

Commentary: Development of Perception-Action Systems and General Principles of Pattern Formation

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TURVEY, M. T., and FITZPATRICK, PAULA. *Commentary: Development of Perception-Action Systems and General Principles of Pattern Formation*. *CHILD DEVELOPMENT*, 1993, 64, 1175-1190. Our commentary on this special issue devoted to *Developmental Biodynamics: Brain, Body, and Behavior Connections* is divided into 3 main sections. The first section is an overview of the individual contributions. 5 major themes are identified: (1) inappropriateness of computational treatments of development and the need for more biologically and physically relevant treatments; (2) significance of tailoring muscular to nonmuscular forces in developing movement coordination; (3) importance of spontaneous movements as exploratory and formative mechanisms; (4) influences of action capabilities on the development of perception capabilities, and vice versa; (5) applications of methods and techniques of nonlinear dynamics to developmental processes. In the second section, we provide a synopsis of current ways of thinking about prototypical developmental processes, namely, pattern formation and pattern differentiation, in various classes of physical and biological systems. It is suggested that efforts to understand the progressive formation and differentiation of patterns in terms of very general principles provide a valuable resource of concepts and methods for students of child development. In the third section, hypotheses about the development of perception-action systems are generated from juxtaposing the themes and conjectures of this special issue with general principles of pattern formation. The hypotheses suggest the possibility of a pattern formation or dynamics approach to child development as an alternative to the conventional approaches emphasizing maturation (nativist), specific learning experiences (empiricist), cognitive stages (Piagetian), and strategies of encoding and retrieval (information processing).

The articles reported in this special section are directed at the development of locomotion and reaching and at the interdependencies of perceptual and motor development. They are not written from a common perspective, but they do share an inclination to open up the repertoire of concepts and methods by which the development of action and perception capabilities in children might be addressed. In our com-

mentary, we present first an overview of the papers, highlighting their major themes. We then provide a synopsis of contemporary theories about the progressive formation and differentiation of patterns in physical and biological systems as foundational to an understanding of how perception-action systems develop. Finally, we extract from the articles an inventory of ideas that are suggestive of more general principles of dynamic pattern

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formation and that could provide an important departure point for future research on perception-action development in children.

Overview

Theme 1: Inappropriateness of Computational Treatments of Development and the Need for More Biologically and Physically Relevant Treatments

Sporns and Edelman (1993, in this issue) offer the most explicit criticism of information-processing explanations (and their close kin, neural network models) that attempt to explain motor development in terms of control mechanisms and feedback loops. In particular, they point out that information-processing theories do not provide adequate explanations for motor redundancy and variability, cannot explain complementary changes in brain structure and body mechanics, and have only marginal biological relevance. Sporns and Edelman suggest that the major challenge for developing motor control is solving Bernstein's (1967) problem, that is, learning how to convert a high-dimensional system of very many (redundant) degrees of freedom into a controllable system by forming synergies. In their paper, Sporns and Edelman offer an account of synergy formation based on selectional principles. Their bottom line is that synaptic changes are the consequence of both environmental and internal constraints and result in the selection of optimal neuronal groups (which are tantamount to synergies). The investigations and hypotheses of Myklebust and Gottlieb (1993, in this issue) seem to be consonant with such a view. The elementary stretch reflex is more diffuse in infants, suggesting the influence of multiple connections involving several spinal levels. With development, the spinal circuitry underlying this basic mechanism—responsible for detecting and adjusting to externally induced changes in muscle force—appears to become more focused, confining the elementary pattern to the adaptive form of reciprocal inhibition.

Thelen, Corbetta, Kamm, and Spencer (1993, in this issue) reject the traditional computational account of the development of reaching (namely, that the matching of seen object and felt hand builds a reaching schema). They suggest, instead, that in learning to reach, infants discover how to modulate their spontaneous movements in order to achieve a goal (i.e., to reach and grasp a desired object). In particular, infants learn to modulate arm stiffness and force.

Similarly, Clark and Phillips (1993, in this issue) reject traditional maturational accounts of the development of walking and suggest instead that the developmental course of learning to walk is one in which the infant is first attracted to an unstable and weak dynamic solution (i.e., limit cycle) and then learns to stabilize the regime through experience.

Theme 2: Significance of Tailoring Muscular to Nonmuscular Forces in Developing Movement Coordination

There is a definite recognition of the importance of "Bernsteinian" concepts and an attempt to demonstrate empirical support for the same. Bernstein's (1967) insight that the degrees of freedom of a motor system can be reduced by forming synergies is embraced by many of the authors in this special section (as suggested above). Furthermore, two papers attempt to provide empirical evidence to support Bernstein's insight that an important component of motor learning and development is discovering how to use reactive forces effectively in executing a movement. For example, Zernicke and Schneider (1993, in this issue) demonstrate that in both adults executing a complex motor learning task and infants learning to reach, becoming more skilled entails learning optimal muscle torque patterns to counterbalance motion-dependent torques. Similarly, Thelen et al. demonstrate how torque patterns change in four infants learning to reach.

Theme 3: Importance of Spontaneous Movements as Exploratory and Formative Mechanisms

Several of the authors in the issue contend that (a) spontaneous movements are not merely random but are organized, and (b) spontaneous movements are important for perceptuomotor development. That is, motor development is a process of learning to control and sculpt undirected, spontaneous movements into controlled, goal-directed movements. To support this claim, the patterning and structure of spontaneous movements are empirically evaluated. For example, Robertson (1993) investigated the persistence and structure of cyclic motor activity (overall body movement) beyond the neonatal period. He found that cyclic motor activity does persist in active sleep and remains irregular across the 4 months studied. Motor activity during awake states, however, increased in temporal complexity at about 2 months, suggesting that more complex dynamics are "shaping" the spontaneous activity. Hofsten and Rönnqvist (1993, in this issue) examined the spontaneous arm

movements of young infants (3–5 days at outset) to see whether the structure of these movements is similar to reaching movements. They report that spontaneous arm movements exhibit temporal and spatial patterning similar to that found in reaching movements at 5 months. Also, Thelen et al. demonstrate how initial preferred modes of movement (with their own intrinsic dynamics) are modulated in the development of reaching.

Theme 4: Influences of Action Capabilities on the Development of Perception Capabilities, and Vice Versa

Bushnell and Boudreau (1993, in this issue) propose that the emergence of certain motor abilities may play a role in determining the developmental sequence of certain perceptual abilities. That is, proficiency in certain motor activities may be necessary for revealing information that is necessary for perception. They present two examples, one from haptic perception and one from depth perception, to support their claim. Clifton, Muir, Ashmead, and Clarkson (1993, in this issue) demonstrate that muscle-joint proprioception can be used in guiding early reaching movements. Traditional theory holds that early reaching depends on continual visual monitoring and matching of hand and target. Clifton et al. demonstrate, however, that infants are able to reach successfully for objects in the dark, with only muscular proprioceptive hand-location information available. Similarly, Ashmead, McCarty, Lucas, and Belvedere (1993, in this issue) investigate the role of visual guidance of reaching in a task in which the target changes location during the reach. They report that at 9 months infants are able to adjust their reaches, but only when their hand is visible. Further, reaching adjustments were made predominantly in the second half of the reach segment. Five-month-old infants were not able to adjust their reaches, with performance comparable on trials in which the hand was and was not visible.

These results suggest that visual guidance of reaching is critical in older infants in challenging reaching tasks. Taken together, the results of the Clifton et al. and Ashmead et al. studies suggest that the role of visual guidance in the development of reaching has most likely been misconstrued. That is, (a) visual guidance is not necessary for young infants just learning to reach (nonvisual proprioception is good enough), and (b) visual guidance appears to play a more crucial role in adjusting reaches for older infants. Thus, visual guidance/adjustments

seem to emerge after reaching appears, suggesting that an alternative to hand-target matching is needed. (Both Clifton et al. and Ashmead et al. interpret their results in terms of traditional hand-target matching theory.)

Adolph, Eppler, and Gibson (1993, in this issue) examine crawlers' and toddlers' ability to perceive geographical slant. Specifically, they explore the abilities of crawlers and walkers to perceive whether sloping surfaces afford safe traversal. Results indicate that walkers are able to perceive affordances for locomoting over sloping surfaces. Walkers were more cautious descending slopes than ascending, often shifting from walking to sliding during descent. Crawlers were relatively inept at perceiving the controlled locomotion permitted or not by a slope, attempting to go up and down most slopes, and often falling. The authors conclude that between 8 and 14 months infants learn a good deal about affordances for locomotion. Results from the crawlers are interpreted in terms of sensitivity to a continuous optical gradient specifying a continuous surface.

Theme 5: Applications of Methods and Techniques of Nonlinear Dynamics to Developmental Processes

It seems that a major aim of this special section was to demonstrate how the concepts and tools of dynamics can be applied to studying perceptuomotor development. Goldfield, Kay, and Warren (1993, in this issue) examined a relatively simple task, namely, bouncing in a jolly jumper. This task was chosen because Goldfield et al. had a specific model (and predictions) they could test. In particular, they modeled bouncing as a forced mass-spring, with muscle and joint stiffness and damping, as well as intrinsic timing. Such a mass-spring system has two important characteristics: (a) a resonant frequency, and (b) a maximum amplitude achieved by matching leg and spring stiffness. Their results indicate that in learning to bounce infants assemble and tune a forced mass-spring system oscillating at its resonant frequency. Their conclusions are supported by the data, and they suggest further manipulations of the system in order to gain more empirical support for the model.

In the papers by Thelen et al. (1993, in this issue) and Clark and Phillips (1993, in this issue), the authors advance dynamical treatments of their data on reaching and walking, respectively. The Thelen et al. paper is mainly descriptive, comparing the

forms of limb trajectories to show how limb stiffness and torque profiles might be changing developmentally. A dynamical interpretation is presented of the data, suggesting that it provides evidence of limit cycle dynamics that evolve into point attractors as well as implicating mass-spring dynamics. This interpretation would be enhanced significantly by a model of reaching as a time-evolving functional organization and by experimental manipulations directly suited to testing the claims for limit cycles and point attractors. As of now, both of the preceding requirements are difficult to come by. Similarly, the interesting and provocative dynamical claims in the Clark and Phillips article are in need of more detailed and rigorous support. The main points of the article are that (a) inspection of phase portraits suggests that even young walkers exploit limit-cycle dynamics, and (b) the pattern of relative phasing changes developmentally. Acceptance of these claims would be enhanced by a model of (b) and by systematic analyses of dependent measures directly relevant to testing them.

An additional and important application of ideas from nonlinear dynamics is to be found in the article of Robertson (1993, in this issue). The spontaneous cyclic motor activity (CM) exhibited by an infant is highly irregular and looks like noise. It could, however, be due in part to an underlying system that is deterministic—that is, there is a definite dynamic that is producing the irregular pattern. The problem is that we cannot guess the system's relevant observables or degrees of freedom. An important theorem of nonlinear dynamics reveals that, on the basis of any one quantity associated with the phenomenon, and a time series of it, it is possible to create "fake observables" that permit a reconstruction of the underlying dynamic despite one's ignorance of the type and number of its degrees of freedom. Robertson's application of this strategy to identify structure in CM bodes well for future efforts to understand the spontaneous and ill-defined activities that seem to be precursors to coordinated behavior.

General Concepts of Pattern Formation

The progressive formation and differentiation of patterns in physical and biological systems is a topic of great contemporary concern. In large part this is because of the increasing availability of physical and

mathematical tools for examining and understanding morphogenesis or the "forming of matter." Although the insights gained to date are impressive relative to intuitions of a generation ago, the general theory of pattern formation in dynamical systems is very much in its infancy. The time-evolution of patterns (spatial, temporal, spatiotemporal) is most adequately addressed by contemporary methods when the process in question is representable as a single dynamical system with a single control. For the pattern-formation processes encountered commonly in biology and psychology, a continuum of spatially coupled dynamical systems is imaginable together with a continuum of controls (Abraham, 1987). Elaboration and formulation of the generic behavior of such systems lies in the future, with a promise of rich metaphors and models for the developmental processes of concern to the biologist and psychologist.

In the following we provide brief summaries of current ways of thinking about pattern formation and differentiation—that is, prototypical developmental processes—in various classes of systems. Our main goal is to provide a context for the articles of this special section through a survey of the kinds of concepts, both established and under exploration, that bear on development as a very general feature of nature. Our suspicion, and our hope, is that this survey will be illuminating, especially in respect to providing insight into the relevant observables. A system's relevant observables or degrees of freedom are the ways in which it might change. Although it is the case that observables of any number and kind can be chosen to describe a system, the right observables lead to experiments that are more straightforward (elegant) and to interpretations that are both easier to express and more profound (Krieger, 1992).

Pattern formation in physical systems.—In a nutshell, a specific emergent form is a solution to a generalized stability problem (Haken, 1977, 1983, 1988; Iberall & Soodak, 1987). There is a fluctuation-dissipation principle that varies according to the scale and kinds of subsystems involved. Small fluctuations generated at lower levels of organization may be rapidly dissipated (damped out), or they may be amplified and stabilized within a higher-ordered organization. Thus, the appearance of new forms or patterns is a stability transition—changes of forces and scales make the existing patterns or forms unstable.

From what level, micro or macro, does the instability arise? Physical systems are readily expressed as alternations of atomistic (i.e., atom-like) and continuum levels. For any given system, there is a spatial-temporal scale of analysis at which it behaves as a continuum, that is, as a coherent, field-like, macroscopic structure. At a finer scale of analysis, however, the continuum is revealed as a collection of interacting and fluctuating atomisms (e.g., the molecules of a fluid). The pattern-generating capability of a physical system lies in the interplay between the processes characterizing the two levels. With respect to the source of instability inducing pattern formation, it is generally a demand at the continuum scale that impresses itself upon the atomisms as impositions on their interactions. The simplest example is provided by pressure-driven fluid flow in a pipe. Increasing pressure amounts to a scaling up of the energy swept into the fluid system at the continuum level. Unpatterned or laminar flow becomes unstable, that is, the fluctuations amplify, as the convective continuum flow outstrips the ability of the atomistic level to dissipate the injected energy through diffusion. The homogeneous field is fractured by symmetry-breaking into new and large collective behaviors of many molecules. Laminar flow gives way to vortices, that is, flow characterized by local regions of spiral-like patterns.

Particularly rich examples of pattern formation in fluid flows are the Rayleigh-Bénard and Couette-Taylor instability sequences (see, e.g., Abraham & Shaw, 1988; Nicolis, 1990). Coordinate with critical (bifurcation) values of a nonequilibrium constraint—an increasing temperature gradient in the Rayleigh-Bénard case and an increasing velocity gradient in the Taylor case—one observes a hierarchy of stability transitions yielding quantized spatial and spatiotemporal patterns of increasing complexity, each with some degree of autonomy (i.e., relative indifference to changes in the boundary conditions that forged them). The forms created in the Couette-Taylor device, a stirring machine, are shown in Figure 1. The device consists of two concentric cylinders mounted on a common vertical axis, with a fluid contained between the two cylinders. To stir the fluid, the inner cylinder can be rotated at various speeds. Increasing the speed results in a succession of patterns. Importantly, these patterns are not present beforehand in the atomistic level, and their details are not prescribed by the “control

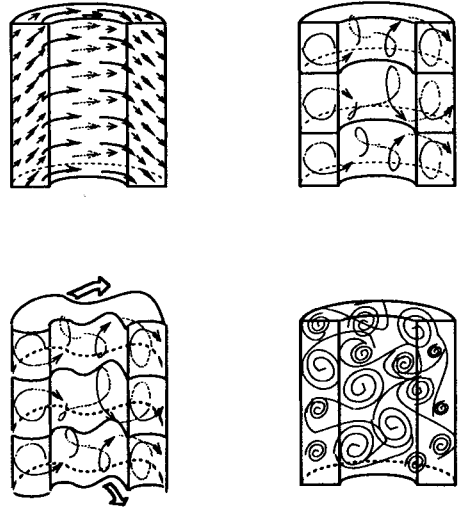


FIG. 1.—A schematic of the successive patterns induced in the Couette-Taylor stirring machine as a function of increase in the velocity difference (the control parameter) between the inner and outer cylinders housing the fluid. Top left, With a stirring rate just above zero, the fluid flow is slow and lamellar. This lamellar flow has the one-dimensional symmetry of the vertical axis. Top right, Annular vortices or cells appear in the fluid (so-called Taylor cells) as the stirring rate passes a critical value. The stack of vortices has the zero-dimensional symmetry of a discrete set of points within the vertical axis. In the transition to annular vortices, a spatial symmetry breaking has occurred. Bottom left, At the next critical value of the stirring speed, the Taylor cells exhibit waves that rotate within the fluid. Temporal symmetry is broken, with periodic variation occurring at each point in the fluid. Bottom right, A further increase in stirring leads to weakly turbulent fluid motion. Segments of dislocated Taylor cells move about chaotically. [Adapted from Abraham & Shaw (1987).]

parameters” (e.g., stirring velocity) whose changes led to their appearance. Through an instability sequence, the atomisms (the fluid molecules) are permanent, but the collective patterns come into existence, persist, and die under the indirect control of the nonequilibrium constraints (Haken, 1983; Iberall & Soodak, 1987; Nicolis & Prigogine, 1989).

As intimated, fluctuations are of special significance to the appearance of new patterns. Particularly important is the role they play at the crucial moment of transition, where the system has to perform a critical choice. In the Rayleigh-Bénard system, the choice is associated with the appearance of

a right-handed or left-handed cell. The macroscopic cells formed at the first instability comprise in the order of 10^{20} atomisms behaving in a singularly coherent fashion: They rotate in a rightward or leftward direction, with adjacent macroscopic cells rotating in opposite directions. The direction of rotation is decided by chance, through the dynamics of fluctuations. In effect, the system explores the dynamical landscape via its fluctuations, testing the different collective motions of the atomisms, and making a few initially unsuccessful attempts at stabilizing. Eventually, a particular fluctuation takes over and becomes stabilized. At this juncture the system now has a history in that its subsequent evolution depended on this critical choice. Borrowing ideas from biological evolution, "fluctuations are the physical counterpart of mutants, whereas the search for stability is the equivalent of biological selection" (Nicolis & Prigogine, 1989, p. 73).

Chance or randomness plays a decisive role in the choice of new structures by taking the system increasingly further away from equilibrium (the stable state that it currently occupies) in an unpredictable direction. The choices are magnified immensely by chaos, a process of deterministic or constrained randomness. Many physical systems that are *deterministic* in the typical sense that the immediately next state follows unequivocally from the present state are at the same time *random* in that their trajectories in the long term are unpredictable. Small differences in the conditions from which the system begins its trajectories lead eventually to extremely large differences among those trajectories; as observers, we cannot determine a chaotic trajectory unless we are first given it. This randomness, however, is constrained because the system lives in a well-defined, albeit complex, space or manifold of states and so its meanderings are bounded in the long run. Further, the deterministic nature of the system means that its trajectories cannot intersect. In consequence, its nonrepeating trajectories continually bend and fold to penetrate all points in the manifold. Chaos, therefore, is tantamount to an exploratory process in which every one of a system's dynamical possibilities is examined.

Once discovered and stabilized, the new pattern formed by the interplay of continuum level and atomistic level processes persists by means of balancing the losses and gains in energy and materials. The losses are from the system to the surround and the gains are from the surround to the

system. The balance is achieved by the cyclic transport of energy and matter across the system's borders. As a general principle, a cooperativity of cyclic processes, interpreted technically as thermodynamic engine cycles, is responsible for pattern persistence (Iberall & Soodak, 1987). Spectroscopic analysis is needed to reveal the component periodic mechanisms, the time domains in which they occur, and the manner in which energy is distributed among them.

Issues of pattern formation in biological systems.—The preceding examples of statistically unstable physical systems generating a hierarchy of patterns are addressed by theories in which fundamental laws and principles are of primary importance and initial conditions assume only a minor role. Within biology, embryology and evolutionary biology are the subdisciplines most dominated by questions of progressively ordered forms and the emergence of new patterns. Unlike accounts of the physical systems just discussed, the most common treatment of these phenomena of biological systems emphasizes special initial conditions and constraints and relies only weakly, if at all, on general laws and principles. It is often suggested that all the information necessary for generating a time-evolving pattern is present in the parts (the atomisms), its spontaneous emergence or assembly occurring simply as a consequence of their interactions. Thus, the self-assembling process of embryogenesis is by means of a genetic program that determines an organism's molecular components together with the spatial and temporal details of their appearance, and by interactions among these components via short-range forces. Under this interpretation there is little room for general laws formative of biological pattern. A genetic program is the result of random permutation and natural selection, that is to say, determined by contingency, not by law. It is constrained only by the measures of survival success and number of offspring.

Von Baer in the early 1800s provided modern embryology with its major departure points, in particular, the understanding that development proceeds from the general to the special, from the apparently homogeneous to the patently heterogeneous, from the simple to the complex (Oppenheimer, 1967). In sum, he advanced the idea of embryogenesis as differentiation: "All is transformation, nothing is development *de novo* If a part is formed by internal differentiation there was not a hole there be-

fore" (Oppenheimer, 1967, p. 298). The core problem, therefore, is that of how cells that are initially undifferentiated "know" the site and manner of their differentiation. Because differentiation is a process in time and not a fixed state, the ultimate challenge is accounting for the successive order. Hypotheses about spatial distinctions among embryonic parts, however profound, are secondary to hypotheses about the progression of differentiation.

Aspects of the interplay between adjacent and successive order suggest that the molecular composition basis to the program-driven account of differentiation is overvalued. Stated simply, composition alone does not determine pattern (Goodwin, 1987). Of particular significance are the empirical manifestations of Dreesch's (1929) field concept and of the classical gradient theory (see Child, 1941)—relative position in the whole embryo is an important determinant of cell fate. A cell's development is dictated not by its composition but by its field position. Transplanting a cell from one region of the embryo to another causes it to develop along the lines typical of cells in the host region. It appears that the parts that emerge in differentiation do so as the result of local and global ordering strategies.

Important alternatives to the strict program-driven account are available. Although they are far from uniform in their emphases, they may be viewed as approximations to a thoroughgoing *execution-driven* account (Kugler & Turvey, 1987; Yates, 1987a) of the embryogenic process. The structural and functional order characteristic of embryogenesis could follow from crude (sparsely detailed, fuzzy) initial conditions if attractor portraits—singular states (attractors) and surrounding gradients (basins)—evolve in the course of "executing" embryogenesis and can act as constraints upon it. In the evolving dynamic of execution-driven development, upcoming states depend upon current states rather than upon prior (e.g., stored, programmed) states. All that is required of the initial conditions is that they put the system into the basin of the first-evolving attractor. Embryogenesis can then (self) organize by converging onto the successive attractors via the gradients of states associated with their respective basins.

One major line of thought on general strategies of biological pattern formation as an execution-driven process was initiated by

Turing (1952). He proposed that a reaction-diffusion mechanism, in which unequal diffusion rates of the reactants are destabilizing, could generate heterogeneity from homogeneity. Specifically, if at some point reaction rates adjusted too slowly to establish equilibrium, then any small spatial disturbance (a spatial fluctuation) could become unstable and a pattern could emerge in a previously unpatterned distribution (see Fig. 2). In the Turing process, a "prepattern" is established in a concentration of chemicals referred to as "morphogens," chemicals (as yet unknown) that have specific effects on morphogenesis. The prepattern notion expresses the idea that antecedent to the pattern of interest (e.g., the visible coat markings of a zebra) there exists a spatial variation in something that resembles in some way the pattern of interest (for the zebra markings, a chemical pattern in or under the zebra's epidermis). The Turing chemical prepattern depends strongly on the geometry and scale of the domain where the chemical reaction takes place (Murray, 1988, 1990). With all other parameters held constant (e.g., reaction and diffusion rates), patterns change as geometry changes (e.g., from a cylinder of uniform diameter to a tapered cylinder) and as scale changes. With respect to the latter, a Turing mechanism reproduces the fact that the coats of animals change from uniform to patterned and back to uniform as animal size changes from small (e.g., mice), to intermediate (e.g., leopards, zebras), to large (e.g., elephants) (Murray, 1988, 1990).

In the chemical prepattern perspective, cell differentiation, changes in cell morphology, and cell migration occur after the formation of the prepattern. That is, morphogenetic processes are separate from and subsequent to the process constraining their nature and direction. There is, however, an alternative dynamical perspective in which chemical patterning and morphogenesis occur simultaneously as a unitary process and in which there is no need for the questionable hypothesis of chemical morphogens. In the mechanochemical approach, as this alternative dynamic is called (Murray, 1990), chemical patterning, form-shaping cellular movements, and the embryological tissue enveloping the cells interact continuously to generate the observed adjacent and successive order. Central to this approach is the fact that because most nerve cells are born close to the inner surface of the neural tube, they have to migrate past cells born at earlier

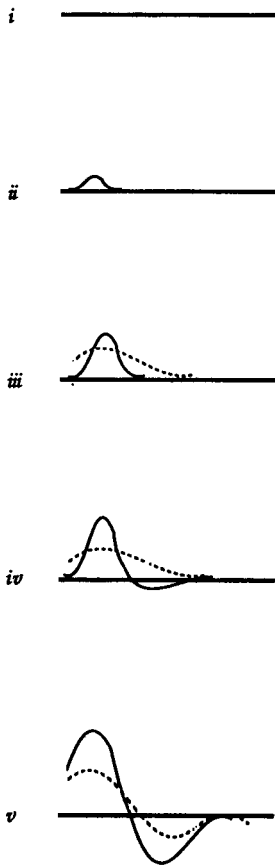


FIG. 2.—A depiction of Turing's (1952) model of pattern formation by reaction-diffusion processes. (i) The uniform distribution of the morphogen. (ii) A fluctuation in the morphogen distribution. (iii) The morphogen grows by stimulating its own production. Through reactive processes, morphogen growth is accompanied by an amplification in the chemical (dotted curve) that dampens the growth of morphogen. Because this inhibitor has a higher diffusion constant, it spreads out at a faster rate than the morphogen. (iv) At any spatial region where the inhibitor is more plentiful than the morphogen, a further decrease occurs in the morphogen due to reactive processes. (v) A decrease in morphogen decreases reactively the inhibitor which causes, in turn, an amplification in the morphogen. The result is a pattern of peaks and troughs in the spatial distribution of morphogen. [Adapted from Beltrami (1987).]

stages in order to reach their final positions (Brown, Hopkins, & Keynes, 1991). Cells move by exerting forces on their surroundings, deforming them. The deformations induce spatial inhomogeneities, which in turn constrain the cell motion. In overview, migratory movements constitute a dynamics shaped by many influences (e.g., an extracel-

lular matrix that deforms to create compression and tension wrinkles extending several hundreds of cell diameters; density, chemical, and adhesive gradients permitting directed upward and/or downward motions; a field generated by electrical potentials creating preferred directions, and so on). Collectively, these various influences of a largely mechanical nature specify locally how individual cells should differentiate and globally how multiple individual differentiations should coordinate over large length scales. The relevant equations of state and equations of change capturing these influences express conservation of cell population density, interplay between cellular and extracellular forces, and conservation of the extracellular matrix (Murray, 1990). It becomes evident from these representations of the dynamics of morphogenesis that specific patterns arise as a function of the residency of the control parameters in specific regions of the parameter space, and that a slow variation in a given parameter can bring about either a gradual or a discontinuous change in form depending on the parameter's nature and its position in the parameter space. It also becomes evident why certain lines of development and the patterns they would give rise to, such as a trifurcation (a branching of one element into three) in the cartilage patterning of developing limbs, rarely occur. The range of parameter values dictating a trifurcation is extremely narrow and the resultant pattern is unstable.

The preceding presents mechanical forces as the principal players in the production of the sequential order of tissue patterning and shape changes in the developing embryo (Murray, 1990). It paints a picture of embryogenesis that seems to accord with a very general principle, namely, force and form joining locally to create forms of greater size and time scales (Iberall & Soodak, 1987). It highlights that each level of the patterning process has its own dynamics imposing, in turn, constraints on what developments are subsequently possible. And it suggests that the morphological complexity of mature organisms and their intermediate embryonic patterns may not be irreducibly complex, and that general dynamical laws and principles may render the diversity intelligible (see Goodwin, 1987).

The contrast between biological and physical pattern formation.—Despite important analogies, there are profound differences of principle between embryogenesis and the emergence of structure in physical

and chemical systems. First, the order that emerges in the Rayleigh-Bénard simmering machine and the Couette-Taylor stirring machine (see above and Fig. 1) is not determined by the molecules comprising the fluids. It is truly spontaneous. In contrast, embryogenetic form is specific to the one-dimensional DNA string. Different strings determine different forms in (increasingly) predictable ways. Second, the spontaneous order observed in physical and chemical systems is brought about by manipulating a boundary condition as a control parameter. That is, the control is exerted globally, at the continuum level. The nonspontaneous and predictable order observed in embryogenesis is brought about largely by controlling influences exercised by DNA. That is, the control in embryogenesis, to an important degree, is exerted locally, at the atomistic level. Third, the phenomena expressed by the Rayleigh-Bénard and Couette-Taylor convective instabilities are affected significantly by microscopic fluctuations, as noted above. In contrast, embryogenesis is often remarkably unaffected by nonsubtle alterations of the biological tissue, as was also noted above. Taking an extreme case, hydroid can reassemble following a complete rearrangement of its parts.

The challenge of biological morphogenesis is to understand how a global organization (in both structure and function) is achieved in which all the specialized details at all process scales are in place and interrelated. By definition, patterns are field or continuum properties; they are defined globally. The challenge of biological morphogenesis seems to be understanding how localized interactions can exercise global control or, more precisely, the coordination of local sources of influence with the global conditions needed to engender the requisite patterns. An advantage of the previously discussed mechanical perspective on embryogenesis is that it provides intuitions about modes of local-global coordination.

Morphogenesis based on synergetic, specificational information.—It is possible to gain further insight into the local-global relation by examining an instance of morphogenesis that is provided by social insects. To set the stage, consider that the growth of an individual organism looks so mysterious from a strictly local vantage point because the components that grow differently all have the same DNA. If one chose to interpret this fact as each molecule possessing the basic blueprint for development,

then one would be faced with explaining how each cell takes responsibility for executing different parts of the overall plan. Retaining the local perspective, one might conjecture a metaplan instructing each cell as to its duties. The metaplan could exist only in the DNA, however, leading to an infinite regress (Davis, 1988). Efforts to address cooperative, self-organizing phenomena in social insects have often taken the preceding form (e.g., each insect carries the global blueprint) without recognizing the infinite regress enjoined by such an account.

Flying termites build large structures through the collective activity of several million participants. Each individual insect abides by two injunctions: (a) move in the direction of the strongest pheromone gradient, and (b) deposit building materials (which contain the pheromones) at the point of maximal concentration. These injunctions are a kind of information that is carried by each insect. Like the DNA in an individual cell, they do not distinguish among the participants in the growth process. The control constraints that organize the local and global building activities arise in the low-energy pheromone field (low relative to the energy scale of the individual insect) that is linked to the individual insect via a chemical affinity. The low-energy linkage forms a circularly causal process in which the forces of an insect (those that move it around the building site according to the gradients) affect the distribution or flow of pheromones (because the insect is biased to deposit at one particular location rather than another), which in turn affects how the insect moves, that is, the forces it generates, and so on. This simple circular process between local insect motions and global pheromone patterns realizes a succession of discontinuities in the pheromone field, a hierarchy of symmetry-breaking instabilities that correspond to distinct phases of the collective nest-building act (Kugler & Turvey, 1987, 1988).

We elaborate briefly on two key ideas. One is that the pheromone field induces long-range correlations in the behaviors of the termites. As the number of insects participating increases beyond some critical value, random deposit sites tend to receive further deposits because of the increased probability that an insect will be captured by a pheromone diffusion gradient. Further, sites that randomly gain the edge in size will be sites that attract more termites because of greater surrounding gradients. In consequence, these sites will grow into pillars au-

tocatalytically (the more material they have, the more material they will get), and the trajectories of the termites will become more correlated (they converge on common successions of points). The second key idea is that cooperative and competitive processes within the pheromone field result in the emergence of a finite number of converging and diverging flow regions, originating and terminating in critical states (e.g., point attractors and saddlepoints). These flow patterns constitute a kind of information that can be termed (a) *synergetic*, because they are produced by the cooperativity of the system (Haken, 1988), and (b) *specificational*, because they are specific to evolving states of the nest and constrain the flights and deposits of the termites so as to bring about the requisite material configurations (pillars, arches, domes) (Kugler & Turvey, 1987). For example, the interactions of the diffusion streams from the pinnacles of two neighboring pillars form a gradient field containing a saddlepoint (between the two pillars) and two point attractors (one at each pinnacle). An insect may enter this field from a direction that carries it to the saddlepoint. Once there, there are two orthogonal routes that lead directly to the inner edge of the tops of the two pillars. A fluctuation at the saddlepoint determines which route the insect follows. The saddlepoint is a symmetry-breaking mechanism for biasing deposits away from the centers of the two pillars. The result is an arch that curves upward toward the saddlepoint.

In sum, the nest building is a self-complexing phenomenon that is driven by the locally defined expedient behavior of the insects coupled to the global diffusive patterns of the pheromone field. In the self-organization of the nest, only crude initial conditions common to all participants are needed to get things going; once started, the process becomes parasitic upon, and driven by, reaction-diffusion processes, and it becomes highly differentiated. Termite nest building is a paradigmatic example of execution-driven morphogenesis. It is also a paradigmatic example of a self-organizing *information* system. Unlike the cells in embryogenesis that are directed by mechanical forces, the termites are directed by time-evolving patterns of a low energy field that constitutes for them information specific to the emerging nest.

Development of patterns of neural connectivity.—Returning to morphogenesis in individual organisms, a most important fea-

ture of neural circuitry in mammals and other vertebrates is that its formation extends well beyond birth. Intuitively, the mechanisms that extend the time scale of the genesis of synapses have general significance for a developmental theory of perception-action systems.

The phrase *neural connections* refers to the number and patterning of axonal and dendritic branches together with the synaptic relations established by them. The classical accounts of the basis for neural connections and the manner of their development are associated with Paul Weiss and (his student) Roger Sperry. On the basis of experiments on limb transplantation in amphibians, Weiss proposed that the specificity of the fit between nerve cells and their targets (e.g., muscles, sensory receptors, other neurons) was functional (see Weiss, 1968, for a retrospective overview). An extra limb transplanted in the neighborhood of a normal limb exhibited the same spatiotemporal locomotory pattern. A resonance was suggested between the neural target and its innervational pattern. Subsequently, this resonance notion was advanced as the idea of myotypic specification: Muscle targets (and thus, somatic function) dictated the central pattern of connections of motor units contacting the targets in a random fashion (Weiss, 1941). Sperry (1963) challenged this conception of highly malleable connections open to reorganization as function dictated. His experiments on optic nerve regeneration in amphibia with a surgically rotated eye revealed that axons reestablished their original connections; the new functional demands did not inspire a change of pattern. A chemoaffinity hypothesis was proposed suggesting a rigid prescription for the formation of connections based on the unique chemistry of individual neurons. With further research on the retinotectal system, however, it became evident that regenerating retinal neurons do in fact contact target cells different from those originally innervated (e.g., Schmidt, Cicerone, & Easter, 1978). It is now understood, contrary to Sperry's conjecture, that cellular chemical affinities do not fix the pattern of neural connections. The current impression is that, by and large, the experimental evidence supports neither Weiss nor Sperry (Purves, 1988).

The preceding ideas and their criticisms are well known and can be found in any standard textbook. Less well known are two perspectives that are, to a significant degree, contemporary responses to the inadequacies

of the earlier formulations. Gaining in popularity is a notion of nervous system development that emphasizes selective and regressive processes analogous to the Darwinian theory of natural selection. For anatomical or functional reasons, some connections from an initially established repertoire of connections are selected while others are eliminated, so that overall there is a net reduction in connectivity (Changeux, Courrège, & Danchin, 1973; Changeux & Danchin, 1976; Edelman, 1981, 1987). A paradigmatic finding motivating such a view is the transformation from the neonatal organization of many motor neurons innervating a given bundle of muscle fibers to the adult organization of a single source of innervation (e.g., Bennett, 1983). An influential reading of observations of this latter kind is that they indicate a neuronal competition arising from the dependence of neurons on a resource that comes in limited supply. Any motor neuron seeking to acquire a given target resource faces competition from other motor neurons seeking the same resource. In resolving the competition, participants are gradually eliminated until only one remains.

Founded upon very much the same data base, but with potentially different implications, is the trophic theory (e.g., Brown et al., 1991; Purves, 1980, 1986, 1988). The core assumption of this theory is that the patterning of neural connections is subject to ongoing regulation by interactions with the cells that they contact. Nerve cells and their targets nourish (hence the term *trophic*) each other in their two-way interactions. By this theory, the repertoire of connections is never complete. There is a continuous making and breaking of connections suggestive of a self-reorganization or rearrangement rather than elimination. The continuity means that the mature nervous system is characterized by a continual remodeling; the mature connective pattern is an ongoing dynamic, an actively produced and maintained organization rather than a temporarily frozen architecture. From the vantage point of trophic theory, whether there is a net decrease or net increase in connections is immaterial. Of primary significance is the capacity of nerve cells to reorganize their connections continually (Purves, 1988).

It was intimated above that chaos frees dynamics from the restrictions of order and predictability, permitting a system to investigate in random fashion all of its dynamic potential. Intuitively, deterministic randomness is a highly effective strategy when-

ever and wherever a system must respond adaptively to conditions that are unpredictable in their nature and their timing. Chaos can provide solutions nondeterministically with a probability of one (Ford, 1990). Accordingly, neural pattern formation by the foregoing accounts is analogous to chaos with feedback. If the formation of neural connections was fully program driven, then the program would have to catalogue all likely environmental and biodynamic challenges. The alternative is to possess a means for generating variations of synaptic patterns randomly (i.e., chaos) and a means of pruning them according to their success in addressing the given problem (i.e., feedback). A chaotic system with feedback eschews foreknowledge of the kinds of challenges it would face and the kinds of resolutions it would achieve.

Developmental issues in physical-symbol systems.—In the above expressions of pattern formation in physical and biological systems, it is largely the free interplay of forces that realizes stationary and transitory states. New orderings are consequences of conditions on a system's continuous dynamical processes. Efforts to understand the new orderings characteristic of the developing child commonly take a very different perspective, however—one in which the focus is discrete symbolic processes. Perception and action are interpreted as computations over representations, suggesting that these biological capabilities—in their mature and developing forms—can be accounted for (simulated by) discrete occurrences in automata. This is, of course, the now-classical physical-symbol system hypothesis (Newell, 1980), which holds that any system of sufficient complexity to be called intelligent is a symbol-manipulating system.

It is important to inquire whether a strictly symbol-manipulating system can indeed develop. The question has to be sharpened somewhat: Can there be a progressive emergence of truly new levels of order? Suppose that perception and action capabilities develop according to a strategy in which hypotheses are advanced and evaluated; for example, "If I close the shoulder joint angle at rate u and the elbow joint angle at rate v then I will get an arm trajectory of the kind T ." A hypothesis would have to be represented by the concepts available to the child, as would the evidence (e.g., muscular sensory data, visual impressions, environmental consequences) for its evaluation. If the evidence is sufficient to confirm the hy-

pothesis, then the fact (in our example, a movement control strategy) to which the hypothesis refers can be registered in the representational (symbolic) medium. It must be the case, however, that the range and variety of hypotheses that can be entertained, and the range and variety of evidence statements that can be considered, are restricted to the expressive range of the symbols available to the child at that particular point in time. The child's symbol system must be sufficiently rich to represent the conditions referred to by hypothesis and evidence. Any hypothesis or source of evidence that requires other symbols, different from those comprising the child's current representational medium, are ruled out.

An argument of the preceding kind is a criticism of the idea that the development of a child's perception-action capabilities is fundamentally the development, through concept formation, of increasingly more powerful representational-computational systems (Fodor, 1975). The argument rejects a computational means of increasing the representational complexity of a strictly symbol-manipulating system. Such a system cannot develop the capacity to represent more states of affairs (hypotheses, evidence) at some later date than it can represent in the present. What it can do, on the basis of its experiences, is increase its appreciation of the states of affairs that do in fact obtain. With respect to the question posed above ("Can there be a progressive emergence of truly new organizations?"), the answer is "no" if the only mechanism of change is concept formation. Accordingly, if one is inclined to the idea that child development does entail transitions from weaker to stronger conceptual systems underlying perception-action, and does entail new orders of complexity, then one must look elsewhere for the basis of such development. Within the computer metaphor, one would need to consider, for example, ways in which the physical structure of the "computer" is altered. Considerations of this kind would return the discussion of the child's development of perception-action capabilities to the types of symmetry-breaking characteristic of continuous dynamical processes and/or to the processes formative of neural collectives.

To round out these comments, we note that the issue of how the concepts in the computational-representational perspective are grounded, that is, how they can refer to the child's body and to its environment, is

usually ignored. Similarly ignored is the issue of the origins of the constraints on the inference mechanisms, that is, the reasons that these mechanisms should function in just that way that renders their consequences relevant to the control of action. (For a variety of discussions of the significance and implications of these issues, see Carello, Turvey, Kugler, & Shaw, 1984; Clancy, 1992; Edelman, 1985; Harnad, 1990; Johnson-Laird, Herrman, & Chaffin, 1984; Turvey & Shaw, 1979; Turvey, Shaw, Reed, & Mace, 1981). The neural network perspective promises resolution of these issues in that concepts and constraints are emergent, arising from the interactions among very many subsymbolic processing units nested within interactions of the body and its surroundings. NETalk (Sejnowski & Rosenberg, 1987) is often cited as an example of successful emergence. A recent critical examination reveals, however, that the conceptual distinctions eventually exhibited by the network are encoded implicitly in the patterns fed to the network (Verschure, 1992). An unequivocal case of true emergence in subsymbolic systems remains to be demonstrated.

Hypotheses about the Development of Perception-Action Capabilities

To conclude, we take major themes from the articles of this special issue and express them through the concepts identified in the preceding survey of theories of pattern formation. The result is an inventory of developmental hypotheses. This inventory suggests the possibility of a dynamics approach to child development (Kugler, Kelso, & Turvey, 1982) as an alternative to conventional approaches emphasizing maturation (nativist), specific learning experiences (empiricist), cognitive stages (Piagetian), and strategies of encoding and retrieval (information processing).

Hypothesis 1.—Development is not of perception and action separately but of unitary perception-action systems in which the components relate mutually and reciprocally. Mutuality implies a sameness, a sharing by perception and action of a common basis. Reciprocity implies that they function in distinct but complementary ways.

Hypothesis 2.—The development and functioning of perception-action systems are pattern formation processes. That is, perception-action systems are macroscopic dynamical systems formed from the collective ac-

tion of many degrees of freedom. They are identified by one or more collective variables and associated with one or more attractors.

Hypothesis 3.—The specific perception-action patterns developed by the child are not present beforehand; that is, they are not encoded in either the neural or biomechanical degrees of freedom.

Hypothesis 4.—Growth-related changes of forces and scales are one source of new perception-action patterns. The forces are those acting upon and produced by the child. The scales are the lengths and masses of the child's body and of the supporting and opposing features of the environment. At critical values of force and scale, existing patterns become unstable and new patterns emerge.

Hypothesis 5.—The properties, features, dimensions, and so on, whose changes lead to new perception-action patterns, are unspecific to the new patterns, neither resembling them nor prescribing their details. Conventionally, these changes are referred to as *control parameters*.

Hypothesis 6.—Specific perception-action patterns arise most generally as a function of the control parameters residing in specific regions of the parameter space. Most generally, therefore, developing a new pattern requires that the child discover the appropriate region of control parameter values.

Hypothesis 7.—With respect to limb control, the child explores how forces (muscular and nonmuscular) and forms (limb configurations) join locally to create spatiotemporal organizations of greater size and time scales (interlimb movement patterns).

A. Nonspecific and aperiodic movements of the infant provide a rich source of random interactions with the body's appendages and with the surroundings. These permit the infant to explore, in chaos-like style, various parameter spaces.

B. Achieving fluency in intra- and interlimb coordination is the progressive discovery of how to sculpt the force structures associated with spatiotemporal configurations of limb segments and environmental objects (e.g., gravitational, elastic, and reactive forces) into the force structures that are required. The discovery is of patterns of muscular forces that are economical in time and magnitude.

C. Limb segments and combinations of limb segments are rendered controllable by the formation of neuromuscular collectives or synergies that behave as single functional units. This development occurs through autonomous principles that rely on explorations for their manifestation.

D. Spontaneous limb movements and variations of limb movements often constitute specific explorations of the intrinsic dynamics of limbs and tasks. These explorations reveal the stable patterns of those dynamics and contribute to the selection of the neuronal groups underlying the relevant synergies.

Hypothesis 8.—Pattern selection through exploration exploits the information produced by the collective action of the many degrees of freedom involved. Most important, this synergetic information is of a higher order and specific to the states (stability, instability) of the child-environment system. The changing sensitivity of the child to information in this synergetic, specificational sense is a key feature of the developmental process.

Hypothesis 9.—A slow variation in a given control parameter can bring about either a continuous or a discontinuous change in perception-action patterns depending on the parameter's nature and its position in the parameter space. Patterns will differ in the manner in which they emerge (gradually, abruptly), and children will differ in the manner in which they develop a given pattern and in the pace at which they develop a given pattern.

Hypothesis 10.—Each perception-action pattern that develops has its own dynamics, imposing, in turn, constraints on what developments are subsequently possible. Child development is execution-driven, with upcoming states dependent upon current states rather than upon prior states.

Hypothesis 11.—Certain lines of development and the perception-action patterns they give rise to are rare because the ranges of control parameter values dictating the patterns are narrow and hard to resolve, and the resultant patterns are unstable.

Hypothesis 12.—Because pattern formation is a function of the control parameters assuming certain values, the appearance of new perception-action patterns in the child can be followed by their disappearance, which in turn can be followed by a subse-

quent reappearance, as control parameters drift in and out of critical regions.

Hypothesis 13.—Development of perception-action systems expresses a weak coupling of cyclic processes at different time scales. A spectroscopic approach is implicated, directed at revealing the relation between the important repetitive processes going on within the child-environment system and the time domain in which they occur.

The preceding 13 hypotheses vary in degree of specificity. Some are more suggestive of concrete experimental questions than others. Further, the preceding 13 hypotheses vary in scope. Some are considerably broader in the range of developmental processes they are intended to cover than others. Ideally, the reader can discern the joint origins of the hypotheses in the articles of this special issue and the survey of pattern formation principles. The list of hypotheses is certainly neither complete nor correct in all of its details, and there are surely redundancies. It does, however, convey the kinds of conceptions that would be included in a theory of child development that took general principles of pattern formation as its departure point.

Concluding Remarks

There are a number of motives for relating perception-action capabilities to processes of pattern formation (e.g., Kelso, Delcolle, & Schöner, 1990; Kugler & Turvey, 1987; Turvey, 1990), for emphasizing information in its synergetic and specificational sense (Gibson, 1986; Haken, 1988; Kugler & Turvey, 1987; Turvey, 1992), and for expressing developmental issues in general dynamical terms (see Kugler et al., 1982; Schöner & Kelso, 1988; Thelen, 1989). The immediate benefits of pursuing a dynamics approach are radically new and potentially productive ways of thinking and inquiring about child development. The long-term benefits are disclosures of the intimate connectedness between human behavior and the rest of nature (Haken, 1983; Iberall, 1987; Yates, 1987b).

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