Neal E. Miller

1909–2002

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
Edgar E. "Ted" Coons

NATIONAL ACADEMY OF SCIENCES

NEAL ELGAR **MILLER**

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Elected to the NAS, 1958

By Edgar E. "Ted" Coons

In 2002 the newsletter[1] of the American Psychological Association (APA) ranked Neal E. Miller among the ten most eminent psychologists of the 20th Century. Highly influential as a learning theorist, neuroscientist, science statesman, educator, and, above all, consummate experimentalist, Neal wrote 8 books and more than 270 articles.

The great variety of areas in which Neal made important conceptual and research contributions mainly concerned reward and motivation mechanisms: 1) underlying thought processes and behaviors related to problem solving in psychotherapy, 2) as mediated by the nervous system, and 3) involved in learning control over voluntary (conscious) skeletal-muscle and autonomic (normally unconscious) internal-organ response systems for minimizing stress, treating disease, and promoting health. Neal summarized much of this work late in his career in "Behavior to the Brain to Health" (1992). Furthermore, in those respects, Neal's long career epitomizes the translation of the rough-and-ready and mainly theory-driven but data-impoverished individualism of American psychology before World War II into the multimodal, collectivist pursuits of scientific discovery and application that now integrate a vast body of clinical, social, and physiological knowledge. As a confirmatory aside it would be instructive to compare Neal's 1964 article "Physiological and cultural determinants of behavior" (*Proceedings of the National Academy of Sciences*, 51:941-954) with developments since then, especially given that the NAS has in 2014 reached its sesquicentennial. [Neal noted that the piece was the result of an assignment to represent behavioral sciences, from physiology through anthropology, in a lecture on the program celebrating the centennial of the Academy.]

With the above in mind, my intent here for Neal, my mentor and dear friend, is to give a shorthand sketch of the full autobiography he intended but only completed one-third of before he died in 2002. Although my sketch draws largely on the portrait of him I've already written for the *New Dictionary of Scientific Biography*, I'll flavor it with a few views and anecdotes from his students, associates, and family. But the flavoring that is perhaps the most revealing is the following introduction he had written for himself.

> *One of the things I hope to accomplish by this autobiography is to illustrate what the life of a scientist is like. Hopefully this will be an interesting contribution to an understanding of the process by which science develops. Such an understanding can contain significant lessons for the young scientist. But an understanding also is vitally important for the citizens of an industrialized democracy whose current lives and children's futures depend on technology that is the product of advances in scientific knowledge. Unfortunately most people's current scientific education emphasizes memorizing facts that science has discovered instead of the much more significant understanding of the process of how such facts are discovered. The material relevant to these goals will begin in the description of my research…after a brief sketch of my background and early life that begins after the end of this Introduction.*
>
> *I feel especially lucky that I love my work so much that I choose to continue it even after my salary has retired* [upon his reaching 70 at Rockefeller University in 1980]. *One source of satisfaction is learning new things by studying the work of others and especially by my own basic research on how the laws of nature work in the area of animal and human emotions and behavior. I get an especial aesthetic pleasure from theories and experiments that fit neatly and parsimoniously together to reveal a better understanding of how the laws of nature work. Other great sources of satisfaction are seeing the success of my students, or, when at professional meetings, strangers come up to me and say how my research has stimulated theirs, or helped their patients. Do not think, however, that all of my life has been happy-go-lucky. There have been episodes of misery and frustration.*

Early years

Born in Milwaukee, Neal was the only child of Irving E. and Lily Rose Miller. His father held a Ph.D. from the University of Chicago where he studied with John Dewey and James Rowland Angell (later president of Yale University) and after several teaching positions elsewhere became professor of educational psychology at what is now Western Washington State College. During the moves of that "several teaching positions" period, Neal, often the new kid on the block, developed a lifelong appreciation of the fairness that should be but often wasn't accorded a newcomer or outsider. He was a gifted child and avid reader who gave his father credit for surreptitiously guiding his education by bringing home books and articles and leaving them lying casually about. Neal noticed that after he read them they disappeared to be replaced by others.

Neal earned his bachelor's degree in 1931 at the University of Washington where he had a major learning theorist, Edwin R. Guthrie, as a teacher. Only in his senior year did he decide on psychology as a career, perceiving that he could be near its frontier and get into research without first having to go through so much specialized work and also because it combined his interests in writing, people, and science in general. He moved on to Stanford University for his 1932 master's, where he worked with Lewis M. Terman, famed I.Q. researcher. While at Stanford, he took advanced experimental psychology with Walter R. Miles and, because he was proficient in physics and chemistry, helped Miles put all the apparatus in the Stanford Laboratory in good working order. When Miles was invited to join the psychology faculty at Yale, he took Neal with him for doctoral work.

Laws of learning and foresight: seeking a unified theory

At Yale, Neal came under the influence of Clark L. Hull, the most prominent learning theorist of his time. Hull's program aimed at showing how the principles of classical conditioning, discovered in Pavlov's lab, could be applied to understanding Edward Thorndike's trial-and-error learning, human verbal learning, and higher mental processes such as purposeful, goal-oriented and foresightful behavior, now described as cognitive. For example, in his 1935 Ph.D. dissertation Neal demonstrated, as described on pp. 464-65 in "Learnable Drives and Rewards" (1951), that by using the letter *T* as the critical cue (stimulus) predicting a shock and the number *4* as the neutral one predicting no shock, a learned change in the electrical conductivity of a person's skin—now elicited by the critical cue but not by the neutral one—could be transferred from the cues' overt presentations to the person's merely thinking about them.

He long regretted he had turned down at least one analytic session with Freud himself because an hourly $20 fee, for which Freud in a letter apologized as necessarily high to support his own family, seemed more than Neal could afford

From this finding emerged the idea that the mental acts of thinking, remembering, and imagining are themselves responses that can then function as cues (*response-produced cues*) to which other responses can be made and are subject to the same laws of learning as are external responses and cues. These mental responses, unconstrained by the real-time sequencing of cues in the physical world, permit the playback of events in reverse order of their actual occurrence. Thereby, one can work backward in the mind's eye from a hoped-for goal along a route that better illuminates how to reach it than from the start groping blindly forward. It is such use of response-produced cues that Neal identified as the basis for much foresightful behavior in problem solving.

Extending the quest to Freudian and social phenomena

As a result of an insight Neal had about the similarity between Freud's conception of repression and Pavlov's conception of inhibition, he resolved to extend Hull's program to an examination of Freudian theory and practice in terms of the laws of learning. Accordingly, he obtained a postdoctoral Social Science Research Council Fellowship to study in Vienna at Freud's Psychoanalytic Institute where he underwent a didactic analysis with one of Freud's favorite students, Heinz Hartmann. He long regretted he had turned down at least one analytic session with Freud himself because an hourly $20 fee, for which Freud in a letter apologized as necessarily high to support his own family, seemed more than Neal could afford.

In 1936, Neal returned to Yale as an instructor in psychology and a research assistant psychologist in the multidisciplinary Institute of Human Relations. Observing a dominant male monkey self-mutilate when prohibited from attacking a competitor given his harem suggested to Neal the Freudian concept of aggression turned inward. The result was his book, *Frustration and Aggression* (1939), co-authored by, among others, John Dollard and Hobart Mowrer. Its major hypothesis was that when a segment of society is frustrated from attaining its goals, it tends–depending on what avenues are open or closed for expressing that frustration–to relieve it through angry persecutions against an innocent, less-powerful segment. Examples included Neal's European encounters with German anti-Semitism inflamed by the still-lingering economic privations from reparations required of Germany after World War I.

Hull had originally hypothesized that a response is reinforced (strengthened) if immediately followed by a reduction in a need. However, Hull's assumption was that all needs drive (motivate) responses to reduce them. But some needs can't do so because they can't be detected–for example, the need to escape carbon monoxide. Thus, in *Frustration and Aggression*, Mowrer and Neal restated Hull's hypothesis as the "drive-reduction hypothesis" which now dealt only with detected needs, henceforth defined as drives. In its strong form, the drive-reduction hypothesis asserts that the *only* events capable of acting as reinforcers of a response are those that immediately follow it and are themselves soon followed by a reduction in the drive motivating it or are highly associated with that drive's later reduction. Note: the weak form of the drive-reduction hypothesis does not *limit* reinforcers to being only those drive-reducing events. Assessing the strong form's validity was the concern of much of Neal's later research.

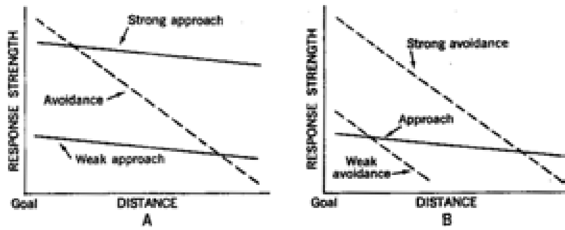

Figure 1. Effects of Changes in Strength of Approach and Avoidance. Diagram A demonstrates that, with an increase in the strength of approach tendencies, the intersection of approach with avoidance is not only moved nearer to the goal but also occurs at a higher point on the avoidance gradient. Diagram B demonstrates that decreasing the strength of avoidance increases the height of the point of intersection. Thus, in both cases, even though the goal in conflict is more closely approached, the amount of anxiety actually aroused at these intersections will be greater, a seeming paradox that accords with Freud.

While testing in rats the Freudian idea of reaction formation, Neal noted that hungry rats trained to go down a short alley for food and then given an electric shock at the goal tended on subsequent trials to approach part way and then stop, stopping farther away the stronger the shock had been. From such observations, aided later by Kurt Lewin's inquiry[2] into three types of motivational competitions within oneself, emerged Neal's brilliant and extremely impactful theoretical-experimental analyses of approach-avoidance conflict behavior. Published in "Experimental Studies of Conflict Behavior" (1944), these analyses stated that, if a goal is something an organism both wants to attain and fears to try attaining, there is an approach tendency to it, called an approach gradient, that grows stronger the nearer one gets to the goal, but there is also an avoidance gradient that does the same. The avoidance gradient, however, increases more rapidly with nearness than does the approach gradient. Plotted on a diagram the gradients often will cross each other—at that intersection the organism's approach will stop. But just how close to the goal that will be depends on the relative strengths of the approach gradient versus the avoidance one (see Figure 1).

In 1939, Mowrer[3] hypothesized that any fear (or anxiety as it is called when its source is vague or unconscious) induced by a noxious situation is then acquired from the cues associated with that situation. Thus, the fear subsequently can be induced by those cues alone and can motivate responses to them. Most importantly, a reduction of this acquired fear accomplished by escaping or avoiding those cues will reinforce any specific response producing such escapes. Neal (see "Learnable Drives and Rewards") rigorously tested this hypothesis of *fear as an acquirable*—that is, *learnable—drive* by first shocking rats in the white side of a two-compartment box until they learned to run rapidly through a door into the black side to escape the shocks. Afterwards, when put in the white side with the door closed but with no shock administered, they defecated and showed other signs of having learned to fear the cues there with which shock had become associated. If, by trial and error, they then rotated a small wheel by the door, which opened the door and allowed them to escape the white side's cues and, thus, the fear itself, they quickly learned to rotate the wheel for escape on subsequent nonshock trials. This experiment confirmed Mowrer's hypothesis.

Principles of learning in the acquisition of social behavior

The year Neal became Associate Professor, he and Dollard, a sociologist by training, wrote another book, *Social Learning and Imitation* (1941). Their intent was to show how a wide range of human behavior can be understood by knowing a few important principles of learning discovered in the lab plus the social-condition contexts outside the lab in which the learning takes place. They listed four fundamentals necessary for instrumental learning—that is, for the remembering of which behaviors, guided by which signposts, have proven to be instruments of success in achieving one's goals:

> DRIVE (or motivation); a person must want something. A drive may be innate as with hunger, or it may be learned as with fear or the desire for money.
>
> CUE (or stimulus); a person must notice something. A cue may be response-produced, as with the thought of the letter T in the experiment already described.
>
> RESPONSE; a person must do something. A response may be an overt act or a central nervous system event, such as a thought, a perception, or paying attention.

REWARD (or reinforcement); a person must get something that is wanted. A reward following a response to a cue strengthens the tendency for the cue subsequently to elicit the response. A reward may be a learned one, such as getting money. Pain is a stimulus that elicits fear, and a reduction in pain or fear strengthens (rewards) any response immediately followed by that reduction.

Contributions in the war years

In World War II, Neal served as a captain in the Army Air Corps, helping develop tests to select cadets likely to succeed in pilot training. He also initiated a study of factors contributing to fear and courage in combat. After being promoted to major, he helped identify behavioral and perceptual areas where improvements could be made in pilot training and in hitting targets via fixed gunnery. John C. Flanagan, one of his Army Air Corps colleagues, years later commented that Neal also instituted a pilot flight-check evaluation list "which provided the basis for today's procedures, making my flights on commercial airlines much more pleasant and giving me more confidence that the airline pilots will do the right things [unpublished letter, September 3, 1980]."

Retrospectively, in "Education for a Lifetime of Learning" (1987), pp. 11-12, Neal wrote that his program's success "resulted from three factors: (a) finding something the Air Force needed—initially, selection of personnel, (b) that psychologists could deliver, and (c) then providing data proving it had been delivered." These wisdoms he adapted to achieving success in the many other missions for which he later served as a statesman in psychology and other behavioral sciences.

Learned basis of Freudian phenomena revisited

After the war Neal returned to Yale, where he attained tenure in 1947. He married Marion Edwards, a social worker there, in 1948. He was awarded a full professorship in 1950 and became the first appointee to the James Rowland Angell Chair of Psychology in 1952. Again he collaborated with Dollard, taking psychoanalysis as a point of departure for analyzing psychotherapy as learning. As part of that effort Neal published "Theory and Experiment Relating Psychoanalytic Displacement to Stimulus-Response Generalization" (1948), in which, harking back to his "Experimental Studies of Conflict Behavior," he posited that when the approach to a stimulus is inhibited by conflict with an avoidance of that same stimulus, responses tend to displace to other stimuli that are still similar enough to motivate the prospect of a successful approach but are dissimilar enough to minimize the interfering avoidance. For example, given the Freudian Oedipal conflicts between a young son's erotic love of his mother and fear of his father's retaliation, one can understand the displacement implied in the old vaudeville song, “I want a girl just like the girl [but not the same one, God forbid] that married dear old dad.” This and other predictions were borne out by three other studies on displacement, all in 1952 (see pp. 99-120 in *Neal E. Miller: Selected Papers*, 1971).

In 1950 Neal published another book with Dollard, *Personality and Psychotherapy: An Analysis in Terms of Learning, Thinking, and Culture*. It was immensely influential in training the first post-World War II generation of clinical psychologists in the treatment of the neuroses and was, for years, widely used as a text in learning theory. It paid special attention to how in therapy the appropriate use of response-produced cues, particularly verbal ones, can facilitate generalizations between likenesses that should be perceived in one’s life but maladaptively aren’t and distinctions between differences that, likewise, should be perceived but, again, aren’t.

While writing *Personality and Psychotherapy*, Dollard and Neal submitted a proposal, encouraged by the Ford Foundation, to study coping behavior in normal people. But the Foundation responded that, because of a policy change, it would take over a year to decide whether to fund studies in that area. This unendurable delay forced the two researchers apart to formulate separate projects to support themselves and their families. From the National Institute of Mental Health Dollard found funding for the analysis of psychotherapeutic interviews. From the same source Neal found funding for studies of the mechanisms of reinforcement.

Into the gut and the brain

In the early 1950s Neal started turning to physiological interventions because they offered unique opportunities to test the strong form of the drive-reduction hypothesis of reinforcement against competing possibilities. For example, instead of the reinforcing value of food for a hungry animal residing in the food’s ability to reduce hunger, might it instead be either the pleasures of taste or of the swallowing of the food that is reinforcing?. On the other hand, if one could reward behavior by reducing hunger while bypassing both taste and swallowing, that would clearly support the drive-reduction hypothesis. Indeed, as described in Neal and M. L. Kessen’s “Reward Effects of Food via Stomach Fistula Compared with Those of Food via Mouth” (1952), delivery of food to a hungry rat via a tube directly into its stomach rewarded the learning of correct choices in a T-maze for that delivery. This supported the drive-reduction hypothesis of reward but did not discount that taste and swallowing could also be rewarding.

Figure 2. A rat whose ventromedial nucleus of its hypothalamus has been destroyed causing it to ravenously eat until it has gained many times its normal weight. Note, the pointer on the scale does not indicate that the rat weighs 80 grams but rather 1080 grams.

A preliminary step to yet another plan for testing the drive-reduction hypothesis was to lesion (destroy) the ventromedial nucleus in the hypothalamus of a rat's brain which then causes overeating and obesity (see Figure 2). If this overeating had all the aspects of normal hunger, Neal could then proceed to the test proper. However, contrary to hunger motivation, as reported in "Decreased 'Hunger' but Increased Food Intake Resulting from Hypothalamic Lesions" (1950), these lesioned rats, while eating a larger amount of highly palatable foods than normal rats, worked less hard for food and were less tolerant of less palatable foods. This result spoiled his plan but taught him the importance of taking a variety of measures before inferring the nature of an underlying state—a cautionary tale that he strongly communicated to his students and other psychologists working in the brain.

The salience of the brain approach was heightened by two dramatic findings in the mid-50s. One was the discovery by James Olds and Peter Milner[4] of sites in the lateral hypothalamus that rats find rewarding to self-stimulate with volleys of brief electrical pulses by pressing a lever. The other was a reverse discovery by Jose Delgado, Warren Roberts, and Neal of sites where electrical stimulation would motivate cats to learn a response to escape or avoid the stimulation. But it was puzzling that at some sites cats would learn a response to terminate stimulation but not a response to avoid it—an observation leading to the discovery of the reward-escape effect that Gordon Bower was more fully to investigate in "Rewarding and Punishing Effects from Stimulating the Same Place in the Rat's Brain" (1958). Implanted rats showing this effect cycled repeatedly between pressing a lever to turn on the stimulation and rotating a wheel to turn it off.

A year earlier Neal had seized this opportunity for an unusual test of some drugs detailed in "Experiments on Motivation: Studies Combining Psychological, Physiological and Pharmacological Techniques" (1957). He showed that methamphetamine enhanced and chlorpromazine reduced the rewarding aspects of the cycle while leaving the punishing aspects unaffected. This was a first evidence of what later was recognized as the involvement of the neurotransmitter dopamine in promoting reward. Neal and colleague Herbert Barry presented these data and others to drug companies to advertise the potential benefits of behaviorally evaluating pharmacological agents (see Reference 32 in "Chemical Coding of Behavior in the Brain," 1960). With Neal's encouragement, this approach was to become the field of behavioral psychopharmacology.

Another advantage of implanting electrodes in the lateral hypothalamus was to search that site in rats for where W. R. Hess[5] had seen in cats that stimulation could induce them to eat. But as Neal much later reported in his autobiographical article, "Behavior to the Brain to Health" (1992), the search took two years before yielding success. In my own research (see "Experiments on motivation...," 1957, and Coons[6]) I discovered the site where rats, even thoroughly satiated, would eat ravenously while the current was on but stop immediately when it was turned off. Behavioral tests confirmed that the electrically-elicited eating had all the earmarks of normally motivated hunger. Then why, contrary to the drive-reduction hypothesis, would these animals not press a lever to turn the hunger off but would press to turn it on? Neal noted in "Motivational Effects of Brain Stimulation and Drugs" (1960) my observation that amphetamine raises the threshold required to elicit feeding and lowers that required to sustain self-stimulation, showing that a single system does not subserve both self-stimulation and feeding. Also, I later[7] found that, at the lowest current required to elicit eating, the rat would NOT press a lever for it unless food was available to eat while the current was on—just as the drive-reduction hypothesis would predict. Another outcome was the confirmation of Neal's work with Arlo K. Myers (see *Neal E. Miller: Selected Papers*, pp. 201-216) that hunger, unlike fear, could not become a learned drive.

Perhaps the most exciting and final developments from Neal and his lab's so-called *colonization of the brain with behavioral quests* while still at Yale are reported in "Chemical coding of Behavior in the Brain" (1965). In it he describes how he and his students, beginning with S.P. Grossman, and continuing with Quartermain, Booth, Coons, Chun-Wuei Chien, Wolf, and others demonstrated that stimulating the same place in the brain with different chemicals—for example, adrenergic vs cholinergic—can elicit different types of behavior such as eating or drinking. Those investigations, garnering wide attention, also led to discoveries and deep appreciations of how neural and behavioral mechanisms interlock in maintaining the various aspects of homeostasis. It was the beginning of a much more sophisticated look at brain and behavior throughout the scientific community and certainly in Neal's own research programs that were to follow when he moved to Rockefeller University in 1966.

A snapshot of life in Neal's lab at Yale

For a personal starter, it was 1956 when I witnessed a few undergraduate honors majors hanging-out in Neal's outer office arguing vigorously over the meaning and validity of the Gestalt concept of "insight" they'd just encountered in their class on history and systems. Neal, until then out of view in his inner office but obviously overhearing the heated discussion, suddenly poked his head into the room to offer a wry interpretive comment: "While we behaviorists at Yale don't believe in insight, we like to practice it."

Just how he practiced it emerges from consulting *The Millernium*[8], a book of 95 enthusiastic tributes written to Neal by his former students (including me) on the occasion of his retirement in 1980. There his lab is described as very busy and well-funded, a place justifiably nicknamed "Miller Industries." In almost every corner there were us graduate students like me working on our as well as his projects (all of which he equally encouraged and kept assiduously in touch with), undergraduate apprentices getting first-hand acquaintance with empirical research, postdoctoral fellows, visiting scholars, research technicians, collaborating colleagues—all immersed in the quest for new knowledge. It was an environment suffused with the mysterious excitement of digging for buried treasures. In it Neal created or simply let happen an "intellectual democracy" without respect to person, status, or theory with him as its leader being neither overawed by big reputations nor dismissive of small ones. The search for scientific truth, whether it conformed to one's personal preferences or not, trumped all else.

In our weekly lab meetings and elsewhere, if we were planning an experiment, Neal first had us carefully consider what *could* be the possible cause of the matter in question. Then he had us explore what might be the mediating mechanisms and processes by which the prospective cause exerted its self so as to find ways to manipulate them. His reasoning was that, when actually manipulated, the mechanisms and processes resulting in an essential change in the matter of interest would indicate on which of them, in their un-manipulated states, the matter was in fact dependent—that is, which was its cause, its controlling variable. Since Neal was interested in many different lines of investigation we got a lot of practice not only in broadly generalizing his approach to asking research questions but also in particularizing them down to the great variety of nitty-gritty equipment designs and details required for answers.

In an effort to help us in that regard and to formalize some of his own thinking, he wrote for us two unpublished manuals on how to do research: *Notes on Sources of Difficulty in Creative Thinking* and *Some 'Rules of Thumb' for Scientific Work*. These were replete not only with detailed advice but with pithy sayings such as, for example (re thinking too far ahead of your data), "Don't cook your fish until you've caught it," and (re getting too caught up in high-flung theories), "The best support of a philosophical position is an empirical demonstration."[9] These tracts also became required reading in his learning course, which every graduate student in psychology had to take.

This engrossing focus on research fostered by Neal became so much a part of our daily life habits that we tended to observe it at all times in the lab except, say, when talking casually around the coke machine or in the lunch canteen. But engaging with Neal in those informal contexts showed him to be surprisingly socially awkward. Science talk, absolutely yes, but social chit-chat in those days was not something he could comfortably manage (although he became more adept at it later). Even at the dinner parties that he and Marion had at their home for us in his lab once or twice a year, he couldn't halfway loosen up until after a couple of rounds of martinis (which he was good at making).

But there finally did come a time when, after dinner, one of his doctoral students, Bob Fromer, a professional jazz pianist in a former life, sat down at the piano to play a few tunes. After a couple of great swing pieces of the 1930s and 40s such as "String of Pearls" and "Celery Stalks at Midnight," Neal, a great lover of jazz, suddenly exclaimed "Marion, he's playing our song. Let's dance!" Up rolled the rugs, and a party that ordinarily disbanded around 10 p.m. was still going strong in the wee hours. At that point Neal finally wondered guiltily to Marion if maybe their children, York and Sara, in their teens and pre-teens, might still be awake upstairs because of all the partying. Marion responded "Neal, I certainly hope they are—they think we're both such old fogies." From then on, parties at Neal and Marion's home became very lively indeed.

Major recognitions and high public service

By 1962 Neal's growing reputation and impact as a scientist were such that he was asked to chair a panel that made a report to the President's Science Advisory Committee on "Strengthening the Behavioral Sciences" (*Science*, 1962) and how to meet their needs. Neal said he "sweated blood" over the document. In further recognition of his impact on

Figure 3. Neal receiving the National Medal of Science from President Lyndon Johnson in 1964.

behavioral science Neal received in 1964 the country's highest scientific award, the National Medal of Science, handed to him in person by President Johnson (Figure 3) and again by President Carter when the original medal was stolen from his home (Figure 4). The citation accompanying it reads: "For sustained and imaginative research on principles of learning and motivation and illuminating behavioral analysis of the effects of direct electrical stimulation of the brain."

Figure 4. Neal again receiving the Nation Medal of Science, this time from President Jimmy Carter as a replacement for the original Medal which was stolen from Neal's home.

As Neal explained in a 1983 oral interview sponsored by the Brain Research Institute of UCLA[10], at the time he moved to Rockefeller University in 1966, practitioners in the many disparate disciplines conducting research on the nervous system were feeling an urgent need for some kind of coordinating network to be set up. By 1969, while Neal was chair of the Committee on Brain Science of the National Research Council, this urgency had become a clear mandate. "Like a crystal dropped into a supersaturated solution," as he characterized it, a committee motion proceeded quickly to the action of forming the Society for Neuroscience (today numbering 50,000 memberships). Neal, as always, exercised his uncanny ability to see to the heart of what needed to be done in organizations as well as in research. Unasked, he took the initiative to secure from the Sloan Foundation a grant of $20,000 to help cover the start-up costs of forming the

Society. As a result, he is considered a critical founding member. At the Society's first meeting in 1970, he was voted president elect. It constituted for him one of the pinnacles of his career, along with being elected to the National Academy of Sciences in 1958, holding the office of APA President in 1960-61, and receiving the National Medal of Science.

Learnable voluntary control of autonomic functions?

K. M. Bykov's book, *The Cerebral Cortex and the Internal Organs* (translated from the Russian by W. H. Gantt in 1959), reported that autonomic responses in a wide variety of internal organ (*visceral*) systems, when elicited by their innately triggering stimuli, can then become elicitable by other stimuli that routinely closely precede and, thus, strongly predict these innate triggers. The well-known Pavlovian prototype for this classical conditioning is the learning of a dog to anticipatively salivate to the sound of a tone that he has come to associate as being followed immediately by meat powder to which he automatically salivates.

The book stimulated Neal to follow up on a long-standing hunch. He had entertained the possibility, against popular opinion, that autonomic responses in visceral motor systems are not limited to becoming learned reactions to stimuli but, if properly rewarded, can be trained—like ordinary "voluntary" responses—to become "intended" behaviors to obtain those rewards. For example, if one could learn how to consciously control internal body processes, the medical benefits would be enormous and success would fulfill Hull's and Neal's overarching hope to show an underlying relatedness of all laws of learning, spanning across voluntary, cognitive, and, now, autonomic domains of behavior.

Indeed, in "Modification of a Visceral Response, Salivation in Thirsty Dogs, by Instrumental Training with Water Reward" (1967), Alfredo Carmona and Neal showed that thirsty dogs were able to increase or to decrease their autonomic response of salivation in order to obtain water rewards. However, puzzlingly, the dogs displayed different postures: head and tail held high during increases in salivation compared with head and tail drooping during decreases. Maybe only the different postures were learned to get the water rewards but somehow triggered— via some associated mood states having autonomic correlates?—the different salivation response levels. To rule this out, Neal had Jay Trowell and, later, Leo DiCara in his lab treat rats with curare which completely paralyzes the voluntary muscle system to disable such postures but leaves the autonomically controlled visceral muscle system unaffected. Then, the autonomic response of increasing (or, alternately, decreasing) the rats' heart rates was designated the specific response basis for the rats obtaining very rewarding brain stimulation.

Just as predicted, and reported in two articles adjacent to the Carmona study (J. A. Trowell[12], and with L. DiCara—see pp. 754-766 in *Neal E. Miller: Selected Papers*, 1971), the autonomic changes in heart-rate responding required for rewards did seem dramatically to occur. Over many studies from 1965 to 1972, even the general public, vis-a-vis *The New Yorker* (Jonas[13]) and other media, became aware of the medical benefits this discovery seemed to promise. But then Neal and Barry Dworkin in his laboratory began finding that these results mysteriously diminished until they could no longer be replicated even after repeated and varied attempts, as detailed in "Failure to Replicate Visceral Learning in the Acute Curarized Rat Preparation" (1986). When finally convinced of failure, Neal, though heartbroken, courageously took great pains to publicize it widely.

Despite such a disappointment, this line of research led to advances in technology to measure otherwise impossible-to-detect subtle changes in heart rate and other physiological responses. After finding that paralyzed rats failed to learn autonomic control, Neal shifted this technology to seeing whether people who had been paralyzed by gunshot wounds that severed their spinal cords could gain that control. They differed from the rats in being better candidates in terms of the following four fundamentals necessary for effective instrumental learning that Neal and Dollard identified in *Social Learning and Imitation*: As indicated in italics, first, these patients had a high *drive* to try gaining control because their blood pressure was so low that whenever they sat or stood up they fainted. Second, unlike the rats, they were shown their own amplified heart rate and blood pressure readings, thus, providing them, via this biofeedback, informational *cues* about their own performance. Third, to this biofeedback information, the *response* they initially reported using to try to change their readings was to think emotional, often erotic, thoughts to which the desired blood pressure changes are normally reflexively connected. As these paralyzed patients became successful, they were gradually able to command these changes "directly" as Neal and Bernie Bruckner reported in "A Learned Visceral Response Apparently Independent of Skeletal Ones in Patients Paralyzed by Spinal Lesions" (1979).

Fourth and last, whenever there was a desired response, even if too small an increment initially to be clinically relevant, the mere detectable fact of it was a *reward*, given the paralytics' high achievement motivation. But the sum of such increments mounted to clinically significant levels, and as they did, the rewards became enormous, because not only could the paralytics now sit up without fainting, but, as a result, they could now also attend plays and ball games. Interestingly, how the patients achieved voluntary control of blood pressure via the autonomic nervous system remains unknown; with a severed spinal cord the usual route of elevating blood pressure via the sympathetic component of the autonomic nervous system is also cut off. Parasympathetic (vagal) or blood-borne humoral factors are suspected, or perhaps there was some subtle respiratory mediation still surviving paralysis.

This and other studies using biofeedback in motivated humans (unlike in rats who may have been too "distracted" by their locked-in paralytic state to be suitable subjects) finally convincingly argued that an ability exists to bring autonomic responses under voluntary control, whether directly or indirectly, just as Neal had thought ("Biofeedback and Visceral Learning," 1978). Indeed, Neal loved to point out that toilet training, particularly the learning of control over the autonomic bladder sphincters, is a well-known—and rewarded—universal fact of life. Certainly, by 1985 the application of biofeedback methodology promoted by Neal and his associates had proved highly beneficial medically in treating a wide variety of problems, such as idiopathic scoliosis, enuresis, and migraine, problems involving both voluntary and autonomic response systems.

From the mid-1970's until a few years before his death in 2002, Neal's research inquiries into biofeedback and learned control of psychophysical processes took on a new emphasis—that of their use to maintain homeostasis and minimize stress ("Motivation and Psychological Stress," 1982). This emphasis—also reflected in the more than 30 analytical and integrative articles of assessment he wrote from 1973 onward—contributed substantially to the establishment not only of biofeedback as a discipline (and a therapeutic methodology), now represented by the Association for Applied Psychophysiology and Biofeedback (AAPB), but also the fields of behavioral medicine ("Behavioral Medicine: Symbiosis between Laboratory and Clinic," 1983) and health psychology ("Education for a Lifetime of Learning," 1987), all of which consider Neal a founding father.

One of Neal's last and most highly prized research contributions was his collaboration with Edward Taub on "An Operant Approach to Rehabilitation Medicine: Overcoming Learned Nonuse by Shaping" (1994). It used constraint-induced movement therapy, a very effective treatment to rehabilitate stroke victims with motor impairment by overcoming their learned non-use, which in turn also promotes neuroplastic changes in the brain that further enhance motor recovery. As a result, a fitting research epitaph to his entire career, devoted to understanding to what the laws of learning apply, can be the following statement: *The brain controls learned behavior but, in turn, learned behavior also controls and even modifies the brain—a biofeedback cooperation.*

Research mentor and educator

There were a number of research ventures in Neal's lab that don't fit nicely into the trajectory of his life characterized in this biography but that he strongly encouraged, supported, and included in his *Selected Papers* (1971). Recommended readings there are his collaborations with, among others: 1) Richard Bugelski, Edna Kaufman, Doris Kraeling, and Edward Murray on conflict and displacement, and references there to his early work in that context with Judson Brown, John Conger, and Seymour Klebanoff; 2) David Egger on findings premonitory of the Rescorla-Wagner model, which now dominates studies in learning; 3) David Quartermain concerning memory consolidation as growing out of a study by Neal and me; and 4) studies devoted to understanding the signals for thirst with Don Novin, salt appetite with George Wolf and Edward Stricker, and hunger with Jack Davis, Eleanor Adair, Stan Tenen, David Booth, and Sarah Leibowitz. Among others, whose research he fostered in his lab, were Sebastian P. Grossman[14] for chemical coding of behavior; Frank Krasne, who later became well-recognized for his research on the neural basis of learning in the cray-fish; and, as cited below, E. E. Krieckhaus and George Wolf[15] on latent learning, and Jay M. Weiss[16] and Bruce S. McEwen[17] for their studies on stress.

Because Neal knew how to design experiments that not only could examine a great range of possible causes but also contained controls that sorted among these with certainty and efficiency as to which were true causes, he became widely known and emulated as a master of the scientific method–so much so that in some respects that may be his greatest achievement—helping psychology to grow into a mature science. As Edward Taub[18] has carefully documented in an article from an entire issue (vol. 8) of *Biofeedback*[19] honoring Neal's 2009 Centennial, Neal—insightfully or not—was in reality brilliantly practicing the method of strong inference[20]. He always sought for parsimonious explanations of cause and effect but required that the hypotheses involved be rigorously defined in empirically testable ways that allow them to be confirmed or disconfirmed, ideally by a variety of measures. In his 1960 Federation Proceedings article Neal cautioned against "stopping as soon as a hypothesis is confirmed by a single test. [Especially in a] new field of investigation [such as the brain was in the 1950s-'60s], it is essential to design careful behavioral tests of all conceivable alternatives." In an interview taped in 2000[21], he said an experiment should be designed not only to discover something but also to communicate it and that it would be best to design experiments so that the results would be rather obvious, wouldn't demand elaborate data analysis and could be clearly stated for publication. He warned investigators to keep an eye out for unexpected findings while running experiments because sometimes these are more important than the findings sought for. "And regarding things in an experiment that give you a lot of difficulty," he wrote "it may be something fairly important or it wouldn't be an important difficulty. So, perhaps you may want to change your goal and decide that the difficulty is a more important variable to study than what you originally started out with." Indeed, as consulting editor of the *Journal of Experimental Psychology* for seven years, Neal passed on his research wisdoms widely. When he resigned, its chief editor, Arthur W. Melton, wrote: "It will be difficult, if not impossible, to replace you with another so keen at picking the flaws in logic or design [unpublished letter, September 29, 1956, from A. W. Melton to Neal]."

During his emeritus years at Rockefeller begun in 1980, Neal became quite alarmed by the dangers posed by the animal rights movement to research on treating illness and promoting health. Then, and after his return to Yale in 1985 as a research affiliate, he conducted vigorous efforts to educate the scientific and lay communities about the benefits of behavioral research on animals ("The Value of Behavioral Research on Animals," 1985). He was an important figure in mobilizing the opposition of these communities to this threat.

Finally, as summarized in his last publication, "How to Prepare for Our Future of Totally Unexpected Opportunities" (1997), he conducted vigorous efforts to communicate to the scientific and lay communities a basic understanding of the scientific method and the enormous benefits it has yielded and will continue to do, if well fostered. He served, thus, as an exemplary model for the more than 150 students he trained in research, many of whom became distinguished researchers themselves. In 2000 this was the theme of the final of his countless honors, the Award in Neuroscience Education, bestowed by the Association of Neuroscience Departments and Programs with Edward Stricker, another former student of Neal's, serving then as its president.

Neal died in Hamden, Connecticut, in 2002. He was survived by his son, York, and daughter, Sara Rose Mauch, children of his first wife, Marion Edwards Miller, who died October 13, 1997. He was also survived by his second wife, Jean Shepler Miller, whom he married on July 21, 1998, and who had been a friend of the family and music teacher to his children. To these partners he gave enormous credit and thanks: Marion for protecting him from so much flotsam and jetsam of daily life—such as paying bills—so that he could concentrate on his science, and Jean for providing him so much comfort and tolerance in his few remaining years. Nevertheless, he regretted leaving this world, commenting to me wistfully not long before he died that just as he was "beginning to understand what life is all about, it's all over."

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