Available online at www.sciencedirect.com
SCIENCE DIRECT®

Biochemical Pharmacology 68 (2004) 1639–1647

Biochemical Pharmacology

www.elsevier.com/locate/biochempharm

Proposal for a basic law of neural communication: response = $a(\text{stimulus})^{0.5} + b$

Eugene Roberts*

Department of Neurobiochemistry, Beckman Research Institute, City of Hope Medical Center, Duarte, California, CA 91010, USA

Received 4 June 2004; accepted 12 July 2004

Abstract

A basic law of neural communication is proposed to be: response = $a(\text{stimulus})^{0.5} + b$, whether referring to operation of a particular nervous system as a whole or to portions thereof, from receptors to effectors. This differs from previous formulations in that the exponent is set at a constant value of 0.5 rather than being considered to vary from one instance to another. Supporting data is presented.

1. Introduction

Those of us who study biological systems are faced with "a mixture of detailed facts, conflicting viewpoints, evolving theories, simulations, models, and ultimate limitations that either are absolute in principle or insurmountable in practice" [1]. From time to time, in 55 years of work on the nervous system, I have striven to reduce as much as possible the description of that which has been observed to simplified models, so that the apparently enormous complexity which I faced might become intellectually manageable and emotionally tolerable (e.g., see [2–7]). This was done in the spirit expressed by Gibbs [8] and Einstein [9], respectively, two of the greatest scientists of all time: "one of the principle objects of theoretical research in any department of knowledge is to find the point of view from which the subject appears in the greatest simplicity [8]" and "man seeks to form for himself in whatever manner suitable for him, a simplified and lucid image of the world, and so to overcome the world of experience by striving to replace it so some extent by this image [9]".

Among my several research endeavors, the discovery of γ-aminobutyric acid (GABA) in brain [10] and consequent studies of its role in neural inhibitory processes [11,12] and of the roles of inhibition, in general [6,7], afforded me an opportunity to search for fundamental patterns in nature.

I have proposed that one of the major organizing principles in living systems is disinhibition coupled to variability generation. Facile traverse of adaptive functional ranges is made possible by activities of inhibitory (attenuating and/or time-delaying) influences. These maintain barriers to physico-chemical perturbations, so that interactions between the external environment and living systems release activities within them. Coupling exists between the driving force (forcing function) and the generation of variability (information-processing capacity) among subunits of particular systems, i.e., there is expansible capacity for processing information in relation to demand. Metaphorically, metabolically generated energy is used to wind the biological springs. Hierarchical nesting of inhibitory command-control exists at levels of membrane, metabolism, genomic expression, brain function, and internalization of societal prohibitions (conscience).

The human brain, its function enhanced by invention and uses of language, tools, and social devices, has assumed a dominant position among the inhibitory command-control systems that have arisen on the way from primordial single cell to conscious human being. The neuroendocrine system, the control of which is centered in the brain, regulates to a greater or lesser extent aspects of structure and function throughout the body. The extended brain with its emergent properties increasingly is learning how to manipulate various aspects of the environment.

Neural inhibition is not sufficient by itself to enable individuals, biologically programmed to be hedonic optimizers, to govern their activities in an adaptive manner in

---

* Tel.: +1 626 301 8476; fax: +1 626 357 1929.
E-mail address: eroberts@coh.org.

0006-2952/$ – see front matter © 2004 Elsevier Inc. All rights reserved.
doi:10.1016/j.bcp.2004.07.021

settled communities. For modern civilization to exist at all, it is necessary for there to be appropriate attenuation and time-delay of the direct gratification of instinctual needs or of their symbolic equivalents. For this purpose have been devised taboos, religions, and laws which, assiduously taught by word and example from early childhood and reinforced by rewards and punishments, are used in an effort to prepare individuals in their adulthood to walk the tightropes of the tensions arising from the interplay between instinctual demands and social inhibitions. The latter consist of the learned restrictions that have become part of the extended brain (conscience) and of the externally existing legal and policing systems.

Extents and variabilities of the cascades of multichannel informational flows, inward and outward, are coupled to demand at all times at all levels in healthy organisms. Changes in activities with changes in forcing function occur everywhere in accord with principles of nonlinear dynamics. This is as true for overt behavior of an individual in a complex social setting as for the activities within a membrane of an individual neuron.

The necessarily intimate coupling between brain and sensorium is easily seen from behavioral abnormalities that result from brain lesions or during sensory isolation. However, it is the dominant extended brain that ultimately abstracts and interprets environmental patterns and supervises the organization and release of adaptive behavior by making appropriate choices from among available options.

2. Response = $a(\text{stimulus})^{0.5} + b$

Unquestionably, all activities in nervous systems are critically modulated and shaped by inhibition. However, with regard to functions of nervous systems as a whole, an overarching question that has remained unanswered is whether or not there exists a single invariant physical law governing transduction of information of all sensory modalities and the passage of subsequent signals from one neural station to another that subsumes all processes of excitation and inhibition and their modulation. A basic law of neural communication is proposed herein to be: response = $a(\text{stimulus})^{0.5} + b$, whether referring to operation of a particular nervous system as a whole or to portions thereof, from receptors to effectors. This differs from previous formulations in that the exponent in the above equation has the constant value of 0.5 rather than being considered to be variable from one instance to another. What follows is an account of a labyrinthian journey taken in reaching the above conclusion.

To date, the search for an answer to the above question largely has been the province of physiologists and psychologists who have been studying quantitative aspects of stimulus (S)–response (R) relations, a so-called black-box approach. My interest in the S–R problem initially was kindled in 1965 [3] by meticulous landmark studies of Werner and Mountcastle [13] in which measurements were made in cats and monkeys of the evoked neural activity of the first-order mechanoreceptive fibers ending in Iggo corpuscles [14] in the skin (early steady state: displacement sensitivity). The equation describing the relationship of stimulus intensity to response was found to be the power function $R = aS^n + b$, where values for the exponent, n, ranged from 0.209 to 1.169 for individual fibers. I was particularly impressed by the clustering of values for n around the mean of 0.5 in a particular set of individual fibers and by the finding that the equation for 10 selected afferent fibers among those measured normalized to percentile scores was $R = 9.4(S)^{0.52}$. From the above and other measurements made at several levels in the nervous system it was generalized that "the implication is, we believe, that the neural transform between input and the final verbal description of an introspective magnitude must be linear for the intensive continuum. This does not imply that the intervening neural transforms must be linear, but that the serial superposition must be so" [13].

Heuristically and intuitively attractive, the above supposition did not appear to be supported by the available data. Although the intervening neural transform was shown to be a power function, as is the case in most S–R studies [15], a wide range of values for n was inevitably observed (see Table 1 on p. 372 of [13] and Table 1 on p. 1045 of [15]. This seemed to preclude the possibility that there could be *simple* serial superposition of such neural transforms, since this only would be possible if the exponent, n, were to remain constant from one site to another and one sensory modality to another. Regretfully accepting the latter conclusion, I left consideration of the S–R problem for 37 years, and only recently have returned to it. My renewed interest was based on results of more recent study of transmembrane transport of hydrophilic solutes [16] together with my supposition that many mutually shaping informative transactions among cells in living systems take place by transmembrane transport processes at all membrane surfaces, mutual shaping taken to mean "the interactions of cell assemblies which align or disalign their neighbors into information-processing modes conforming to or opposite from their own" [17]. I conjectured that an invariant law that would be applicable to transport processes, in holographic-like fashion, might help reveal existence of a similar law for the operation of nervous systems as a whole.

For a number of years, I sought in vain for possible lawfulness among extensive experimental transport data collected in my own laboratory and that reported by others, but failed to find evidence for it. Finally, discarding the Michaelis–Menten method for calculating such data and devising a non-equilibrium, essentially irreversible pump-pore model for transmembrane transport, a simple descriptive power function was derived from relevant kinetic considerations relating velocity of transport (V) to concentration of transported substance (L), $V = a(L)^{0.5} + b$ [16]. It described accurately results of transport experiments in which the uptake was studied of many different substances that were transported into various types of intact cells as well as into comminuted vesicles prepared from membranes obtained from different tissue sources (Fig. 1). Neither function-retaining mutations of transporter proteins nor action of potent inhibitors altered the basic exponential nature of the transport equation [16]. The above strongly suggested that a common operational mechanism might exist for transport (export, import, and countertransport), the nature of which is not altered or obscured by the filigree of different molecular detail that exists among various transport systems.

Both the proposed transport and *S–R* equations are power functions. In the case of transport [$V = a(L)^{0.5} + b$], V is a measure of the rate of operation of complete cycles of transport, in which L becomes associated with the transporter on one side of a membrane and is transported to the other side, the unbound transporter becoming available for undergoing another cycle of activity. L can be considered to be the stimulus (S) for operation of the transport cycle since transport is proposed to be initiated only after L is attached to the transporter. Substituting the symbol S for L, the equation becomes $V = a(S)^{0.5} + b$. Since the *S–R* equation often is measured in terms of rate of firing of neurons, $R = a(S)^n + b$, the transport and *S–R* equations differ from each other only in that in the former the value of the exponent S is invariably set at 0.5 while in the *S–R* equation the exponent of S generally has been calculated to be a widely varying quantity [13,15]. Could it be that variation in n in the *S–R* equation is a result of the usual method of calculation employed and that n might be a constant with a value of 0.5, as in the case of transport? Were the latter the case, the original conjecture from [13] quoted previously would be more likely to be correct and the possibility would exist that the basic law of operation of a system as complex as the nervous system might be based on iteration [18] of the relatively simple principle of transmembrane transport, a process that even may have arisen prebiotically [7,19,20].

3. *S–R* relation between Iggo corpuscle and fibers of the saphenous nerve in the monkey [13]

Iggo corpuscles in the skin contain the endings of myelinated fibers. When effective mechanical stimuli are applied to the corpuscles, discharges of impulses are elicited in these fibers. Stimuli to the skin receptors were delivered by an electromechanical transducer. Under carefully controlled conditions the rates of discharge of impulses in the absence of intentional mechanical stimuli were found to be negligibly low in single mechanoreceptive fibers dissected from the saphenous nerve [13].

In Fig. 2A is shown a typical curve of nerve response as a function of stimulus intensity. Note its great similarity to the transport curves shown in Fig. 1. To the right of the curve in Fig. 2A is shown the log–log transformation of the original data, the slope of which became the exponent of S and from which was calculated the best fitting power function, $R = 2.16S^{.509}$. Taking the values for R and S directly from the curve (see [16]) in Fig. 2A and plotting the impulses per response (R) versus the square-root of the intensity ($S^{0.5}$), a straight line was obtained (Fig. 2B) from which was calculated the power function, $R = 2.13S^{0.5}$. Points from the *S–R* curve calculated from the latter power function, represented as open circles superimposed upon the curve shown in Fig. 2A, were very similar or identical to those obtained by the far more cumbersome and potentially error-amplifying log–log plotting procedure. The *S–R* relationship appeared to be fully described when the exponent of S was fixed at 0.5. A result similar to the above was obtained when pooled data normalized to percentile scores was plotted for 10 different fibers (Fig. 3). The *S–R* curves obtained when varying intensities of stimuli were applied for different periods of time to a particular fiber are shown in Fig. 4A. Square-root plots (Fig. 4B) gave power functions that closely described the curves shown in Fig. 4A, the values of a and b increasing with length of time of stimulation in the manner shown in Fig. 5.

4. *S–R* relation in the monkey between limb position and frequency of discharge of relevant neurons in the thalamus [21,22]

It was important to determine whether the application of the square-root relationship would hold for the *S–R* relationship when other types of receptors were stimulated and response frequencies were measured in neurons many stations removed from the receptors giving rise to the responses.

Changes in limb positions result in impulse generation in nerves innervating the joints, resulting, in turn, in impulse generation in particular neurons in the thalamus, which are many neural stations removed from the original site of perturbation of the joint receptors. Precise control of the stimulus was obtained using a joint-rotator machine. Discharge rates in particular thalamic neurons were measured with closely lying extracellular electrodes. Remarkably, as in the case of skin-located mechanoreceptors, the results also could be accurately described by an easily derived power function in which the exponent of S was 0.5 (Figs. 6 and 7).

On the basis of the above results obtained from arguably the best quantitative data available to me, I have eschewed recalculation of data from myriad other experiments on *S–R* relations in other species and other sensory modalities. I urge those who have access to original, accurately derived, data in other *S–R* experiments to calculate the data both in the usual log–log manner and by the square-root method in order to determine whether or not the latter will yield power functions with a fixed exponent of 0.5 that describe

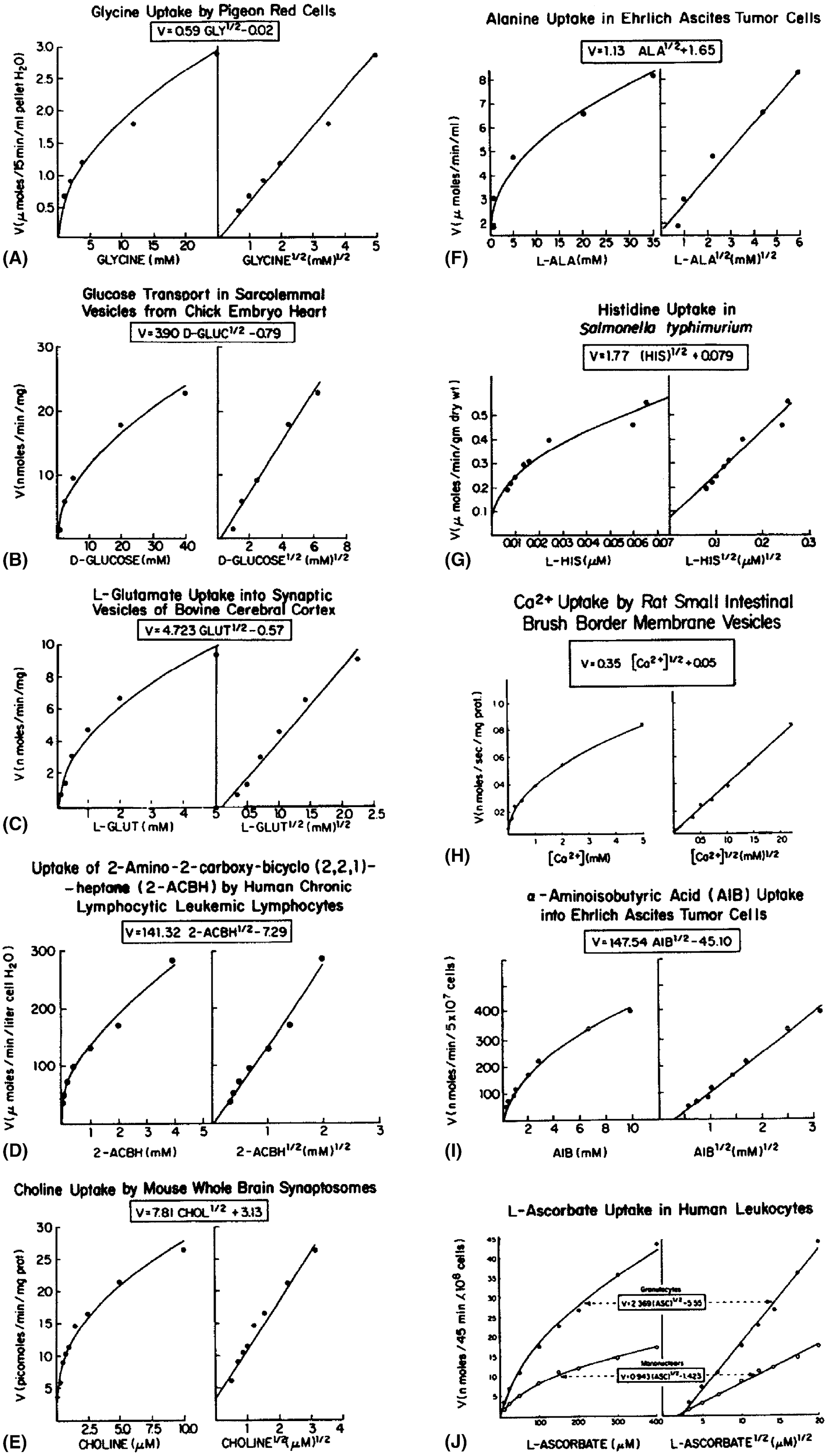

Fig. 1. Taken from Fig. 2 of [16]. Application of the equation, $V = aL^{0.5} + b$, to transport data. The sources of the data in the figure are given in the bibliography of [16].

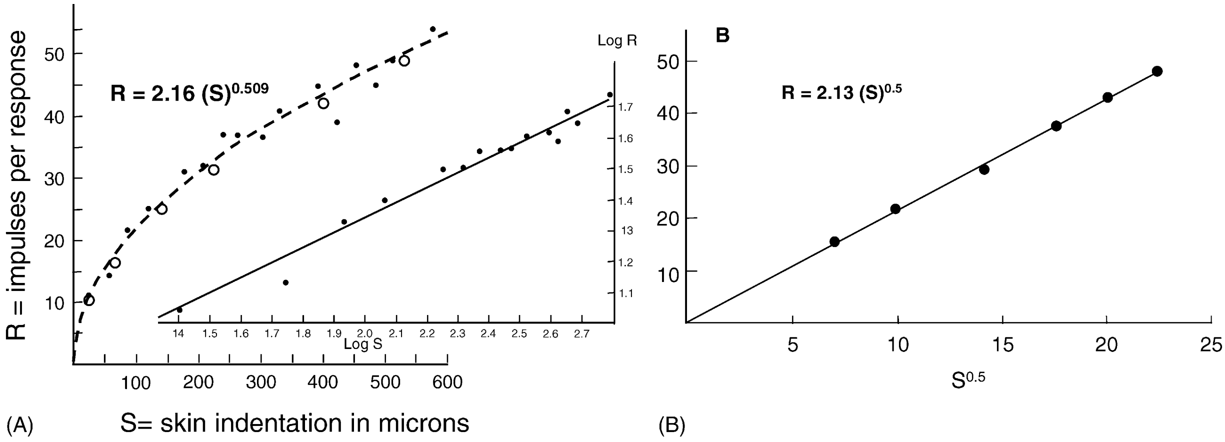

Fig. 2. The frequency of response (*R*) measured in a single afferent nerve fiber, isolated by dissection of the saphenous nerve, in response to intensity of stimulation (*S*) of skin on the inner surface of the leg of a monkey. For each intensity, 30 identical stimuli, each 450 ms long, were delivered at intervals of 3 s. Taken from Fig. 7 of [13].

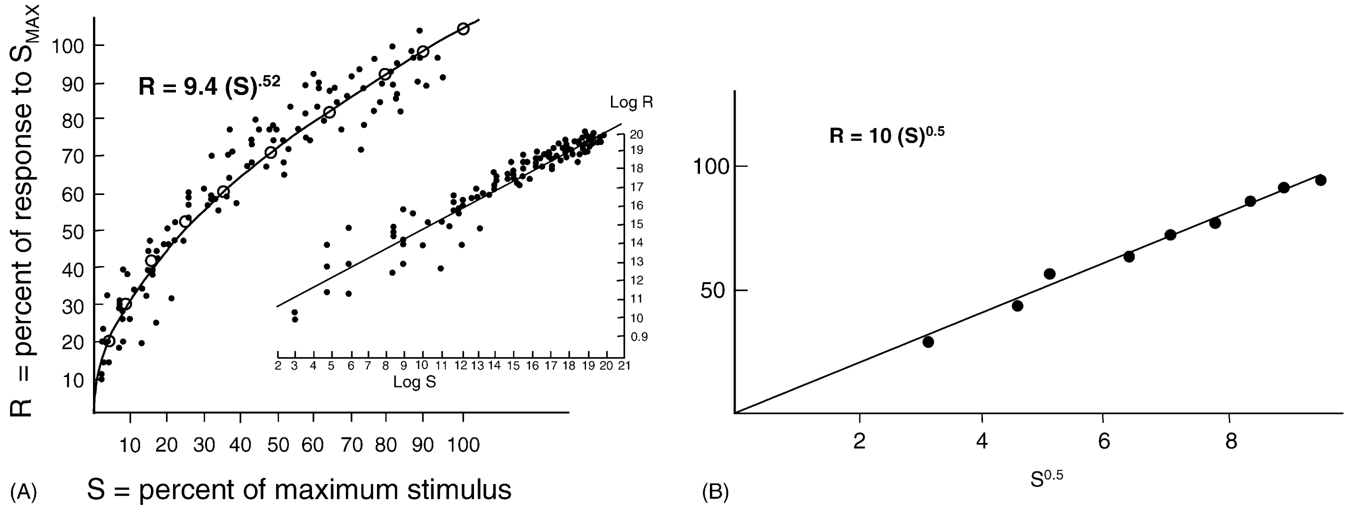

Fig. 3. Pooled data for 10 afferent fibers normalized to percentile scores. Data for each fiber was normalized by conversion of stimulus values measured in microns of skin indentation to percent of the maximal indentation and response number values to percent of the responses evoked by the maximum stimulus. Taken from Fig. 8 of [13].

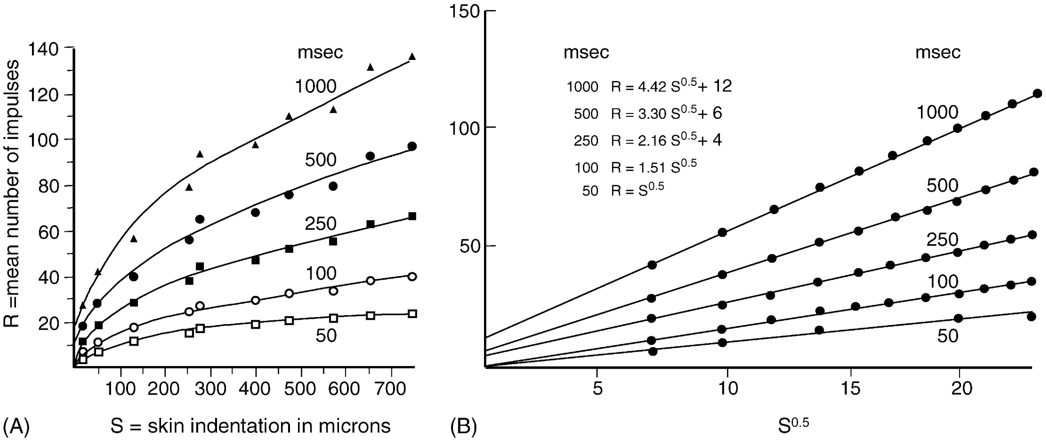

Fig. 4. *S–R* curves obtained when varying intensities of stimuli were applied for different periods of time to an afferent fiber. Thirty stimuli were delivered, at each intensity, at a repetition rate of one in 3 s. Taken from Fig. 9 of [13].

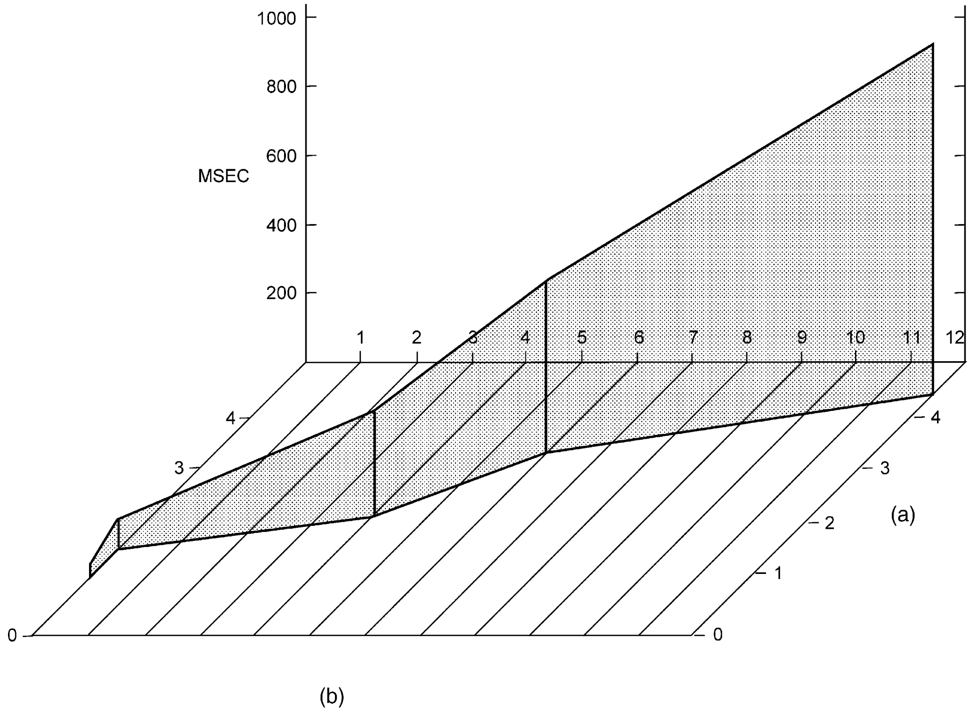

Fig. 5. Variations of *a* and *b* in equation $R = aS^{0.5} + b$ in Fig. 4 as a function of time of stimulation. Starting with $a = 1$ and $b = 0$ at 50 ms of stimulation, both *a* and *b* increased with time of stimulation, but at different increments.

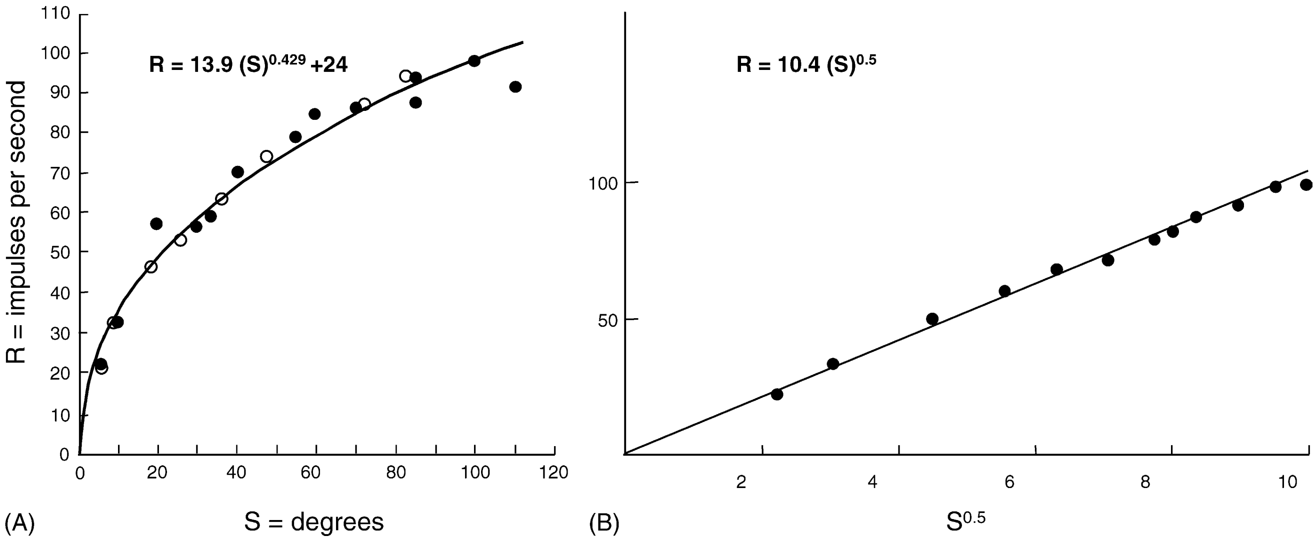

Fig. 6. Plot of impulses per second in the steady state firing of a ventrobasal thalamic neuron driven by extension of the contralateral knee vs. the joint angle in degrees. See [21,22] for details.

the data as well as the best power function derived otherwise. In the current absence of a theoretical basis for a mechanism for the proposed law, only the extension of testing of its experimental applicability will help test its validity and generality.

5. Discussion

The following brief overview illustrates the immense complexity of the phenomena, the collective adaptive operation of which is proposed to be described by the apparently simple law, $R = aS^{0.5} + b$.

An awake organism continually scans with specialized receptors its multisensory environment, internal and external, for physical and chemical changes. At any particular time, the changing *pattern* in the perceived environment is the stimulus for the organism. A novel effective stimulus pattern activates receptors in a unique fashion, i.e., the types and numbers of receptors activated and their sequences and intensities of activation result in receptor and neural activation patterns different, at least to some

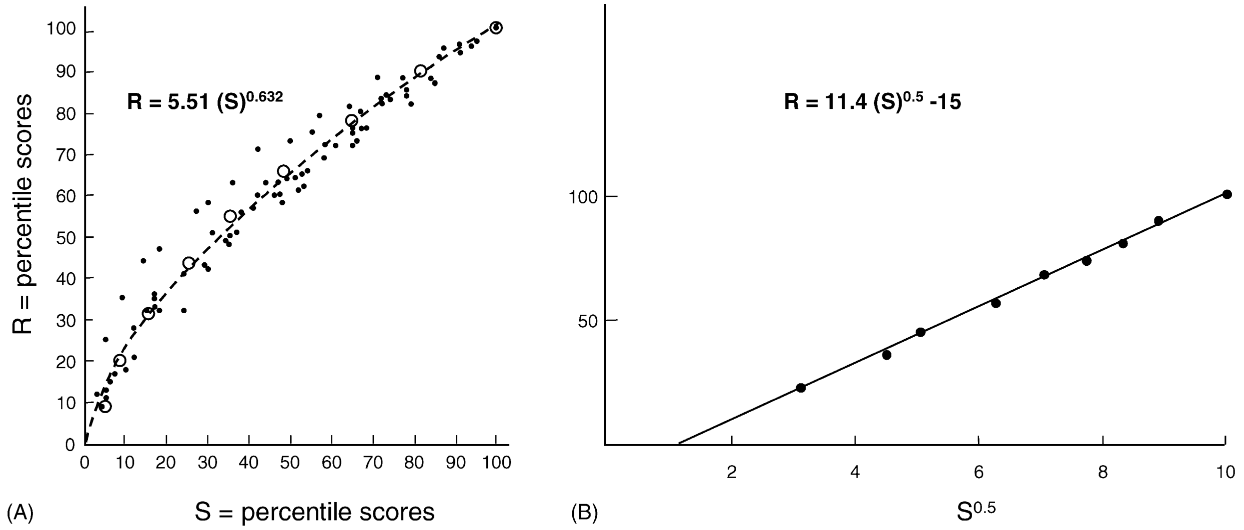

Fig. 7. Plots of calculated points determining the best fitting power functions for 14 hinge-joint ventrobasal thalamic neurons. See [21,22] for details.

extent, from any experienced previously by the organism. Release occurs of neural circuits, which may be considered to consist of cascades of serially aligned neuronal assemblies in which coded patterns of information entering from sensory transducers are progressively refined by the reduction of redundancy and the selection of particular features. The transformations of coded patterns in different neural sectors are achieved to a considerable extent by negative feedback loops that exist between and within the sectors and their temporal and spatial integration is achieved by activity of neural command centers, such as the cerebellar cortex, hippocampus, basal ganglia, reticular nucleus of the thalamus, and association cortex. The "hard-wired" neuronal elements of the through-put and command neuronal circuits, the blueprints for the construction of whose framework largely are inherited by the organism, are surrounded by local-circuit neurons whose specific commitments may be made during development, as well as later in life, and which not only participate in virtually all phases of information-processing but also may undergo plastic changes that may be involved in long-term retention of experience. Communication between neural elements takes place largely through synaptic and gap junctions on a millisecond time scale and through virtually instantaneous influences of low frequency electromagnetic fields that are generated by events occurring at membrane surfaces [23]. Thyroxine, peptides, steroids, prostaglandins, and a host of other substances serve to optimize regional nervous system activity in relation to functional demands without themselves necessarily being involved directly in specific information transmittal. Their actions and the consequences of their actions may persist for minutes, hours, or longer. Some peptide or steroid hormones, for example, may temporarily "line-label" neural pathways, differentially facilitating behavioral options related to consummatory activities such as eating, drinking, and sex. Some may exert relatively long-lasting effects on the cellular elements, possibly setting the gain on the efficacy of individual synapses, on specific types of synapses, or on all of the synapses in given regions or specific circuits. An inappropriate balance between their availability and distribution with the activities in through-put and command neural circuits can result in gross malfunction of the CNS and in maladaptive behavior of an organism.

Work on information-processing in the sensory pathways, as exemplified by the findings in the visual system, shows that the nervous system can abstract from the unanalyzed stimulation impinging on the receptors qualities of the perceived objects which are more relevant for behavior than the unprocessed signal itself. Thus, similarity and contrast, onset and termination of stimuli, motion, and geometrical shape are singled out for perceptual attention. A still higher level of perceptual integration takes place before the organism can respond adaptively to a pattern of sensory input. The stimulus pattern is brought into relation with memories of past stimuli and their consequences and with the drive state of the organism (associative integration). In other words, some information-processing system calls up from memory storage stimulus patterns similar to the one at hand, and a decision is made as to whether or not the stimulus presents opportunities for need satisfaction or a potential threat to survival. The result of the impingement and processing of information is behavior, some reaction of the organism to the environment and/or action upon the environment.

An year-long search for a hint as to where to search for *mechanisms* that would directly link the proposed law of neural communication to aspects of membrane transport on the one hand, and the complex processes described above on the other hand has not met with success. The search largely was made based on biochemical and neural circuitry considerations. As indicated below, perhaps now is the time to cross the border between chemistry and physics.

But, only a new generation of scientists may be able to "enter into the promised land".

Large multigene families exist that code for cell surface transporters that govern critical chemical communication with the environment. During development, transporter genes are differentially expressed in combinatorial fashion so that in adult organisms various combinations of transporters are expressed in a manner that optimally subserves the functions of cells in particular tissues. For example, this is reflected in the finding that each normal tissue or subdivision thereof (e.g., auricular and ventricular portions of heart) has a highly characteristic distribution of easily extractable amino acids, the pattern of which is remarkably stable to perturbation, even when the metabolic turnover rates of the individual constituents are differentially altered [24].

In developing the relationship $V = aL^{0.5} + b$, I posited that hydrophilic molecules (L), charged or uncharged, have coats of H-bonded water on their surfaces that adhere in Velcro-like fashion to hydrated membrane surfaces, largely via H-bonding. The respective water layers on L and on membranes exert dielectric (insulating) effects and also limit closeness of approach. Thermal agitation and/or other asymmetrical physical forces may result in detachment of L or may cause rapid rolling movements of L over membrane surfaces either randomly or along specific molecular tracks until movement is retarded upon contact with specific macromolecular recognition sites (R), such as those on transporters. It is presumed that the half-life of adhesion of L to the membrane surface is long enough to be compatible with a high probability of occurrence of eventual contact with R. Anchored by H-bond formation, coulombic interaction, and favorable steric factors, L and R orient dynamically with each other until attractive energy between them becomes great enough to squeeze out intervening water; in this manner, minimizing the energy of the system. In other words, the attractive forces between R and L are proposed to be so much greater than that of either one of them for water that they associate preferentially with each other, releasing bound water in the process, and concomitantly causing conformational changes in R that result in internalization of L and subsequent reorientation of R to a state of receptivity for L, once again. The productive association of L and R is proposed to be the rate-limiting step in transport. Rates of transport are non-linear function of transmembrane potential.

The above projected sequence of events during occurrence of membrane transport involves a concatenation of processes that could affect membrane potential slightly but the electromagnetic field (EM) at cell surfaces hugely [23]. Because each transporter differs from the others to some extent, the effect of its operation on EM could be different from all of the others and the effects of operation of different patterns of transporters simultaneously could create EM signals carrying a symphony of wave-transmitted information traveling at many orders of magnitudes faster than that of synaptic transmission.

Thus, while the S–R law describes the operation of the neural *machinery*, it is dissociated from an understanding of the nature of *information transmittal* in the nervous system consequent to the use of the machinery. For example, the relatively coarse measure of firing rates of a neuron, a non-linear expression of the extent of depolarization, by an extracellular electrode could not possibly give information about effects of the movement of hinge-joints on the EM effects of the neurons, the rates of response of which are being measured.

We may take some solace from Feynman's statement: "what is gravity? But is this such a simple law? What about the machinery of it? All we have done is to describe *how* the earth moves around the sun, but we have not say *what makes it go*. Newton made no hypotheses about this; he was satisfied to find *what* it did without getting into the machinery of it. *No one has since given any machinery.* It is characteristic of the physical laws that they have this abstract character. The law of conservation of energy is a theorem concerning quantities that have to be calculated and added together, with no mention of the machinery, and likewise the great laws of mechanics are quantitative mathematical laws for which no machinery is available. Why can we use mathematics to describe nature without a mechanism behind it? No one knows. We have to keep going because we find out more that way" [25].

6. Afterword

What a pleasure it is in my 85th year to be invited to attend this symposium and to contribute to the monograph that will issue from it! The three organizers, N.G. Bowery, S.J. Enna, and R.W. Olsen all are celebrating their 60th birthdays this year. This means that they were about five years old when GABA was first found to be present in the brain. I knew all of them as promising young scientists and celebrate the fact that each of them has made uniquely individual major contributions to knowledge of the GABA system that have established them as leaders in the field. They are to be commended for assembling such a distinguished group of participants, a number of whom I know personally and whose work I admire. May they and their students prosper and continue to explore further the GABAergic domain.

References

[1] Yates F. Complexity and the limits to knowledge. Am J Physiol 1978;235:R201–4.

[2] Roberts E. The synapse as a biochemical self-organizing microcybernetic unit. Brain Res 1966;1:117–66.

[3] Roberts E. Models for correlative thinking about brain, behavior, and biochemistry. Brain Res 1966;2:109–44.

[4] Roberts E, Matthysse S. Neurochemistry: at the crossroads of neurobiology. Ann Rev Biochem 1970;39:777–820.

[5] Roberts E. Disinhibition as an organizing principle in the nervous system—the role of the GABA system. Application to neurologic and psychiatric disorders. In: Roberts E, Chase TN, Tower DB, editors. GABA in nervous system function. New York: Raven Press; 1976. p. 515–39.

[6] Roberts E. What do GABA neurons really do? They make possible variability generation in relation to demand. Exp Neurol 1986;93: 279–90.

[7] Roberts E. Living systems are tonically inhibited, autonomous optimizers, and disinhibition coupled to variability generation is their major organizing principle: Inhibitory command-control at levels of membrane, genome, metabolism, brain, and society. Neurochem Res 1991;16:409–21.

[8] Gibbs JW. Letter to American Academy of Arts and Sciences (January 1881). Quoted by Tanford C. Science 1978;200:1012.

[9] Einstein A. Cited by Brecher K. Nature 1979;278:215–8.

[10] Roberts E, Frankel S. γ-Aminobutyric acid in brain. Fed Proc 1950;9:219.

[11] Roberts E. γ-Aminobutyric acid (GABA): from discovery to visualization of GABAergic neurons in the vertebrate nervous system. In: Bowery NG, editor. Actions and interactions of GABA and benzodiazepines. New York: Raven Press; 1984. p. 1–25.

[12] Roberts E. GABA: the road to neurotransmitter status. In: Olsen RW, Venter JC, editors. Benzodiazepine/GABA receptors and chloride channels: structural and functional properties. New York: Alan R Liss Inc.; 1986. p. 1–39.

[13] Werner G, Mountcastle VB. Neural activity in mechanoreceptive cutaneous afferents: stimulus–response relations, Weber functions, and information transmission. J Neurophysiol 1965;28:359–97.

[14] Iggo A, Muir AR. The structure and function of a slowly adapting touch corpuscle in hairy skin. J Physiol 1969;200: 763–96.

[15] Stevens SS. Neural events and psychophysical law. Science 1970;170:1043–50.

[16] Roberts E. A pump-pore model for transmembrane transport of hydrophilic solutes. Proc Natl Acad Sci USA 1993;90: 7456–60.

[17] Matthysse S. Spontaneous generation of selectable variation in the brain. Neurochem Res 1991;16:397–408.

[18] Wolfram S. A new kind of science. Champaign, IL: Wolfram Media Inc.; 2002.

[19] Smith TF, Morowitz HJ. Between history and physics. J Mol Evol 1982;18:265–82.

[20] Cavalier-Smith T. The origin of cells: a symbiosis between genes, catalysts, and membranes. Cold Spring Harb Symp Quant Biol 1987;52:805–24.

[21] Poggio GF, Mountcastle VB. The functional properties of ventrobasal thalamic neurons studied in unanesthetized monkeys. J Neurophysiol 1963;26:775–806.

[22] Mountcastle VB, Poggio GF, Werner G. The relation of thalamic cell response to peripheral stimuli varied over an intensive continuum. J Neurophysiol 1963;26:807–34.

[23] Adey WR. Cell membranes: the electromagnetic environment and cancer promotion. Neurochem Res 1988;13:671–7.

[24] Roberts E, Simonsen DG. Free amino acids in animal tissues. In: Holden JT, editor. Amino Acid Pools. Amsterdam: Elsevier; 1962. p. 284–349.

[25] Feynman RP, Leighton RB, Sands M. Lectures on physics, vol. 1. Reading, MA: Addison–Wesley; 1977 [chapter 7, units 7–9].