of Oceanography Archives)

obtained through this approach, they determined the synaptic delay to be of the order of 1–2 ms. Although they did not explicitly mention the possibility of chemical signaling at the synaptic junction, one of their major conclusions was that "transmission cannot be electrical" (Bullock and Hagiwara 1957, p. 575). This was an important step, as it opened the prospect of identifying the chemical nature of this transmission mechanism.

Electrical transmission between neurons

Another area in which Ted Bullock and his co-workers succeeded in a landmark discovery was that of electrical transmission between neurons. He had developed interest in the intercellular effects of direct current and slowly changing fields during his work in the laboratory of Harold Burr at Yale, who was widely known for his (sometimes controversial) studies on the role of electricity in development and disease. As in the case of the squid giant synapse, Bullock's success was based on the choice of a favorable model system. In 1932, Jerzy Stanislaw Alexandrowicz had described the cardiac ganglion of crayfish and lobsters as a miniature model of the brain, consisting of only nine cells (Alexandrowicz 1932). Four of these cells are pacemakers that exhibit spontaneous firing at a rhythm corresponding to the heartbeat, whereas the remaining five cells are followers that amplify, filter, and integrate their input.

Some earlier work of Watanabe (1958) and Hagiwara et al. 1959) had indicated the possible existence of relatively low-resistance pathways between cells in the cardiac ganglion. Through intracellular stimulation of follower cells, Bullock, in collaboration with Watanabe, showed that these connections can spread slow and sustained subthreshold potentials from the follower to the pacemaker cells, but cannot propagate or transmit action potentials (Watanabe and Bullock 1960). By demonstrating this property, their study was one of the first to provide compelling evidence for electrical communication between neurons—in line with earlier work of Watanabe (1958) and independent investigations by Edward J. Furshpan and David D. Potter on the crayfish giant motor synapse (Furshpan and Potter 1959). The study of Watanabe and Bullock was also the first to directly demonstrate that such cross-talk between cells can take place at sub-threshold levels, without the generation of action potentials. Watanabe and Bullock, furthermore, foresaw a possible structural correlate mediating the observed process of electrical transmission by proposing that "some relatively low resistance path must exist between neurons" (Watanabe and Bullock 1960, p. 1044). This assertion anticipated the existence of a novel type of membrane-to-membrane apposition—subsequently to become known as the electrical synapse.

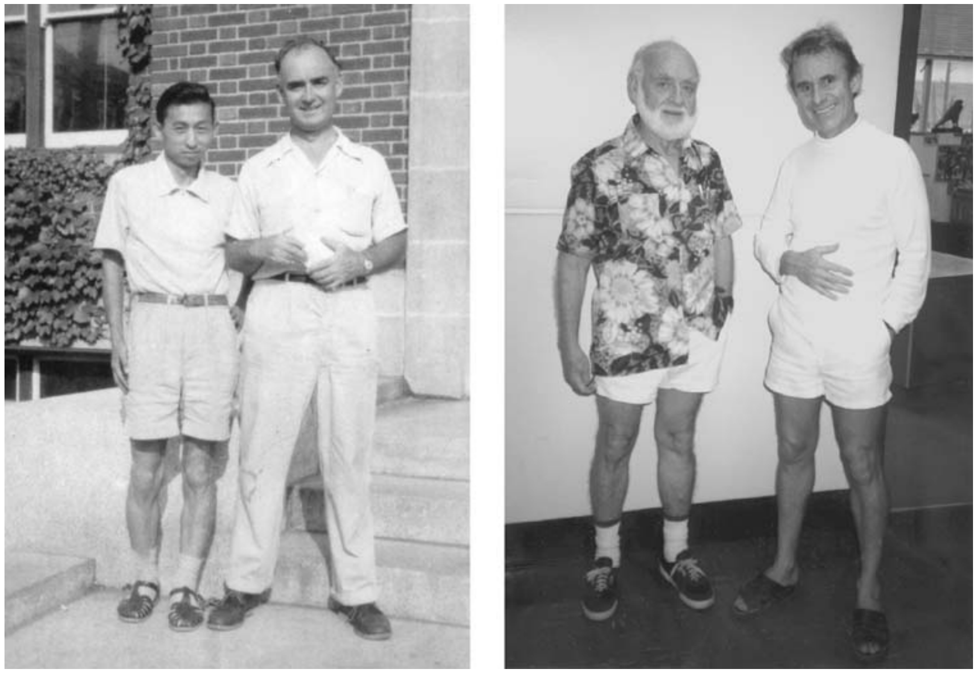

Fig. 5 Ted Bullock and close associates. *Left* With Susumu Hagiwara (1922–1989) at the University of California, Los Angeles, in the 1950s or 1960s. *Right* With Walter Heiligenberg (1938–1994) at the Neurobiology Unit of the Scripps Institution of Oceanography, in 1987 or 1988. (Photographers unknown; courtesy Scripps Institution of Oceanography Archives.)

Influence of sub-threshold electric fields on firing of neurons

Neurons may exert an influence upon the firing of other neurons even if no specialized contact zones between these cells do exist. In a key study carried out in collaboration with Carlo A. Terzuolo, Ted Bullock was the first to accomplish a quantitative analysis of such an effect, using the slowly adapting stretch receptor of crustaceans as a favorable model system (Terzuolo and Bullock 1956). The cell body of this sensory neuron is located in the periphery, where it makes contact via its dendrites with a special muscle fiber bundle. The axon of this cell travels to the central nervous system. Under steady stretch, the cell maintains a steady discharge of spikes at a certain frequency. Since this discharge is highly regular, even small alterations in frequency are readily detected.

As Terzuolo and Bullock showed, the frequency of firing of the stretch receptor neuron can be modulated by extracellularly applied voltage gradients as small as 0.1 mV/100 µm (in the most effective axis of polarization), thus demonstrating an enormous sensitivity of the neurons. In the intact animal, this effect is likely to be especially strong if the somata, dendrites, or axons of neurons are closely apposed to each other, exhibiting specific, non-random orientations so as to maximize electric field effects. Other investigators demonstrated such ephaptic interactions, three decades later, in the hippocampus (Richardson et al. 1984; Taylor and Dudek 1984). Interaction of neurons via extracellular electric fields may lead to an averaging of the responses of individual neurons, making the response of the whole cell cluster more predictable than the sometimes erratic response of individual neurons.

Discovery of infrared receptors

In 1951, two herpetologists of UCLA, Raymond B. Cowles (then professor of zoology) and Ken S. Norris (then graduate student working towards his Master's degree in desert zoogeography) pointed out to Ted Bullock the facial pit of pit vipers (Crotalinae). This structure is located midway between the nostril and eye on either side of the head and enables the snakes, even in absolute darkness or when blindfolded, to correctly strike warm-blooded prey animals. Although the function of the facial pit as a sense organ for detecting the temperature of the snake's prey and the estimation of its direction had been proposed earlier—notably by the work of Noble and Schmidt (1937)—information on its structure was fragmented, and virtually nothing was known about its mode of operation. Stimulated by the absence of this information, Bullock and associates conducted a series of studies which culminated in the publication of three "classics"—one paper on the anatomy (Bullock and Fox 1957) and two papers on the physiology of the facial pit (Bullock and Cowles 1952; Bullock and Diecke 1956) (Fig. 6).

This work demonstrated that the membrane, which forms the floor of the pit and separates the outer chamber from the air-filled inner chamber, functions as the sensory surface of a receptor organ specialized in detecting radiant heat. This membrane is composed of two layers of

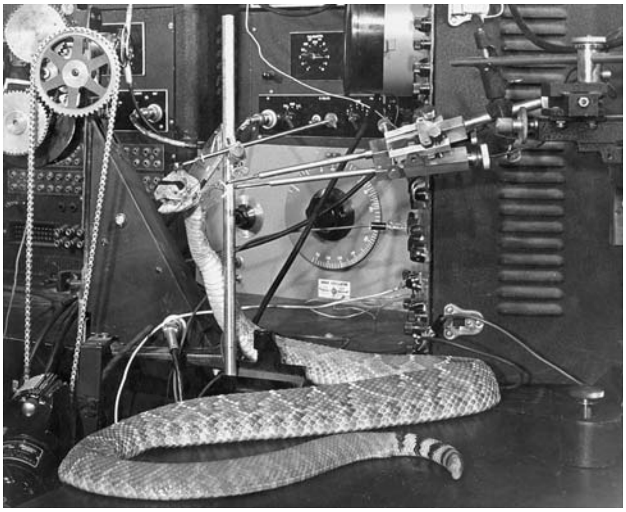

Fig. 6 Experimental set-up in the laboratory of Ted Bullock at the University of California, Los Angeles, used to study the physiological properties of facial pits in rattle snakes. (Photographer unknown; courtesy Scripps Institution of Oceanography Archives.)

extremely thin epidermis which enclose a single layer of specialized parenchyma cells. The membrane is heavily innervated by fibers originating from three branches of the trigeminal nerve. All of these sensory nerve fibers appear to act as warm receptor fibers. An adequate stimulus is provided by radiant energy in the medium and long infrared range, as long as an object emitting this energy contrasts with that of the background. This property of the receptors is independent from the temperature of the snake or the ambient air. The sensitivity of this system is enormous—under optimal conditions temperature changes at the pit membrane as little as 0.003°C are sufficient to evoke a physiological response.

In addition to presenting for the first time a conclusive model of the structure and function of the facial pit, Bullock and Diecke (1956) also described an integrator—an electronic device for automatical and continuous plotting of the intervals between successive nerve impulses in a single unit as a function of time. This simple device, based on condenser charging, performed a similar function as certain modules of modern physiological analysis software programs, but was invented long before the advent of digital computers.

Discovery of electroreceptors

The work Ted Bullock carried out with Carlo Terzuolo (Terzuolo and Bullock 1956) on the stretch receptor neuron of crayfish showed that even a very weak sub-threshold electric field could induce changes in tonic firing (see "Influence of sub-threshold electric fields on firing of neurons", above).

> *This surprisingly high sensitivity was one of the main motivating factors that led me to look into electroreception in electric fish, where still higher sensitivity, by orders of magnitude, must be found—small fractions of a microvolt per centimeter in the water around the fish,*

as he recalled four decades later (Bullock 1995, p. 218). During the 1950s, the studies carried out by Hans W. Lissmann of the University of Cambridge had pointed to the possible existence of such specialized sense organs. Ted Bullock had followed this research since Lissmann had reported in a note in *Nature* in 1951 (Lissmann 1951) the discovery of weakly electric discharges produced by certain fish. In 1958, in the March issue of the *Journal of Experimental Biology*, Lissmann published another landmark paper, which summarized his studies of the electric discharges of Mormyridae and Gymnotidae in laboratory and field (Lissmann 1958). As a key discovery, he reported that, by using their discharges, these fish can locate objects whose conductivity differs from that of water. He proposed that this ability of "electrolocation" evolved as an adaptation to life in turbid water. He furthermore predicted the existence of specialized receptor organs, in the following terms

> *...a major prerequisite for the evolution of electric organs appears to be a receptor sensitive to electrical stimulation*

(Lissmann 1958, p. 188).

Ted Bullock immediately followed up this idea but, before beginning his own work, he evidently wanted to make sure that he would not interfere with possible plans of other researchers to identify the putative electroreceptors. In a letter dated 16 September 1958, he wrote to Hans Lissmann:

> *As I discussed with you over the telephone, Dr. Watanabe and I are interested in the possibility of doing some elementary experiments on electrical recording from the sensory nerves involved in the electric reception... As I explained to you we do not wish to get involved in electrophysiological recording and attempts to prepare single fibers from sensory nerves if someone else has already started on this, especially yourself. As I understand it, you do not have intentions along this line, and when I visited Möhres and Grundfest this summer, it was my understanding that they also were involved in other aspects and had no designs on the sensory physiology.*

Lissmann replied on 23 September 1958:

> *I am very glad to hear that you intend to examine the sensory impulses in electric fish. As I told you, my own efforts in that direction were frustrated by*

working conditions in Africa, and I wish you every success... I feel the more qualified people are trying the sooner we shall begin to understand these creatures.

Soon thereafter, Bullock's group succeeded in the identification of electroreceptor organs (Bullock et al. 1961). These organs are embedded in the skin and spread over the body of the fish. Each of these organs is formed by electroreceptor cells highly sensitive to various kinds of electric signals. Among the various subtypes are electroreceptor cells specifically tuned to the electric signals produced by the fish themselves and by conspecifics.

Remarkably, after the initial discovery of this novel sense organ, Ted Bullock left it to others, notably his close associate Susumu Hagiwara (who had returned to UCLA), to perform a detailed characterization of the physiological properties of the electroreceptors—without having his name included on any of the papers (Hagiwara et al. 1962, 1965a, b; Hagiwara and Morita 1963).

In search of feature detectors

Another area in which Ted Bullock opened new vistas for research done by many other investigators was in the identification of feature detectors. The concept of feature detectors is based on a common observation made by ethologists—that a tiny fraction of the enormous amount of information provided to the animal from its environment is sufficient to elicit a specific behavior. At the end of the 1950s, one widely discussed hypothesis was that this ability is mediated by specific cells that respond selectively to specific features of a sensory stimulus. A few earlier investigators had reported the existence of feature detectors potentially involved in recognition of prey in the retina, including what later became widely known as "bug detectors" in frogs (Lettvin et al. 1959). However, at the beginning of the 1960s, virtually nothing was known about such cells in higher processing areas of the brain.

At that time, the laboratory of Ted Bullock was among the first to study this phenomenon in brain regions beyond the retina. In collaboration with Ursula Grüsser-Cornehls and Otto-Joachim Grüsser—a couple of visiting scientists from Germany—he focused on the frog, *Rana pipiens* (Grüsser-Cornehls et al. 1963). While stimulating the curarized animal with various visual stimuli, they examined the response of neurons to moving stimuli through recordings from single axons in the stratum superficiale of the optic tectum, one of the major projection areas of retinal ganglion cells. Among the cells from which they recorded were "movement detectors"—cells that respond best to changes in the position of objects. Over the following year, numerous other investigators showed that such feature detectors respond specifically to many other features of a behaviorally relevant stimulus, and that electrical or pharmacological stimulation of these cells can evoke proper behavioral responses.

Computational neuroscience

In collaboration with Donald H. Perkel of RAND Corporation in Santa Monica, California, as well as Joseph H. Schulman, George P. Moore, and José P. Segundo of UCLA, Ted Bullock published, in 1964, a paper in *Science* that set the stage for the application of computational approaches to the analysis of neurophysiological data (Perkel et al. 1964). In their study, the authors examined how inhibitory or excitatory synaptic input to pacemaker neurons of the abdominal ganglia of the sea slug, *Aplysia californica*, and the stretch receptors of the crayfish, *Procambarus clarkii*, can modulate the discharge pattern of these cells. Both types of pacemaker neurons exhibit oscillatory activity. In the intact system, input often consists of regularly spaced inhibitory postsynaptic potentials (IPSPs) evoked by another pacemaker cell.

Using experimental data obtained through stimulation of the pacemaker cells with IPSPs or excitatory postsynaptic potentials (EPSPs), the research group developed a mathematical model which enabled them to predict the output of a functioning neuron in response to various inputs. Through application of this model, they could show that stable discharge patterns can occur over a clearly defined range of input frequencies, without feedback—that is, without closed-loop or reciprocal interactions. This is an important consequence because it makes such systems capable of maintaining stable phase relationships among discharging units—as required, for example, of antagonistic and synergistic motor units responsible for coordinated movements.

The historical significance of this modeling study lies not only in the fact that it opened a new perspective in the analysis of rhythmic central pattern generators, but also that it demonstrated the enormous potential of computational tools for the definition of a new field of neurobiology—that of computational neuroscience.

Structure and function in the nervous system of invertebrates

In addition to his landmark discoveries, another piece of work produced by Ted Bullock during his tenure at UCLA has had an enormous influence on generations of other scientists—the two-volume treatise *Structure and Function in the Nervous System of Invertebrates* (Bullock and Horridge

1965). In the 1950s, Ted Bullock started to work on this book, using the classical work of Bertil Hanström, *Vergleichende Anatomie des Nervensystems der wirbellosen Tiere*, published in 1928, as a forerunner. At the end of the 1950s, he communicated with a number of colleagues regarding this book, sending out drafts of chapters for comments or seeking permission to reproduce figures from original publications. Among these colleagues was G. Adrian Horridge of the University of St. Andrews in Scotland. In a letter dated 10 February 1958, Bullock invited Horridge to become a co-author:

> *I would like to invite your serious consideration of the proposition that you join me in this project. I do not wish to undertake a team affair, such as Prosser's* Comparative Physiology *or Roeder's* Insect Physiology*, but neither have I any thirst for the glory of authorship...I could elaborate at some length as to why you have the special qualifications needed for this task but will not because it really does not matter to you!*

Horridge initially rejected the offer, arguing that he would like to give preference to his research work over the coming years, and that the library at St. Andrews was not sufficiently well equipped to obtain the literature necessary to co-author the book. This triggered the following counter-reaction from Bullock, as documented in a letter dated 17 March 1958:

> *Excuse my returning to item A, but I would like to respond to your candor about the co-authorship proposition. There may, of course, be factors which I do not appreciate and you must not feel obligated to explain your reasons. But just in case you would actually like to undertake it if external factors permitted, I would like to offer any assistance I can to the proper arranging of external factors. Would it alter the picture for you if your institution would grant a leave of absence of, say 9–12 months and if I could find funds to provide a stipendium for that period here? ... You probably do not take into account your own unique qualification for this job. Assuming you admit the serious need for a modern work summarizing the state of knowledge in the area, you will see upon reflection that not any active worker in the neurophysiology of some invertebrate animal or in the histology of some groups would do at all. It requires precisely someone who is worried about the functional attention paid to fibrils, recesses and such details, who looks ahead but has a healthy respect for earlier work, who thinks for himself, etc. Horridge, having these gifts as you must admit you do, I call upon your sense of social obligation!*

After this letter, Horridge finally agreed to join Bullock as co-author. A good part of the manuscript was written, while Bullock and Horridge spent a considerable amount of time together—at St. Andrews, UCLA and, most importantly, as Fellows in Residence during an entire year at the renowned Center for Advanced Study in the Behavioral Sciences, immediately adjacent to Stanford University, California.

At the University of California, San Diego

In 1966, Ted Bullock moved from UCLA to the University of California at San Diego (UCSD) in La Jolla, a campus of the University of California inaugurated only six years earlier. Bullock had known La Jolla since his childhood. During his visits from China, he frequently saw his older cousin Mary Beckwith, who had a house in La Jolla and who introduced him to shell collecting. He was, furthermore, familiar with the Scripps Institution of Oceanography in La Jolla, which became an integral part of UCSD after the foundation of the latter one. Records belonging to Harald Ulrik Sverdrup, director at Scripps from 1936–1948, document that Ted had visited the institution between December 1938 and January 1939 to collect the acorn worm *Balanoglossus*.

Among others possible reasons, two were likely key for Ted's decision to join UCSD. First, the existence of the Physiology Research Laboratory at the Scripps Institution of Oceanography, which was founded in 1963 at the initiative of Roger Revelle (Fig. 7), then director at Scripps, and Per F. Scholander as director of the laboratory. Part of the support for the laboratory came from UCLA's Brain Research Institute, resulting in the establishment of a Marine Neurobiology Facility headed by Susumu Hagiwara. The second reason was probably related to the appointment of Robert B. Livingston as chairman of what was then the world's first Department of Neurosciences. Bullock had known Livingston from the time of his tenure at UCLA, and their relationship was marked by deep mutual trust. In a letter to Livingstone, dated 5 November 1965, in which Bullock confirmed in writing his acceptance of the appointment at UCSD, he wrote:

> *In fairness to UCLA, its Department of Zoology, the Deans and Chancellors and the Brain Research Institute, I must put on record that this was not a case of jumping at the chance, but an excruciatingly difficult weighing of factors as incommensurate as apples and pears. UCLA has been very good to me and I am extremely happy there. I will leave with great reluctance and poignancy after twenty golden years. Other highly attractive invitations gave me very little*

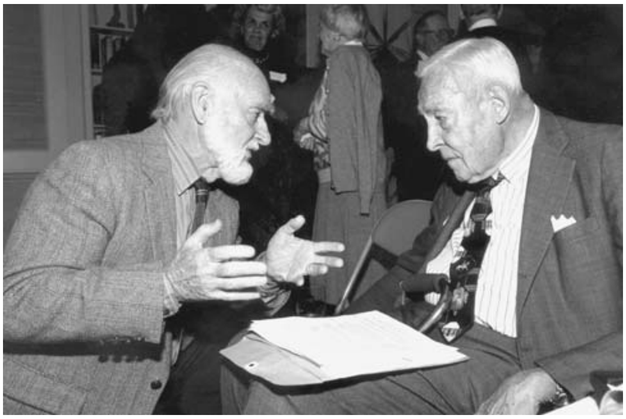

Fig. 7 Ted Bullock and Roger Revelle. Revelle (1909–1991), a leader in the field of oceanography and former director of the Scripps Institution of Oceanography, was instrumental in the formation of the University of California, San Diego. (Date unknown, probably in the 1980s; photographer unknown; courtesy Scripps Institution of Oceanography Archives.)

> *temptation to leave. One hears a good deal about institutional loyalty these days. I believe I feel deeply and hope I have manifested in actions over the years something that deserves that name. This effusion is not irrelevant to you because it indicates the degree of my confidence in you, in the School of Medicine here and in UCSD, and of my intention to serve with all I've got.*

Over the following years Bullock and Livingston played a key role in attracting some of the world's leading neuroscientists to the new department. In numerous letters Bullock approached colleagues all over the world and asked them for advice in the nomination of new faculty. Among them was Konrad Lorenz, then director of the Max Planck Institute for Behavioral Physiology in Seewiesen, Germany. In a reply letter dated 22 February 1966, Lorenz commented on a number of candidates and then moved on:

> *I emphatically agree that you should indeed include very young people who show very much promise. There is one man who did his doctor thesis at my department and is now at Mittelstaedt's whose real chief interest is the bridgework of which you are speaking, his name is Dr. Walter Heiligenberg. I honestly consider him as a genius. He is not only an excellent ethologist but at the same time an excellent neurophysiologist and a brilliant bio-cyberneticist. He is only about 27 years old... His analytical aims notwithstanding, he is definitely a man who is studying the behavior of the whole organism.*

This was perhaps the first time Bullock came across the name of Heiligenberg, who became one of his closest collaborators and friends after Heiligenberg arrived at UCSD in 1972, first as a postdoctoral fellow in Ted Bullock's lab, then, one year later, as a member of the faculty (Fig. 5). As he had done several times before, Bullock left it to Heiligenberg to work out details of an important phenomenon. In the early 1960s, Akira Watanabe and Kimihisa Takeda had discovered that exposure of the weakly electric fish *Eigenmannia* sp. to a sinusoidal stimulus near its own frequency causes accelerations or decelerations of its own electric organ discharge (Watanabe and Takeda 1963). Through this reflex-like behavioral response, the frequency difference between the fish and the interfering signal is increased, thereby reducing the interference ("jamming") of the two signals. Together with one of his postdocs, Henning Scheich, Bullock carried out a thorough characterization of the jamming avoidance response (Bullock et al. 1972a, b). Using this work as a foundation, Heiligenberg demonstrated soon thereafter a behavioral function of this response, namely to maintain the fish's ability to electrolocate. Over the following two decades, he identified the major components of the neural pathway controlling the jamming avoidance response (for review see Heiligenberg 1991; for an historical account see Zupanc and Bullock 2006). The result of this work is what has been widely acknowledged as one of the best case studies in neuroethology.

The laboratories of Bullock and Heiligenberg, together with those of R. Glenn Northcutt, James T. Enright, and Ad Kalmijn formed the core of the Neurobiology Unit, a rather informal group of scientists who shared interest in comparative neurobiology. Although Ted Bullock and Glenn Northcutt were primarily affiliated with the Department of Neurosciences of the School of Medicine, the laboratories of all investigators of the Neurobiology Unit were located at the Scripps Institution of Oceanography.

Expeditions on the Alpha Helix

One of the great achievements of Ted Bullock during the time of his tenure at UCSD was the lead he took in the allocation of the *R/V Alpha Helix* for biological research. This research vessel (Fig. 8) was a so-called National Oceanographic Facility of the University-National Oceanographic Laboratory System for Experimental Biology. It was funded by a grant awarded by the National Science Foundation, and operated by the Scripps Institution of Oceanography. The ship, designed as a floating laboratory, carried a crew of 12 and provided berth for a team of ten scientists.

The mission of the *Alpha Helix* was defined in the original grant proposal written by Per Scholander:

> *The prime objective of this proposal is the creation of a unique facility for experimental studies of organisms associated with the oceanic environment. Its*

Fig. 8 Research vessel Alpha Helix. (Courtesy Scripps Institution of Oceanography Archives.)

focal point is a laboratory ship with supporting home-based laboratories and technical facilities which would provide experimental biologists, both here and abroad, with the opportunity to apply their wits and various skills to the many tasks which can be handled only by a well-equipped laboratory on the site of the natural habitat.

Ted Bullock was on the National Advisory Board of the *Alpha Helix* program between 1963 and 1971 and chaired this committee for a total of three years. One of the core functions of the Board was to select the general area of operation each year and to solicit proposals for specific programs of research.

Bullock was chief scientist on two of these expeditions. The first took him and other investigators (most of whom worked on projects independent from Bullock's), in 1966, to the Great Barrier Reef in Australia. As part of the program, Bullock himself succeeded in the first underwater motion picture filming of the response of corals to electrical stimulation. These cine recordings enabled him to perform the first accurate quantitative measurement of such responses, and thus to carry out an analysis of nerve excitation mediated by the simple nerve nets of corals. He also studied interrelations in neuronal activity in the nine-celled cardiac ganglion of mangrove crabs, and performed a statistical analysis of nervous rhythms driven by rather simple neuronal pacemakers, as recorded from scyphomedusan and hydromedusan swimming pulsations.

In the second expedition, which took place in 1967, the *Alpha Helix* sailed two thousand kilometers up the Brazilian Amazon River to conduct research near the Rio Negro and the Rio Branco. Bullock himself performed experiments on infrared receptors in snakes of the family Boidae; examined the brain of sloths, *Bradypus*; investigated the behavior and electroreceptor properties of gymnotiform fish; and studied the freshwater ray, *Potamotrygon hystrix*.

Comparative analysis of neural events associated with expectation

During the last 15 years of his life, Ted Bullock became increasingly interested in a comparative analysis of neural events associated with cognition. Among the types of cognitive event-related potentials discovered in human scalp recordings are specific waves that occur a few hundred milliseconds after the moment a missing stimulus is due in an ongoing series of regular stimuli presented at a certain frequency (for review see Hillyard and Picton 1979). These waves are frequently referred to as "omitted stimulus potentials". Similar event-related potentials that are time-locked to the due time of an omitted stimulus have been reported in non-human mammals. They were recorded by using intracranial electrodes from several cortical and subcortical areas (Başar-Eroglu et al. 1991). Omitted stimulus potentials are regarded as signs of moderately high-level processing, reflecting anticipation of a certain sensory input, and triggering responses like "there's one!" or "what's that?". These potentials are frequently called "cognitive waves"; they are not necessarily associated with a conscious experience.

The cognitive process of expectation has been explained by a neural mechanism that learns, after a few stimuli at a regular interval, the pattern of the inter-stimulus interval and prepares a discharge with a fixed latency (Bullock et al. 1990). If the next stimulus arises on schedule, the discharge is suppressed and an evoked potential is produced. If, on the other hand, the stimulus fails to arrive on schedule, the discharge is not suppressed and the omitted stimulus potential is emitted after its characteristic latency.

In the late 1980s, Ted Bullock started to examine such omitted stimulus potentials from a comparative point of view. He and his co-workers demonstrated that similar potentials occur also in lower vertebrates (Bullock et al. 1990, 1993) and even in invertebrates (Ramón et al. 2001). Omitted stimulus potentials are, for example, produced in response to missing or delayed flashes in a train of visual stimuli in elsmobranchs—not only in the forebrain and midbrain, but even in the retina (Bullock et al. 1990). In association with electrosensory stimuli, they occur at the level of primary sensory nuclei in the medulla and, in a modified form, at midbrain and telencephalic levels (Bullock et al. 1993). Thus, the findings of his group disproved the widely held notion that omitted stimulus potentials originate only from higher-order neurons that respond to a mismatch between the input and an image in a short-term sensory store, and, therefore, depend on higher brain level processing (Jones 1992).

Traveler around the world

Ted Bullock's cosmopolitan feelings, which emerged during his childhood in China, seem to have found a platform for further evolution during his adult life in the form of his extensive travel activities. There was hardly any year when he did not travel abroad. Often, he was away from his laboratory for many weeks or months, directing his students and staff via air-mail letters, telegrams, telephone calls, and later e-mail messages. It was typical of Bullock to carefully plan his trips, accommodating as many meetings as possible with colleagues and other people. His characteristic tight schedule is illustrated by his "round-the-world trip" (as he called it later) in 1966. In the two weeks that preceded and the two weeks that followed the Great Barrier Reef expedition on the *Alpha Helix*, he visited Papeete, Bora Bora, Auckland, Wellington, Christchurch, Sydney, Canberra, Brisbane, Cairns, Hong-Kong, Bangkok, Teheran, Tel Aviv, Rome, Rio de Janeiro, Sao Paulo, Buenos Aires, Santiago de Chile, and Mexico City. It was also typical of Bullock to document his trips in very detailed notes, and to take a tremendous number of pictures of the places he visited and the people he met. The photograph shown in Fig. 9 was taken during such a trip—to Caracas, Venezuela, where he met, among many other people, Bernard Katz. These visits often marked the beginning of new collaborations and friendships—and, thus, they are important elements to explain his scientific success and the affection shown to him by so many people.

Fig. 9 Ted Bullock (*right*) in conversation with Bernard Katz in Caracas, Venezuela, in 1957. Katz (1911–2003) pioneered the study of physico-chemical mechanisms of neuromuscular transmission, for which he received the Nobel prize in 1970. (Photographer unknown; courtesy Scripps Institution of Oceanography Archives.)

Honors and the legacy of his school

Ted Bullock received numerous honors over his lifetime. They included the election to the American Academy of Arts and Sciences in 1961, to the National Academy of Sciences in 1963, and to the American Philosophical Society in 1970; the Karl Spencer Lashley Award of the American Philosophical Society in 1968, the Gerard Prize of the Society for Neuroscience in 1984, and the Berkeley Citation of the University of California at Berkeley in 1988; and honorary doctorates from the University of Frankfurt, Germany, in 1988 and the Loyola University in Chicago in 2000.

Ted Bullock regarded these awards not as a reflection of his sole merits, but as recognition of a collaborative contribution made by him and his co-workers to science. When the American Philosophical Society informed him about the award of the Lashley Prize, he wrote in a reply letter dated 7 December 1967:

> *Your communication of November 28...has stunned me into a two-day stammering silence. The honor of the Karl Spencer Lashley Prize and of recognition by the American Philosophical Society is profoundly moving. It is both humbling and a spur to new effort to be listed with the eminent holders of the Lashley prize in previous years. My co-authors, colleagues and associates are honored by this action since their contributions have been decisive and major in both tangible and intangible ways.*

In conversations, Ted Bullock hardly ever mentioned any of these distinctions, and no award certificate or plaque was decorating the walls of his office. When Franz Huber, then director of the Max Planck Institute for Behavioral Physiology in Seewiesen, informed him that he would receive the honorary degree from the University of Frankfurt, Ted Bullock replied, in a letter dated 31 August 1988, with the kind of humor characteristic of him:

The Univ. of Frankfurt honor is so astonishing, I am overcome. I can understand it simply because I know that Universities, too, make mistakes—sometimes nice ones!

By one honor, however, he seemed to have been touched. It was the decision by the National Institute for Amazonian Research in Manaus, Brazil, to name, in 2002, one of the laboratories in honor of him and Walter Heiligenberg—the "Bullock–Heiligenberg Pavilion for Behavioral Physiology". Although he was already 87 years old, he accepted the invitation of the Institute to travel to Manaus to cut the ribbon, as part of the opening ceremony.

His CV lists 34 Ph.D. students and 120 postdoctoral fellows who were supervised by him. They included people from all over the world, thus creating an international spirit in the laboratory that greatly facilitated an exchange of ideas and the design of new project proposals. Most of his associates established their own labs, and many of them have become leading figures in their areas of research. Four of them were elected to the National Academy of Sciences—Melvin J. Cohen, Susumu Hagiwara, Eric I. Knudsen, and Nobuo Suga. It was the success of former students that seemed to give Ted Bullock more satisfaction than the honors he had received himself.

Although Ted Bullock initiated an immense number of investigations and sponsored many of them through his own funds, it was typical of him to encourage students to work independently and to take projects with them after they had left the lab. This unusual degree of independence is also reflected by the numerous publications of his students and co-workers on which he did not appear as author or co-author.

Advocate of integrative and comparative neurobiology

Ted was president of the American Society of Zoologists (now Society for Integrative and Comparative Biology; 1964–1965), third president of the Society for Neuroscience (1973–1974), and first president of the International Society for Neuroethology (1984–1987). At the time of his presidencies, both neuroscience and neuroethology were still in their infancy. He shaped the development of these disciplines by reminding the science community time and again of the need to include integrative and comparative approaches in their studies. He was convinced that such a strategy was the only way to understand how brains (he deliberately used the plural) work. He did this by sharing his vision with the science community in numerous lectures and commentaries (Bullock 1966, 1984a, b, 1986, 1993, 1995, 1999, 2005).

He was also a firm advocate for values about which he felt strongly. When at the end of the 1980s there were clear indications that the Max Planck Society would terminate future support for behaviorally oriented neurobiology, Ted Bullock asked Heinz A. Staab, then president of the society, to reconsider its position. In a letter dated 12 January 1990, he wrote:

I am concerned about the future of integrative neuroscience in Germany and particularly neuroethology in the MPG [Max-Planck-Gesellschaft—Max Planck Society]... I appreciate that the broader field of neuroscience has expanded in many directions at once, especially on the cellular–chemical–molecular frontier—and I do not regret this. It is a very yeasty frontier, with many breakthroughs. Precisely because of the success of this most reductionist and component-oriented aspect of neuroscience, it is important to prevent the neglect of the integrative, system-oriented aspects of neuroscience.

"Rigorist", humanist, and humorist

One of Ted Bullock's distinctive features was the rigor with which he addressed scientific problems and conducted research. In discussions, his arguments were characterized by breadth, clarity, and critical judging. However, as much as he regarded it to be essential to critically analyze the arguments of others, he was also willing to accept criticism himself. When a student of the University of Missouri Medical School evidently felt inadequately criticized in an exam, Ted Bullock sent him the following letter dated 9 November 1945:

A personal note of criticism in your blue book is a genuine compliment—it means I recognize a soul with whom I can argue real questions of academic significance—the life blood of science...bravo to one who is willing to use his own noodle. Do not expect everyone to appreciate you in this respect, however, expect instead rebuff and argument. Thinking, like virtue, is its own reward.

When asked a question, it was not uncommon that Bullock paused for a long time, sometimes so long that it appeared that the question had gone unnoticed; yet, afterwards, he would give a well-articulated answer, demonstrating that he had taken the time to thoroughly think through the problem raised. On the other hand, he readily admitted his limits when he felt he lacked competence to satisfactorily address a problem. This approach to reasoning and communication—evident in his publications—was formally taught to generations of students in his course on scientific communication.

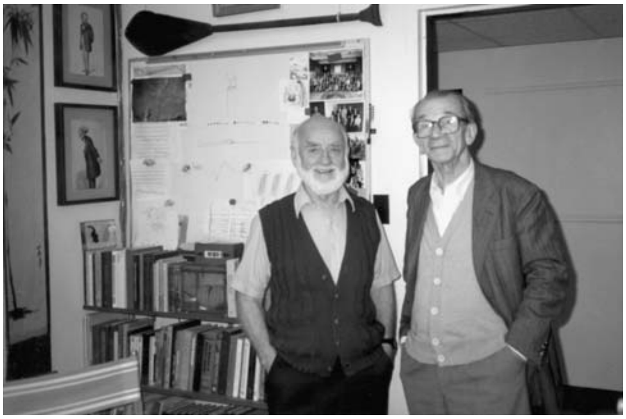

Fig. 10 Ted Bullock in his office at the Scripps Institution of Oceanography in 1989, together with Hansjochem Autrum (1907–2003). (Photographer unknown; courtesy Scripps Institution of Oceanography Archives.)

Although he was an exceptionally gifted writer, he spent an enormous amount of time revising manuscripts, trying to condense text and figures as much as possible, and restricting interpretations to the framework set by the results. In a letter written to Friedrich Diecke on 9 February 1956 (in which he informed the latter that he was working on the manuscript of their joint paper on the physiological properties of infrared receptors in pit vipers; Bullock and Diecke 1956), he spelled out this approach as follows:

I feel it is the obligation of the scientist to boil down his information to the shortest possible form and short of making an equation or formula.

This approach created a style of writing that Howard A. Bern, Professor at the University of California, Berkeley, very rightfully characterized, in a letter to Ted Bullock (dated 13 December 1962), as

...simply superb and superbly simple.

Despite his rigor, Bullock was famous for his hospitality. When he had visitors, he seemed to have unlimited amount of time available just for them. The photograph in Fig. 10 shows him with one of these numerous visitors—Hansjochem Autrum, sensory physiologist from Germany and former Editor-in-Chief of the Journal of Comparative Physiology-A. As his daughter Christine Kasman remembers (personal communication to G.K.H. Zupanc on 28 July 2007):

His idea of family, and one's responsibility to family, extended beyond his own biological one. Visitors who came from all over the world, as well as graduate and postdoc students, were so often added to our family life! I still have a Christmas tree decoration made by a visiting Russian...when I must have been ten or less. And I've got memories of one of his students, Mel Cohen, reading me books before I went to bed—these people were incorporated into our family!

His attitude of serving others, and the loyalty by which he was attached to people, defined the framework for both his scientific activities and his life outside the lab. He was President of the UCLA Chapter of the American Association of University Professors in 1955–1956. He was an active member of the Methodist Church community and the Amnesty International Chapter—something he kept strictly separate from his professional life. He stayed in contact with most of his former students throughout life, archived all their announcements of weddings, birth of children, and other news, and replied in very personal letters. Above all, he was deeply devoted to Martha Runquist (Fig. 11), his wife of more than 68 years, their children Christine and Stephen, and their five grandchildren.

Final years

In 1983, when Ted was forced by law to retire at the age of 68, he became Professor Emeritus at UCSD. He continued to run his lab, attract visitors from all over the world, and perform cutting-edge research. Over the following 22 years of official retirement, his lab continued to produce an immense number of publications. They included "classics", like the two monumental books entitled "Electroreception"—the first edited by him and Walter Heiligenberg (Bullock and Heiligenberg 1986) and the second edited by him, Carl D. Hopkins, Arthur N. Popper, and Richard R. Fay (Bullock et al. 2005). In 1993, his Researcher-Oriented ("R-O1") grant of the National Institutes of Health ceased after 45 years, as one of the first received under the then new funding schema and as one of the longest unbroken ever maintained by a grant holder. When, at the age of 88, he finally ran out of funding to pursue experimental

Fig. 11 Ted Bullock and his wife Martha in La Jolla, in July 2005. (Photograph by G.K.H. Zupanc.)

research, he re-initiated, jointly with Terence Sejnowski of the Salk Institute for Biological Studies in La Jolla, a modeling study that went back to the 1960s, when Ted Bullock was among the first experimentalists to apply computational approaches to the analysis and modeling of neurobiological data.

Even at the age of 90, he remained youthful and vigorous. He still went to his office at the Scripps Institution of Oceanography two or three times a week, worked many hours from home, and made plans for future projects. He also worked on 19 December 2005. After he went to bed in the evening, he experienced breathing problems. By the time he was admitted to UCSD's Thornton Hospital, he had passed away. He had probably died shortly after midnight. On 5 January 2006, a memorial service was held at the La Jolla United Methodist Church. During the service, the following verses, written by Ted at the age of ten, were recited:

When the stars start nodding at you,
Winking as if sleepy too,
When you get quite tired and weary,
Then the crickets sing to you.

Theodore H. Bullock: a personal reflection (by Günther K.H. Zupanc)

I first met Ted in 1987 when, as a graduate student, I arrived at the Neurobiology Unit of the Scripps Institution of Oceanography of UCSD. The following years, with discussions over lunch, Friday afternoon seminars, and numerous informal meetings, were among the most enjoyable of my life—especially because of Ted. When he served on my thesis committee, I asked him what he expected of a candidate to know in a thesis defense. He replied: "Someone who is about to receive a Ph.D. should be familiar with more than just his own field of research. He should also know something about knowledge in the broadest sense, including the philosophy of scientific inquiry, the history of academic institutions, etc." At first, I was somewhat puzzled by the unexpected answer, but since then this approach to knowledge has reinforced my own way of thinking and doing research. After I left UCSD, Ted invited me, time and again, to the Scripps Institution of Oceanography, and we collaborated on a number of projects. Over these years, the relationship between our families developed into close friendship, and he became "Opa Ted" to our three children. As much as we miss him, his spirit will continue to guide our lives.

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References

Alexandrowicz JS (1932) The innervation of the heart of the Crustacea. I. Decapoda. Q J Microsc Sci 75:181–249
Başar-Eroglu C, Başar E, Schmielau F (1991) P300 in freely moving cats with intracranial electrodes. Int J Neurosci 60:215–226
Bennett MVL (1985) Nicked by Occam's razor: unitarianism in the investigation of synaptic transmission. Biol Bull 168(suppl):159–167
Bullock TH (1946) A preparation for the physiological study of the unit synapse. Nature 158:555–556
Bullock TH (1948) Properties of a single synapse in the stellate ganglion of squid. J Neurophysiol 11:343–364
Bullock TH (1966) Strategies for blind physiologists with elephantine problems. Symp Soc Exp Biol 20:1–10
Bullock TH (1984a) Understanding brains by comparing taxa. Perspect Biol Med 27:510–524
Bullock TH (1984b) Comparative neuroscience holds promise for quiet revolutions. Science 225:473–478
Bullock TH (1986) Some principles in the brain analysis of important signals: mapping and stimulus recognition. Brain Behav Evol 28:145–156
Bullock TH (1993) How are more complex brains different? One view and an agenda for comparative neurobiology. Brain Behav Evol 41:88–96
Bullock TH (1995) Neural integration at the mesoscopic level: the advent of some ideas in the last half century. J Hist Neurosci 4:216–235
Bullock TH (1996) Theodore H. Bullock. In: Squire LR (eds) The history of neuroscience in autobiography, vol 1. Society for Neuroscience, Washington, DC
Bullock TH (1999) Neuroethology has pregnant agendas. J Comp Physiol A 185:291–295
Bullock TH (2005) In praise of "natural history". Cell Mol Neurobiol 25:217–221
Bullock TH, Cowles RB (1952) Physiology of an infrared receptor: the facial pit of pit vipers. Science 115:541–543
Bullock TH, Diecke FPJ (1956) Properties of an infra-red receptor. J Physiol (London) 134:47–87
Bullock TH, Fox W (1957) The anatomy of the infra-red sense in organ in the facial pit of pit vipers. Q J Microsc Sci 98:219–234
Bullock TH, Hagiwara S (1957) Intracellular recording from the giant synapse of the squid. J Gen Physiol 40:565–577
Bullock TH, Horridge GA (1965) Structure and function in the nervous system of invertebrates, vols 1 and 2. W.H. Freeman, San Francisco
Bullock TH, Heiligenberg W (1986) Electroreception. Wiley, New York
Bullock TH, Nachmansohn D, Rothenberg MA (1946a) Effects of inhibitors of choline esterase on the nerve action potential. J Neurophysiol 9:9–22
Bullock TH, Grundfest H, Nachmansohn D, Rothenberg MA, Sterling K (1946b) Effect of di-isopropyl fluorophosphate (DFP) on action potential and cholineesterase of nerve. J Neurophysiol 9:253–260

Bullock TH, Grundfest H, Nachmansohn D, Rothenberg MA (1947) Generality of the role of acetylcholine in nerve and muscle conduction. J Neurophysiol 10:11–21

Bullock TH, Hagiwara S, Kusano K, Negishi K (1961) Evidence for a category of electroreceptors in the lateral line of gymnotid fishes. Science 134:1426–1427

Bullock TH, Hamstra RHJ, Scheich H (1972a) The jamming avoidance response of high frequency electric fish. I. General features. J Comp Physiol A 77:1–22

Bullock TH, Hamstra RHJ, Scheich H (1972b) The jamming avoidance response of high frequency electric fish. II. Quantitative aspects. J Comp Physiol A 77:23–48

Bullock TH, Hofmann MH, Nahm FK, New JG, Prechtl JC (1990) Event-related potentials in the retina and optic tectum of fish. J Neurophysiol 54:903–914

Bullock TH, Karamürsel S, Hofmann MH (1993) Interval-specific event related potentials to omitted stimuli in the electrosensory pathway in elasmobranchs: an elementary form of expectation. J Comp Physiol A 172:501–510

Bullock TH, Hopkins CD, Popper AN, Fay RR (2005) Electroreception. Springer, New York

Del Castillo J, Katz B (1954) Quantal components of the end-plate potential. J Physiol (London) 124:560–573

Feldberg W, Fessard A, Nachmansohn D (1940) The cholinergic nature of the nerve supply to the electrical organ of the Torpedo (*Torpedo marmorata*). J Physiol (London) 97:3P–5P

Furshpan EJ, Potter DD (1959) Transmission at the giant motor synapses of the crayfish. J Physiol (London) 145:289–325

Grüsser-Cronehls U, Grüsser O-J, Bullock TH (1963) Unit responses in the frog's tectum to moving and nonmoving visual stimuli. Science 141:820–822

Hagiwara S, Morita H (1963) Coding mechanisms of electro-receptor fibers in some electric fish. J Neurophysiol 26:551–567

Hagiwara S, Watanabe A, Saito N (1959) Potential changes in syncytial neurons of lobster cardiac ganglion. J Neurophysiol 22:554–572

Hagiwara S, Kusano K, Negishi K (1962) Physiological properties of electroreceptors of some gymnotids. J Neurophysiol 25:430–449

Hagiwara S, Szabo T, Enger PS (1965a) Physiological properties of electroreceptors in the electric eel, *Electrophorus electricus*. J Neurophysiol 28:775–783

Hagiwara S, Szabo T, Enger PS (1965b) Electroreceptor mechanisms in a high-frequency weakly electric fish, *Sternarchus albiforns*. J Neurophysiol 28:784–799

Hanström B (1928) Vergleichende Anatomie des Nervensystems der wirbellosen Tiere. Springer, Berlin

Heiligenberg W (1991) Neural nets in electric fish. MIT Press, Cambridge

Hillyard SA, Picton TW (1979) Event-related brain potentials and selective information processing in man. In: Desmedt JE (ed) Cognitive components in cerebral event-related potentials and selective attention. S. Karger, Basel

Hodgkin AL, Huxley AF (1952) A quantitative description of membrane current and its application to conduction and excitation in nerve. J Physiol (London) 117:500–544

Jones SJ (1992) AEPs at the onset and offset of repetitive sound modulation, due to mismatch with the contents of an auditory sensory store. Electroencephalogr Clin Neurophysiol 84:149–156

Lettvin JY, Maturana HR, McCulloch WS, Pitts WH (1959) What the frog's eye tells the frog's brain. Proc Inst Radio Eng 47:1940–1951

Lissmann HW (1951) Continuous electrical signals from the tail of a fish, *Gymnarchus niloticus* Cuv. Nature 167:201–202

Lissmann HW (1958) On the function and evolution of electric organs in fish. J Exp Biol 35:156–191

Nachmansohn D (1959) Chemical and molecular basis of nerve activity. Academic, New York

Nachmansohn D, Lederer E (1939) Sur la biochimie de la cholinestérase. I. Préparation de l'enzyme, rôle des groupements-SH. Bull Soc Chim Biol 21:797–808

Noble GK, Schmidt A (1937) Structure and function of the facial and labial pits of snakes. Proc Am Phil Soc 77:263–288

Perkel DH, Schulman JH, Bullock TH, Moore GP, Segundo JP (1964) Pacemaker neurons: effects of regularly spaced synaptic input. Science 145:61–63

Ramón F, Hernández OH, Bullock TH (2001) Event-related potentials in an invertebrate: crayfish emit "omitted stimulus potentials". J Exp Biol 204:4291–4300

Richardson TL, Turner RW, Miller JJ (1984) Extracellular fields influence transmembrane potentials and synchronization of hippocampal neuronal activity. Brain Res 294:255–262

Taylor CP, Dudek FE (1984) Excitation of hippocampal pyramidal cells by an electrical field effect. J Neurophysiol 52:126–142

Terzuolo CA, Bullock TH (1956) Measurement of imposed voltage gradient adequate to modulate neuronal firing. Proc Natl Acad Sci USA 42:687–694

Watanabe A (1958) The interaction of electrical activity among neurons of lobster cardiac ganglion. Jpn J Physiol 8:305–318

Watanabe A, Bullock TH (1960) Modulation of activity of one neuron by subthreshold slow potentials in another in lobster cardiac ganglion. J Gen Physiol 43:1031–1045

Watanabe A, Takeda K (1963) The change of discharge frequency by a.c. stimulus in a weak electric fish. J Exp Biol 40:57–66

Zupanc GKH, Bullock TH (2006) Walter Heiligenberg: the jamming avoidance response and beyond. J Comp Physiol A 192:561–572