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Multi-stability in a Dynamic Model of Language Development

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Abstract

Development is a serial changes within a complex dynamic system. During development, children reach and pass different stages while their dynamical development systems change their states. We hypothesize that in a developmental process, each stage can be accounted as a stable point and the system can be considered multi-stable due to different stages of development. We propose a dynamical model for language development which can explain some developmental disorders in this field, such as pragmatics impairment in autistic children.

Keywords: Dynamical System Theory, Multi-stability, Pragmatics Language Impairment, Autism.
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1. Development as a multi-stable dynamic system

A dynamical system consists of a set of variables that describes its state and a law that specifies the evolution of the state variables over time [5, 8]. Dynamical systems theory deals with the qualitative behavior of dynamical systems. In other words, this theory is a tool of describing how one state develops into another one over the course of time [5, 8]. Based on this theory, developmental

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process can be described as changes in cognitive abilities through time. Development is a global phenomenon emerging from local interactions between environmental factors and intrinsic dynamics [9].Therefore, it can be said that development is a serial changes within a complex dynamic system. These chronological changes create something more from something less, e.g. a talking toddler from a speechless infant [7]. During development, children reach and pass different stages while their dynamical development system changes its states.

In a dynamic system, a stable point or attractor is a kind of fixed point that represents a state to which the system evolves over time and to which it returns after being perturbed [5, 8]. An attractor can be portrayed as a valley in a hilly land. As illustrated in Figure 1, a new element entering an attractor's basin of attraction, represented by a ball, will roll down the hill and come to rest in the valley. The wider the basin of attraction (the width of the valley), the greater the range of states that will converge on the attractor. The depth of the valley represents the strength of the attractor.

It should be noted that a system may have two or more attractors. Such systems are named multi-stable systems [9].
During development, there are two main characteristics:

I) Development has cascade stages with defined sequences. It means that the duration of each stage can vary but stage missing or order changing may not happen in a normal development.

II) In developmental process, real-time changes in local stages, lead to an emergent global product that is actually the developed ability of the person.

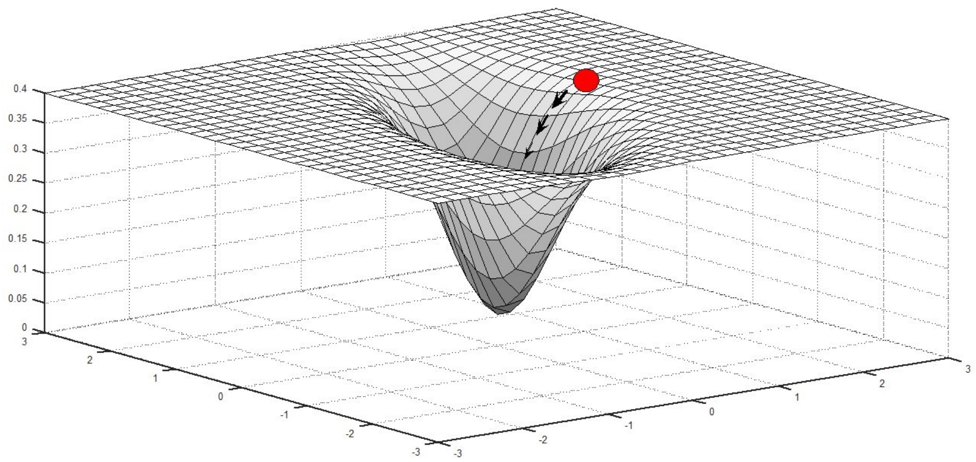

Figure 1: The landscape for an attractor. The wider the basin of attraction (the width of the valley), the greater the range of states that will converge on the attractor. The depth of the valley represents the strength of the attractor.

2. Multi-stability models language development

According to the literature, language in a Typically Developed (TD) child has 5 levels of development: 1) Understanding and recognition of pre-linguistic informative actions, 2) Intention to communicate and learning how to get and convey the communicative messages, 3) Lexical-semantic processing, 4) Syntactic analysis and acquisition of grammatical rules, and 5) Pragmatic integration. It should be noted that the above-mentioned levels have hierarchy and each level lays the ground for the higher ones [1].

We hypothesize that according to dynamical system approach, in a developmental process, each stage can be accounted as a stable point and the system can be considered multi-stable due to different stages of development. We propose a dynamical model for language development which will explain some developmental disorders in this field. In this model, each level is considered as an attractor. It means that in the trajectory of development, each level can be defined as the valley of a stable point. One will stay in that level regardless of small perturbations. However, these stable points are actually locally stable; it means that after a time (while they reach a threshold), they lose their stability. At this time, the development trajectory goes to the next level that corresponds to the next locally stable point in the model. Finally, after passing all levels of development, the trajectory reaches a globally stable fixed point in which the completion of development happens (Figure 2). The key question is that how a transition happens from one attractor to the next.

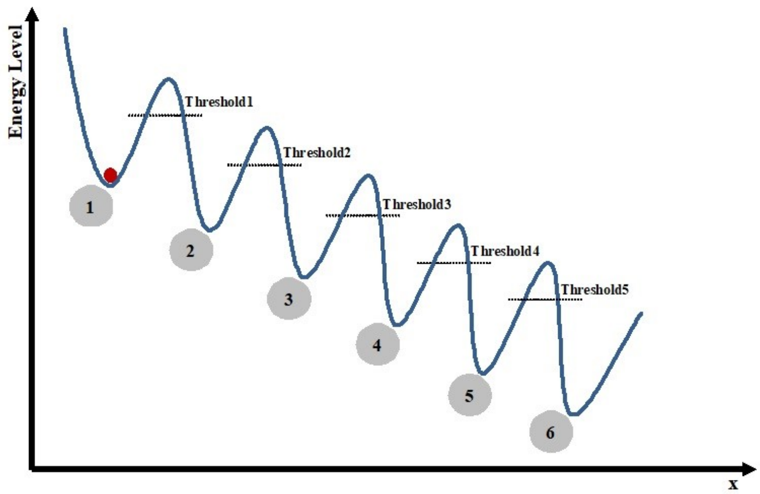

Figure 2: Multi-stability in language development's levels; each stage is a locally stable point and it loses its stability after reaching a threshold. Then the development trajectory goes to the next level and after passing all levels of development, the trajectory reaches a globally stable fixed point (attractor 6).

In a multi-stable system with M attractor states, $x_1^*, x_2^*, \cdots, x_M^*$, we would like to obtain the ordering of the attractor states by some energy-like functions, $U_1, U_2, \cdots, U_M$. The function $U(x)$ for any point x, in the state space of the system, gives us information about the probability of transition between attractor states in a developing system [11].

Let us consider a system of N variable x_i for evaluating language development (x_i can be Mean Length Utterance (MLU), Type-Token(TT) ratio or any other variable for measuring the changes of language);the values of x_i describe the language state $x(t) = \big(x_1(t), x_2(t), \cdots, x_N(t)\big)^T$.

The dynamics of these states is determined by the first-order ordinary differential equations (ODEs):

$$\begin{cases} \frac{dx_1}{dt} = F_1(x_1, x_2, \cdots, x_N) \\ \frac{dx_2}{dt} = F_2(x_1, x_2, \cdots, x_N) \\ \qquad \vdots \end{cases} \tag{2.1}$$

Or in vector form:

$$\frac{dX}{dt} = F(X) \tag{2.2}$$

$F(X)$, is the force which changes the states of the inertia-free system. Potential function in 1D gradient system when we go from state A to state B [11]:

$$U_{AB} = U_B - U_A = \int_{x_A}^{x_B} F(X)dx \tag{2.3}$$

And

$$F(X) \sim -\frac{dU}{dx} \tag{2.4}$$

In this system, we can consider a transition probability for going from state A to state B; $P_{x_A \to x_B}$.

According to the laws of classical physics, this transition probability has an inverse relation with U_{AB}. The larger the potential U_{AB}, the more likely the transition is [11].

If we have a Hamiltonian system, there exists a function $U(x)$ with the following properties:

$$\frac{\partial U}{\partial x_1} = -F_1(x), \cdots, \frac{\partial U}{\partial x_i} = -F_i(x), \cdots, \frac{\partial U}{\partial x_n} = -F_n(x) \tag{2.5}$$

By integration, the potential function $U(x)$ can be obtained [11]:

$$U(x) = -\int F_1(x)dx_1 + \cdots + F_i(x)dx_i + \cdots + F_n(x)dx_n \tag{2.6}$$

In this system, the transition from state A to state B, follows the Least Action Path (LAP), and $P_{x_A \to x_B}$ is determined by the potential of attractor states and saddle points between them [3]. The transition rate $P_{x_A \to x_B}$ is related to $U_{AS}(x) = U(x_S) - U(x_A)$. Here x_S is the saddle point between two attractors x_A and x_B, as shown in Figure 3.

By our proposed model, we can explain some kinds of language impairments such as pragmatics problems in autistic children. Autism Spectrum Disorders (ASDs) are neuro-developmental disorders characterized by serious impairments in the domain of communication and social interaction [2]. Language as the result and the tool of communication is impaired in individuals affected by ASD. Language impairment in ASD has a spectrum. At one extreme, there are autistic patients with no language impairment. At the other extreme, there are autistic patients with impairments in structural language abilities (e.g. phonology, syntax, and semantics). Most of the autistic individuals have language impairment in pragmatics that is related to the context. They have difficulties in understanding some expressions such as irony or metaphors and proverbial phrases [4, 6]. In this regard, we hypothesize that a kind of bifurcation happens in language development trajectory of autistic children. This bifurcation in fact, leads to losing a local stable point (Figure 4). For the autistic individuals with pragmatics impairment, the 5thstable point (that is related to pragmatic integrations) is destroyed. According to dynamical systems theory, the qualitative structure of the trajectories can change as controlling parameters vary. For instance, fixed points can be created or destroyed, or their stability can change. These qualitative changes in dynamics are called bifurcations, and the parameter values at which they occur are called bifurcation points [5, 8]. At the beginning of language development, the trajectory corresponds to the lower level processing of language. As the trajectory evolves, higher level aspects of language such as syntax and pragmatics

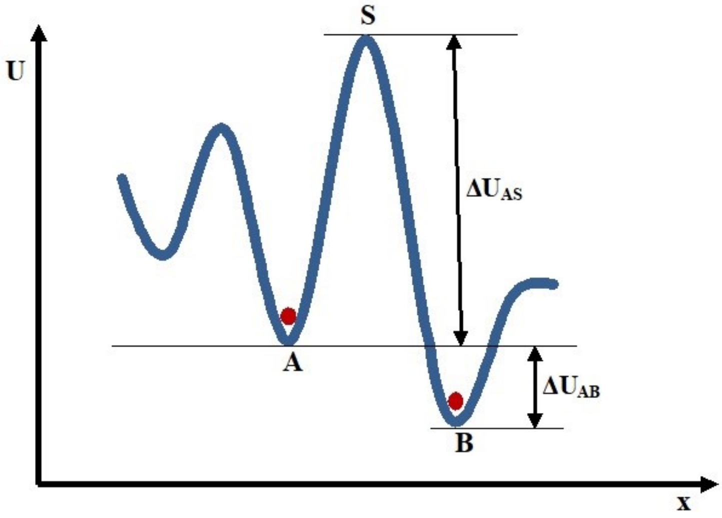

Figure 3: Schematic potential U and attractors in one-dimensional multi-stable dynamical system. The transition rate $P_{x_A \to x_B}$ is not determined by ΔU_{AB} but by ΔU_{AS}.

will be emerged. Therefore, it could be concluded that autistic individuals with normal language, have the same trajectory of language development as autistic individuals with pragmatics impairment until they reach a point in which a kind of bifurcation happens. At this point, their common path differentiates to two different ones: a normal trajectory which approaches the highest level of language development i.e. pragmatics integration, and a trajectory with inappropriate variations that leads to misunderstanding the pragmatics. According to our proposed model, in the latter trajectory, the saddle point between the 4^{th} and the 5^{th} attractor state does not exist and these two attractor states are actually merged. At the bifurcation point, the initial values of the system determine the future path of the system which is corresponding to the normal or impaired state of language. Therefore, the parameters of language development system (such as age of individuals, environmental factors, and social conditions) determine the final state of language trajectory.

In another point of view, it can be said that variation in language development trajectory of autistic children becomes very slow when reaches the higher level processing such as pragmatics. At the beginning, while the trajectory is corresponding to the lower level processing of language, the variation has normal speed. According to dynamical systems theory, the trajectory of language development in pragmatics level, has a slow passage through a bottleneck and spends practically all its time getting through it. Therefore, it could be concluded that the trajectory of language development in autistic individuals with pragmatics language impairment reaches a bottleneck in higher level aspects of language and their language development does not complete normally. According to our proposed model, potential of the saddle point between the 5^{th} and the 6^{th} attractor state is very high. Therefore, the transition rate $P_{x_5 \to x_6}$ has a small value that means the 5^{th} level of development can hardly be passed (Figure 5). The time that the trajectory spends in the bottleneck is related to the environmental and social conditions. According to dynamical system theory, exerting an external force may drive the system to come out of the bottleneck; consequently, the trajectory continues its normal path instead of trapping in a bottleneck. In this regard, there are some intervention packages that improve pragmatics in autistic children [10]. We suppose that these packages work as an external force. According to dynamical system theory, suitable external force should be consistent with

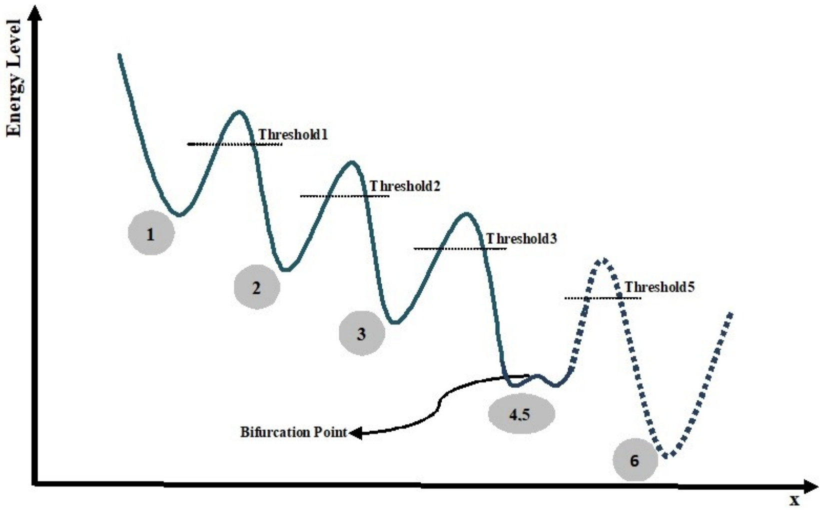

Figure 4: Pragmatics impairment in language development of Autistic children; A bifurcation happens before the last level of language development. For the autistic individuals with pragmatics impairment, the 4^{th} and the 5^{th} attractor state are merged.

system's characteristics, such as natural frequency. Therefore, the intervention packages should be designed as an external force and in accordance with the system's characteristics. Understanding the language developmental process can help speech-language pathologists choose the best intervention method for designing a package.

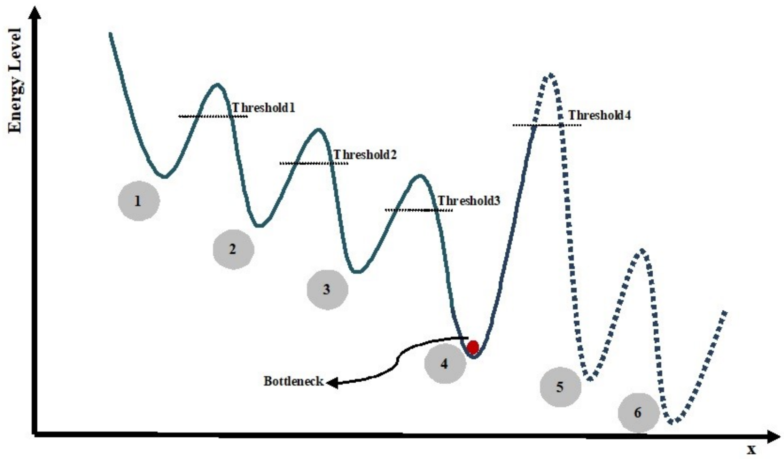

Figure 5: Pragmatics impairment in language development of Autistic children; Trajectory traps in a bottle neck in level of pragmatics processing never reaches the globally stable state.

3. Concluding remarks and future perspectives

We believe that our proposed approach may help modeling developmental problem in autistic individuals' language. Considering language development as a dynamic multi-stable system shows how the language trajectory evolves through development. To study the model in the practical field, we focused on pragmatic language impairment of autistic children. We showed that in high level of language development i.e. pragmatics, a bifurcation or a bottle neck trap happens in their development trajectory. By finding and tuning the bifurcation parameter or reducing the time spent in the bottleneck with appropriate intervention strategy, the problem may be managed. Surely, additional researches in both experimental and computational fields may shed light on this approach.

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