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The objectives of this research are to analyze the properties of identified neurons and neural circuits that exhibit nonassociative and associative plasticity and to examine the role of neuronal plasticity in learning. During the period between August 1, 1988 and July 31, 1989, progress has been made in four areas. First, a model of the biophysical processes within sensory neurons that contribute to nonassociative and associative learning was developed. Second, a model of biophysical and cellular processes underlying rhythmic bursting patterns of activity in neuron R15 was developed. Third, a real-time model of associative learning was incorporated into small neural networks, which include facilitatory and inhibitory interneurons, and the ability of these networks to stimulate higher-order features of classical conditioning was examined. Fourth, a model which stimulates aspects of classical conditioning was incorporated into a small neural network, and the ability of this neural network to simulate features of operant conditioning was examined.

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Analysis and Synthesis of
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I. Summary

The two overall objectives of this research are to analyze the properties of identified neurons and neural circuits in *Aplysia* that exhibit nonassociative and associative plasticity and to examine the role of neuronal plasticity in learning. During the period between August 1, 1988 and July 31, 1989, we have made progress in four areas. First, we have begun to develop a Hodgkin-Huxley type of model of the biophysical processes within sensory neurons that contribute to nonassociative and associative learning. Second, we developed a Hodgkin-Huxley type of model of biophysical and cellular processes underlying rhythmic bursting patterns of activity in the neuron R15. Third, we incorporated our real-time, neuron-like model of associative learning into small neural networks, which include facilitatory and inhibitory interneurons, and we demonstrated the ability of these networks to simulate some higher-order features of classical conditioning. Fourth, we incorporated our neuron-like model, which simulates aspects of classical conditioning, into a small neural network, and we demonstrated the ability of this neural network to simulate features of operant conditioning. Aspects of these results have been either published, presented in lectures to professional gatherings, or are being prepared for publication.

II. Research Objectives

The research that was proposed in AFOSR Grant 87-0274 has four specific aims: **1)** to analyze the membrane properties of sensory neurons and to incorporate this information into our neuron-like model of learning, **2)** to examine the ability of our neuron-like model of learning to simulate higher-order features of classical conditioning,. **3)** to analyze the properties of facilitatory and inhibitory interneurons that might contribute to associative learning, and **4)** to develop a cellular preparation that is amenable to the cellular analysis of operant conditioning, and to simulate features of operant conditioning in small neural networks. Two interrelated approaches are being used, one empirical and the other modeling. The empirical approach utilizes cellular neurophysiological techniques in order to analyze the particular ionic conductances and cellular processes that underlie forms of neuronal plasticity. The modeling approach involves formulating mathematical descriptions of the neuronal mechanisms and neural circuits, and examining whether simulation of the resultant model can simulate the empirical data and features of learning. The two approaches are interrelated in that empirical data are used to constantly test and improve the quality of the models, and predictions of the models are used to guide the design of new experiments.

III. Status of Research (Progress Report)

Progress during the past year has been in four areas. The first has been the development of a Hodgkin-Huxley type model of the sensory neurons that mediated nonassociative and associative learning in the tail withdrawal reflex. The second area has been the development of a mathematical model of the bursting neuron R15 in the abdominal ganglion. The third area has been the implementation of our neuron-like model for learning into small networks and simulation of higher-order features of classical conditioning. The fourth area has the simulation of features of operant conditioning with a neuron-like model of learning that was originally derived in order to simulate classical conditioning.

A. Mathematical Model and Simulation of Spike Broadening and Enhanced Excitability in Sensory Neurons of *Aplysia* (Byrne, Cleary and Baxter, 1990)

The voltage- and current-clamp experiments, which have been described in previous progress reports and which have been published, indicate that the effects of 5-HT on the duration of the action potential and on the excitability in sensory neurons is due to the modulation of at least two membrane currents, $I_{K,S}$ and $I_{K,V}$. In order to assess the quantitative contribution that each current makes to the overall modulatory effects of 5-HT, we have begun to construct a Hodgkin-Huxley type membrane model of the somata of the sensory neuron. Initial components of this model include an equivalent electrical circuit that consists of a membrane capacitance; the voltage-dependent currents I_{Na}, I_{Ca}, $I_{K,V}$; a Ca^{2+}-dependent K^+ current ($I_{K,Ca}$); and the cAMP-sensitive $I_{K,S}$. Since detailed analyses of the kinetics and voltage-dependence of these currents in the sensory neurons have not yet been performed, we have begun by using parameter estimates available from analyses on other molluscan neurons, and making reasonable adjustments so that we could simulate the kinetics of the membrane currents, the action potentials, and the spike frequency-intensity relationship that are observed normally in sensory neurons.

One action of cAMP is to initiate the closure of S-channels, which results in a reduction in the amplitude $I_{K,S}$. Thus we simulate the cAMP-dependent actions of 5-HT on membrane current by reducing the maximum conductance of $I_{K,S}$ in the model by 75%. The characteristics of the simulated $I_{K,S}$ can be revealed by isolating a cAMP difference current, just as we have done experimentally. The properties of the simulated and the experimental I_{cAMP} appear to be identical. Each is relatively voltage-independent, noninactivating, increases slowly during the voltage-clamp pulse, and is active over a wide range of membrane potentials. Indeed, the simulated $I_{K,S}$ contributes significantly to the steady-state membrane conductance at the resting

membrane potential (-45 mV). Thus, just as is observed experimentally, a reduction in the simulated $I_{K,S}$ results in the depolarization of the resting membrane potential that is associated with a decrease in membrane conductance.

Although the mechanism underlying the cAMP-independent modulation of $I_{K,V}$ by 5-HT is not known as yet, we have speculated that 5-HT may lead to a slowing in the rates of activation and inactivation of $I_{K,V}$. Thus we simulate the cAMP-independent actions of 5-HT on membrane current by altering the voltage-dependent time constants for activation and inactivation of $I_{K,V}$ in the model. Slowing the kinetics of the simulated $I_{K,V}$ results in a decrease in outward membrane current early in the voltage-clamp pulse, followed by an increase in outward membrane current later in the pulse. This action of 5-HT is revealed by isolating a cAMP-independent 5-HT difference current. The simulated cAMP-independent $I_{5\text{-}HT}$ appears to be identical to the experimental $I_{5\text{-}HT}$.

Given a reasonable fit of the normal electrophysiological properties of sensory neurons, we then adjusted the parameters of those membrane currents that are modulated by 5-HT separately to try to gain insights into the specific role they play in regulating spike broadening and excitability. Reducing only $I_{K,S}$ in the model produces a modest (11%) broadening of the simulated spike. This simulated broadening is similar to the amount of spike broadening observed following application of analogs of cAMP. In contrast, modifying only $I_{K,V}$ (*i.e.*, in this simulation the amplitude of $I_{K,S}$ is returned to normal values) produces a significant (54%) broadening of the simulated spike. While reducing $I_{K,S}$ did not significantly increase spike duration, it did produce a significant increase in excitability. In simulations in which $I_{K,S}$ was reduced, the number of spikes elicited by 1 s test pulses were doubled. In contrast, simulations in which only $I_{K,V}$ was altered did not show any increase in excitability.

We should note that in addition to reducing $I_{K,S}$, other experiments in this laboratory have found that 5-HT produces a cAMP-dependent reduction in a slowly developing Ca^{2+}-dependent K^+ current ($I_{K,Ca}$). Simulations in which both $I_{K,Ca}$ and $I_{K,S}$ were reduced produced greater increases in excitability than simulations in which only $I_{K,S}$ was reduced (simulations not shown). However, modulation of both $I_{K,S}$ and $I_{K,Ca}$ did not result in any further increase in the duration of the simulated action potential. Thus the cAMP-dependent modulation of $I_{K,S}$ appears to be sufficient to account for the observed increases in excitability.

These initial simulations must be repeated after more detailed information on the properties of the sensory neuron membrane currents is available. Nevertheless, the results of these simulation are remarkably similar to the physiological actions of cAMP and 5-HT. These simulations support the hypothesis that the cAMP-dependent

modulation $I_{K,S}$ by 5-HT plays a key in regulating excitability of sensory neurons, while the cAMP-independent modulation of $I_{K,V}$ by 5-HT appears to be critical for regulating the duration of the action potential.

B. Mathematical Model of a Bursting R15 Neuron (Canavier, Clark and Byrne, 1990*a,b*)

The R15 cell in the abdominal ganglion of *Aplysia* is one of the most widely studied cells in the field of electrophysiology. Many models of this cell exist in the literature. All models attempt to mimic the endogenous bursting behavior of R15, since it is primarily this feature that makes the cell interesting. We have extended this earlier efforts, and have developed a model of R15 that: 1) incorporates as much quantitative experimental data as possible into the model in a manner consistent with currently accepted mechanisms; 2) to provide a calcium ion balance within the model; and 3) to simulate the electrical behavior of R15 to the fullest extent possible. Our model is a lumped parameter electrical equivalent circuit (*i.e.*, a Hodgkin-Huxley type of model) with twelve state variables, including membrane potential, internal calcium concentration, calcium buffer occupancy and nine membrane gating variables. On the basis of available data, we have developed a model that contains the following components: inward currents (fast sodium current, I_{Na}; background sodium current, $I_{Na,B}$; spiking calcium current, I_{Ca}; slow inward current, I_{Si}), outward currents (delay rectifier current, I_K; calcium-activated potassium current, $I_{K,Ca}$; anomalous rectifier, I_R), a non-specific cation current (I_{NS}), and pump and exchanger currents (sodium-calcium exchanger current, I_{NaCa}; calcium pump current, I_{CaP}; sodium-potassium pump current, I_{NaK}).

The model proved to be capable of reproducing the bulk of the attributes of the R15 neuron, including endogenous bursting modes, rhythmic beating modes, and alterations in the waveform of the action potential during bursting activity. We are current exploring two further implementations of this model of R15. First, because of its periodic activity, it can be used as a driver element for network simulations of rhythmic activity; including those involved in operant conditioning (see below). Second, the emergence and mechanisms of chaos in neural systems.

Chaos in neural systems can be defined operationally as activity that appears random but that is generated by a deterministic system rather than by additive noise. It has been suggested that chaotic discharge patterns may be involved in such large scale neuropathological phenomena as seizures, epilepsy, tremor and convulsions. In addition, it has been suggested that chaos in neural systems can have several advantages; for example, biological chaos may help to prevent various functional units

in a neural system from becoming entrained, or phase-locked, into period activity. Our simulations of the model of R15 exhibit chaos. Thus, chaotic behavior can be a results of intrinsic properties of individual neurons and need not be an emergent property of neural assemblies. While the existence of chaotic behavior in R15 has not been examined experimentally, our modeling results predict that the potential for such behavior exists.

C. Empirically Derived Neuron-Like Elements and Neural Networks Simulate Higher-Order Features of Classical Conditioning (Baxter, Buonomano, Raymond, Cook, Kueniz, Carew, and Byrne, 1990; Buonomano, Baxter and Byrne, 1990; Byrne, Buonomano, Corcos, Patel, Baxter, 1989)

As described in previous progress reports, , we have developed a model of a neuron-like element that incorporates descriptions of cellular processes that contribute to plasticity of the sensory neurons. Our simulations have illustrated that this neuron-like element is capable of predicting features of nonassociative learning, such as habituation, dishabituation, and sensitization, and simple features of associative learning, such differential classical conditioning and an interstimulus interval (ISI) function. We have begun to extend these observations by examining the ability of small neural networks that include this neuron-like element to predict more complex features of associative learning, such as higher-order features of classical conditioning.

Although little is known about the neural mechanisms responsible for higher-order forms of conditioning, several quantitative models of small networks have shown that in theory the same learning rules that are capable of simulating classical conditioning can also simulate some higher-order features of associative learning. We have begun to examine the extent to which a neuron-like element based on the activity-dependent modulation learning rule can account for higher-order features of classical conditioning, specifically second-order conditioning and blocking. Our approach is to incorporate the neuron-like element into plausible networks, and make a minimum of assumptions regarding the properties of the non-adaptive elements within the circuit.

We have implemented two small neural networks that are derived from the characteristics of the neural circuit mediating the withdrawal reflexes of *Aplysia*. In each network, two sensory neurons (SN1 and SN2) with identical properties make synaptic contact with a motor neuron (MN). Activity in the individual sensory neurons represents separate pathways for conditioned stimuli (CS1 and CS2). The amplitude of the EPSPs at the sensory-to-motor synapses represent the ability of each CS to activate the response system and produce a conditioned response (CR). A key aspect of the architecture of this network is that the sensory neurons also make excitatory synaptic

connections with a facilitatory interneuron (FN). This connection has two consequences, one practical and the second theoretical. First, from a practical point of view, the circuit can be simplified by removing the motor neuron and using the EPSP at the sensory-to-facilitatory synapse as measure of changes in the synaptic strength of the CS. Second, from a theoretical point of view, a sensory neuron can 'take control' of the facilitatory interneuron as the strength of its sensory-to-facilitatory synapse increases. This possibility has fundamental implications with respect to neural models of higher-order features of classical conditioning. Because there is little experimental data on the properties of the facilitatory neuron, it is modeled as an element that simply sums its synaptic inputs, and if the inputs are equal to or exceed a threshold, a simulated action potential is initiated. An important assumed property of the facilitatory neuron is that its output diminishes or accommodates rapidly, and that its recovery from accommodation is relatively slow. Normally, the presentation of the unconditioned stimulus (US) always activates the facilitatory interneuron and stimulates the release of the facilitatory transmitter, which in turn activates an adenylate cyclase in the sensory neuron.

In a preliminary attempt to develop a network that incorporates recently described features of inhibition, we implemented a five-cell network that incorporates inhibitory interneurons. As a first step, we assumed that the inhibitory interneurons only act on cellular processes mediating associative plasticity in the sensory neurons. This form of inhibition is a hypothetical mechanism that could occur at numerous loci, such as blocking the influx of Ca^{2+} or blocking the Ca^{2+} priming component of cAMP synthesis. In this simulation, we assumed that activity of the inhibitory neuron transiently blocks further Ca^{2+} priming of cAMP synthesis in the sensory neuron, but not priming that results from Ca^{2+} present before the onset of activity of the inhibitory neuron. We also assumed that the inhibitory neuron has a burst-like property. The duration of activity in the inhibitory neuron was a function of the amount of time its input remained above threshold. The output of the inhibitory neuron was constant during its activation.

The simulations demonstrate that neuron-like elements and network architectures that reflect the cellular processes contributing to activity-dependent neuromodulation can simulate higher-order features of classical conditioning. In other simulations (not discussed here), we have examined the relative contributions of network and cellular properties to the overall performance of the network, and have identified several critical parameters that determine the ability of the networks to exhibit second-order conditioning and blocking. For example, simulations indicate that the biophysical properties of the facilitatory interneurons significantly influence the performance of the networks. Experiments that are in progress will test many of the predictions made by

these simulations and will provide empirical data critical to the continued development of biologically derived neuron-like elements and neural networks.

D. Simulations of Features of Operant Conditioning with a Classical Conditioning Learning Rule (Baxter, Buonomano, Raymond, Cook, Kueniz, Carew, and Byrne, 1990; Baxter, Raymond, Buonomano and Byrne, 1989; Raymond, Buonomano, Baxter and Byrne, 1990)

Despite operational distinctions, it is not known whether the cellular processes underlying classical conditioning and operant conditioning are fundamentally different or whether they share aspects of a common underlying mechanism. Recent theoretical studies indicate that the same neural networks and learning rules that can simulate features of classical conditioning can also simulate elementary forms of operant conditioning. Therefore, we were interested in determining whether a small network containing elements with the activity-dependent neuromodulation learning rule, which simulates features of classical conditioning, can also simulate features of operant conditioning. In order to test this hypothesis, we have taken the mathematical model of the sensory neurons in *Aplysia*, which we developed previously, and incorporated this neuron-like element into a small neural network and examined its ability to simulate features of operant conditioning.

Our simulations of operant conditioning were closely based on operant conditioning of head-waving behavior. Head-waving in *Aplysia* is a naturally occurring behavior in which the animals sweep their heads from side to side. *Aplysia* can be operantly conditioned to wave their heads preferentially to one side of their body. Although the neuronal elements and circuit underlying this behavior are not yet known, we have developed an artificial neural network that produces a pattern similar to the side-to-side movement in head-waving. This network contains three classes of elements: pattern generating elements (PGs), associative elements (AEs), and motor neurons (MNs). The pattern generating elements produce the spontaneous behavior that serves as the target of operant training. Two spontaneously active and mutually inhibitory neurons (PG_A and PG_B) comprise a central pattern generator that drives the network between two 'behavioral' or output states (Output A or Output B). Each pattern generating neuron makes an excitatory connection onto an associative element (AE). The properties of these associative elements are similar to our model of sensory neuron, but they have been modified slightly in order to reduce the transmitter depletion that would otherwise occur during the prolonged periods of activity during these simulations. These associative elements are the only elements in the network that are capable of activity-dependent neuromodulation (*i.e.*, associative enhancement of synaptic

strength). The motor elements (MN_A and MN_B) are driven by the associative elements. Activity in the motor elements serves as the measure of network behavior, and it feeds back onto the pattern generating elements. This excitatory feedback from the motor elements contributes to the maintenance of bursts of activity in the pattern generating elements. The neural pathways for reinforcement impinge on both associative elements. Positive reinforcement, like the US in the simulations of classical conditioning, facilitates the connection between the associative and motor elements. This synaptic facilitation is enhanced by prior activity in the associative element via the activity-dependent neuromodulation learning rule. In addition, we have incorporated a negative modulator into our model, but thus far we have not used negative modulation in any of our simulations.

Our simulations demonstrate that an associative element and a learning rule, which were originally derived in order to simulate features of classical conditioning, can also simulate behavioral data on operant conditioning. Specifically, we are able to demonstrate a change in the time spent performing a reinforced behavior, and this change is dependent upon a contingency between the occurrence of that behavior and the occurrence of reinforcement. Our network also exhibits extinction and reversal learning. Thus, the results of these simulations illustrate that, at least in theory, the same cellular mechanisms that are believed to underlie classical conditioning in *Aplysia* could also underlie operant conditioning.

An alternative (but not mutually exclusive) hypothesis for the cellular basis of operant conditioning is that the critical locus is not at the level of the synaptic connections, but rather at the level of the intrinsic properties of the pattern generator. In order to examine this possibility, it is necessary to have a more detailed description of a pattern generator. Our original pattern generator (PG_A and PG_B) was based on highly simplified assumptions. As a first step toward developing a more realistic pattern generator, we have developed a Hodgkin-Huxley type model of the R15 bursting neuron in *Aplysia* (see above). This neuron has the unique feature of generating a several second burst of spikes every 15-30 seconds. Because of its periodic activity, it can be used as a driver element for network simulations of rhythmic activity; including those involved in operant conditioning. The model that was developed includes descriptions of membrane currents that are found in R15 and that are critical for the bursting behavior. The resultant Hodgkin-Huxley type model accurately simulates most of the firing properties of the cell that are observed experimentally. As the mechanistic analyses of operant conditioning at the cellular level succeed, it will be interesting to see to what extent activity-dependent neuromodulation of synaptic connections and/or modulation of the intrinsic properties of pattern generators might contribute to operant conditioning.

IV. Publication

A. Abstracts:

1. Baxter, D.A. and J.H. Byrne. Reduction of voltage-activated K^+ currents by forskolin is not mediated by cAMP in pleural sensory neurons of *Aplysia*. *Soc Neurosci Abstr*, **14**: 153, 1988.
2. Byrne, J.H., D. Buonomano, I. Corcos, S. Patel and D.A. Baxter. Small networks of adaptive elements that reflect the properties of neurons in *Aplysia* exhibit higher-order features of classical conditioning. *Soc Neurosci Abstr*, **14**: 840, 1988.
3. Baxter, D.A., J.L. Raymond, D.V. Buonomano and J.H. Byrne. Operant conditioning can be simulated by small networks of neuron-like adaptive elements. *Soc Neurosci Abstr*, **15**: 1263, 1989.

B. Articles:

1. Gingrich, K.J., D.A. Baxter and J.H. Byrne. Mathematical model of cellular mechanisms contributing to presynaptic facilitation. *Brain Res Bull*, **21**: 513-520, 1988.
2. Susswein, A.J. and J.H. Byrne. Identification and characterization of neurons initiating patterned neural activity in the buccal ganglia of *Aplysia*. *J Neurosci*, **8**: 2049-2061, 1988.
3. Baxter, D.A. and J.H. Byrne. Serotonergic modulation of two potassium currents in the pleural sensory neurons of *Aplysia*. *J Neurophysiol*, **62**: 665-679, 1989.
4. Buonomano, D.V., D.A. Baxter and J.H. Byrne. Small networks of empirically derived adaptive elements simulate some higher-order features of classical conditioning. *Neural Networks*, in press, 1990.

C. Manuscripts in Preparation or Under Review:

1. Canavier, C.C., J.W. Clark and J.H. Byrne. Routes to chaos in a model of a bursting neuron. *Biophysical Journal*, under review.
2. Baxter, D.A. and J.H. Byrne. Differential effects of cAMP and serotonin on membrane currents, action potential duration and excitability in pleural sensory neurons of *Aplysia*. In preparation.
3. Baxter, D.A. and J.H. Byrne. Reduction of voltage-activated K^+ currents by forskolin is not mediated by cAMP in pleural sensory neurons of *Aplysia*. In preparation.

4. Raymond, J.L., D.V. Buonomano, D.A. Baxter and J.H. Byrne. Simulations of features of operant conditioning by a classical conditioning learning rule. In preparation.
5. Canavier, C.C., J.W. Clark and J.H. Byrne. A model of a bursting R15 neuron. In preparation.

D. Chapters:

1. Byrne, J.H., K.J. Gingrich and D.A. Baxter. Computational capabilities of single neurons: relationship to simple forms of associative and nonassociative learning in *Aplysia*. In: *Computational Models of Learning in Simple Neural Systems (Vol. 23 The Psych Learn Motiv)*, Eds. R.D. Hawkins and G.H. Bower, New York, Academic Press, 31-63, 1989.
2. Byrne, J.H. and K.J. Gingrich. Mathematical model of cellular and molecular processes contributing to associative and nonassociative learning in *Aplysia*. In: *Neural Models of Plasticity: Experimental and Theoretical Approaches*, Eds. J.H. Byrne and W. Berry, Orlando, Academic Press, 58-72, 1989.
3. Byrne, J.H.. Learning and memory in invertebrates. In: *Neurobiology of Comparative Cognition*, Eds., R.P. Kesner and D.S. Olton, Hillsdale, Lawrence Erlbaum Associates, Inc., in press, 1990.
4. Baxter, D.A., D.V. Buonomano, J.L. Raymond, D.G. Cook, F.M Kuenzi, T.J. Carew and J.H. Byrne. Empirically derived adaptive elements and networks simulate associative learning. In: *Neural Network Models of Conditioning and Action*, Eds., M.L. Commons, S. Grossberg and J.E.R. Staddon, Hillsdale, Lawrence Erlbaum Associates, Inc., in press, 1990.
5. Byrne, J.H., L.J. Cleary and D.A. Baxter. Aspects of the neural and molecular mechanisms of short-term sensitization in *Aplysia*: modulatory effects of serotonin and cAMP on duration of action potentials, excitability and membrane currents in tail sensory neurons of *Aplysia*. In: *The Biology of Memory*, Eds., L. Squire and E. Lindenlaub, Stuttgart, F.K. Schattauer Verlag, in press, 1990.

E. Books

Byrne, J.H. and W.O. Berry (Eds.). *Neural Models of Plasticity: Experimental and Theoretical Approaches*, Orlando, Academic Press, 1989.

V. Professional Personnel

Baxter, Douglas, Ph.D.

Buonomano, Dean (Graduate Student)

Byrne, John, Ph.D.

Canavier, Carmen (Graduate Student)

Raymond. Jennifer (Graduate Student)

Susswein, Abraham, Ph.D.

VI. Interactions: Presentations to Professional Organizations, Special Meetings, and Invited Lectures

1. "Analysis and Simulation of Cellular and Network Properties Contributing to Higher-Order Features of Associative Learning" This abstract was presented by Dr. Baxter at the Cold Spring Harbor meeting on the *Cell and Molecular Neurobiology of Aplysia* on September 28, 1988.

2. "Neural Networks: Real Life *vs.* Parallel Computer" Dr. Byrne along with Drs. Robert Barlow, James Bower, Christof Koch, Eve Marder, Terrence Sejnowski, and David Tank discussed aspects of neural network models at a special interest dinner at the *18th Annual Meeting of the Society for Neuroscience* in Toronto on November, 17, 1988.

3. "Simulation of Higher-Order Features of Classical Conditioning" This abstract was presented by Mr. Buonomano at the *Houston Bioengineering Conference* on February 18, 1989.

4. "Empirically Derived Adaptive Elements and Networks Simulate Associative Learning" This lecture was presented by Dr. Byrne, to The Society for Quantitative Analysis of Behavior, in Cambridge, MA during their symposia on *Neural Network Models of Conditioning and Action*, on June 2, 1989.

5. "Aspects of Neural and Molecular Mechanisms of Short-Term Sensitization in *Aplysia*: Modulatory Effects of Serotonin and cAMP on Duration of Action Potentials, Excitability and Membrane Currents in Tail Sensory Neurons" This lecture was presented by Dr. Byrne, at the *Symposium Medica Hoechst 23: The Biology of Memory* in Munich, FRG on October 16, 1989.

6. "Operant Conditioning can be Simulated by Small Networks of Neuron-Like Adaptive Elements" This abstract was presented by Dr. Baxter, at the *19th annual meeting of the Society for Neuroscience*, in Phoenix, AZ, on Nov. 3, 1989.

VII. New Discoveries and Specific Applications

It is too early in the research to comment on specific applications of this research but eventually the results will be relevent to aspectis of artifical intelligence. No inventions were made.