INTRACELLULAR MECHANISMS OF ADAPTATION AND SELF-REGULATION IN SELF-ORGANIZING NETWORKS: THE ROLE OF CHEMICAL TRANSDUCERS

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This paper describes mechanisms of intracellular and intercellular adaptation that are due to spatial or temporal factors. The spatial mechanisms support self-regulating pattern formation that is capable of directing self-organization in a large class of systems, including examples of directed intercellular growth, transmitter production, and intracellular conductance changes. A balance between intracellular flows and counterflows causes adaptation. This balance can be shifted by environmental inputs. The decrease in Ca²⁺-modulated outward K⁺ conductance in certain molluscan nerve cells is a likely example. Examples wherein Ca²⁺ acts as a second messenger that shunts receptor sensitivity can also be discussed from this perspective.

The systems differ in basic ways from recent diffusion models. Chemical transducers driven by membrane-bound intracellular signals can establish long-range intercellular interactions that compensate for variable intercellular distances and are invariant under developmental size changes; diffusional signals do not. The intracellular adaptational mechanisms are formally analogous to intercellular mechanisms that include cellular properties which are omitted in recent reaction–diffusion models of pattern formation. The cellular models use these properties to compute size-invariant properties despite wide variations in their intercellular signals.

Mechanisms of temporal adaptation can be derived from the simplest laws of chemical transduction by using a correspondence principle. These mechanisms lead to such properties of intercellular signals as transient overshoot, antagonistic rebound, and an inverted U in sensitivity as intracellular signals or adaptation levels shift. Such effects are implicated in studies of behavioral reinforcement, motor control, and cognitive coding.

1. Introduction. This paper discusses several basic issues concerning the processing of patterned data by individual cells and by networks of cells. These issues can be loosely grouped under three general headings. (I) Pattern registration without noise or saturation. This heading includes phenomena such as neural short term memory and the maintenance of morphogenetic patterns with properties such as sensory adaptation, con-
trast enhancement, and self-regulation. (II) Pattern learning by parallel sampling sources. This heading includes phenomena such as environmentally directed growth, enhanced transmitter production, and altered conductance or other receptor sensitivity changes in response to intercellular signals. (III) The establishment of long range order in intercellular interactions by chemical, as opposed to electrical transducers. These mechanisms lead to such phenomena as intracellular adaptation, overshoot, antagonistic rebound, and transient sensitivity changes in response to input fluctuations. Such phenomena occur regularly in psychological experiments on reinforcement mechanisms, but are still not recognized to be adaptational effects due to the action of chemical transducers. The issues are often motivated below by neural examples, but they apply equally to other biological systems, and therefore have a universal significance.

We start by noting that certain phenomena, which have often been treated as central biological facts—e.g. self-regulation (Wolpert, 1978)—are automatic properties of deeper design principles; e.g. pattern registration. One reason for this oversight in earlier work seems to be the omission of cellular structure from many models of cellular interactions, including the popular reaction–diffusion models. The results herein argue that cells have been chosen as an ubiquitous evolutionary design for important functional reasons, and that cellular structure should be reintroduced into cellular models.

We then suggest some mechanisms of intracellular processing that have analogs in mechanisms of intercellular processing by networks of cells; e.g. intracellular adaptation of photoreceptors (Baylor et al. 1974a, b; Baylor and Hodgkin, 1974; Normann and Werblin, 1974) vs intercellular adaptation due to lateral inhibition of retinal bipolar cells (Cornsweet, 1970; Werblin, 1971). These intracellular mechanisms can be interpreted as network interactions among intracellular components; e.g. of the cell membrane as a network of macromolecules. The homology between intracellular and intercellular network properties helps to clarify how several levels of hierarchical cellular organization can stabilize and regulate each other.

2. Pattern Registration, Intercellular Adaptation, and Self-Regulation. All cells face the noise-saturation dilemma, which can be solved either by intercellular mechanisms, or by homologous intracellular mechanisms. The dilemma can be stated as follows. Let a pattern of inputs $(I_1, I_2, \ldots, I_n)$ excite a collection of cells $v_1, v_2, \ldots, v_n$. All cells in vivo experience a certain amount of noise, and all cells possess only finitely many excitable sites. If the inputs in the pattern are too small, they get lost in the noise. If they are too large, they can turn on all the excitable sites in all the cells; that is,