NATIONAL ACADEMY OF SCIENCES

HALLOWELL DAVIS

1896—1992

A Biographical Memoir by

ROBERT GALAMBOS

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August 31, 1896–August 22, 1992

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WHEN HALLOWELL DAVIS began his experiments on the nervous system in 1922, the number of American neurophysiologists he might talk to—the neuroscientists of that day—could be counted almost literally on the fingers of one hand. When he died seventy years later there were more than 15,000 members of the Society for Neuroscience (U. S. A.), and he was universally recognized as the world's leading authority on the ear and hearing. He owed this position in part to an uncanny knack for selecting exactly the right moment to begin working on a problem, and because throughout his life he was simultaneously performing a new experiment and writing up a finished one. These activities, plus his interactions with a small army of friends, students, and associates here and abroad took him to the top of his profession and kept him there.

The first brainwaves seen on the American continent came out of his own head in 1933, recorded by his graduate students using equipment he had designed. At about the same time he was among the first anywhere to record animal cochlear potentials, human evoked brain potentials, and the activity of single nerve cells at work inside an animal brain. And because he believed scientists should develop

useful products out of their discoveries, his name appears prominently in the history of the hearing aid, the audiometer, and the test procedures used in hearing clinics throughout the world.

He was admired for his ability to organize apparently unrelated facts in novel and logical ways, and then to speak and write clearly about them. This friendly, witty man—teacher, writer, organizer, and toiler at the bench—said he aimed in life to serve science, his country, and mankind, and that is exactly what he did.

PERSONAL HISTORY

Hallowell Davis was born in New York City, the oldest of the four children of Horace A. Davis, a lawyer, and Anna Norwood Hallowell. He died in St. Louis nine days before his ninety-sixth birthday. When he was twelve the family moved to Boston, where he graduated from a private boy's school in 1914, Harvard College in 1918 (chemistry, summa cum laude), and the Harvard Medical School in 1922. He married three times and with his first wife Pauline Allen (1896-1942) fathered three children, Allen Young (1924), Anna Norwood (1925), and Rowland Hallowell (1933). Hal and Pauline married in May 1923 in a refugee camp near Istanbul, while they were members of a medical relief team treating war-displaced persons suffering from typhus, smallpox, and cholera. In 1939, still working with her husband, this time in his laboratory in the Harvard Medical School, Pauline published the first systematic report of human cortical evoked responses, and a landmark in the history of brain research. Pauline died in 1942. Davis married Florence Eaton in 1944. In 1983, three years after Florence's death, he married Nancy Gilson.

Davis classified himself as an independent liberal politically and by religion first a Quaker, then a Unitarian, and

finally a member of the American Humanist Association. He took positions on matters of public interest and supported causes such as Planned Parenthood, Physicians for Social Responsibility, and the American Civil Liberties Union, but he did not think or behave like an activist. His hobby was travel, which meshed nicely with his view that "an important secondary function of a scientific career (is) to promote international friendships and understanding as an aid to world peace."

During a 1953 radio interview with Edward R. Murrow he listed his concerns, convictions, and beliefs, some of which appear in the following edited list:

- "The survival of mankind is the yardstick by which I measure good and bad." His 1959 past president's address to the American Physiological Society views the growth of the human population as alarming, cites the inevitability of the Malthusian equation, and urges his listeners to study the situation and find ways to contain the explosion and alleviate its consequences.
- "It is my duty and privilege to learn what I can about the ways of nature and man and, if this knowledge is to help mankind, to share it with others." He welcomed classroom teaching and he sought out and enjoyed the intellectual interactions provided by the countless committee, seminar, and scientific meetings he attended here and abroad. He spent years hunting for the best way to identify children with hearing loss and to define the requirements of the hearing aids they should wear.

He listed what he believed in:

- "The brotherhood of mankind, not just the yellow, the brown, the black, or the white;

- The integrity of speech (let thy yea be yea and thy nay be nay).
- Tolerance, freedom of thought and speech, and the golden rule.
- Respect for man-made law, which must include the rules for lawful change.
- Patience—evolution is slow, young liberals become moderate conservatives, and extremists fade away."

His list echoes positions taken by many of the gentlemen who wrote our Constitution; or it might have come from a New England abolitionist 150 years ago. And he lived by what he believed: I never heard him speak harshly to or about anyone—nor was I ever there when someone uttered unkind or disparaging remarks to his face or behind his back.

Davis was favored with a healthy physique and by regular exercise kept himself fit and trim into his old age. During his postdoctoral year in England he was a runner; he once admitted, or claimed, he lost a foot race with the 1922 Olympic mile champion Abrams, who was featured in the movie *Chariots of Fire*.

Hal loved fun, enjoyed a good joke, and constantly manufactured them himself. He said he invented the word "audiology" in the mid-1940s because the military equivalent then in use, "auricular training," sounded like a project to teach people how to wiggle their ears. He relished word games and was a notorious punster, like Shakespeare, whose plays are said to include 3,000 of them. Allen Davis recounts a fragment of the final conversation with his father that sums up this side of the man. The topic was cryogenics, and specifically whether people could in fact be held in suspended animation indefinitely on ice, whereupon his father suggested that a good motto for the company provid-

ing such a service might be "Freeze a jolly good fellow." Typical—although some that remember might call this sample one of his better ones.

PROFESSIONAL HISTORY

> During my school days I never doubted that I would be an experimental scientist. I had a "laboratory" in either a cellar or attic from the time I learned to saw wood and drive nails.

Davis cites as his first scientific discovery the fact that a 10-inch-long electric spark produced by the Tesla coil he built in high school would punch a needle-size hole through a sheet of glass, but only if the surface was first smeared with oil. His final contribution to science are the stained histological sections of his temporal bones, which reveal to the experts in such matters the cochlear hair cell abnormalities typical of a severe hearing loss. In the eight decades between these offerings he published 7 books and 326 papers (of which fewer than 1 in 6 appear in the bibliography below), as well as countless technical reports filed away in Army, Navy, Air Force, state, national, and foreign archives.

As an undergraduate at Harvard he was an ardent chemist, by his senior medical school year he had become a physiologist, and during his postdoctoral year in England (1922-23, with E. D. Adrian) he became a neurophysiologist. On his return to Boston he joined Alexander Forbes in Walter B. Cannon's Department of Physiology at the Harvard Medical School as an instructor; when he left for St. Louis twenty-four years later he was an associate professor without tenure. In 1947 he became the director of research at the Central Institute for the Deaf in St. Louis, with additional appointments at the Washington University

Medical School as professor of physiology and research professor of otolaryngology (1947-87).

With a few notable exceptions his Harvard and St. Louis experiments all deal with the ear or with brainwaves, sometimes separately, often simultaneously. He began with the cochlea, that biological transducer within which eardrum vibrations become nerve impulses. He promptly realized that interesting results would require improved stimulus generation and response recording equipment, and in a few years he had created the prototypes of the research and clinical electrophysiological instruments used today.

INTRUMENTATION

In this attention to equipment Davis took after his mentor Alexander Forbes, who had welcomed Davis into his laboratory in 1923. In those days the only device sensitive enough to record nerve action potentials was the string galvanometer, a gold-plated quartz filament stretched tight between the poles of a strong magnet. Forbes, who had been using one since 1912, encountered vacuum tubes in military radios as a naval officer in World War I, and in 1920 he published, with Thacher, the paper titled "Amplification of Action Currents with the Electron Tube in Recording with the String Galvanometer." When the definitive history of modern electrophysiology is written it will surely cite this remarkable paper as among the first, if not actually the first, to use electronic amplification in biology.[1]

Davis used this system for studies on the nerve impulse, then helped produce an improved version a decade later.[2] In 1931 he conceptualized an integrated electrophysiological system consisting of stimulus generator, response amplifier, cathode ray tube, and camera and put the laboratory's engineer E. L. Garceau to work preparing its circuit diagrams. When completed three years later in 1934 the in-

strument filled five 6-foot-tall relay racks, one of which was "well weighted down by 300 pounds of batteries" to prevent sources of vibration such as footsteps from shaking the most sensitive of its 47 vacuum tubes. Davis invented his standing-wave method for comparing nerve responses at this time: you focus the camera on the oscilloscope tube face and leave the shutter open as the triggered individual responses race across it. The resulting photographic superimposition was his pre-computer way to identify response similarities and differences [examples appear in our joint publication on single auditory neurons (1943)].

It was my good fortune to enter this laboratory as a graduate student in 1937. By then it had become a major center of both brainwave and auditory research. Albert M. Grass, a 1934 graduate in electrical engineering from the Massachusetts Institute of Technology, was now its research instrument engineer. He had greatly improved the Garceau brainwave recording system and was building a new version—his Grass model 1 EEG machine—in his own shop for Boston's brainwave research pioneers. He also continuously updated and improved the laboratory's electronic equipment.[3]

Grass brought to the Davis enterprises an admirable level of energy, skill, and intelligence. Davis identified for him the instruments a modern electrophysiological laboratory must have and brought him face to face with both the clinicians and the basic scientists who use them. Davis was a good teacher, and Grass an apt pupil. They remained close friends to the end, and the amplifiers, signal generators, and EEG machines the Grass Instrument Company sells, more than a half century later, are still the gold standard against which others are judged.

ANIMAL EXPERIMENTS

Still following in his mentor's footsteps (Alex Forbes was the first to record auditory nerve responses from an animal, in 1927), Davis decided in 1929 to concentrate on the auditory system. A few years later, with collaborators E. J. Saul and A. W. Derbyshire, he had traced the auditory pathway physiologically from cochlea to cortex; dissected the Wever and Bray phenomenon into its two parts, cochlear hair cell (microphonic) and auditory nerve; and described the auditory nerve barrage a cochlea delivers to the brain (1933, 1935). Then, with S. S. Stevens and M. H. Lurie, he directly confirmed the Helmholtz theory of cochlear action by correlating the place where a small lesion has been made along the length of the cochlea with the stimulus frequency band that then fails to produce a response (1935). Finally, in the last of his Harvard animal experiments—and the ones in which I was involved—we isolated single auditory neurons with microelectrodes inside the cat brain, showed that each nerve responds to a limited band of tone frequencies delivered into the ear (1943), and demonstrated that the central processing of the incoming sensory message is a complex mix of inhibitory and excitatory events (1944).

In St. Louis he continued the animal experiments for more than twenty years with a series of distinguished collaborators, notably Ichiji Tasaki and D. H. Eldredge. They devised intracochlear electrodes and used them to map the space-time distribution of stimulus frequency in the cochlea; discover the summating potential; exploit the endocochlear potential Bekesy had reported; and to invent the derived response method for analyzing compound action potentials. He became the principal auditory theorist of his time by incorporating new information of this sort—his own and that of others—into a progressively more specific and real-

istic model of cochlear action, which he presented in final form in 1965.

BRAINWAVES

In his autobiography Davis dates the discovery of the EEG alpha rhythm in the United States to "the winter of 1933-34" and to the exact moment he closed his eyes while two students, Arthur W. Derbyshire and Howard Simpson, were watching the wavy line of his brainwaves move across an oscilloscope tube face (they are reported to have shouted, "There it is! There it is!"). Then "in December 1934," after Garceau had built the world's first ink-writing oscillograph, Davis connected the device to the electrodes on the scalp of a patient brought to the laboratory, whereupon the Boston EEG pioneers (Davis, his wife Pauline, Fred and Erna Gibbs, and William G. Lennox) saw the spike and wave abnormality characteristic of petit mal epilepsy for the first time. Investigators in both old and New England were by then also busy following up the Berger claim, but the Harvard clinical discovery was unique for its time, and it established the Boston group as the founders of clinical encephalography with one of its most dramatic manifestations.

Pauline Davis, who was active in brainwave research for nearly ten years, published the first human auditory cortical responses from this laboratory in 1939.[4] The remaining sections of this memoir will show that her husband made frequent use of her discovery.

NOISE

Davis was a birthright member (through his mother) of the Society of Friends (Quakers), whose creed includes conscientious objection to war. During World War I he served as an ambulance driver in France, but at the start of World

War II he resigned his membership in the society and participated actively in several military research projects.

The first of these projects, in 1940, was as a member of the National Defense Research Committee (NDRC) in its section dealing with loud sounds. When the military asked the NDRC whether intense sounds were dangerous enough to be developed into an offensive weapon, Davis collected a small group of investigators, made the necessary measurements in underground test rooms at Harvard University and submitted a secret report concluding that loud noise was an unlikely offensive weapon, but it was a certain way to produce permanent hearing loss (1950).

These experiments initiated the scientific study of the auditory and non-auditory effects of high intensity noise on human beings. When the 1943 findings and recommendations became obsolete because postwar jet aircraft generate noise levels tens of decibels greater than their propeller-driven ancestors, he re-did the study, quantified the jet-noise environment on carrier flight decks, and in 1958 again concluded "sound won't hurt a man except for his ears," but he warned that this might no longer be true if a few more decibels are added.

Davis was also involved in a forgotten non-auditory effect of noise on man: noise can reduce or abolish pain. In 1959 noise delivered through earphones was reported to be as effective as novocaine injections for patients undergoing dental procedures. Davis promptly discovered that some of the noise makers the dentists used could easily damage the ear, whereupon he published the specifications for a noise generator, along with the rules for its use, that would produce the desired result without hearing loss. He also published his opinion that a lawsuit claiming sudden deafness while in a dental chair would be difficult to contest, and maintained that the fear he might be right is the reason

audio analgesia machines were soon withdrawn from the market, and audio analgesia research came to an end.

Concern about the effects of noise on man occupied some part of his attention for fully thirty years (1940-70). He made his final contribution as a member of the National Academy of Sciences Committee on the Sonic Boom and Supersonic Transport. Its charge: should the U.S. Congress support the development of a passenger plane that travels at speeds beyond mach 1? As was his custom he had an opinion and he stated it clearly. "I was quite strongly against the project, partly because of anticipated continued public irritation with the booms and landing and take-off noise, but even more because I considered the SST project a very bad economic risk." His voice may have been heard; Congress voted the project down by a small margin.

SERVICE AND OTHER UNCELEBRATED ACCOMPLISHMENTS

During most of his life, and to discharge a perceived civic responsibility, Davis chaired, or was a member of, many local, national, and international committees dealing with clinical, scientific, and military matters. The documents he helped create are now embedded in the laws of the land or locked in the archives of the National Academy of Sciences, the American National Standards Institute, and many other organizations. His committees struggled with a surprising variety of charges—to estimate before the fact the number of World War II casualties; establish international standards for the performance of audiometers and hearing aids; predict for Congress the probable damage produced by a sky full of commercial airplanes making sonic booms; list the requirements for a comprehensive and efficient clinical diagnosis of hearing loss; and devise a fair compensation schedule for workers who suffered hearing loss on the job. Some documents received numbers instead of names and all rep-

resent endless hours debating terminology, standards, specifications, methods, and tests. He called some of the resulting recommendations "only an educated guess," but he enjoyed the intimate intellectual interplay required to produce them.

It was customary to have Davis come last on the program of a scientific meeting where many speakers, including himself, had spent two or three days delivering papers to each other. He was famous for the summaries he produced—comprehensive, insightful, and fair, delivered with humor, at once a useful take-home gift to his listeners and a virtuoso display of his remarkable ability to listen with care and remember, organize, and integrate apparently miscellaneous items of information. In his younger days he delivered these essays, often hour-long, without notes. (He once advised me as I was preparing, with sweaty palms, to deliver the first of our joint papers from the platform, to write out and read the first and last paragraphs, but to deliver the rest looking straight at the audience.)

In the mid-60s he produced such a commentary at a meeting we attended in Honolulu. A few hours later in the airport he wrote it out seated on a bench, yellow pad on knee. What he then handed me to read was later published with almost no changes. Apparently he came early to this skill; his autobiography tells of the paper he ghostwrote for a Dr. Blackfan in 1930. It summarized a White House conference on child health called by President Hoover and was apparently well received when Dr. Blackfan read it to his audience of 3,000.

AUDIOLOGY

Audiology, the study and assessment of normal and impaired hearing, was given its name during discussions between Davis and others in the mid-40s. It is first defined as

a discipline in *Hearing and Deafness: A Guide for Laymen*, a 1947 book Davis edited. This book synthesizes his extensive civilian and wartime involvement in such diverse fields as cochlear anatomy, acoustic physics, psychology, noise trauma, and the rehabilitation of the deaf into an organized plan for how to think about the entire collection of hearing-related phenomena. He does this in six sections with nineteen chapters, of which he wrote five, while other expert colleagues contributed the rest. At that time no single discipline existed where budding professionals could learn to become experts in the hearing arts and sciences, so he invented it. Not accidentally, its content closely resembles an outline of his life's work.

Almost everything Davis did before and after he created his discipline of audiology can be classified as audiology—the seven books, some thirty chapters and review papers, hundreds of journal publications, and the endless committee work. To top all that, he was for many years an active member of the International Society of Audiology, served as its vice-president (he says he "narrowly escaped" being elected president in 1966), and was still a member of the editorial board of its journal *Audiology* two years before he died.

In 1968 he organized the International Electric Response Audiometry Study Group and served at its chairman and then chairman emeritus until his death. This organization, which survives to this day, was a special pet of his. Its goal is to develop and improve electrophysiological methods for estimating hearing threshold.

THE COMPLETE MAN

Can it be that in his distinguished career Hallowell Davis made no wrong guess, suffered no defeat, experienced no dashed hope? Let me summarize here his personal foray

into electric response audiometry, which he calls "a tale of successive frustrations," an example "of how nature can place unexpected obstacles in one's path."

Around 1950 he set out to develop a hearing test for patients, such as newborn babies, who cannot cooperate with the tester. He began with electrodermal audiometry, a method that brings to mind Pavlov's dog, which salivated when a bell sounded. A mild shock anywhere on the body activates sweat glands everywhere, a physiological event readily measured as a resistance change between electrodes attached to the hand. When such a shock is paired several times with a sound, the sweat glands come to respond to the sound alone, an example, like the dog's salivation, of a learned habit. In 1952, with Robert Goldstein, Davis found this test to be useless because some normal babies never respond and others soon stop. They next studied the way a sound alters the more-or-less steady brainwave flow, finding the correlations capricious, the necessary instrumentation complicated, and the procedures unlikely to appeal to busy clinicians.

They then turned to the evoked potentials, which are synchronized bursts of brainwaves time-locked only to those sounds a person can hear. There are three varieties of these—early, middle, and late, according to latency—and they are best studied after a computer extracts them from the EEG and creates an average. Davis was at last ready to do this in 1963, using the new computer he and J. R. Cox had designed and built (suitable commercial computers did not yet exist and so, true to form, he built one himself). With several collaborators he then spent more than a decade on basic and applied clinical studies of the late and middle latency evoked responses, concluding at last that the late ones would not make a useful test, but that a version of the

middle latency response he named SN10 could be the infant hearing test he had in mind.

Meanwhile, others began reporting success using the early, or auditory brainstem response (ABR). Davis evaluated this ABR on a population of St. Louis newborns and found it to be unsatisfactory (1982), a conclusion greatly at variance with the results coming from other clinics. Hal would not be happy to learn that a recent Medline search for publications on infant hearing tests yielded 5 SN10 papers and 796 ABR publications (for 1991-96). His pursuit of the objective neonatal hearing test was protracted, aggressive, and intelligent, but in the end the method most used did not come from his laboratory.

During a conversation with him in the mid-80s I suggested his deviant St. Louis ABR findings might have been due to mistakes made by the technician who tested the babies. Characteristically, he pointed the finger only at himself, figuratively, with the remark, "That was not one of my best efforts." The single flaw in the beautiful hand-tied Persian rug is what makes it perfect, they say.

HONORS

Davis prized most his National Medal of Science, awarded in 1966 at the White House. His election to the National Academy of Sciences came in 1948, and he co-chaired its physiological section in 1963. He was also an elected member of the American Academy of Arts and Sciences, American Philosophical Society, and the international Collegium Oto-Rhino-Laryngologicum Amecitiae Sacrum (which awarded him its George C. Shambaugh Prize in Otology). He was president of the American Encephalographic Society (1949), the Acoustical Society of America (1953), and the American Physiological Society (1958)—a record unlikely ever to be matched. His honorary Sc.D. degrees were

from Colby College (1954), Northwestern University (1962), Washington University (1973), Syracuse University (1979), and the University of Michigan (1983).

Davis did not practice medicine, but his work on the ear profoundly influenced diagnosis and treatment. Several organizations recognized these clinical contributions by adopting him. He was named an honorary fellow of the American Academy of Ophthalmology and Otolaryngology. The American Otological Society claimed him as an associate and gave him its Gold Medal. And he received the honors of the American Speech and Hearing Association, the Carhart Memorial Award of the American Audiological Society, Award for Merit of the Association for Research in Otorhinolaryngology, Award for Hearing Research from the Beltone Institute, and the Amplifon (Italy) International Prize.

The book *Hearing and Davis* celebrated his eightieth birthday with forty-two essays by students and associates.[5] Eldredge and Calvert have added the testimonials of thirty-four additional professionals whose lives he enriched.[6]

SUMMARY

In summary, it is not unduly extravagant to claim modern electrophysiology was born around 1930 in Boston and that Hallowell Davis was its principal midwife. In his mid-30s at the time and fully prepared by training and inclination to play the part, he created the electronic devices needed to investigate two startling, newly reported experiments—Berger's human brainwaves and the Wever and Bray animal cochlear response. His immediate reward was a highly productive decade turning out one classic brain experiment after another, and he then went on for five more decades doing basic and applied research on what he had uncovered. He coined the word "audiology" (the science of hearing) to identify the new discipline that so much of this

work defined. Many colleagues and collaborators helped on the way, of course, but at every stage he was out in front, leading the effort.

The Acoustical Society of America awarded him its Gold Medal in 1965 "for his versatile concern with bioacoustics, psychoacoustics, audiology, physiology, and otolaryngology, and for his service to the Society." To this tidy summary one can add that he effectively promoted ideas, those of others as well as his own; he was an able teacher and a prolific writer of useful books and reviews, and he was invariably a modest, generous, and courtly advocate for the best in science.

MY MAJOR SOURCE for this memoir was *The Professional Memoirs of Hallowell Davis*, a 70,000-word autobiography published by the Central Institute for the Deaf in 1991; most of the quoted text comes from it. The "Appreciation" in *Hearing and Davis*, the festschrift volume honoring his eightieth birthday, supplied additional facts, as did some of my personal papers. Another source was *The Electroencephalographic Heritage*, a 41-page illustrated history of the EEG prepared by Albert Grass in 1984, which deals with Davis's early instruments and associates. I thank Allen and Rowland Davis, Don Eldredge, Ellen Grass, J. E. Hawkins, Jr., Ira and Shirley Hirsh, and Pat Kuhl for their anecdotes, ideas, and information.

NOTES

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4. P. A. Davis. Effects of acoustic stimuli on the waking human brain. *J. Neurophysiol.* 2(1939):494-99.

5. S. K. Hirsh, D. H. Eldredge, I. J. Hirsh, and S. R. Silverman,

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6. D. H. Eldredge and D. R. Calvert. *Developing Research Careers for Scientists*. St. Louis: Central Institute for the Deaf, 1987. The preface of this 187-page monograph states, "As one of his many gracious customs, Hallowell Davis exchanged photographic portraits with each of his associates in research on or shortly after the occasion of their departure." Over the years, he posted more than seventy of these in the third floor corridor of his research building. The monograph collects testimonials from almost all of the graduate students, postdocs, and advanced scientists who worked with Davis in St. Louis.

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