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THE ACQUISITION OF PHONOLOGY IN A DYNAMICAL MODEL OF HUMAN INFORMATION PROCESSING: A PRELIMINARY ACCOUNT

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ABSTRACT. The problem of the acquisition of first language phonology is dealt with within the general information-processing perspective. In this sense, language acquisition is viewed as a process of biologically founded pattern formation due to information exchanges between an adult and a child. Moreover, the process is cognitive in that the child, as a goal-seeking and error correcting individual, undertakes an intricate task of compressing a huge variety of linguistic stimuli in order to build an effective information code. It is further assumed that the basic mechanism which leads to the establishment of fully articulate linguistic ability is that of simulation. The mechanism works through a compression of a set of initial variables (i.e. initial conditions) into a minimum length algorithm and a subsequent construction of an integrated system of language-specific attractors. It is only then that the language user is capable of participating in an information transaction in a fully developed manner.

1. INTRODUCTION: OUTLINE OF THE PROBLEM

The paper is commenced with some cautionary remarks. Namely, its aim is not to examine in any detail the "diachrony-in-synchrony" of language acquisition, that is, I do not intend to (a) review the various phases of first language acquisition in the style presented by numerous scholars who have contributed significantly in the area (cf. Jakobson, 1941; Lenneberg, 1967; McNeill, 1970; Ferguson and Garnica, 1975; Ingram, 1976; Blache, 1978; Wode, 1981, to quote but a few prominent names), and (b) discuss the acquisitional changes in an exclusively data-based (i.e. empirical) framework. Nor will I discuss the problem strictly in the machine-analogue framework (perhaps best instantiated by the question "Can computers think?") as would be expected for the occasion. Rather, I shall set out on the task of presenting the problem of the acquisition of phonology within the general information-processing perspective.

First and foremost, this perspective entails that language is a communication system which, in turn, is a hierarchy of interconnected parts. Any communication system is specialized for the transmission of information. Most generally, the components of such a system include, according to Shanon and Weaver (1949), an information *source* and a *destination* connected by a *channel* which is capable of carrying messages from one to the other. In addition, an effective communication system requires a device called a *transmitter* which transforms the messages produced by the source into signals that the channel can carry, and a device called a *receiver* which, in turn, transforms the signal into a form that the destination can accept. The components of the communication system thus described are shown in Fig. 1 below.

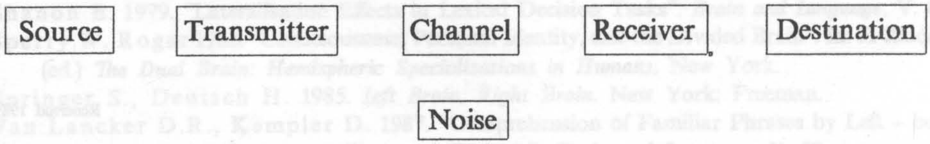

Fig.1

The signal carried by the channel is called an *information code,* and the activities of the transmitter and receiver are called *encoding* and *decoding,* respectively. The component of *noise* present in the flow chart refers to the sources of error in the transmission of messages, in particular to disturbances in the communication channel. Of course, errors can also be generated during encoding and decoding. Let us emphasize at this point that language acquisition is part and parcel of human communication which, except for the medium that carries messages (e.g. air) is entirely biological. Moreover, every human being can function both as a source, transmitter, receiver, and destination. In other words, every human individual is a *self-contained communicational unit.* We must, also remember that decoding implies comprehension (i.e. bottom-up process), whereas encoding refers to an executive activity of production (i.e. top-down process). Obviously, such succinct definitions of the hierarchic transmitter/receiver activities would be overly simplistic since between the two phases there run complex thought processes which transmit *cognitive information* also carried as some kind of neural code along the complex fabric of the human brain.[1] Can this information-processing

[1] As regards the definition of "information", I follow Shanon and Weaver who have defined it as the reduction of uncertainty.

perspective be of any value in analyzing the problem of the acquisition of phonology? If so, how can it deepen our understanding of the problem? It is precisely these questions that the present paper aims to deal with.

Let us begin our conjectures by expressing the fundamental truth that biological organisms are involved in *information transactions* and that they do so permanently. We must also stress that these transactions come in the form of some kind of "struggle" (or confrontation) both between whole species and between particular individuals within one species. The aim of this confrontation seems to be the *simulation of the "opponent", its prediction (especially, the prediction of its behaviour), and ultimately its control,* that is, the shaping of the opponent's behaviour that would not jeopardize the other interacting organism's life. This tri-partite structure of information transaction, generally, provides the most universal background of information transactions between (and among) biological organismal entities that I would like to propose here.

Seen in this light, language acquisition may be viewed as a process of biologically-based pattern formation that is accomplished as a result of information exchanges between the Softwares (i.e. "Minds") of the "contesting" human individuals one of whom is an adult and the other is a growing child. Let us digress at this point and observe that information processing by a *biological central nervous system* is *not* to be equalled with information processing by *finite-state automata* (such as Turing machines or computers). The latter generate outputs through sequential dependencies (e.g. from left to right), piecemeal, that is, one bit at a time in a so-called Markov process, which may lead to a purely mechanical generation of output strings of elements (e.g. letters, morphemes, words, sentences, etc) and to further expansions by simply adding new bits to the end of the previously-generated string.[2] This does not mean that the machine-like style of computation is hereby totally denounced, as sequential (i.e. linear) computation constitutes a part of human information processing. Rather, I wish to emphasize that the metaphor of the computer has its rather serious shortcomings. Thus, it seems that the major restrictions on finite-state automata are these:

– they are more mathematical than physical objects; as such they are not capable of adaptive behaviour (e.g. writing or modifying any input element);

– they are devices for manipulating symbols, but as Bieri (1988: 171) rightly put it: "the manipulation of symbols according to certain rules *by itself* creates no understanding whatsoever on the part of the system";

– subsequently, one may conclude that a computer implementation may not be sufficient, since it is completely blind to the meaning of the symbols it manipulates.

We can thus say that finite-state automata are in some important respects rather "aimless", i.e., they do not seek a goal by either computing the most

[2] Fine illustrations of strings of elements generated by an automaton can be found in Gross (1972).

desirable states or improving their performance with repeated trials. In other words, they are incapable of cognitive behaviour, that is, incapable of simulation, prediction, and control in their information processing.

On the contrary, most biological systems are *goal-oriented, goal-seeking* (or "error correcting"). Biological central nervous systems are never aimless in the sense that their workings ultimately lead to the understanding of effective strategies (or "unearthing" of algorithms) in the process of mutual simulation between the individual contestants, where each contesting individual tries to *compress* the variety of environmental stimuli it receives from the "opponent" and thus tries to classify him accordingly. In the particular case of language acquisition, information processing by a goal-seeking biological central nervous system of an infant leads not only to the simulation of the external world but also to the formation of an *effective information code* (i.e. language) which is required in the further course of information transaction. Obviously, this effective information code is also needed to compromise two conflicting requirements of any information processing by biological organisms, that is:

– *speed of transfer*, and

– *reliability* (defined here as degree of errorless reproduction of an abstract pattern sent from the first contestant). In addition to what we have just said, we must remember that biological systems are also *self-organizing* (a feature which cannot be attributed to automata) by virtue of their being capable of improving their performance while pursuing their communicative (i.e. interactive) task, and also in the sense that they can do so without explicit *outside* help (cf. Bremermann's (1967) view on this point). Moreover, such systems are called *cybernetic*, since they pursue their goal and generate their outputs while interacting with an *environment*. Doing so, they behave adaptively. According to Bremermann (1967: 60) "different goal-seeking systems have one aspect in common: The search for improved performance involves searching through very large numbers of alternative configurations". It is apparent that this is exactly what happens in language acquisition, and the acquisition of phonology in particular: the "tuning" to the spatial and temporal parameters of a language-specific sound system requires a search through a large number of alternatives.

2. THE NATURE OF COMMUNICATION TRANSACTION

The acquisition of a natural language is not a phenomenon which occurs in a vacuum, i.e. it is not *deterministic* in the sense that it materializes *unconditionally* (that is, no matter whether any external stimuli exist or not).[3]

[3] As shown convincingly by Fromkin et al. (1974), a child suffering from an extreme degree of social isolation is deprived of language to a considerable extent; its delayed acquisition is also heavily hampered.

Rather, the process will proceed most effectively if the child, viewed as a *hierarchical, goal-seeking* and *self-organizing cognitive system* (see also Pask, 1970), will get involved in information exchanges with other systems of the same kind and will receive a sufficient number of auditory-linguistic stimuli. Let us therefore address the issue of communication between two such systems. In the information-processing framework, communication may be viewed as a sequence of *mappings* (e.g. many-to-one, one-to-many, one-to-one) between a set of messages from the transmitter and a set of "operational regimes" of the receiver (which can be treated as a cognitive apparatus) undertaken in order to simulate (or model) one physical system by another with the ultimate goal of predicting its behaviour and controlling it. Let us remark at this juncture that Shanon and Weaver's static information channel only provides a one-to-one mapping between the transmitter and the receiver. This type of mapping should in a way be associated with the act of "cognition", for, as Nicolis (1987:20) put it: "The sole role of a classical channel is the mere *copying* (emphasis mine – S.P.) of the transmitted patterns, *as they are*, at the receiving end with the greatest possible reliability".

In light of the foregoing remarks, communication is to be treated as *information transfer* whereby a simulation of the "opponent" takes place with the use of optimum mapping (or optimum code) that compromises the requirements of the speed of transfer and reliability. However, we must at the same time remember that in the particular case of language acquisition we have to deal with the fact that one of the "contestants", that is, the child, is additionally involved in the complex operation of construction of an effective information code (i.e. language) that the adult contestant already possesses. In this sense, the child is simultaneously involved in a very special type of *decision-making process* whereby it makes an evaluation of incoming evidence that is interpreted and "thrown against", as it were, an emerging criterion or a set of criteria (organized into an emerging percept). The process of gathering sensory evidence and the subsequent *matching* of it with the emerging percept would then require *simultaneity* rather than strict *linearity* of operations. Once we have accepted that standpoint, it becomes possible for us to adopt the view that every single act of linguistic observation by a perceiving child imposes on it the necessity to differentiate among a multitude of perceived speech signals. This means that the child must get involved in the parallel tasks of selecting relevant signals, rejection of irrelevant ones, subsequent reduction of excessive noise inherent in the vocal-auditory channel (e.g. excessive nasalization, stuttering, various linking phenomena, etc.) and the ultimate storage of discrete sound types in long-term memory where they are deposited and await an easy retrieval and (re)production. We might say at this point that "memory load" becomes an integral part of the information-processing framework.

In light of the above prefatory remarks, it seems that in order to attain a fuller picture of what happens in language acquisition it is necessary to concern ourselves with modelling information transactions in the following four respects:

- perception processes
- memory processes
- problem-solving processes, and
- production processes.

Obviously, a comprehensive description of the interplay of the four is a gigantic venture and by far exceeds the limits of the present paper. Therefore, in what follows I will limit myself to a rough indication of some of the problems that one can face while setting out on the task of examining the problem of the acquisition of phonology in the information-processing perspective.

3. SIMULATION

Let us commence this part of the paper with a description of the process of information exchange that results in the simulation of the "opponent", that is, another interacting biological system. In the framework adopted here, an information interaction is a *dynamic* process whereby a given biological system simulates another system. The goal is accomplished when it is capable, out of a finitely long temporal span which it receives at its disposal, of constructing *minimal length algorithms or compressed descriptions of the second interacting system. More precisely, we can say that the goal of simulation is accomplished if there follows a reduction in the number of degrees of freedom* in *state space* (which includes all possible states of the system in space), where the dynamic cognizing system starting from a set of *initial conditions* (or "variables"), of dimensionality N sooner or later locks in at a compact subset of the state space of much smaller (lower) dimensionality. This process of *convergence* (i.e. many-to-one mapping) is shown in Fig. 2.

	x_1	y_1	
initial	x_2		a compact subset of
conditions	x_3		lower dimensionality
(a set of	x_4		(collective preparties)
variables)	x_5	y_2	
	x_6		

Fig. 2

Let us imagine two self-organizing cognitive systems, System I and System II, which are involved in a process of mutual information transaction. In this case, for System I to be able to simulate System II, an important sine qua non prerequisite is demanded, namely:

The system must be hierarchical, that is, it must possess at least a *hardware level* (H) (which comprises energetic and structural properties), and a *software level* (S) (which comprises cognitive, symbolic, and functional properties). The mutual interactions between the levels and Systems are shown in Fig. 3.

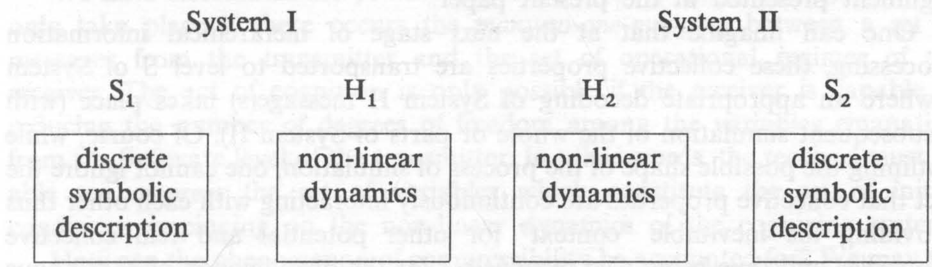

Fig. 3

It is implicitly assumed that human subjects who indulge in an information transaction satisfy the above-mentioned demands. Thus, in normal and healthy individuals, linguistic information in the form of a host of auditory variables emanating from the S-level of System II impinges on level H of System I. At this level there occurs a number of *cross-correlations* (or "convolutions") among the variables received and the intrinsic dynamics of System I at level H. It is also implicitly assumed that the dynamics at this level is *chaotic*, i.e. non-linear. Let us at this point briefly digress on two systems: linear and non-linear. According to Nicolis (1987), the crucial difference between them is that the former system is said to be *structurally neutral* in the sense that it demonstrates no preferred solution or set of solutions in its behaviour. Thus, the space through which the trajectories of a linear system are moved by varying the parameters is a space that is flat and smooth like a billiard table – any location is as good for the ball as any other. We can simply say that the space can be populated evenly with trajectories, and there are no locations, no *attractor points*, where the trajectories become especially and consistently dense. On the contrary, a non-linear system is *structurally stable* in the sense that it has a preferred solution or a set of solutions. The trajectories of a non-linear system move in a space which is not flat and smooth but wrinkled and indented with attractor points on which the trajectories consistently converge. The above description of linear and non-linear spaces provides a suitable metaphor for the activities of a cognizing self-organizing system that is involved in an information transaction, such as, for example, the acquisition of L_1 phonology by a child. Obviously, the cross-correlations which take place on H level of System I are non-linear and they result in the emergence of *collective properties* possessing fewer degrees of freedom than the initial set of variables sent from the interacting System II. Once again referring back to Fig. 2, we would say that the collective properties on the right-hand side of the Figure represent attractor points of much lower dimensionality to which a set of initial conditions (i.e. variables) finally converge in the process of *compressing* the "opponent's" phonological code. This point has a great bearing on the argument presented in the present paper.

One can imagine that at the next stage of hierarchical information processing, these collective properties are transported to level S of System I where an appropriate decoding of System II message(s) takes place (with a subsequent simulation of the whole or parts of System II). Of course, while outlining the possible shape of the process of simulation, one cannot ignore the fact that collective properties are continuously interacting with each other thus providing the inevitable "context" for other potential and real collective properties and thus being also responsible for the phenomenon of continuous "self-reference". In fact, self-reference constitutes part of the discrete description of the symbolic content of the cognitive system's Software level. Furthermore, one should not ignore the fact that, hierarchically speaking, the S level exercises *feedforward control* on the H level (c.f. Puppel, 1988). This latter mechanism considerably facilitates and enhances the process of formation of collective properties (it enhances and improves convergence) in the acquisition of phonology. Indeed, the crucial function of the S level is that it brings forth "memory effects". In this sense, the S level serves as a long-term memory tank of symbols the content of which participates in the cross-correlations mentioned above.

The problem of the existence of collective properties links up with the hierarchical nature of the cognizing device (in our case: the human processing, cognitive system). In the model developed here, the interacting variables (and/or parameters) are at a higher level formed into collective properties as a result of the non-linear, non-equilibrium dynamics going on at the level just beneath. Thus, we can say that as information moves to a higher level, we witness a tremendous reduction in the number of degrees of freedom. Simply, the higher level, organized in terms of attractor points, receives selective information from the lower level and it automatically exercises feedforward control which, in turn, considerably harnesses the further dynamical cross-correlations on that lower level. At this point let us emphasize that the human processing cognitive device (i.e. the brain) is an *open system* and as such it is markedly distinct from isolated *closed systems* (e.g. a physical system at its lowest hierarchical level, namely the level of equilibrium thermal mixing) in that it need not – and does not – tend toward a state of thermodynamic equilibrium. As such, the human brain that is maintained by a continual flow of energy, is capable of generating new information (and new organization) as an open, non-linear, non-equilibrium, self-organizing cognitive system. Above all, it is capable of simulating any other interacting system in a process of information transaction.

4. COMPRESSIBILITY

We have stressed in the previous sections of the paper that cognition can only take place if there occurs the *many-to-one-mapping* between a set of messages from the transmitter and the set of operational regimes of the receiver. The act of cognition is only possible if the receiver is capable of reducing the number of degrees of freedom among the variables emanating from the Software level of the transmitter. In other words, the receiver must be able to *compress* the set of variables which constitute the set of initial conditions impinging on the non-linear dynamics of the cognizing system.

How can the phenomenon of compressibility be accounted for? We may try to explain it by pointing out the fact that humans are permanently involved in performing hosts of meticulous observations of a certain phenomenon (or a set of phenomena) and then trying to "theorize" about it. What they actually do is compress the strings of observations into an essentially simple brief analytical formula (i.e. the "algorithm") which may then be conveniently stored in dynamic memory. Obviously, the storage of an algorithm from which individual patterns can be produced is much more economical than the storage of the bare patterns themselves. One might also add that this unique capability of compressing long and complex strings of impinging environmental stimuli (or observations) and then using the constructed *minimal length algorithm* in order to simulate physical phenomena, constitutes the essence of information processing in human cognition. It is also at the base of language acquisition. Moreover, let us not neglect the fact that compressibility partly results from the limited channel capacity of humans. As was shown by Miller (1956) in his classic paper, the channel capacity of human subjects or the number of categories of non-dimensional (i.e. one-channel) stimuli from which unambiguous judgments can be made is of the order "Seven plus or minus Two". A dynamical model of information processing by a self-organizing system should be able to reproduce the magic 7 ± 2 based on a mechanism which possesses the ability of squeezing or compressing practically an unlimited number of bits per *symbol*. Such a mechanism gives rise to a phenomenal memory which offsets our pitifully small capacity for processing information by abstracting the essential features of the perceived external stimuli in a hierarchical fashion thereby allowing the expression of our experiences in the form of simple "laws" (or "rules") or brief words. This demonstrable ability to compress varied stimuli (or to map information from higher to lower dimensionality) offers a number of evolutionary advantages. Namely, it enables the storage of information in dynamic memory and, when triggered by incoming external stimuli, an extremely broad array of complex behavioural repertoires of the system. Needless to say, this ability constitutes the base of the dynamical model of human information processing. Let us now try to construct a possible scenario for the acquisition of phonology in the information-processing framework.

5. A POSSIBLE SCENARIO

Both the human transmitter and receiver should be understood as information processors (analogue or digital). Obviously, since our focus is exclusively on language acquisition, it is the receiver that is the main target of our considerations. Thus, we may define it as a cognitive agent which is capable of tracking and identifying the parameters of an unknown signal or "pattern", usually contaminated by a certain amount of noise. In order to identify the signal, the brain processor must perform the following operations:

(a) it must generate patterns from "within" a wide variety of spatial-temporal patterns (we shall also call them "attractor-templates") which define the higher levels of the processor's Software;

(b) it must cross-correlate (i.e. compress) the incoming variables with the generated pattern; and

(c) it must be able to select (or "filter out") the pattern which forms the closest cross-correlation with the received unknown signal or trigger. The filtering is usually non-linear so that the impinging stimuli can converge on the selected set of attractor-templates. As was emphasized in the previous sections, the process essentially consists in the reduction of the degrees of freedom of the variables.

One can now ask the following question: "What happens when information begins to flow from, say, System II to System I?" However, before we answer the question let us observe that the human brain functions as a non-linear oscillator. We may repeat after Nicolis (1987:67) that the brain of an infant as well as that of an adult in the phase prior to excitation (i.e. in the absence of any environmental input, in the so-called Rapid Eye Movement phase of sleep) is "free running" on an unstable limit cycle with a fundamental ("sampling") frequency 10 Hz (the "α-rhythm"). In terms of a neural regime of the receiver, one can imagine that at the outset of a mental task such as a perceptual activity, information begins to flow along the ascending (i.e. afferent) branch of the reticular formation system[4] or through other pathways of the peripheral nervous system, carrying from the outside or from the inside, specific sensory

[4] Structure in the brain stem central region on both sides of medulla oblongata.

inputs to be identified by the cortex. The thalamocortical oscillator is now under the impact of a fluctuating input and as a result the sampling intermittent limit cycle is deleted in favour of a *metastably chaotic cycle* (Nicolis, 1987:68) whose scanning manifestations turn into a *spasmodic* (i.e. excitable) and non-periodic oscillation. Under these neural conditions, that is, when there occurs a coupling between the environmental stimuli and a limit cycle oscillator in the spasmodic chaotic regime, cognition ensues. It is manifested at the cortex as a result of a matching process between pairs of spatial-temporal patterns, each containing a great number of elemental units (i.e. neurones). Obviously, in each pair one pattern represents the unknown information. It is embodied in incoming triggers, coded in sequences of pulses from the peripheral nervous system. The other pattern of the pair is one of the attractor-templates created by the processor. The coupling (or cross-correlation) between the above two patterns of each pair takes place dynamically and the result of this cross-correlation (in phase and amplitude) determines the *degree of cognition* between the incoming and unknown and expected patterns. So much for the neural side of the perceptual process which underlies the acquisition of phonology.

We noted in the previous sections that the process of simulation starts with a set of initial conditions impinging on the receptive apparatus of interacting System I. We also noted that next they are compressed into a subset of lower dimensionality in an operation of matching the variables with the attractor-templates. It is assumed that simulation is complete when the cognizing system has the greatest *sensitivity* to the initial conditions. In our tentative scenario, the acquisition of phonology is a dynamic process which starts with some initial degree of an infant's sensitivity to the initial stimuli and finishes off in a period of acquiring the greatest degree of sensitivity to the perceived set of initial conditions. The process is illustrated in Fig. 4.

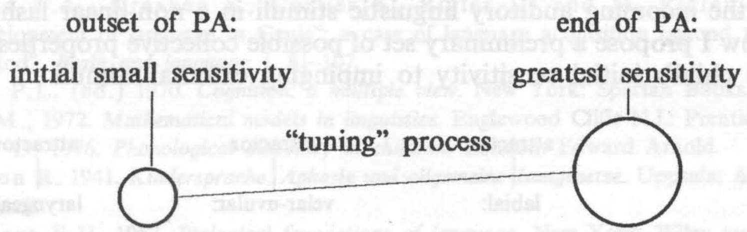

Fig. 4

where:
"a" – a small subset of discrete phonological language-free units,
"b" – a complete set of discrete phonological language-specific units.

It is suggested that the degree of sensitivity is directly proportional to the amount of knowledge about the initial conditions and a number of attractor-templates with which the acquisitional process starts. We should observe at this juncture that it has been known for some time now that even one-month-old infants can discriminate between two syllables that differ only with regard to the feature of voicing, [ba] versus [pa] (cf. Eimas et al., 1971). It follows that one can assume the existence of some initial inborn sensitivity which, upon increasing and random exploration of large portions of the limited space of the vocal tract, grows in proportion to the deepening process of partitioning and category formation in the receiver's Software. As indicated earlier in the paper, the process involves the non-linear topology of space. It is characterized by the presence of "indentations" in the form of "preferred" regions on which the system converges and in which it demonstrates greatest stability. In our case, it is the limited space of the vocal tract with its discrete attractor points (e.g. labial, velar, laryngeal) to which the neuro-muscular complexes traverse. In the present tentative scenario we suggest that the acquisition of phonology by a child may be characterized by the following:

(a) in the very beginning it has at its disposal a very small subset of inborn (and therefore "language-free") attractor-templates which serve as *primitive attractors* in the ensuing process of simulation of the adult's phonological code via compressibility. The existing evidence suggests that the child's neuro-motor system traverses the limited space of the vocal tract through the most preferred and genetically endowed (so-called "phylogenetic tail") points of attraction which most certainly comprise the *labial, velar-uvular* and *laryngeal* areas. The collective properties generated at these primary attractor points are interpreted here in terms of two parameters, namely, at which point in space the system *remains* at some point of time and what it *does*, that is, in what *event* the system participates. Looking at collective properties in this way we may say that the space of the vocal tract is initially perceived (or understood) in terms of the above-mentioned primitive attractors and events. As collective properties, they compress the incoming auditory linguistic stimuli in a non-linear fashion. In Fig. 5 below I propose a preliminary set of possible collective properties which define the child's initial sensitivity to impinging external stimuli.

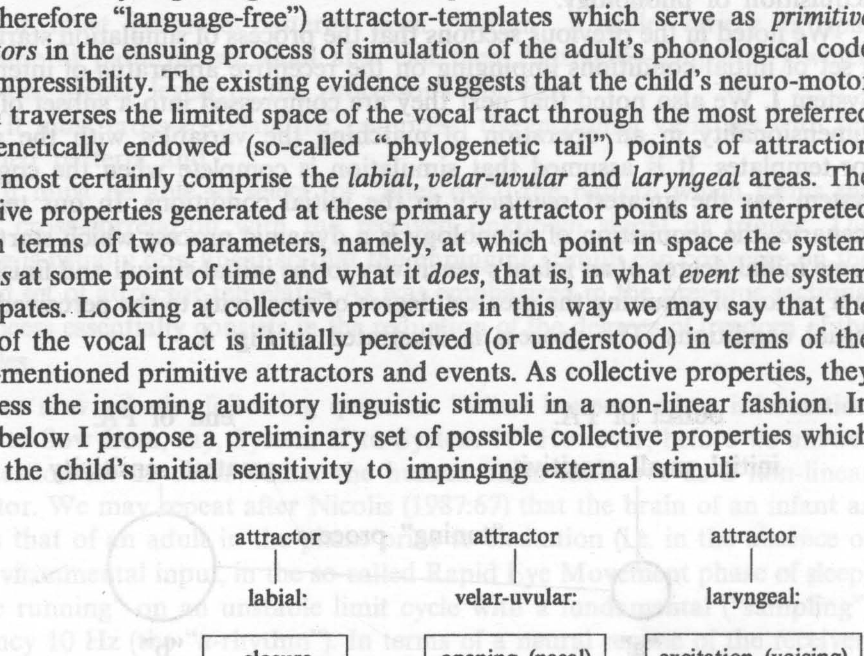

Fig. 5
(a possible initial set of collective properties)

(b) With passing time and continual searching through a large number of spatial and temporal alternatives, that is, when the child randomly explores large portions of the vocal tract, it gradually improves its storage capacity and increases its tuning abilities by establishing an increasing number of language-specific discrete attractor-templates. Obviously, it also adds new events (e.g. lateral closure, intermittent closure, delayed release, etc.) to the old ones. This process may assume the shape of a Markov chain (it is well seen in so-called "implicational phonological universals").

(c) The process of the acquisition of L_1 phonology is considered accomplished when the limited space of the vocal tract is finally perceived in terms of a complete set of language-specific collective properties arranged into a *system* and when the child has been able to construct a minimum length algorithm which is a replica of the phonological algorithm possessed by an adult speaker. We may simply say that the child has reached the highest degree of sensitivity which enables it to participate in an information transaction in a more developed manner owing to a more or less successful simulation of the linguistic code of the adult speakers.

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