Example 8 Let us consider the following contingency matrices D and E:

$$D = \begin{pmatrix} 1 & 2 & 3 & 0 \\ 4 & 5 & 6 & 0 \\ 7 & \mathbf{11} & 9 & 0 \\ 0 & 0 & 0 & \mathbf{1} \end{pmatrix}$$

$$E = \begin{pmatrix} 1 & 2 & 3 & 0 \\ 4 & 5 & 6 & 0 \\ 7 & \mathbf{10} & 9 & 0 \\ 0 & 0 & 0 & \mathbf{1} \end{pmatrix} .$$

The numbers of examples of D and E are 49 and 48, respectively, which can be comparable to that of B. Then, from Theorem 8,

$$\det D = 18 < (49/4)^4 = \frac{5764801}{256} \sim 22\,518$$

$$\det E = 12 < (48/4)^4 = 20\,736 .$$

Thus, the maximum value of the determinant of A is at most $\left(\frac{N}{n}\right)^n$. Since N is constant for the given matrix A, the degree of dependence will decrease very rapidly when n becomes very large. That is,

$$\det A \sim n^{-n} .$$

Thus,

Corollary 2 *The determinant of A will converge to 0 when n increases to infinity*

$$\lim_{n \to \infty} \det A = 0 .$$

This result suggests that when the degree of granularity becomes higher, the degree of dependence will become lower due to constraints on the sample size.

However, it is notable that N/n is very important. If N is very large, a rapid decrease will be observed when N is close to n. Even when N is 48 as shown in Example 8, $n = 3, 4$ may give a strong dependency between two attributes. For the behavior of $(N/n)^n$, we can apply the technique of real analysis, which will be our future work.

Conclusion

In this paper, a contingency table is interpreted from the viewpoint of granular computing and statistical independence. Matrix algebra is a key point of the analysis of a contingency table and the degree of independence, and rank plays a very important role in extracting a probabilistic model. From the correspondence between contingency table and matrix, the following results are obtained: First, the value of determinants gives the degree of of dependency between attribute-value pairs for a set of submatrices with the same size. Second, from the characteristics of the determinants, the larger the rank a corresponding matrix has, the more the two attributes are dependent. This result is shown by a monotonicity of a sequence of determinantal divisors. Third, elementary divisors give a decomposition of the determinant of a corresponding matrix. Finally, the constraint on the sample size of a contingency table is very strong, which leads to an evaluation formula in which an increase of degree of granularity gives the decrease of dependency.

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Development, Complex Dynamic Systems of

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Article Outline

Glossary

Development In the context of developmental psychology, development implies the process of increasing knowledge, skill, capacity and so forth across the life span, in an ordered and directional process, leading to a stable state of maturity. Development implies an increase in complexity of the developing person or system.

Education A co-adaptive process involving asymmetrical relationships between educators (parents, teachers, ...) and young persons (children, pupils, ...); the process of the upbringing of children, by means of teaching, providing resources, models, teaching, guidance and so forth

Learning and teaching The process of gaining knowledge or skills, often in the context of help by a more competent person, who enables the learning through teaching, consisting of guidance, transmission of knowledge, structuring, promoting and confining the learner's zones of action, often in the context of explicit learning and teaching goals (e. g. teaching and learning how to write, teaching and learning how to weld iron on a construction site, etc.)

Complex developmental system A developmental system consisting of components such as the persons involved, material and cultural artifacts, properties attributable to individuals, that shows development as defined earlier, through the interactions between and interdependence of the components

Dynamic systems (developmental) A way of describing how one state of a developmental system changes into another state, as defined by a developmental state space (the whole of possible states distinguishable in the system, described by the set of dimensions or variables needed to specify the system as being developmental)

Developmental states, stages and ages A developmental state is any possible state in the developmental state space, which is defined by the dimensions used to describe development; with continuous dimensions, the number of possible states is continuous and infinite; stages are states characterized by a stability that lasts over a sufficiently long time span (a few years) and by a pattern of mutually dependent properties, i. e. values of the developmental dimensions, stages are characteristic of the founding theories, such as Piaget's theory; ages are periods in the lifespan characterized by sufficient stability of the properties to qualify as properties characteristic of that period, ages often coincide with stages as distinguished in classical theories but often comprise additional properties required for coherent description.

Developmental domains Physical, neurological and sensorimotor development; cognitive development; language development; emotional development, social and personality development; self-, gender- and identity development, moral development; domains follow characteristic paths of development, can be distinguished from one another on the basis of their components and laws of change, but closely interact with one another and form interdependencies on the level of action and developmental time scales.

Developmental time scales Development takes place across various time scales, characterized by their characteristic event duration, the laws or principles that govern change on that particular time scale and interdependencies with other time scales; in order of descending duration the time scales relevant to human development are the scale of biological evolution; the time scale of socio-cultural historical development; the time scale of development across the human life span; the time scale of action and real-time experience and the time scale of underlying neurobiological processes.

Definition of the Subject

Developmental psychology concerns the study of developmental changes in human beings across the life span. Developmental changes are broadly defined as changes in the organism that are mostly progressive – in terms of increasing complexity, adaptation to the environment, efficiency of actions and operations and so forth. The subject of developmental psychology is the individual person, embedded in a particular social, cultural and material context. Although it is now widely accepted that development is a life-long process, the main developmental events take place during the first part of the life span, which cooccur with physical growth and development and coincide roughly with the age from birth to adulthood. Developmental changes through adulthood and old-age are often referred to as processes of aging and imply processes of loss, for instancing due to aging of the nervous system, and processes compensating for such losses.

Developmental psychology is also concerned with problematic development, for instance in the form of developmental psychopathology, studying the life-span development of conditions such as autism, attention deficit disorders, oppositional behavior and so forth.

The aim of studying development from the perspective of complex dynamic systems is to apply the concepts of complexity and dynamic systems to the phenomena, theories and explanations currently found in developmental psychology, including the educational sciences, in order to arrive at a comprehensive theoretical approach on the subject that focuses on the mechanisms and forms of change.

Introduction

Terms of Change

Developmental psychology deals with various terms of change, some of which have already been defined under the Glossary terms: Development; education; learning. Other terms referring to developmental change that are worth considering are the life span (the period between conception and death in a single individual); socio-cultural evolution (the historical process of changes in human cultures and societies as they pertain to the life span and development of individuals); and variability and fluctuation. The latter refer to non-permanent changes in a developmentally relevant property or variable that are in principle occurring over the short-term (as compared to the long-term of the preceding forms of change), variability and fluctuation typically occur around one (or several) central tendencies or pivotal points.

Etymologically, development means unwrapping or unfolding, as in the unwrapping or unfolding of a book roll, or the unwrapping or unfolding of a flower bud [317,330,341,345]. Development thus carries an implicit notion of an inner logic in the sequence of the unfolding, a notion of potentiality (what is in there must come out) and a notion of finality (the unfolding comes to an end when the folded object is spread out). Although the historical meaning of development can of course not determine how we see or define development in scientific discourse, the deliberate application of this term in a particular context – instead of words like maturation, learning etc. – implies that we wish to refer to a phenomenon that is characterized to a more than a trivial extent, by these notions of inner logic, potentiality and finality. Development implies a directed process of change towards or unfolding of a mature state. It is a directed process, from an immature to a mature state, implying increasing complexity in terms of a system that differentiates (incorporates more and more elements, features, knowledge …) and at the same time integrates (constructs connections between the components).

Readers familiar with dynamic systems will immediately recognize these notions as metaphorical representations of self-organizing dynamics. The inner logic corresponds with the evolution term or the change function that governs the dynamics, and the potentiality and finality refer to self-organization or the systems tendency to move towards a particular attractor state. The notion of increasing developmental complexity refers to theories of complexity and emergence [60,146,147,362]. In short, given its core assumptions, developmental psychology is a natural domain of application for the approach of nonlinear, complex dynamic systems. Development, moreover, concerns a complex dynamic system characterized by adaptation in various senses, namely adaptation of the developing individual to the environment, adaptation of the environment to the developing individual (in the sense of education, but also in the sense of long-lasting historical and cultural adaptations as a result of intergenerational effects on development). In short, in order to describe human development, we need three grounding notions: complexity, dynamic systems and adaptation.

Complexity

A Working Definition of Complexity In the context of our discussion of the complex dynamics of developmental processes, we shall use the following working definition of complexity.

- A complex system consists of many components or elements; the magnitude of "many" typically depends on the nature of the system
- The components are interacting; the interactions occur on the basis of a few, simple interaction principles, with a system-characteristic degree of connectedness among the components
- The components change because of their interactions with other components
- And are thus interdependent
- The complex system shows characteristic higher-order properties (exceeding the properties or behaviors of the single components, implying characteristic patterns of related behaviors among many components)
  - Examples are sub-systems, trajectories of long-term change or development, and events at various time scales (see further)
- That are emergent on the interactions, i. e. they occur through self-organization

- Complex systems naturally divide and organize into sub-systems
  - Sub-systems are also complex in the sense of the current definition
  - Sub-systems are defined by the strength of the connections between the components of the sub-system, and these strengths may vary over a broad range, thus allowing the possibility of hard- as well as soft-assembled subsystems
- Complex systems are characterized by patterns and mechanisms of change that occur on various interdependent time scales
  - A characteristic distinction is that between short-term versus long-term processes, that are interdependent, with long-term processes determining the constraints and parameters of the short-term processes, and short-term processes determining the constraints and parameters of the long-term change
  - Patterns of change are characterized by non-linear phenomena such as the emergence of attractors, phase transitions, "tipping point" or "domino" effects, slow and gradual change, surge or peak phenomena, bimodal states and fluctuations, and so forth
- Complex social or human systems are characterized by the embeddedness of the observer
  - The observer is a member of the system he or she studies, and thus makes self-referring statements when explaining and describing the complex system
  - To the embedded observer, complexity often corresponds with various cognitive states, that relate to properties of the complex system, such as ambiguity, fuzziness, contradictions, superposition and entanglement, surprise and so forth, that are not necessarily in principle reducible to unambiguous, crisp, non-contradictory and independent statements or beliefs.

An Application of Complexity to Development

Networks of Interacting and Interdependent Components and Subsystems They depend on the level of organization (and corresponding time scale) or system component chosen. For instance, for a student of language development, the major component chosen is that of language. To understand its development, one must reckon with the fact that language must be subdivided into various subsystems, e. g. the lexicon, syntax, meaning and so forth. Each subsystem, for instance the lexicon, can be further subdivided into components, such as the lemma's (words) in the lexicon. The subsystems interact, but they also interact with non-linguistic systems, such as the members of the community of language users (e. g. the parents, siblings), the perceptual-motor system of the child itself, and so forth. A theory of the development of such collection of elements or components will need to specify the dynamic relationships between them. For instance, across development, the development of language is dynamically related to the development of social understanding (e. g. theory-of-mind) and vice versa. Hence, the developing language of a child is a network of interactions among components. Interdependency means that connected components cannot be treated as independent variables, or independent components. For instance, a child's current linguistic skill is dependent on its effective environment, in terms of learning opportunities, and its the effective environment is interdependent on the child's mind (in terms of the language addressed to the child).

In addition to the notion of subsystems, we can also invoke the term "levels of organization", which refers to levels of particular types of patterns or structures that are stable at their characteristic time scale. An example is the life-span history of a person with a number of characteristic properties, including those of the person's characteristic life spaces; another example at a shorter time scale is the example of a counting strategy in which a child uses his fingers to count and make simple artihmetic calculations.

In a complex dynamic system like development, all phenomena are interconnected. A major theoretical insight from dynamic systems is that the patterns of action, thinking, or development in the long term, result not from any single factor (plus some additional "noise"), but from the local and temporal confluence of many factors, operating on many time scales [19,271]. In order to study a phenomenon, for instance the development of abstract thinking, or of language, that phenomenon must be isolated for study. However, although it is possible to take a phenomenon out of a complex system, it is not possible to take the complex system out of the phenomenon. That is to say, while isolating a phenomenon for study, the model must explicitly account for the complex system properties from which the phenomenon is taken.

Time Scales Time scales are characteristic durations of processes or phenomena, corresponding with characteristic levels of organization. An example most directly pertaining to development is the time scale of developmental phenomena, spanning developmental events taking place over years or decades and limited by the duration of the human life span

These time scales are

- Scale of biological evolution: practically speaking, this time scale accounts for static constraints, i. e. constraints that do not change across the number of generations that developmental theories customarily address; exceptionally, rapid evolutionary changes can occur based on intergenerational links between developmental processes, such as certain food tolerances under high survival pressure (famine)
- Scale of socio-cultural historical development
  - The constraints and affordances at this time scale change relatively rapidly, it is virtually impossible to formulate an a-historical developmental psychology, i. e. a developmental psychology that takes the historical conditions as a constant; Baltes, Reese and Lippsit [13] made a distinction between normative-historical and normative age-related influences, for instance, the influence of war (normative historical) on a generation of adolescents (normative age-related); other examples are the influence of computers and the internet on young children growing up with them, in contrast with parents who did not use computers at that age.
  - Socio-cultural development can be conceived of as as a Complex Dynamic System in the following way. Its components are agents (many, of different ages, forming intergenerational networks), cultural tools, social organizations and channels of communication and interaction and so forth. The emergent phenomena emerging from the interactions between the agents are: the historical production of the life space, historical production of tools, products for human action, continuous innovation and elaboration of the human life space of human environment or Umwelt, which are emergent phenomena of mass interaction in the social networks of human culture and human society.
  - Scale of development across the human life span: this time scale encompasses changes describable only at the level of the human life span and involves processes such as development in the sense of increasing complexity, skill, and so forth, and processes of aging which refer to losses and negative changes, e. g. decrease of information-processing speed as a consequence of aging. These changes form the topic of the current article.
  - Scale of action and real-time experience: this time scale encompasses actions as goal-driven or intentional behaviors and require the duration characteristic of actions, lasting from seconds to minutes to hours; the dynamics are explained by means of theories of adaptive agents (see further).
  - Scale of underlying fast neurobiological processes: the time scale of rapid processes in the brain, nervous, motor and visceral system.

Theories of human development differ with respect to the time scale(s) they wish to emphasize. For instance, evolutionary developmental theory explains development from the perspective of innate properties that served the fitness of humans in evolutionary times; socio-cultural and Vygotskyan theory of development emphasized the cultural tools available to individuals and that depend on the historical evolution of their society and the actual socio-economic position they occupy, enabling them to use or not use those tools to various extents; Piaget's theory which emphasizes development as a partial life-span trajectory (from birth to about twelve years of age), dependent on processes taking place at the time scale of action.

Self-Organization, Emergence Self-organization is the spontaneous increase in order, complexity or structure, i. e. structure increases not because it is imposed or transferred by an external source, as in transmission (e. g. transmission of certain knowledge items from one person to another through communication). An example is increasing differentiation and integration in cognitive skills and performance across development that occurs spontaneously out of the interactions among all the components involved. It is not imposed on the human life span by the unfolding of a genetic blueprint or by transmission of knowledge and skill from a teacher to an apprentice. Genes, environment and the person's actions are all interdependent components, the interactions of which lead to a self-organization in terms of developmental levels [314,340].

A common theme among proponents of (complex) dynamic systems theory in development is that they view the developmental system as a self-organizing system, showing attractor states, non-linearity in its behavior, emergence and so forth [185,186,188,190,287,314,337,345,348].

Emergence is the spontaneous appearance or evolving of a new property of a system, in the form of a coherence or pattern on a global or macro level of organization. Emergence is related to the viewpoint of the observer (e. g. [76]) and implies a certain degree of surprise from the side of the observer of the system [121,122]. In the field of developmental psychology, emergence relates to the fundamental issue of whether the mature state of human skills, knowledge and so forth is an emergent phenomenon or not. Developmental viewpoints have traditionally emphasized the emergent nature and have focused on the appearance of (subjective) novelty in a system. A prime example of an emergentist view on development is Piaget's theory. Vygotsky's theory emphasized the emergence of novel forms or innovations on the time scale of cultural-historical evolution through the contributions of individuals and collectives of people. Vygotsky primarily defined ontogenesis as an appropriation by the individual of tools and symbols generated through cultural-historical innovations. The notion of a zone of proximal development may imply emergence, if viewed as an instance of a proper dynamic system [341,352]. Modern theories, such as nativism, assign emergence to the level of phylogeny, i. e. the evolution of the human species leading to heritable biological preconditions for development (as in the concept of core knowledge). Traditional theories of learning equally denied the primacy of emergence for development by emphasizing the role of transmission and appropriation, more particularly transmission of knowledge, skills etc. by instructors [348]. As such, the question of emergence is at the heart of developmental psychology. Notwithstanding the centrality of this question, development originally (see etymology of the term) implied the unfolding of intrinsic properties, i. e. the unfolding or uncovering of what is already there [330,345] whereas emergence implies the coming about of something truly new.

Development as an Increase in Complexity of the Developing System A developing system, for instance a child in a particular familial, cultural and historical context, is characterized by an increase in the system's complexity, often with an asymptotic level of complexity implied as the "final state" of the developmental trajectory. The description of development thus requires a descriptive framework or manifold specifying the space of complexity. Imagine such a space as a multi-dimensional space consisting of all the descriptive dimensions or features needed to specify a distinction between any possible developmental states or levels [330,331]. The simplest possible description entails a single developmental scale or "ruler" specifying the relevant developmental order. For instance, the complexity or structure of a child's thinking and problem solving is given by its position on an ordered scale of cognitive accomplishments, which are often inferred from a relevant content theory. An example is Fischer's theory of iterative embeddings of components, such as single representations of objects or properties and the relations between them, describing an orderly structure of increasingly complex levels [102,103]. A child's developmental level is assessed by letting the child perform a number of actions that map on the developmental scale at issue, which is mostly done in the form of a standardized task setting, i. e. a test.

A typical and enduring problem of developmental psychology concerns the relationship between the structure of the developmental scale with the structure of the child's "mind". The identification of one with the other – the structure of the test and the associations between test results on the one hand with the structure of the mind on the other hand – is a tacit but common stance for many (developmental) psychologists and is an example of an essentialist and primarily Aristotelian view on the nature of the human mind. It does not reckon with the fact that the relationships involved – those between child, observer, theory and observation instrument – are in themselves an example of a complex adaptive system, and not an instance of a straightforward measurement problem, where a property of an object (a child) is measured by a measurement operation that has no effect on the property being measured.

The expression of knowledge in an activity (nonverbal, verbal, symbolic) is a matter of particular stabilities and patternings of the actions (or expressions). For instance the infant's searching for a hidden object in the correct hiding place in the case of "object permanence", or the older child's verbal communications about perceived events in the case of causal understanding or Theory of Mind, reveal the knowledge in the form of certain stabilities of the pattern of reaching (it is not perturbed by a replacement of the hiding object for instance) or in the pattern of certain verbal explanations, which can take various concrete forms. Because the pattern is a temporal, self-sustaining pattern over a state space of possibilities (e. g. reaching and grasping possibilities; the space of words and grammatical relationships), the knowledge is said to be soft-assembled, i. e. existing for the moment and context in which it is actually expressed [314]. This model is very different from a standard mentalistic one, in which the mind entertains a symbolic or conceptual entity – such as the object concept or a Theory-of-Mind – which is then expressed in the form of or linked to overt activities, which borrow their meaning from the mental contents to which they are attached. In this sense, knowledge has no existence outside its expression in the form of real-time action. The stable patterns that express a particular form of knowledge (e. g. the object concept) emerge through coordinations of many components, part of which are "internal" or linked to the individual, part of which are linked to the world in which the action at issue takes place and are given through perception ([271]). Many of the internal components are non-cognitive in the classical sense, and include goals, concerns and emotions [19,303]. Through development, the rules and components of the coordinations change, giving rise to actions, reasoning, and so forth that can be described in terms of formal structures that increase in complexity. Such formal descriptions (e. g. that children's thinking involves systems of relationships between components), however, do not refer to the underlying causes of the developing knowledge expressions and skills, but only to their abstract form. They are ways or frameworks for comparing knowledge and skills at various levels of development.

Development as Increasing Complexity Applied to Language Theory and Theory of Language Development As explained above, a theory of a domain of development – for instance language, cognition, … – serves as a model, eventually as an implicit model, of the state space in which the developmental trajectory is situated. Thus, in order to define what counts as development, the researcher must take a definition or description of the developmental domain and specify changes along developmental time as changes in the quality or quantity of the features that figure in the definition. However, a theory of, for instance, language, need not in itself contain the elements for a complete developmental state space description, i. e. a description of all the possible developmental states relevant to language development. Simply stated, a theory of language can contain a specific description of a state of development, i. e. a mature or ideal state, but be entirely underdetermined in terms of the possible paths that lead to this final state. For instance, assume that using passive constructions is a feature of mature language. Given that passive constructions form part of the description of mature language or language per se, the developmental route towards passive construction use is logically confined to a two-step process, namely no-passive-construction followed by passive-construction. This simple from-nothing-to-all switching process vastly underestimates the variety of observable developmental steps leading to passive constructions. That is, it falls short in specifying the potential developmental state space.

Transformational generative grammar, originating in Chomsky's work, made a major contribution to solving this problem by advancing a theory of language that logically entailed a theory of the possible developmental steps towards mature language [6]. By so doing, transformational generative grammar included a description of the developmental state space. Such a description should not be identified with a description of the developmental process per se, since that process can be any of the possible trajectories through the state space. However, if all states of the state space are conditionally ordered, such that for any state there is only one possible state it can emerge from, the state space description trivially becomes a description of the developmental trajectory, since it is the only one possible. A comparable situation occurs if we take Piaget's theory of cognition, which logically entailed a description of the developmental state space. The possible states are conditionally ordered, and only one trajectory is logically possible (see [330,332,333,334,335,336] also for discussion of developmental models based on Galperin's and Erikson's work). However, if the formal theory of a domain, e. g. linguistic theory, defines – or even simply constrains – the state space for developmental processes, the empirical and theoretical validity of developmental findings becomes conditional on the validity of the formal theory at issue. In short, the developmental findings answer the question of how a developing system reaches a particular developmental outcome, as defined by the domain-theory at issue. However, by studying development as such, it is possible to directly contribute to the formal domain theory itself. For instance, according to genetic epistemology, by studying cognitive development one obtains a better understanding of the nature of human knowledge in general, i. e. of what uniquely defines human knowledge [241].

In a similar vein, by addressing the logical problem of learnability of language as a human competence, Chomsky contributed to the formal definition and specification of that competence [62,63]. The earlier notion of transformational generative grammar has now been replaced by a linguistic theory entailed in the so-called minimalist program, which "… proposes that the computational system central to human language is a perfect solution to the task of relating sound and meaning" [64,181]. A major question is of course what linguistic theory has to say about meaning, how it is structured and what defines its developmental state space. An interesting development in this regard is the work relating catastrophe theory to semantics, thus defining semantics in dynamic systems terms [275,316,369,370]. Meanings are represented in terms of attractor states in morpho-dynamic fields, and such type of representation might be linked to dynamic field theories that were developed in the context of developmental research by Schöner and others [273,273,274,296]. If meaning can indeed be described as a morpho-dynamic field, language development amounts, at least in part, to the dynamic unfolding of this field. Formal theories of how such unfolding can take place can thus form a theoretical basis for a complex dynamic systems theory of language development. Relating meaning and sound, the solution of which is formally described by the minimalist program, leaves the question of why or for what purpose a person would want to relate meaning and sound in a concrete situation. Transformational generative linguistics, which has dominated the field of linguistics in the second part of the 20th century, sees this question as related to the actual use of language, the "performance", that is not part of fundamental linguistic theory. This stance relates to the essentially anti-functionalist view of transformational generative linguistics. However, from an evolutionary and developmental point of view, language is the outcome of complex dynamic and adaptive processes, and it is hard to avoid the conclusion that this adaptive evolution has not fundamentally shaped language down to its deepest layers.

Simulation studies and mathematical models of iterative processes in language evolution and acquisition provide evidence that the formal structure of a language is shaped by the dynamics of language transmission and appropriation by individuals, and more particularly, by its use in social interaction [48,65,66,168,169,229,231,290].

An important feature of these models is the very close dynamic interaction they propose between learning, culture and biological evolution. Over the course of language evolution, these three components transform each other in a process generally known as co-evolution. In that sense, human biology is deeply transformed by human culture and vice versa. For instance, the biological pre-adaptation for language acquisition – in whatever form one wishes to specify it – is the result of a dynamic systems process occurring over the intergenerational (i. e. evolutionary and historical) and intra-generational (i. e. ontogenetic) timescales. In that sense, the dynamic systems approach can help explain – in principle – how language structure emerged through self-organization over the course of generations [165,228]. The evolutionary processes that have shaped language were modified by the fact that they had to pass through the highly specific constraints and opportunities of transmission and appropriation actions in individual agents. They have resulted in language being an essential aspect of the psychological life space of individuals and being appropriated in an extremely rapid and robust way, given the complexities of the task of language development. The question is how language functions in the psychological life space of individuals, and thus, under which constraints and opportunities language develops.

A classical theory in that regard is Vygotsky's, whose work is still of theoretical importance to the field of developmental psychology. Vygotsky saw language as a complex set of evolutionarily and historically developed tools, that individuals use to act with and solve problems [328,361]. Hence, language development can at least partly be understood in accordance with the dynamics of tool use and its development [200]. This view leads to the idea that language is a cognitive niche or a material scaffolding structure that the child and its environment construct during the developmental process, as an additional dimension and partition of the psychological life space (e. g. the name of an object as a feature of the object, relating the object through the linguistic relationships of the word; linguistic forms as objects of action in themselves, related in complex ways to other features of the complex world, an issue which relates to the so-called grounding problem [24,68,69,70,71,75,357,358,375]).

Development and the Embeddedness of the Observer As explained earlier (in the section on developmental level, order and structure), the assessment of a child's developmental level is not a simple measurement issue, of a determinate property (the developmental level) being tapped by an otherwise neutral measuring instrument (a test or observation). For instance, Elbers [92] showed that children bring specific expectations of answers to particular questioning situations and use the (non-)reactions of the test administrators as information, thus turning the alleged test or measurement situation into a social dynamics. For a young child, the test is an educational situation, and the child will react to the situation on the basis of the expected consensual frames [107]. From a measurement-theoretical point of view, this is not a trivial issue. The adult's intended act of measurement co-determines the measured content in a a direct and objective sense, and there is no measurement outside the context in which the adult's probing changes the probe. Exceptions are observations in natural, free contexts, e. g. observations of spontaneous behavior as in language developmental studies, which are observations of relatively unconstrained social interactions. However, the result of these observations should also not be seen as measurements of the "true" level of some developmental property, but as observations of the dynamics of social interactions, involving the dynamics of what children already know and are able to do in an environment that is adapted and reacts to the child's possibilities and, equally important, anticipates on the child's growing potentials.

Another fundamental issue, which is typical of complex human systems, is that in the field of human development, ontological and epistemological issues become entangled. The researcher's view on the cognitive development of a child to an adult, for instance, requires an ontology (a theory of being, in this case of the mental contents, knowledge etc. of the developing persons under study) of a process that ends with an epistemology, i. e. a theory of how humans know, including the researcher. The researcher's level of understanding of the cognitive development of children towards adults is in itself the endpoint (roughly speaking) of his own, personal developmental trajectory.

For most developmental scholars, there is no problem with this entanglement, if any such entanglement is observed at all. For instance, a cognitive developmental theorist, working in the spirit of Piaget's stage theory and using his own mature, formal operational thinking as a tool for understanding the world, can fruitfully and without any internal inconsistency, study the emergence of formal-operational thought starting from its roots in the baby's non-operational, actional and sensorimotor way of understanding the world. However, the understanding of the developmental process will thus be determined by its endpoint, also because that is the tool with which this understanding is accomplished [330]. If we assume that development continues, also because scholars invest in making historical change processes come true and contribute to transforming systems of understanding, the representation of the process of development by developmental scholars will shift, as their own developmental levels (forms of scientific understanding) shift over the course of their lifetime, or over the course of historical time.

Dynamic Systems

A Definition of "Dynamic System" Dynamic systems theory is an approach to the description and explanation of *change*. A simple definition is "a means of describing how one state develops into another state over the course of time" [365], which can be expressed mathematically as

$$y_{t+1} = f(y_t) \tag{1}$$

expressing that the next state (at time $t + 1$) is a function f of the preceding state, at time t. In a slightly different notation

$$\Delta y / \Delta t = f(y) \, . \tag{2}$$

The equation states that the change of a system, denoted by y, over some amount of time, denoted by Δt, is a function f of the state of y. The function f is also referred to as the evolution term or evolution "law". That is, it is important that f specifies some causal principle of change.

An important property of the current equation is that it represents recursive relationships. Thus, y_t leads to y_{t+1}, and according to the same principle, y_{t+1} generates y_{t+2} and so on.

A system can be described as a set of entities that are related to one another and that influence one another, and a state of the system is the set of properties of its components at any particular moment in time. The properties of the system are expressed in terms of dimensions or variables, for instance the variable y from the preceding equations. Dynamic systems can consist of any number of such variables. For instance, if y represents a child's current lexical knowledge, and z represents the child's knowledge of syntactic rules, the dynamic system consists of two dimensions, and the child's current developmental state is a point in this two-dimensional space. The space of developmental dimensions is the developmental state space, and development can then be defined as a trajectory across the developmental state space.

Properties of Dynamic Systems Applied to Development

Iterativeness The iterative or recursive nature of a dynamic system refers to the map or flow that the system instantiates, and which, in qualitative and metaphorical terms can be rephrased as "explaining after by before" [352]. The application to development is – apparently – trivial, in the sense that a developmental process is a process that transforms a current state to arrive at a new state, the "state" being any point or region in the developmental state or phase space, as defined earlier (or alternatively, the symbol string corresponding with a set of properties describing the current properties of a developing person in a co-developing environment). Examples in classical developmental theories are Piaget's notion of assimilation, implying that the representation of given information is a function of the current forms of understanding and representing, or Vygotsky's notion of the zone of proximal development, in which the next attainable level of development is a function of the level already consolidated.

Dynamic Rule/Principle/Function The dynamic rule or function describes the way a current state of the system is mapped onto, or transformed into, another state at some later time. In principle, this dynamic rule corresponds with the basic mechanism of development that a developmental theory entails. In principle, this basic mechanism is any causal mechanism that operates on the current developmental state and that brings about a particular change of that state, including a 0-change, which occurs if the developmental state has reached stability.

Classical developmental theories were usually explicit about the mechanisms operating on developmental states. For instance, for Piaget, the mechanism is one of adaptation, with constituent mechanisms of assimilation and accommodation. The working of these mechanisms is explicitly determined by the properties of the current developmental state. For instance, the child assimilates the information it obtains from its actions to the cognitive structures it currently maintains. The same holds true for accommodation, which is the driving force behind developmental change. A similar logic applies to the fundamental Vygotskyan notion of the zone of proximal development, which implies that a more competent person adapts, in terms of help given, to the current level of development of an apprentice, and by giving this level-adapted help, stimulates a process of interiorization in the apprentice that leads to a new and higher developmental level. Other examples are Werner's notions of differentiation and integration, which are mechanisms explicitly operating on the cognitive, behavioral and emotional structures that are present in a child (or in a child-environment system).

Providing such models of mechanisms boils down to specifying an implicit function for development, i. e. given a state so-and-so, application of the mechanisms or rules will result in a different state, and through iteration or recurrence, to a developmental process. In principle, the mechanism or developmental function itself implies not only the present developmental state of the system, but also any influences – coupled to or indepenent of the state – that are incorporated by the mechanism and that moderate development. For instance, a mechanism explaining the growth of a child's lexicon not only operates on the current state of the lexicon, but also implies external influences, such as the environment's lexicon, teaching activities and so forth.

The majority of modern developmental studies have replaced these implicit developmental functions by explicit ones, which are based on samples of independent subjects. For instance, the time dimension, which is a fundamental kinematical variable for specifying change, can be used in an explicit developmental function, assigning a developmental level (of whatever kind is required) to a particular value of developmental time (most particularly age, but also duration of experience, for instance). Although these explicit models claim to achieve generality (or as it is often called, generalization), they achieve this result at a devastating cost. The cost is that they bypass the actual process, and are in fact completely ignorant as to which causal mechanisms explain actual developmental processes, which are processes applying to concrete, individual systems. For instance, lexical growth is a process occurring with a particular child in a particular environment, which is to a considerable extent dependent on the child's actions. For instance, the linguistic environment tends to adapt itself to the language use and understanding of the child. An explicit model provides a model of the lexicon as a function of a given time (age), other variables such as maternal language proficiency and an additional stochastic influence. The model is achieved by averaging over many individuals, and thus risks to lose all information about actual processes (unless the processes are virtually uniform over all individuals, which is rarely, if ever, the case). This problem, which refers to the fact that such explicit models of associations between independent and dependent variables are not in any way logically related to implicit models describing mechanisms operating on developmental states, has recently come under the attention of statisticians and methodologists working on individual developmental trajectories [136,216] (e. g. Molenaar, Hamaker, ...). The reason why such implicit functions are central to developmental science is that they attempt to specify the causal processes that operate in real time, and thus provide models or prescriptions of actions by practitioners.

Attractor An attractor is a set of points in the phase or state space towards which a system will evolve, given its dynamic function, if it is in the basin of attraction.

The application of the notion of attractor to a developmental system implies that the system will asymptotically evolve towards a particular state if it is under a particular set of conditions (the basin of attraction). More precisely, if the system is in an attractor state and gets perturbed, it will spontaneously return to the attractor state, unless effectively counteracted by some external force. For instance, a particular child, in a particular development, will tend to show certain stabilities or stable patterns in its behavior. The criterion of return after perturbation, under certain limits concerning the strengths of the perturbation, is an important criterion for distinguishing attractor states from accidental states for which the system has no particular "preference" (if any such states exist). Many developmentally relevant attractor states are likely to be rather idiosyncratic, i. e. dependent on individual and local circumstances. Other states may be relatively general and predictable on the basis of broad criteria such as age. An example of the latter type of state are the classical developmental states or stages, for instance the states distinguished by Piaget, by neo-Piagetian scholars, stages distinguished in the progression towards mature language and so forth. An example of a clinical application of the concept of attractor is the notion of resilience, which refers to a child's capacity to spontaneously move back to a healthy psychological state after having experienced highly stressful or adverse experiences. Although resilience can easily be defined as a personality property of the child or as an individual capacity, it is probably more realistic to view it as a an attractor state of the developmental system in which the child is embedded [209]. A comparable example is the emergence and self-sustainment of highly problematic teaching-learning patterns in children with developmental disorders such as ADHD [353].

Developmental State Space and State Space Grids The use of dynamic systems theory to development applies a fundamentally geometric way of thinking to the study, description and explanation of development. Developmentalists are used to thinking in terms of variables that they identify with psychologically real properties of the mind, which implies that their frame of reference is a model of the mind or the brain, i. e. a model with a topology that is similar to the topology of the mind or the brain (since the topology of the mind is difficult to imagine, and the topology of the brain is at least seemingly given by modern brain imaging studies, developmental psychologists are increasingly turning towards the brain as a model; however, see [50] for a critical discussion). From a dynamic systems point of view, however, a developing system is a geometric manifold or space, consisting of all the dimensions used to describe the system (and this number can eventually be very small), including the evolution laws or rules that specify the change of positions (developmental states) in this space. There is no implicit reference to topological similarity with the mind or the brain. The use of such geometric, state space descriptions can free the researcher from "unsolicited" ontological claims, i. e. implicit claims about the nature and composition of the human mind that are relatively standard in mainstream developmental psychological investigations [350].

The notion of state spaces, in particular categorical state spaces, has been promoted by several researchers, mainly working in the field of social interaction and social development [127,128,129,148,149,191,192].

Static Versus Dynamic Models in Development Developmental psychology, has almost exclusively focused on *static* models and has implicitly assumed that change, for instance developmental change in an individual, could be approximated by stretching static relationships over the time axis [352]. A characteristic expression of a static relationship takes the form

$$y_i = f(x_i) \tag{3}$$

with y a dependent variable and x an independent variable, which, for any possible value x_i generates a corresponding value for the dependent variable y. The variable x can also be time, but the use of time as such does not turn the model into a dynamic model.

A difficulty arising with this definition of a static model is that any dynamic model that is expressed as a function of time

$$y_i = f(t_i) \tag{4}$$

must strictly speaking be qualified as a static model [300]. Hence, we should confine static models to those where the x-variable is not time. However, in Sect. "A Definition of 'Dynamic System'" it was claimed that the f in the dynamic equation must specify some causal principle of change, with the implicit assumption that this causal principle, however general, is theoretically justified and based on what we know about how things change. Hence, a model of the form of Eq. (4), $y_i = f(t_i)$, that applies to an empirical sample (e. g. a regression model of time applying to a cross-sectional sample, or a sample with two or a few consecutive measurements), can easily be transformed into a model of change by taking the first derivative of the model. By doing so, however, one does not automatically arrive at a meaningful dynamic model, since the function term f featuring in a descriptive time-serial model is not necessarily *descriptively adequate*. A dynamic model can be characterized as developmentally descriptively adequate if the mechanism implied in the dynamic model (1) corresponds with a developmentally plausible mechanism, (2) in principle applies to the whole developmental time scale of the developmental phenomenon in question [193].

A static system describes a particular value of the variable of interest as a function of the value of another variable (or set of such variables). For instance, for any possible age, or for any level of the mother's lexical knowledge, or for a combination of age and maternal lexicon, the static system or model will generate a predicted or expected size of the lexicon, without any reference to recursiveness.

This distinction between static and dynamic type models has considerable consequences [152,300]. Whereas a dynamic model recursively generates a time series (a state and the next state and the next ...), a static model generates a sample or population of individuals that are in principle independent of one another (an individual with age i and lexicon i, an individual with age j and lexicon j, and so forth). Statements about associations between variables across populations do not necessarily apply to the mechanisms that apply to change in the individuals in the population. However, the behavioral sciences, including developmental psychology, often implicitly take a relationship between variables that holds across a sample as a representation of some dynamic rule or principle (also known as the homology or ergodicity error) [136,216,224]. For example, a study showed that early math skills in 5 to 6 year olds have the greatest predictive power for later school achievement, whereas socio-emotional behaviors, on the other hand, had little or no predictive power, irrespective of gender and socioeconomic background [90]. From such findings, it is easy to infer that increasing early math achievement, e. g. through preschool teaching programs, will thus lead to better school achievement at a later age, implying also that attempts to increase socio-emotional skills should be reduced since they do not relate to academic achievement. However, there exists no logical or direct relationship between the static relationship (how is it associated across a population) and the dynamic relationship (how can something be increased or decreased in individuals).

Adaptation and Adaptive Agent Systems

Adaptation is the process of adapting something to something else, usually in the context of an organism adapting to its environment. An important question concerns the relationship between adaptation and development. There is no doubt that adaptation and complex adaptive systems play a major role in the process of development (for further discussion, see Sects. "Theory Of Complex Adaptive Systems (CAS): Developmental Agent Models" and "Theory Of Complex Adaptive Systems (CAS): Epigenetic Robotics"). A classical theory such as Piaget's conceived of development as a process of adaptation, which shows a clear pattern of increasing complexity. However, adaptation, especially in the sense of organism-environment adaptation, need not be a process of increasing complexity, adaptation can also mean loss of specialization, decreasing complexity etc., if the latter is better adapted to the organism's current environment. In developmental processes, there are also processes of loss of knowledge and of complexity, depending on changes in the environmental circumstances (e. g. language loss [176,234]). An encompassing theory might claim that an adaptive process as it applies to a growing organism (literally as in embryogenesis, metaphorically as in cognitive or language development), must by necessity show an increase in complexity (and size, etc.), given the constraints on reproduction (reproductive activities produce an offspring that is less complex (of smaller size etc.) than the progenitor).

The theory of complex systems refers to complex adaptive systems, which are collections of interacting components (agents) that adapt to each other. A developmental system, e. g. a child in his or her environment, can be conceived of as a complex adaptive system, with the agents or components adapting to each other. Examples of mutual adaptations are given in dynamic reinterpretations of Vygotsky's theory [341,352] or in the theory of transactional development [263,265].

An adaptive system is not necessarily a goal-driven or teleological system. Human beings and organisms in general, however, are complex adaptive systems that are goal-driven or teleological, and in addition to adapting to their environment, they also wish to control their environment [77,167]. Developmental theory that explains the mutuality between the long-term time scale of development and the short-term time scale of action, thus needs a theory of adaptive, goal-driven or concern-driven agents in order to explain the level of action, and the developmental level of changes in goals and concerns [302,303] (for further explanation see Sects "Theory Of Complex Adaptive Systems (CAS): Developmental Agent Models" and "Theory Of Complex Adaptive Systems (CAS): Epigenetic Robotics").

Main Theories in the Field and Short Historical Background

Founding Historical Theories

A brief look into any arbitrary collection of handbooks on developmental psychology illustrates the field's historical concern with the question of whether development implies the unfolding of what is already given at birth (which refers to the original meaning of development as unwrapping) or whether development implies a start from zero and a process of appropriating of whatever is necessary to become a mature person. The main figures embodying these standpoints are John Locke (1632–1704) and Jean-Jacques Rousseau (1712–1778) respectively. Although it is no longer stated in this naïve form, theorists and researchers struggle with this issue even at the present day (see for instance the discussion on gene-environment relationships; [261]). Biologically-inspired theories – seeing development as the unfolding of a biologically given program – are associated with the work of Charles Darwin (1809–1882) and G. Stanley Hall (1844–1824). Historically, however, developmental psychology is based on the confluence of many theoretical strands.

Main Theoretical Viewpoints

Biologically Inspired Explanations The notion that the important components or aspects of the human condition in its mature form are in fact innate and not appropriated thanks to external influences, or constructed on the basis of one's own action, has received a major impetus by the work of Noam Chomsky in generative linguistics. Chomsky argued that language – which is obviously learned from the input received from the environment, in that no child will for instance learn French if confronted with a Dutch language environment and input – cannot be learned or acquired without an innate language acquisition device, which defines the major properties or degrees of freedom, of human language (see the section on Language theory and theory of language development nativism and modern nativism for further discussion [62,63]). The major argument was that language is in fact underdetermined by the input if the learning device has no preset clues about what the input means or implies in terms of structural relationships among identifiable components. A similar line of thought is followed by proponents of *core knowledge theory*, such as Elizabeth Spelke, who claim that the major components of human knowledge about the world – such as the notion of space, number, causality and so forth – must be innately given (see [295] for an overview).

Evolutionary developmental psychology [32,235] is a theory that applies Darwinian principles of evolutionary adaptation to explain the evolutionary emergence of epigenetic programs that evolved under specific selection pressures [33,96,115,194,195]. Examples include early fantasy play, parental investment and cognitive development. Since the epigenetic programs evolved under historical environmental conditions that are no longer present in contemporary environments, mismatches between such programs and the requirements of contemporary life may lead to perturbed development. Evolutionary developmental psychology can be seen as an offspring of ethological theory, a biological theory that tries to understand the adaptive functions of behavior of an organism. Ethological theory, primarily through the work of Konrad Lorenz, has given rise to theories about critical periods, i. e. specific ages at which the development of a particular category of action or skill, such as language, is particularly stimulated and beyond which that development cannot take place. Modern theories of development tend to speak about sensitive periods or windows of opportunity, and eschew the notion of critical periods and the impossibility of development if the period, for some reason or another, is missed [8,49,159,319].

Developmental behavioral genetics attempts to explain development and particular developmental trajectories on the basis of the person's specific genetic endowment [244,245]. Recently, major progress has been made in the study of the effects of "generalist genes" on development [246,275,276]. In the context of learning disabilities, Plomin and Kovas describe "generalist genes" as genes that affect not only the disability but also the normal variation in the behavior at issue (e. g. reading), that affect all aspects of the disability and related disabilities (or normal behavior) and not just a particular aspect.

The influence of genes is not unidirectional: genes and environments are to a considerable extent linked with transactional relationships. Specific genes act so as to make the person more sensitive to or selective to particular environments, whereas environments have an influence on the activation of particular genes or moderate the effect of genetic influence [5,261].

Psycho-dynamically Inspired Theories Psychodynamical theories originated in the work of Sigmund Freud (1856–1939). According to Freud, human behavior and action are determined by energetic forces resulting from basic human drives, which, for Freud, were primarily sexual in origin. The actions required for fulfilling these drives conflict with the exigencies of reality, and actions serve to resolve this perennial conflict, leading to particular psychological structures (such as the unconscious, the Id or superego, etc.). The principle of drive-determined conflicting actions operates from birth on, and leads to a series of psycho-social stages (the oral, anal and genital phases, from birth to about 7 years). Although Freud can be criticized for his narrow view on the importance of sexual drives for the explanation of human behavior and development, his theory is one of the few that actually tries to understand human action and development from the goals and concerns that human beings try to accomplish, and from the problems they encounter in doing so.

In modern developmental psychology, psychodynamic theories mainly survive through the work of Erik Erikson (1902–1994) who emphasized the social, cultural and environmental aspects of the conflicts between the person's drives and the challenges of the environment. Erikson saw the human life cycle as a sequence of basic conflicts, arising out of the demands that culture and society make on the growing individual and that depend on that individual's psychological and biological maturation. These conflicts, for instance the conflict between identity versus confusion which is typical of adolescence form a conditional sequence, in that the solution of an earlier conflict is a condition for the way in which later conflicts will be manifested and solved [115].

Socio-culturally Inspired Theories These theories find their origin in the work of Lev Semenovich Vygotsky (1896–1934) who developed his theories during the early stages of the development of the Soviet state, which may help account for the particular properties of this theory [251,328,359,360,366]. For Vygotsky, development is a process that builds upon the biological predispositions given by biological evolution and that consists of an appropriation of cultural tools for action, including mental action. This appropriation of cultural tools – skills relating to tools in the literal sense as well as symbolic tools such as language and historically developed concepts – leads to the involvement of the person in his culture and is a requirement for his ability to contribute to the further development of his culture and society. Vygotsky emphasized the intertwining of processes on distinct time-scales, such as the historical time scale of societal evolution, the developmental time scale of the human life span and the short-term time scale of human action and tool use. Vygotsky's primary developmental mechanism consists of a combination of principles. One is that of interiorization, which states that children can interiorize or appropriate the actions and skills they first perform with the help of more competent others, such as parents, teachers or more competent peers. The second is that of the zone of proximal development, which refers to the distance between what a child can accomplish on his own and what it can accomplish with the help of others, such that interiorization is likely to take place and thus, development is further advanced. Development of an individual child takes place in direct and intensive interactions and transactions with other people, and is a deeply socially embedded and social process.

To Vygotsky, development of higher levels of thinking, including abstract thinking, is made possible by the appropriation of language-grounded concepts, such as time or causality, or names for numerical digits, and by the availability and use of physical symbolic systems such as writing.

The principle of social embeddedness in the culture has been used by various authors who have extended Vygotsky's work (examples are [255,324,367]. The theory is now more widely known as the socio-cultural theory of development, thus emphasizing the two main forces acting on and shaping human development.

Because of the emphasis on the mechanism of development and the direct causes of change, Vygotsky's major developmental principles lend themselves relatively easily to assimilation in a dynamic systems or agent-based framework [300,340,343,344].

Piaget and Cognitive Approaches to Development For Jean Piaget (1896–1980), cognition is a particular biological adaptation that allows the human organism to control and predict the environment through understanding and mental models. However, being a biological adaptation, it is not innately given but must develop, and it will do so on the basis of primarily biological mechanisms that operate on the child's understanding of the world. These mechanisms are summarized by the term adaptation and involve processes of assimilation and processes of accommodation. It is through these processes that operate under the form of human activities that the child actually constructs his understanding of the world, in a series of stage-like steps, leading to a level of understanding that is self-sustaining under its interaction with the environment. Assimilation involves the transformation of information to the form of the cognitive structures already present, whereas accommodation refers to changes in the cognitive structures to accommodate the information given. Assimilation and accommodation form a dialectical pair of forces, allowing the child to move beyond the direct sensory and motor givenness of experiences, and to come to abstraction. Cognitive structures are interrelated structures of schemes, concepts, skills and so forth, which, through their interrelationships are self-sustaining, at least for a given period of time, after which the working of the adaptive mechanism transforms them in new structures. These sequential structures correspond with Piaget's main stages, the sensorimotor, pre-operational, concrete-operational and formal operational stage. Cognitive structures are constructed, and are thus characterized by structural properties that are not or cannot be inductively inferred from the information given. A core example of such a structural property is the property of reversibility, which develops around the age of about six years and which marks the transition from pre-operational to operational structures. Reversibility is the property that assigns a reversible operation to any operation the cognitive system may have or develop, and it does so by implication. With reversibility, cognitive systems obtain properties of mathematical groups of operations, which greatly increases their power, enabling them, among others, to take their own operations as topic of reflection.

As with Vygotsky, Piaget was mainly interested in the nature of the developmental mechanism and considerably less so in the actual trajectories of development (although the textbook-representation of Piaget focuses mainly on his theory of stages and only superficially on the developmental mechanisms; the reason for this skewed focus is that modern developmental psychology is more a collection of facts about age differences in phenomena and associations of variables within samples than a science of development that primarily addresses the developmental mechanisms).

Piaget's theory was not so much inspired by the wish to learn about the developmental trajectories followed by children than by his interest in the nature of human thought and understanding, which he tried to capture by studying their development. Piaget was first of all a genetic epistemologist, interested in the nature of human knowledge. For Piaget, developmental science is an intellectually reflective science, i. e. a reflection on the nature of the thinking that makes that reflection possible. This interest puts Piaget in the ranks of complexity theorists who view complex systems as systems in which the observer and knower of the system himself is embedded [304].

Because of his focus on the mechanism of development, that is on the process of change itself, Piaget's basic theoretical notions lend themselves naturally to dynamic systems modeling [343,344]. Piaget's notion of development as construction of cognitive systems is closely related to dynamic systems notions of self-organization. Given the constraints and degrees of freedom present in the organism and in the environment, cognitive systems corresponding to the major developmental stages are self-organizing structures that develop towards equilibrium, i. e. they are self-sustaining, until, through the accumulation of experiences and most notably cognitive conflicts, a critical point is reached at which the structure tends to change rapidly towards another equilibrium, through a cascading process of inter-related events of change.

Neo-Piagetian theorists started from the major assumptions of Piaget regarding structural relationships in cognitive systems and the constructive nature of development, and added principles from modern cognitive science, such as biological maturation and brain development, limited working memory and other constraints on information processing [58,102]. Neo-Piagetan theorists have also employed dynamic systems modeling to explain processes of cognitive development, including stepwise growth and temporary regressions preceding developmental accelerations [103].

In addition to Piaget's theory, the theory of information processing has made an important contribution to developmental science. Information processing theory and its recent offspring in cognitive science and neurocognitive science starts with a basic model of human information processing, containing components such as input and effector components, short-and long-term memories and so forth, and studies development as the changes in those components. Changes concern quantitative changes in the operation of the components, for instance processing speed or size of working memory, but also qualitative, i. e. content-related changes, which amount to changes in the information-processing rules [171,210,279]. Information processing has been dynamically modeled by simulation architectures such as ACT-R (adaptive control of thought-rational [3,4,161]).

Learning-Theoretically Inspired Approaches Learning theory is concerned with how experiences shape future behavior and focuses on the addition of new knowledge and skills to what is already present. Classical learning theory remains close to the observable properties of behavior, e. g. under which environmental conditions particular behaviors occur. Learning and behavior are seen as being under the control of the environment. For the explanation of development, two main principles of learning are important. The first is the principle of contiguity and stems from the field of *respondent (or classical) conditioning*, which is mainly associated with the pioneering works of I.P. Pavlov (1849–1936). A stimulus that is contiguous (immediately precedes and overlaps) with a stimulus that evolves a particular response, will automatically obtain the response-retrieving properties of the latter. The second is the principle of functional or operant learning and is mainly associated with the work of B.F. Skinner (1904–1990). Behaviors have different consequences, and if the consequence of a behavior is positively evaluated by the organism, its future frequency will increase. Under the influence of the particular context, every behavior shows a spontaneous variation, and this variation allows for selective consequences, which may alter the frequency of the behavioral variant at issue, which on its turn will also vary spontaneously and be selectively reinforced. Through this principle of *operant conditioning*, behaviors can be shaped towards entirely new forms by applying reinforcements to each variant that comes closer to the goal behavior than other variants [283,285]. The principle is very similar to "survival-of-the-fittest" principles acting in evolutionary biology. If developmental processes must be seen as a result of many such learning processes over the long-term, it is likely that such processes will interfere, for instance in terms of contexts and reinforcements, and thus that complexity principles, involving networks of many interacting components, will apply. The question is to what extent non-linearities, attractor states and phase shifts may arise under these conditions, although principles of operant learning can be very easily transformed in a dynamic systems format [338]. The interaction of many levels of reinforcement is addressed in learning theory with relation to the matching law [142,143]. The *Matching Law* holds that the proportional distribution of behaviors (e. g. how much on-task versus off-task behavior in a child during a math lesson) will evolve towards a value that reflects the reinforcements provided by these behaviors (e. g. how pleasurable or goal-effective, on average, is on-task versus off-task behavior). The Matching Law explains the emergence of what in dynamic systems terms is called a specific attractor state and can be used to explain developmental changes (see [85,301] for an application in the field of social interaction; [30,278,286] for an application in teaching-learning processes and [38,223] for applications with developmental disorders).

Finally *social learning theory*, which originated with the work of Bandura, shows that children learn by imitating other people. Imitation depends for instance on the effect that the imitated behavior has for other people, on the social power and status of the person imitated and on beliefs on whether the imitating person will be able to accomplish the imitation or not (self-efficacy) [1,14,16,52,124,131,132,260]. Imitation tends to be a process that is far more complex than mere mimicry, and even in very young children extends to relatively abstract properties of the imitated behaviors, such as the intentions of the person who is imitated [53,57,320]. Thus, even with a seemingly simple act as imitation, one needs to conceive of the imitating person as a complex system, operating on many levels at the same time. The principle of modeling and imitation, which is maybe better referred to as behavioral contagion, can be fruitfully used in dynamic systems models of social behavior in children, in a developmental context [302,303].

Systems and Dynamically Inspired Theories Developmental systems theory, as it is applied to developmental psychology, explains development as a transactional process, implying transactions (that is, mutual transformations) of individuals and their contexts or life spaces, or of biological and environmental influences [108,184,264]. The theory has its roots in developmental systems theory as a specific approach to evolutionary biology [125,128,194,195], and the theory of nonlinear, complex dynamic systems, which is the focus of the current chapter.

Dynamic systems theory of development is a general approach, relying on the basic definition of a dynamic system as a system explaining the change of a variable, or why a next state follows from a preceding state, for "state" defined as any value on one or many variables describing the developmental state space (see [265,348,352,365] for general introductions in the field of development). In developmental psychology, the term "dynamic systems theory" has a somewhat confusing meaning. It refers to a theory of development based on processes of physically and socially embedded and embodied action, which originates from the work of Thelen and Smith [314]. Another approach is inspired by ecological models from biology and applies principles of resource-dependent change and mutual relationships of competition and support between components of the developing system, and is based on the work of van Geert [337,339]. Finally, dynamic systems theory refers to a variety of applications of general concepts from dynamic systems theory, such as self-organization, attractors, state space, etc. to developmental phenomena, for instance in the work of Lewis, Granic, Hollenstein, Fogel, Dishion and others (these theories will be discussed later).

Content-Driven Approaches A quick glance through the scholarly journals in developmental psychology shows that the field as a whole is theory-poor, in the sense that well-established, non-trivial and fundamental theories of developmental change that lay the groundwork for our understanding of developmental processes are virtually absent from most of the empirical work. Developmental psychology is primarily a science of relatively isolated fields or themes of development. Examples are attachment, theory-of-mind, aggression and bullying, and so forth. The standard research approach is to measure a collection of variables over samples of children of various ages, describe the change of the dependent variable based on averages for the distinct age groups and show how the dependent variable is associated with a host of independent variables (for instance, changes in average levels of theory-of-mind scores or reactions in experimental situations, which are associated with measures on language, intelligence, socio-economic status and so forth.

Conclusion

In its present state the field of developmental psychology is a scattered collection of approaches and fields that do not unite into a common framework or emerge from a common framework explaining the fundamental mechanisms of developmental change. The field lacks a generally accepted notion and theory of development in general, except for relatively trivial collections of principles taken from various (historical) theoretical approaches, such as Piaget's theory, learning theory, knowledge about biological underpinnings of development and so forth, that form the inevitable introductory part of the field's basic textbooks. Theoretical unification may take place by liberally employing principles from dynamic systems theory, theory of complex systems and of complex adaptive systems.

The Study of Individual Development in Light of Complexity Theory

Theory of Development and Complex Dynamic Systems Models

Development and the Theory of Embodied Action According to Thelen and Smith [314], current psychological theories tend to invoke "ghostly" things to explain behavior, namely internal representations and concepts. The representationalist stance, also known as the computational-representational understanding of mind, or information-processing theory, states that thinking can best be understood in terms of representational structures in the mind and of computational procedures that operate on these structures [311]. That is, in order to explain thinking you need internal entities. For instance, if a baby watches an object being hidden by an adult, and then watches how the object is moved to another hiding place, the baby will still look in the first hiding place in an attempt to retrieve the hidden object. This so-called A-not-B error is traditionally explained by the absence of a fully developed object concept, i. e. an internal representation of the object concept [287,292]. According to Thelen and Smith, invoking the notion of "concept" to explain a particular behavior or action related to that concept, is a categorical error, as if one explains the color of the red traffic light by the workings of its inherent redness. It is this categorical mistake that Thelen and others seek to repair by explaining phenomena such as the A-not-B-error by a theory of situated action, in which an embodied subject (not an epistemic subject, such as in Piaget's case) acts with the help of and under the constraints of a physical world that includes the external environment and the physical properties of the body [292].

In essence, cognition, thinking and action are explained as dynamic patterns unfolding from the continuous, "here-and-now" interaction between the person and the immediate environment. A particularly clear description, in the context of cognition and intelligence comes from Linda Smith [287]:

> The embodiment hypothesis is the idea that intelligence emerges in the interaction of an organism with an environment and as a result of sensory-motor activity. The continual coupling of cognition to the world through the body both adapts cognition to the idiosyncrasies of the here and now, makes it relevant, and provides the mechanism for developmental change. (p. 205)

The dynamic system at issue is the continuous coupling between the organism and its environment. This system shows a short-term time-evolution that takes the form of intelligent action, which changes the body and the brain through processes of learning and adaptation, thus giving rise to a long-term evolution we call "development".

In order to explain the short-term dynamics of action, thinking and knowledge in concrete contexts and the long-term dynamics of development, including the interdependencies between these two time scales, Thelen and Smith invoke the notion of dynamic fields, which will be explained in a later section.

Development and Resource-Dependent Competition-Support Systems As for any complex system, a developmental system can be viewed as a collection of elements or components. These components are related through functional relationships, implying that one component can change another, and vice versa. The system is embedded in an environment with which it is also functionally related (it can affect the environment and can be affected by it). The notions of "system" or "environment" refer to distinctions arbitrarily made by the describer of the system. For instance, a developmental system can be defined as a single variable or component, for instance a particular child's social cognition, or a child's lexical knowledge. This single-variable system then defines an environment consisting of any other component that functionally affects the component at issue. For instance, for the social-cognition system of a child, the child's emotional repertoire, intelligence, linguistic knowledge all form part of that system's environment, in addition to components that are not internal to the child, e. g. The child's peers, family, culture etc. In this sense, the notion of environment does not refer to "environment" in the usual sense, namely the child's current life space, family environment etc. (although such components do belong to the system-dynamic definition of environment). A system consisting of two variables, for instance a child's lexical knowledge as one component and the language addressed to the child by the mother as the second component, is embedded in an environment that consists of all sorts of internal and external phenomena that are related to the two variables at issue (such as the cognitive systems of the child and of the mother, their emotions, but also the material and cultural artifacts of their homes, other family members, etc.). Such developmental systems can be easily extended towards any number of explicitly defined and related components, which then define a complementary system set, which is the environment of the system in the abstract sense just introduced.

If the components through which a developmental system is defined can be described as (roughly) numerical variables, the system can be treated as and modeled as a dynamic ecological system. That is, if the system's components can be described by means of variables that specify the level of the component, the system dynamics amount to relationships affecting those levels. For instance, a child's lexical knowledge can be described as a particular number of words actually known or understood by the child. The child's social cognition can be described by means of a variable that distinguishes possible levels of development of social cognition (see Fischer's notion of developmental rulers, capturing the same idea [105,257,350]). This representation by means of numerical variables forms part of the abstract description of the system, and does not necessarily need to correspond with a homologous empirical measure of the variable in question. It suffices that the abstract numerical dimension and the empirical measure of the variable at issue are sufficiently analogous to warrant an eventual empirical test of the resulting dynamic model describing the system. The descriptive use of abstract numerical variables to describe components of the system also makes no implicit ontological claims with regard to the nature of those variables. For instance, describing a child's social cognitive knowledge as an underlying numerical variable does not entail any claim about that knowledge being localizable (e. g. in the child's brain), as internal or symbolic contents. The variable in question can equally well refer to a distributed, soft-assembled property of a child's actions that depends on causal loops between the child and its environment (see [350] for discussion).

The description of the developmental system as a dynamic ecological system makes use of the following general assumptions (for thorough discussions of these principles [334,337,345]). First, development is defined as the growth or increase in level of more developmentally advanced or complex variables and the decline or decrease of less developmentally advanced variables. The growth of a variable (e. g. a child's lexicon, a child's level of social cognitive understanding, and so on) is an auto-catalytic process, in that it depends on the level already attained. Thus, if l is the current level of some developmental variable (e. g. a child's level of lexical knowledge, of social cognitive skill, etc.), the growth or change of l over some time duration is expressed as

$$\Delta l = rl$$

for r any rate or change parameter. In an ecological system, of which developmental systems are examples, growth or change depends on the availability of resources, which are limited. For instance, a resource factor for lexical growth is the language spoken in the environment, but also the child's auditory system that helps it pick up acoustic signals that form the physical basis of spoken and heard language. Given that resources are limited, the growth parameter r approaches a zero limit as l approaches the level that is sustained by the available resources (a simple example is the resource "lexicon of the environment" which limits the number of lexical items that can be learned by a child living in that environment). The effect of the limited resources is expressed mathematically as follows

$$\Delta l = r(1 - l/K)l$$

for K the limit level of l under the given resource conditions. This equation thus corresponds to the well-known and basic logistic or Verhulst equation (see [337] for further explanation). If applied to knowledge-related variables, it basically states that the growth of knowledge depends on what one already knows, and on what one does not know yet, given what there is to know in the current context of the particular person in a particular environment. In the simplest possible case of a single-dimensional developmental system, the resource component corresponds with the system's environment.

For a system description to be really explanatory interesting, it should contain various coupled components, corresponding with the major dimensions of a particular developmental system. For instance, a model of the child's entire cognitive system should consist of variables referring to the major components of the cognitive system, e. g. language, conceptual knowledge, emotions and appraisal components and so forth. Another example concerns a model of an educational system, which should at least consist of a variable that changes as a result of environmental stimulation and interaction on the one hand, and a variable that describes the educational influence on the other hand. These two variables should be coupled, since it is relatively obvious that, as the child's growth (at least partially) depends on educational influences, the educational influences themselves will depend on the developmental or growth level that the child has already attained (one is not going to teach higher algebra to a child who has not even mastered elementary arithmetics, for instance). Coupled variables, each of them dependent on background resource factors, form the heart of a dynamic ecological system. To explain the principle of coupled variables, let us take an example from the field of social and personality development during adolescence (the example is taken from [193]).

The adolescent's main conflicts with the parents are related to the adolescent's wish for growing autonomy and the parents' reluctance to grant this autonomy too easily or too rapidly. The tendency to increase autonomy depends on resources such as physical maturation and cognitive and social skills, which are clearly increasing during the stage of adolescence. However, the tendency to increase autonomy is coupled to a complementary variable, which is the adolescent's connectedness with the parents. We shall represent autonomy and connectedness as two coupled numerical variables, which can thus increase or decrease in level. In psychologically healthy families, the level (including the quality) of the connectedness between parents and adolescent can have a positive effect on the adolescent's wish for autonomy, i. e. increase the growth of autonomy. The other way round, however, autonomy of the adolescent – and later adult – will have a positive effect on the quality of the connectedness and thus – given the principle that differences in quality are implicitly quantified – on the level of the connectedness (it is easy to see that if parents cannot accept the increasing autonomy of their children growing to adulthood, the level of connectedness that exists between parents and children is in fact going back). However, the actual striving towards autonomy (including participation in risk behaviors, staying out late at night, visiting places the parents do not like etc.) causes conflicts that tend to temporally reduce the good relationships between parents and children, i. e. temporally reduce the levels of connectedness they feel towards each other. Hence, the growth in autonomy (through conflicts) is related to the decrease in connectedness, whereas the level of connectedness (in a healthy family situation) is positively related to the growth of autonomy. With both autonomy and connectedness related to their own resource factors, K_{A} and K_{C}, the dynamic relationships between Autonomy A and Connectedness C are described as follows:

$$\Delta \mathrm{C} = r_{\mathrm{C}}(1 - \mathrm{C}/K_{\mathrm{C}}) - a\Delta \mathrm{AC} + b\mathrm{AC}$$
$$\Delta \mathrm{A} = r_{\mathrm{A}}(1 - \mathrm{A}/K_{\mathrm{A}}) + c\mathrm{CA}\ .$$

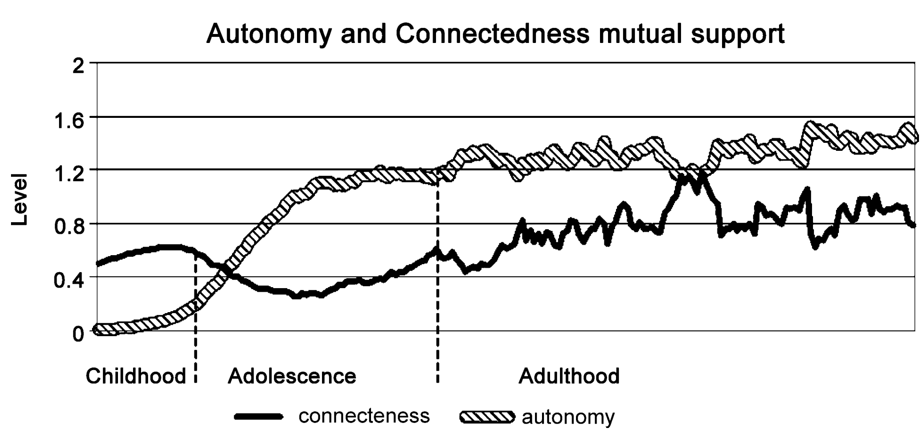
The first part of the equation describing change in connectedness (ΔC) relates to its resource-dependent growth, the second part relates to its being negatively affected by the change or increase in autonomy, which takes place mainly through conflicts; the third part relates to the positive effect of autonomy on the level of connectedness. The first part in the equation describing the growth of Autonomy (ΔA) describes its resource-dependent growth, the second part describes the growth due to support from Connectedness.

A stochastic version of this model produces developmental trajectories as described in the literature on adolescent development. As autonomy grows, connectedness shows a temporary decline, from which it restores and then shows a gradual increase, more or less parallel with the gradual increase in connectedness. The system then stabilizes around an attractor level, with stochastic fluctuations (see Fig. 1). The local regression and restoration is characteristic of U-shaped growth, which is a typical developmental phenomenon [59,117,226,305,337].

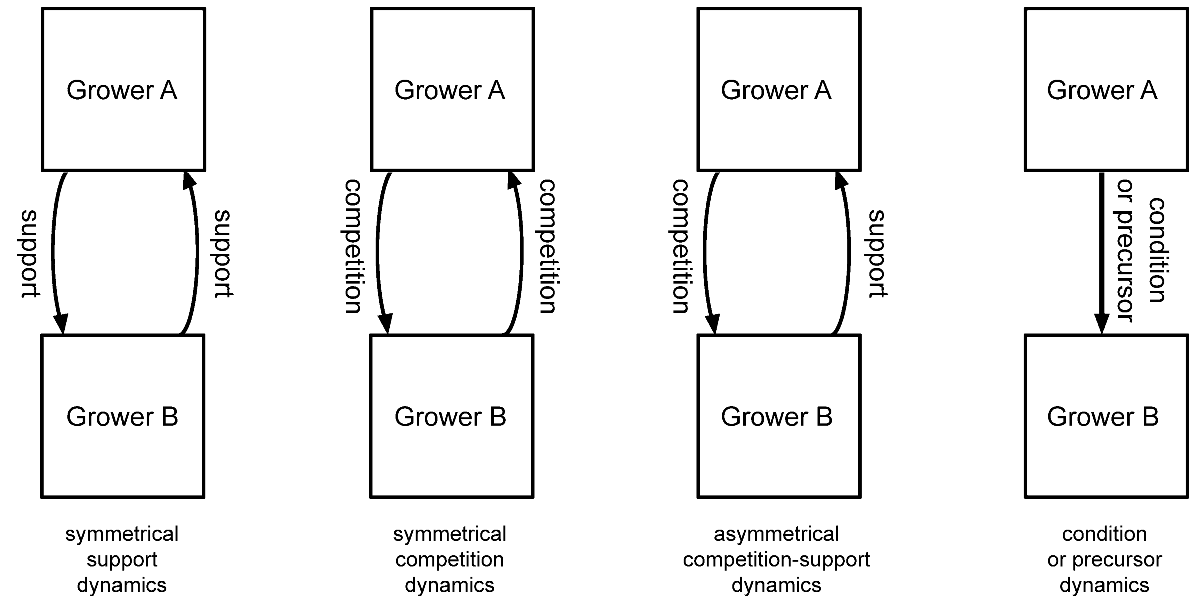
The model is an example of the ecological relationships that can hold for any couple of "growers", i. e. relatively autonomous components of a developmental system. These relationships can be symmetrical supportive, symmetrical competitive, asymmetrical competitive and supportive (as in a predator-prey relationship in a biological model) and, finally, conditional (if a particular, minimal level of a component is a necessary precondition for another component to start growing). The relationships are represented in Fig. 2.

A developmental system is characterized by relationships between any of its components and forms a web of relationships, formally similar to the foodwebs described in biological models [252]. Figure 3 represents an imaginary web of relationships between components in a developmental system.

A major difference between ecological web models used in biology and those used in developmental psychology is that the latter are considerably less supported by em-



Development, Complex Dynamic Systems of, Figure 1
Developmental trajectories generated by a stochastic version of the autonomy-connectedness dynamics



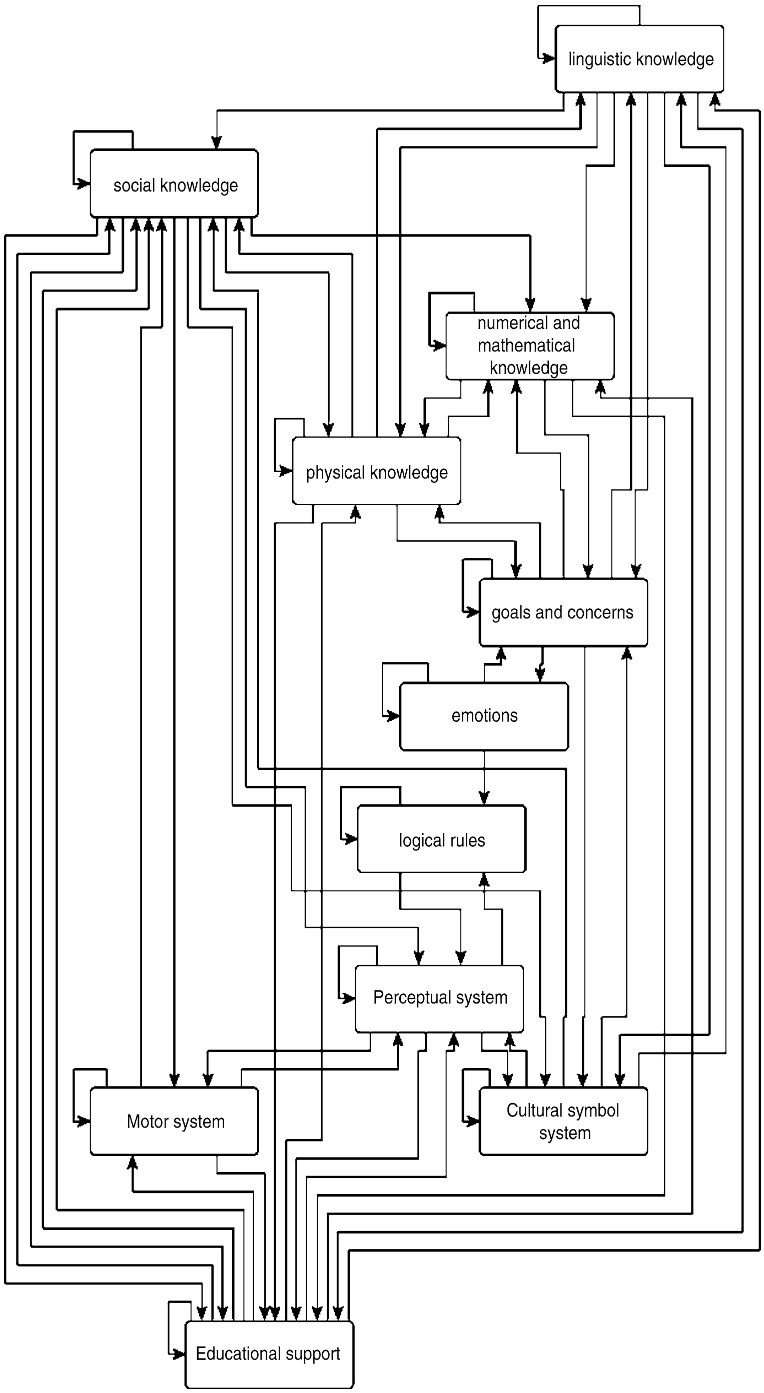
Development, Complex Dynamic Systems of, Figure 2
Four types of dynamic relationships between "growers"

pirical data than the first. The lack of empirical support is due to two factors mainly: the first is that the components distinguished in developmental models are considerably more fuzzy and less tangible than those used in biological models, with the associated difficulty of measurement precision. The second reason is that developmental psychologists are considerably less accustomed than biologists to study real developmental systems over sufficient time spans. Developmentalists mainly focus on statistical relationships between distributions of variables in samples, which tell very little if anything about the dynamics of the developmental system. Exceptions to this rule are the studies carried out in the field of language development, where single-case studies are the rule rather than the exception. By conceiving of language as a developmental system, consisting of components such as semantics, syntax, phonetics etc., or components on a lower level of organization, such as prepositions, adjectives, verbs, nouns etc., ecological network models can be specified simulating the growth of linguistic variables in a single child (see for instance [254,337,340] on lexical development in relation to the growth of plurals; [259] on the growth of closed-class words; and [20] on the pattern of growth and decline of sentences of various sentence length).

A study by Bassano and van Geert [259] illustrates the process of the emergence of three, developmentally successive syntactic generators, the holophrastic, combinatorial and syntactic generators. The holophrastic generator is basically a "one-word grammar", i. e. the set of early grammatical principles that generate utterances with a characteristic word length of one. The combinatorial generator is the developmentally more advanced set of principles that generate combinations of words, typically two per utterance. The syntactic generator is the set of principles that use the syntactic rules of sentence formation typical of mature language. Bassano and van Geert assume a series of asymmetric relationships between a less and a more advanced developmental structure, for instance, the holophrastic and the combinatorial generator. The less advanced structure has a conditional and supportive relationship with the more advanced structure. For instance, a minimum level of one-word productions is needed for the combinatorial generator to emerge, and, in addition, the level of one-word production supports the growth of the combinatorial generator, i. e. the production of two-to-three-word sentences based on a simple combinatorial principle. The more advanced structure on the other hand has a competitive relationship with the less advanced structure. For instance, the use of two-to-three-word sentences negatively affects the use of one-word sentences (see Fig. 4)

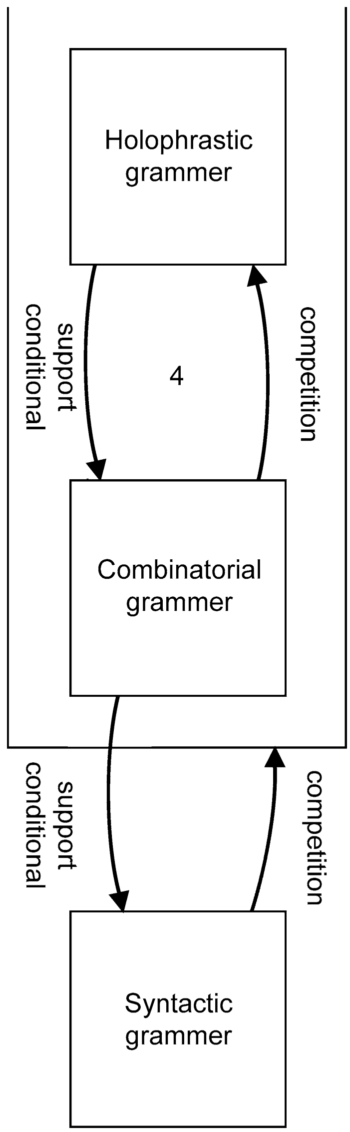
A mathematical model of these relationships with three connected growers (the holophrastic, combinatorial and syntactic grower) provides a good fit of the empirical data (model is shown in comparison with the smoothed data; see Fig. 5)

Another example of a model based on growth relationships between components of the developing system



Development, Complex Dynamic Systems of, Figure 3

An imaginary developmental growth web or network. *Arrows* represent either positive (supportive) or negative (competitive) relationships, in addition to conditional relationships. The *reflexive arrows* refer to the nodes' autocatalytic and resource-dependent growth

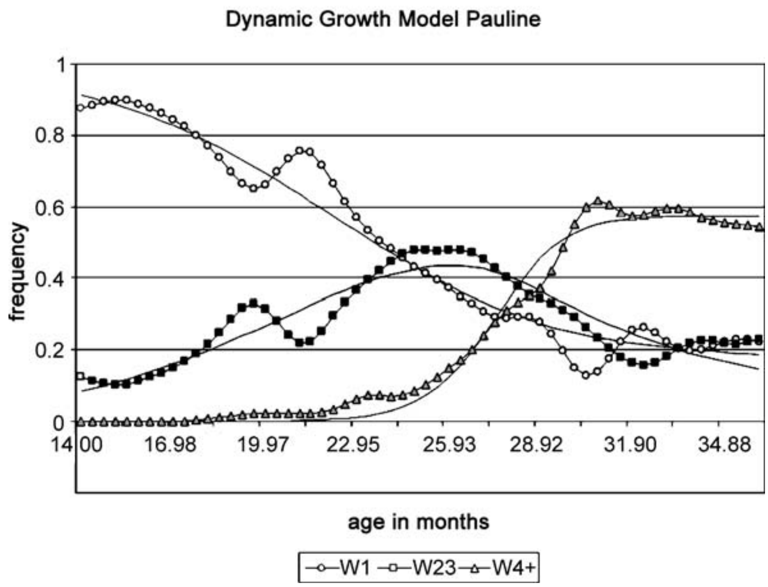


Development, Complex Dynamic Systems of, Figure 4
Asymmetric growth relationships between three developmental levels of grammar (after [259])

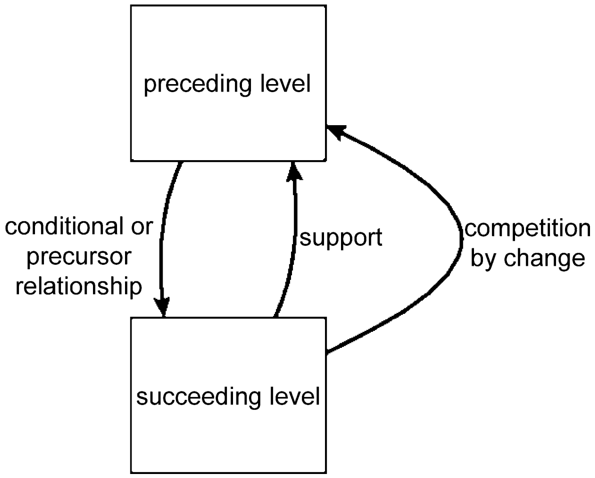
is Fischer's model of development through tiers and levels [103]. The model describes development as the emergence of skills, which are context- and content-specific. Skills are general formats of behavioral control and perception, and they are characterized by general structural properties that develop over the life span through a series of more or less discontinuous changes. Discontinuity is primarily observable in what Fischer calls optimal performance, which is a subject's skill level under optimal conditions, including support from other persons (for instance, more competent persons, as in a context of teaching and learning). Fischer distinguishes three major structural types of skills, which he calls tiers: the tier of action (roughly from birth to two years), the tier of representations (from two to about 12 years), and the tier of abstractions (from 12 years up). Tiers are further subdivided into levels, for instance the tier of abstractions goes through a sequence of single abstractions, then mappings, then systems, and finally, principles. Fischer's model has an additive structure, in that earlier levels do not disappear – as in Bassano and van Geert's model of language development – but are conserved and in fact transformed through the emergence of a more advanced level. The postulated structure of relationships between a preceding and succeeding level of development is as follows (see Fig. 6). First, the preceding level acts as a precursor or condition for the emergence of the succeeding level, e. g. single abstractions are necessary precursors of mappings, because a mapping is a relationship between single abstractions. Second, the succeeding level competes with the preceding level, in that the change (growth) in the succeeding level has a negative influence on the preceding level. Third, the succeeding level supports the preceding level: its positive effect on the preceding level is proportional to its magnitude of occurrence ("level" in the quantitative sense).

Dynamic models constructed according to these growth relationships predict typical developmental patterns, for instance in reflective judgment [103,170] (see Fig. 7). In addition, such growth models have predicted developmentally discontinuous trajectories at high growth rates and smooth trajectories at low growth rates, consistent with the data [104].

Development and Dynamic Field Theory Thelen, Smith and co-workers explain the short-term dynamics of action, thinking and knowledge and the long-term dynamics of development, by means of dynamic fields. A dynamic field is defined by an abstract metric dimension (or a space consisting of various such dimensions) that describes the main variable (or variables) of an action or thinking process. For instance, a major variable in the aforementioned object search task in which babies make the A-not-B error is the spatial position of the hiding objects and hiding places, which also defines the major variable of the child's action, which is the place toward which the infant will reach in order to retrieve the hidden object. For each point of this metric variable, there exists a particular activation value, which, in the case of the current example, would mean a likelihood that the child reaches at a particular location. The whole of activation values forms an activation field, the form of which changes on the basis of "inputs" from various sources. In the present example,



Development, Complex Dynamic Systems of, Figure 5
Smoothed data of the development of one-word, two-to-three-word and four-plus-word sentences in a French girl, Pauline, with fitted growth model based on relationships of competition and support (after [259])



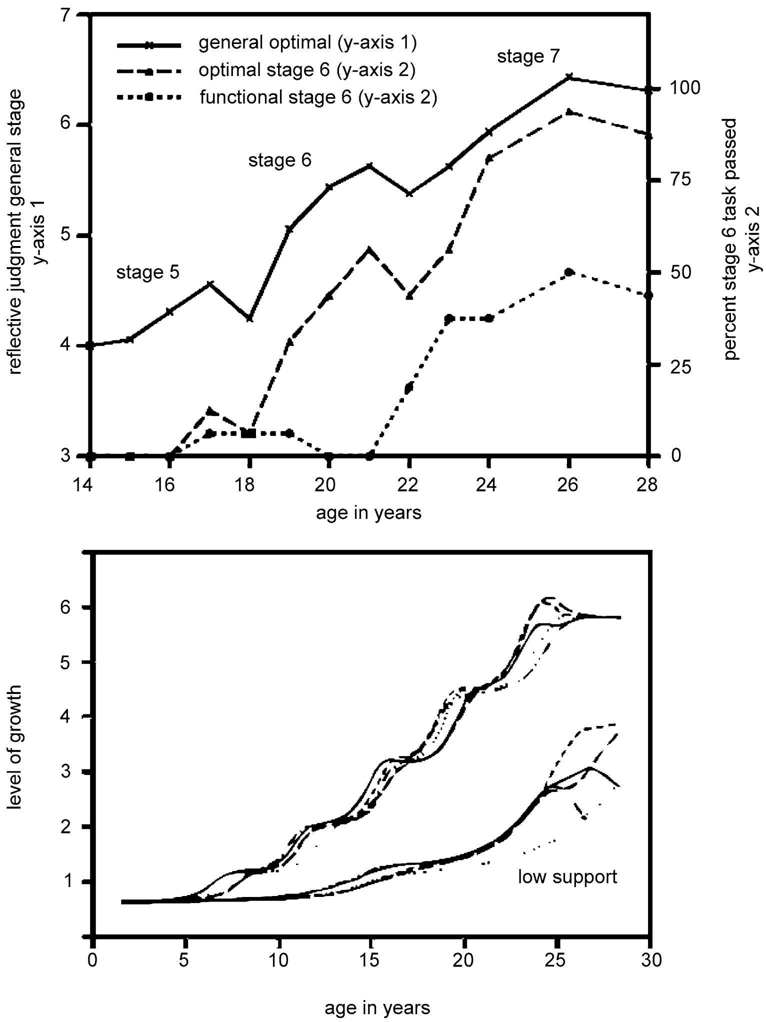
Development, Complex Dynamic Systems of, Figure 6
Growth relationships in Fischer's model of tiers and levels of development

inputs come from the child's perception of the environment, for instance the position of the hiding places, from events taking place in the environment, for instance the adult moving a hidden object to another place; and finally, from the child's memory [273,274,313], which is carried by the neural network that constitutes the brain and that changes as a result of experiences, maturation and self-organizing processes [188,189].

The inputs to a dynamic field are not just linearly superposed: they show cooperative and competitive interactions, leading to self-stabilization of activation patterns [99]. The mathematical properties of that field can be defined rigorously and allow for a dynamic systems model that is no longer just metaphorical. The dynamic field theory that describes the dynamics of this field thus bridges the "representational gap" that exists in current dynamic systems models [296]. This "representational gap" refers to the fact that developmental dynamic systems models of embodied and embedded action have no use for concepts and representations as mental entities that act as mental causes of behavior [74].

In addition to the development of the object concept, dynamic field theory has been applied to development of habituation [273] and development of working memory [274].

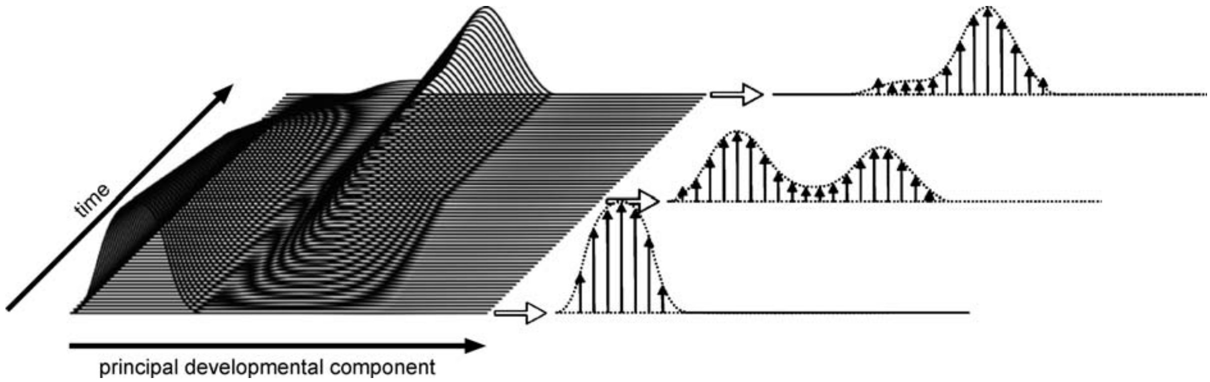
Dynamic fields can also be specified for abstract properties of the developmental state space in order to model long-term changes and mechanisms of development [343]. The starting point is the geometric notion of development as specified earlier, i. e. the developing system defined as a manifold of dimensions or variables, describing all of its relevant developmental properties. Since all those dimensions can be ordered along a scale of developmental progress (a developmental "ruler"), the developmental state space is thus characterized by a principal component (in the statistical sense) that can be used to specify any kind



Development, Complex Dynamic Systems of, Figure 7
Fischer's model of structural stages in cognitive development, with empirical data from reflective judgment. The dynamic model based on growth relationships generates the pattern of stepwise change with intermittent regressions (after [103])

of developmental progress or succession. Any point or region in the developmental state space can be mapped onto the principal component of the space, i. e. the general developmental distance introduced above. Any point on this metric distance dimension has a certain likelihood of being "visited" by the developing system. The actual likelihood, i. e. the actual activation field, is determined by inputs from the child's momentary experience of the context, retrieved memories, actions from other persons, and so forth. These likelihoods can be represented as a vector field, with an activation vector for each point in the developmental principal component or distance dimension. The vector field can specify a single peak, in which case the developmental state of the individual is crisp and uni-modal (the classical ideal), or by a landscape of peaks, in which case the developmental state of the individual is multi-modal, fluctuating and fuzzy (which is more like reality; see Fig. 8). For instance, if a child alternates between solving a problem either in a less or in a more developmentally advanced way, it occupies two regions in the developmental space between which it shifts randomly.

Development can then be represented as the change of the vector field over time, beginning with a dominant mode in the lower and ending with a dominant mode in the upper regions. The short-term dynamics of development consist of the individual's actions, experiences and interactions in real time. These real-time actions have a lasting effect on the structure of the vector field. The effect is moderated through two mechanisms that have already been described by the founding fathers of develop-



Development, Complex Dynamic Systems of, Figure 8
Probability functions of developmental levels assigned to potential actions or experiences of a child across time. The probability wave moves from a dominant mode on the left to a bimodal mode in the middle to a dominant mode on the right (see the three probability functions with vectors at the *right*)

mental psychology, Piaget and Vygotsky. They see development as the result of what I have freely termed *conservative* and *progressive* forces. These forces operate as follows (see [343,344] for an explanation of the model). It is assumed that any activation of components of the developing system in the form of a particular action, experience or event, have a consolidating effect on those components, and hence on the developmental level(s) that they represent. The consolidation depends on the functional success of the action or experience in question, i. e. on its short-term dynamics. The consolidation takes place in the form of increasing the vector values at the levels corresponding with the action or experience in question. The consolidation function spreads out to nearby regions and becomes negative (reducing vector values) for regions farther away on the developmental distance dimension. The consolidation function amounts to some sort of familiarity effect, which decreases with increasing distance from the actual, i. e. familiar level.

The developing system is also driven by a second force, namely novelty, which is a general term for novelty (new things) per se, curiosity, interest, goal-related activity and so forth. Novelty is a function that increases with increasing distance from the familiar. Assuming that familiarity and novelty are governed by their own characteristic parameters, there is a point on the developmental distance dimension where the combination of both has a maximal value or optimum. The vector values corresponding with this point are also upgraded, with an upgrade function the form of which is in principle similar to the conservative upgrade function. The updated vector field will generate new short-term actions and experiences, which will cause the vector field to update again, and so forth.

Simulations based on this model of development show that, depending on the values of the main parameters (familiarity and novelty parameters, rate of vector field upgrading, nature of information activating vector loadings and so forth), a rich landscape of developmental phenomena can be achieved, ranging from stepwise growth as described in the Piagetian and neo-Piagetian theories, to models of overlapping waves of strategies (Siegler), microgenetic fluctuations in performance, and so forth. An interesting effect of these dynamic field models is that they are able to explain discontinuous changes in development.

Theory of Complex Adaptive Systems (CAS): Developmental Agent Models Although development is a prime example of a long-term adaptive process – and according to Piaget, for instance, adaptation is the central developmental mechanism – there is very little work on complex adaptive systems in the field of development. An adaptive system can be defined as a collection of agents and artifacts that interact with one another and through that interaction are aiming at reaching their goals, concerns or interests [7,17,94,288]. Agents pursue their goals by means of their action repertoires, their knowledge of the world and the information they obtain through acting. In a complex adaptive system, agents are interdependent, yet autonomous in achieving their goals. From a developmental viewpoint, agents learn from their experiences and show long-term change in their goals, knowledge, action repertoire and skills, a long-term process we call development [269,303,352]. In a situated and embodied agent, development not only concerns the change in the person, but also changes in the person's niches or preferred environments [68,69].

A characteristic property of agent-based models is that they conceive of agents as being equipped with relatively simple rules, instead of complex internal representational worlds, carrying out extensive computations before acting [288]. Developmental psychology, on the other hand, emphasizes the complexity and the richness of a child's emerging knowledge and skills. However, the two approaches need not be in conflict with one another, in that very simple rules of agent interaction can in fact emerge on the basis of complex, self-organizing processes requiring the interplay of the environment, experience, knowledge and so forth. An example of how agent-based modeling and development come together is Steenbeek and van Geert's work on the development of social status, social power and social skills in young children [301,302,303]. The model describes the dyadic interaction of children by conceiving of children as agents with particular interests or goals with regard to playing alone or playing with other children. The agents in the model have a representation of the social value (popularity) of the other agents in their group, and try to optimize their positive appraisals of the interaction situation by drawing actions from a repertoire of either solitary action or actions aimed at other children. The principles governing the actions – for instance the choice among actions – are very simple at the level of the agent-based model, but such simple principles are in fact emerging out of a complex multitude of components and influences. An example of such emergent simplicity in social interaction concerns the emergence of goals and interests of the agent through the interactions themselves (see for instance [66]).

The agent-model described by Steenbeek and van Geert [299,301,302] simulates patterns of interactions that are empirically validated by data on play interactions between children from various sociometric statuses. The model can also be linked with a model of long-term changes in the peer selection preferences of children and the emergence of social statuses such as popularity or rejectedness. A similar model is used to explain the spreading of risk behaviors among groups of adolescents and the formation of friendship groups or cliques [12].

One possible drawback of agent models for development is that the nonlinear and complex patterns that typically result from interactions between agents do so if the number of interacting agents is high (see [11] for many examples). The typical number of agents in developmental models is small, e. g. two in dyadic interaction, or ten to twenty in small group interactions (e. g. a group of friends, a peer group). In spite of this limitation, agent models are typically suited for simulating short-term temporal patterns of interaction among persons of various developmental levels, and it is from these patterns that the interacting persons learn, adapt and develop.

Agent models have been used to study and simulate language development in connection with language evolution, by modeling generations of language learning, teaching and communicating agents. Such models explain, among others, why language tends to evolve towards a capacity that is optimally adapted to biological and social learning principles, and thus tends to become an increasingly "innate" type of capacity (examples of such studies are [66,165,168,169,290].

Theory of Complex Adaptive Systems (CAS): Epigenetic Robotics A different type of agent models in developmental studies concerns the epigenetic robotics models. The embodied and embedded aspects of developing agents are literally implemented in the form of robotic models, i. e. artificial autonomous agents that wander about, act in real environments and interact with other agents, including humans, and must learn from their experiences. Metta and Berthouze [211] define epigenetic robotics as the study of how a realistically embedded and embodied robot-model of a person, including a brain, sensory and effector organs, changes and develops in interaction with a real world (for introductions and reviews, see [26,27,28,182,202,211,267]. In fact, "... Beyond a certain level, it becomes extremely difficult to study realistic interactions between the agent and the environment without including a real body and real people in it" (p. 130 in [267]). Epigenetic robotics serves two purposes. The first is of a technical nature, and is aimed at designing self-organizing and learning robots that serve practical goals, in cases where direct programming of the robot is too complicated (e. g. [376]). The second is of more concern to the present article, which is to understand developmental processes in humans by studying simulated but embodied (robotic) agents in real environments. Epigenetic robotics approaches have so far dealt with the following aspects of development.

The first refers to the observation that human learning and development very strongly depends on social scaffolding and socially situated processes of cognition and perception. An important issue is joint attention, which occurs at a very early age (approximately around nine months) and involves the infants capacity to infer an object or event of attention to an adult by using the adult's gaze, pointing, etc., and to share that topic of attention with the adult. Joint attention is a typical human capacity, and greatly facilitates the process of cognitive and social learning. A host of robotics studies have been carried out, showing that processes of joint attention or closely related to it can be implemented in a robotic system and greatly enhance the processes of cognitive, linguistic and social learning [163,225,268,306,307]. Joint attention is closely related to empathy, i. e. the ability to intuitively understand the minds of others by picking up their intentions, an ability which is related to specific neurophysiological structures, the so-called mirror-neurons, in human and primate brains (for studies using principles of epigenetic robotics, see [39,212]; and for applications to impaired attentional processes, see [239]). Socially-situated learning rests heavily on imitation learning, or learning through emulation, which means transforming the perceived actions into one's own action repertoires, aiming at the inferred goal or intention of the perceived action (for studies on imitation learning in epigenetic robots, see [47,83,116]. An important aspect of perceptual development concerns the infant's very early capacity to integrate information from the various senses and perceive the world in a multi-modal way. Multi-modal perception can also be accomplished by epigenetic robots through associations of information from various sensory organs [106,248]. Epigenetic robot studies have tested embodied and socially-situated processes of cognitive and language development [86,87,197,200,377] and emotional development and communication [44,45,46,56].

The Forms of Development: Fluctuations, Variability, Continuity, Discontinuity and Critical States

Development and the Notion of Stages Classical developmental theories (e. g. Piaget, Erikson) typically view development as occurring in stages, that is, the course from the initial developmental state to some sort of end state is seen as a stepwise path, or a path moving across various qualitatively distinct states. Piaget's theory, for instance, describes a first stage as a sensorimotor level of thought, after which children proceed to a second level called pre-operational, then to concrete-operational thinking. Development finally stabilizes at a formal operational level, which is characteristic of adult thinking.

Recent stage-oriented theorists, in particular the neo-Piagetians, occupy a considerably more sophisticated standpoint [103]. They see "stages" as in fact qualitatively different forms of thought, or skill in general, that are developmentally ordered but are also context- and domain-specific [58,82,103]. A child may function on stage (or level) 1 in domain A (e. g. simple mathematical operations) and on level 2 in domain B (e. g. social relationships). Within a domain, such stages – or one should say levels – can fluctuate with varying context, because context is a part of a person's skill (e. g. a child who faces a particular problem context may function on level 2 with help and on level 1 without help). The levels or stages may fluctuate strongly over the short-term time scale of a problem-solving event, in a process that Fischer has called "scalloping" [103,130]. Overall, however, there is also a fuzzy but nevertheless convincing ordering in the level or stages. Two-year olds, for instance will show a very different mixture and frequency of context- and domain-specific levels than adults, and are thus characterized by a different major-stage category than adults are (see [80] for an example). The notion of stages advocated by neo-Piagetian theorists reflects the complexity of the developmental system by viewing stages all the way down, in a complex, hierarchical and dynamic organization.

The notion of stage (level, phase,...) entails an idea of internal coherence, a relatively stable structure of interdependent elements such as skills, habits, processes and so forth. The notion of stage is thus highly reminiscent of a basic notion from dynamic systems, namely the notion of attractor. Starting from the theory of complex systems, we can follow the assumption that such systems tend to self-organize into islands of relative stability rather than remain unconnected collections of features where any combination of such features is as likely and (in)stable as any other. From this, we can reach the conclusion that stages, defined in the dynamic and complex way explained above, should be the default option for a system as complex as human development.

Developmental Stages and the Theory of Bifurcations Developmental attractor states do not need to be overall states in the sense of stages, but can amount to any stable pattern of coordinated knowledge or skills at any level of aggregation. The transition from one such state to another represents a discontinuity, since none of the intermediary states, if there are any, is stable. Developmental researchers have used the framework of catastrophe theory to answer their questions about developmental discontinuity (for an overview see [327,351]). By testing for empirical indicators of the so-called catastrophe flags (structural properties of discontinuities in general), they have tried to show that developmental transitions are instances of the so-called cusp catastrophe and thus entail a clear form of discontinuity. Examples of phenomena studied are the transition between non-conservation and conservation understanding in young children [139,150,151,157,158,326], reaching and grasping in infants [373,374] and syntactic development [259,329]. The results show that rapid, jump-wise development takes place in a variety of domains. However it remains unclear whether these changes are real discontinuities in the bifurcation sense. In addition, they seem to occur in some children but not in all. A problem with discontinuities is that the empirical detection depends on the definition given by the researcher (see [329] for discussion). Finally, different attractor patterns can occur simultaneously and in that sense show a form of superposition [343,352]. Children can act according to a less advanced skill pattern and only little later act in accordance with a more developmentally advanced pattern. If such patterns co-occur, they will lead to increased intra-individual variability in performance, which has been shown in the above-mentioned catastrophe-theoretical studies and in studies of language development [20]. As development proceeds, the less advanced pattern will disappear in some cases, but remain unchanged in others. In language development, for instance, less advanced grammatical principles disappear, but on the level of cognition as a whole, earlier patterns – one should not particularly call them less advanced – can survive and be used in contexts where the more advanced patterns are not directly applicable (see the scalloping principle mentioned earlier). Finally, developmentally divergent levels of skill or knowledge can even occur in the same action pattern, for instance if the child's verbal explanation refers to a less advanced level and his non-verbal gestures to a more advanced level of understanding (or vice versa, see [119,156].

Because behavior and action are in themselves highly variable phenomena and because this variability is intrinsic to behavior and not a matter of added measurement error or noise, the continuity issue amounts to the question whether bands of fluctuation or variability in behavior develop continuously or discontinuously [329]. The growth models described above represent development or growth in a variable as a single point on a dimension, but this point should be seen as an estimation of a central point of what in reality amounts to a bandwidth of fluctuation.

Are Developmental Stage Transitions Like Physical Phase Transitions? One possibility is that what has traditionally been called "stages" are comparable, in that sense, to the phases of physical matter (gaseous, liquid, solid) and depend, in essence, on a single parameter or a confluence of parameters. Developmental stages form attractor states because they rely on network-like structures, i. e. on structures of relationships between the components of the system. A developmental attractor state is represented by habitual, coherent patterns of performance, skill or action that self-organize spontaneously in the person's habitual contexts, niches or living spaces. These patterns consist of mutually-supportive and sustaining features. To give a simple example, Piaget's sensorimotor stage defines thought in the form of external action on objects. For instance, reaching to and grasping an object requires the coordination in real-time of a myriad of components or aspects, including the coordination of the muscles in the arm and hand, the coordination of vision and movement, the coordination of vision of the object and vision of the own arm and hand, and so forth. These patterns are not innately given, but self-organize through processes that eventually amount to discontinuous changes (e. g. Wimmer's studies of early prehension development, Wimmers, Beek, and Savelsbergh, 1998a; Wimmers et al., 1998b; [372]). The characteristic feature of these sensorimotor patterns is that their contextual self-organization (e. g. in the form of reaching to and grasping a particular object) emerges on the basis of dominant driving forces or control parameters that are of a sensory and motor nature (see for instance dynamic field theory described earlier). In addition, the sensory and motor control parameters of infant action are likely to be biologically preadapted to important features of the environment, such as object-person distinctions, numerosity, etc. (see for instance [295,372,373,374]).

Are Developmental Transitions Caused by Self-organized Criticality? Irrespective of the stage theory under consideration, the durations of sequential stages tend to increase in a logarithmic manner [340]. One might ask if the distribution of stage durations relates to the power law distribution characteristic of self-organizing phenomena [242,354], and more particularly, to self-organized criticality [10]. The phenomenon of self-organized criticality emerges in complex systems, consisting of many components that entertain local relationships. We have already seen that the embodied-embedded brain is such a system, consisting of many components (perceptions, thoughts, actions, memories, tools, environments) that are temporally and functionally connected. This complex system is under a certain external "tension": there are problems to solve, goals to achieve. The person does so by means of the complex system of skills, knowledge, sensory and motor systems. As not every action is successful, the person will adapt and learn from his experiences and from being taught by other people. This complex, interconnected system exchanging information with the world is a good example of a system that shows self-organized criticality. Its attractor states are critical states, i. e. states for which any external influence can cause patterns of change with a wide variety of magnitude and duration, dissipating the stress that has been build up in the system. Note the major difference with a phase transition model: in a phase transition model the attractor states are the phases, whereas in a critical transition model the attractor states are those where a transition might occur.

The magnitudes and durations of changes are statistically distributed according to a power law distribution, with very few large-scale changes and increasing numbers of smaller scale changes. It is tempting to see development as an example of such a self-organized criticality: a succession of meta-stable states punctuated by changes of various magnitude (e. g. a relatively small change in a relatively context-specific problem solving strategy, versus an avalanche of changes in many aspects and domains of cognitive performance, the latter characteristic of what would count as a stage transition).

If for some reason something changes in one skill (or knowledge, ability, action pattern, habit) it is likely to affect other skills (habits, etc.) to the extent that these two developmental components are interrelated. However, the second component, affected by the first, can eventually affect a third one to which it is connected, and so forth. In principle, such changes can remain quite limited, but they can also grow into an avalanche of changes that affects the whole developmental system. If we assume that in a developing system the "weakest", i. e. the least adapted or effective skills (habits, knowledge) are eliminated (or altered) more easily than better adapted or more effective skills, we wind up with a system that closely resembles the Bak-Sneppen model of biological evolution through punctuated equilibria [9,35]. This model of evolution changes through many events of extinction and speciation, interspersed by periods of stasis.

The pattern of evolution with many small and only a few major extinction-speciation events is clearly reminiscent of the course of human development, with many small and a few major changes. The principle of eliminating or altering the weakest component is also applied in a routine for solving hard optimization problems, called extremal optimization [36]. The solution patterns are characterized by shifts following the power law distribution. In a certain sense, (cognitive) development is like solving a hard optimization problem, an adaptation of knowledge and skills to the complexities of reality. It would thus not be surprising that the general dynamic structure of cognitive development follows a pattern very close to that of the extremal optimization process, including the power law distribution of the changes.

An Overview of the Human Life Span in Light of the Theory of Complex Dynamic Systems

Preliminary Remark

A discussion of the issues of dynamics, self-organization, complexity and so forth in the context of human development requires that the reader has some basic knowledge of how current developmental psychology describes the human life span from the viewpoint of developmental processes. In order to provide such knowledge, I will present an overview of selected themes and topics discussed in mainstream handbooks on developmental psychology [25,51,73,162,227,276,280,356]. The themes are chosen for several reasons, mostly because they are considered of great importance to development, but also because they provide interesting possibilities for applying a complex dynamic systems framework on issues that are usually not seen in this light. The overview presented is therefore, by necessity, only fragmentary and exemplary. Interested readers are referred to a host of introductory handbooks (see above for some suggestions). Because of their importance for starting and guiding development, I shall concentrate more on early processes of development than on the later ones, and confine myself to the period between birth and adolescence.

Most handbooks give a review in terms of stages or phases in the life span, with subdivisions based on major topics or fields of development such as physical and motor development, social and personality development, cognitive and language development as the main sections.

Handbooks often start with a theoretical introduction, discussing major theories such as Piaget, Vygotsky, Freud and so on. These theories mainly or exclusively refer to the work of historical figures who laid the foundations of the field. In addition to such theoretical perspectives, handbooks also discuss basic questions such as the nature-nurture relationship.

Prenatal Development

Prenatal development covers the period from conception to birth. Normal fetal development occurs through three stages. The germinal stage covering the first two weeks after conception is a period of cell division and implantation in the uterus. The second or embryonic period is a period of emergence of essential organ systems, such as the central nervous system, the heart etc. and lasts from week 3 to week 8. The third or fetal stage lasts from week 9 to week 38 in case of full term birth. During the embryonic and fetal stages, the embryo or fetus is sensitive to teratogenic influences, i. e. influences of substances in the mother's body that negatively affect the growth of specific organic systems, due to disease or intake of substances such as alcohol. The influence of teratogenic substances depends on the level of development of the embryo or fetus and is thus related to periods of greater or lesser sensitivity to such influences. During the fetal stage, the child becomes increasingly sensitive to sensory stimulation, which is limited and modified by the child's position inside the body in the amniotic fluid. Of particular importance is the communication with the mother's mental and physical state through the exchange of hormonal and chemical substances that reflect the mother's current psychological state. Such influences can affect the child's later neurophysiological reaction to stress, for instance. Already before birth, the unborn child and the pregnant mother entertain a transactional relationship. The child is affected by the mother through the sensory and neurochemical links described above, whereas the unborn child affects the mother's behavior, moods and evaluations. The effect of the child on the mother ranges from direct effects, for instance the physical stress of pregnancy, to indirect effects via individual, family and cultural evaluations of the mother's current pregnancy. Of particular importance for later development are eventual problems during the birth process, such as hypoxia of the fetus during birth, or premature birth. Most of such relatively minor birth problems are related to diffuse and (very) mild effects on performance, for instance cognitive and academic performance at school age.

Infancy and the Preschool Years (Birth to 4 Years)

General Introduction Infancy is the period that lasts from birth to 24 months. It is the age of sensorimotor functioning, more precisely action that is mainly limited to a direct coupling between sensory and motor systems in an action context. Action itself emerges out of the newborn's reflexes and reflexive actions. The basic sensory capacities are relatively well developed, in that they suffice to allow the infant to make sense of the environment and perceive the environment "as it is". That is, the infant is capable of perceiving the environment as a structure of functional affordances, e. g. as a three-dimensional space with identifiable objects and events that the infant can relate to in its actions. For example, very soon after birth, the infant is able to locate objects in space, for instance by following moving targets with the eyes and turning to objects identified by their sound. Given the early and seemingly automatic adaptation of action of the infant to the core proporties of the physical and social world, various developmentalists have endowed the infant with innate core knowledge of the main features of the world. These core knowledge systems comprise objects, actions, number, space and social partners [295]. The notion of identifiable core knowledge systems has been criticised from a dynamic systems point of view as not presenting a model of the real time mechanisms creating the developmental expression of such knowledge in real, physical situations, and which, in the words of Smith [291] are "general, probabilistic, emergent and distributed across several levels of analyzes".

Cognition and Intelligence Infant *cognition and intelligence* is deeply sensorimotor, that is, intelligent action takes place in the form of real physical action. Infant action, involving looking, grasping, repetitive actions, quitting the action and so forth, must be understood as dynamic processes, the patterning of which unfolds in real time, thanks to the continuous feedback loops between the perceiving and acting infant and the affordances of the infant's proximal environment. By "patterning" one can understand correlational regularities in the action sequences, for instance regularities such as following a moving object with the head and eyes, where the object gets temporally occluded by other objects, for instance. The patterning is a relatively high level patterning, however, in the sense that the regularities are interpretable as expressions of or as being consistent with real-world properties such as the permanence of objects or the existence of causal relations among events. In the mentalistic framework, interpretive patterns such as object permanence or causality were viewed as internally represented structures, generating or producing the observable actions. According to dynamic systems theorists, these patterns are not the cause of, but emerge through the real-time interaction between the infant and the proximal environment (see for instance the studies on the infant's understanding of object-permanence in the A-not-B-error experiment [292,296]. As development proceeds, the dynamics of this real-time unfolding of understanding and acting on the world will become increasingly complex, e. g. by incorporating verbal actions, by enriching memory and by enriching and changing the perceptual organization of the environment.

The infancy-to-toddler phase is characterized by a succession of two major modes of thought. The first is the sensorimotor form, in which thought is entirely expressed through sensory and motor action as described above. In the second phase, thought incorporates forms of representation and symbolization, thanks to the blending of thought and sensorimotor action. In addition to using language for and in thought, for instance in the form of private speech [361], symbolization also typically entails symbolic or make-believe play, which is related to skills needed for thinking about other people's minds (so-called Theory-of-Mind [112]; ToM is further discussed in the section on childhood).

The distinction between perception and symbolization should not be taken too strictly. According to the tradition of Ecological psychology [118], perception means picking up invariants and properties of the environment that "resonate" with the functional abilities of the perceiving organism (this view is also closely related to Thelen and Smith's dynamic systems theory of development [314]).

A typical example of the abstractness of direct perception in infants, in addition to the examples already given on early core knowledge of space, time, causality and so forth, is the perception of the goal-directedness of actions of other persons by infants younger than 1 year of age [31].

Motor Development In the *motor domain*, the infant develops capacities such as sitting alone, crawling, standing and walking. Although such milestones are usually associated with age averages, such as walking around the age of 12 months, individual differences in onset of such motor skills are considerable, for instance between 9 and 18 months for walking. In the motor domain, the disappearance of the early stepping reflex and its replacement by real stepping at a later age provides an illustration of dynamic systems thinking. Thelen and Fisher [314] argued that the disappearance is not due to central, cortical processes, and that it is in fact not really disappearing. Due to more "peripheral" biodynamic processes, namely differential growth in body mass and muscle strength, the reflex is inhibited biomechanically, and "reappears" as soon as the baby's legs are held under water for instance.

Language Development *Language* begins as vocalization, which around the age of six months changes into babbling, i. e. combining vocalizations into larger clusters. Around the 12th month, the first recognizable words begin to appear, notably words referring to caretakers, the meaning of which is probably assigned by the adults instead of actually intended by the children, who form such sound patterns (mama, babab etc.) more or less automatically. Meaning assignment forms an interesting illustration of the transactional nature of early developmental processes, with the adult automatically assigning a meaning to sound patterns uttered automatically by infants, which then sets out an iterative pattern of meaning assignments and language production, resulting in the child's understanding of referential meaning and linguistic significance (around 18 months). Language production in infancy typically consists of one-word sentences expressing various semantic features and nuances (holophrastic speech). Word combinations, mostly in the form of two-word sentences, become abundant around the age of 24 months. Meanwhile, the child's language production and comprehension gradually assimilates the syntactic features of the child's ambient language. The process is typically dynamical, in that it consists of an iterative trajectory of assimilations of syntactic features given the child's current state of language production. Various quantitative features of language development can be described by means of growth processes of linguistic and non-linguistic components connected into a web of mutually supportive or competitive relationships, under the constraints of limited and specific resources [337,340,346]. In addition to continuous growth processes, language development is also characterized by discontinuities, corresponding to the emergence of new strategies of language production [21] or new linguistic forms or categories [259,329].

Our understanding of the dynamics of language development is crucially dependent on how we understand language per se, although – in the spirit of genetic epistemology – our understanding of the nature of language can be greatly enhanced by the study of language development. For a further discussion of this relationship, which is a typical issue of developmental psychological theory formation, see the Sect. "Development as Increasing Complexity Applied to Language Theory and Theory of Language Development."

Brain Development As regards *brain development*, after the prenatal period, productions of new neurons virtually stops or is greatly reduced. Synaptic connections between neurons are abundant in the beginning, and will be selectively lost in a process called synaptic pruning, which relies on experience and practice. During infancy, the two hemispheres become increasingly specialized (lateralization process). Meanwhile, the brain, or more precisely the cortex, remains highly adaptive, a property known as brain plasticity . Brain specialization occurs through complex, non-linear dynamic processes involving interactions inside the brain and interactions between brain and body and body and environment [187,188,189]. Brain plasticity decreases as the person grows older, but does not disappear [175].

Brain plasticity however, is a typical dynamic property which is nonlinearly dependent on the brain's developmental history. The change in plasticity is not linear or curvilinear, as the notion of a gradual decline in plasticity suggests. Rather, there are nonlinear peaks of plasticity, known as critical periods or sensitive periods. These critical or sensitive periods, in which the brain is particularly sensitive to particular experiences, are in themselves also self-organizing and dynamic phenomena [49]. They emerge epigenetically from the brain's development and are thus co-dependent on biological brain growth and the unfolding of experiences, including teaching and learning over developmental time [173,319]. According to a now obsolete view on sensitive periods – critical periods – the sensitive period is like a time window of opportunity that, if missed, will never come back and will leave the person with an irreparable gap in development. This view relates sensitive periods to relatively isolated processes of growth in the brain that unilaterally govern the developmental process. It is incompatible with the view, for which there is now abundant evidence, that sensitive periods are self-organizational states integrating interdependent phenomena of brain growth, experience and environment [159].

A dramatic illustration of how brain plasticity – and development as a whole, for that matter – always passes through the short-term dynamics of action, is the development of children after hemispherectomy. Hemispherectomy is the surgical removal of a brain hemisphere, mostly as a last possibility for curing major and highly frequent epileptic insults that cannot be treated pharmacologically [22,154,355].

Social and Emotional Development Basic *emotions* such as anger, sadness and happiness, are already present during early infancy, which suggests that basic emotions are innate patterns. However, dynamic systems theorists have challenged this interpretation and view basic emotions as the earliest patterns of emotional expression that arise through self-organization of components from various sources (motor, contextual, ...) and become stable attractor patterns [54,55]. Infants are able to interpret emotions of other persons early in infancy. The ability to understand the relation between an other person's emotional expressions and that person's goals and actions is already developed at the end of the first year [218,240].

Temperament is a person's habitual pattern of emotional reaction, activity level, attention and self-regulation. Temperament in the sense of such stable characteristics occurs from early infancy on, with about 2/3rds of the infants falling in the categories "easy child", "difficult child", "slow starter". Temperament, as an invariant property overarching contextual variability in reaction patterns, is a typical short-term form of stability. Temperament changes over the long-term process of development, but it does so to varying degrees, depending on the person (e. g. extreme patterns are less likely to change) and age (e. g. early temperament tends to change more easily than temperament at a later age). In that sense, temperament is a higher-order short-term attractor pattern of behavior and emotion, which over the long-term tends to shift across the temperamental state space with context-, person- and age-specific velocities. The classical study of Thomas and Chess on temperament development [318] provides an example of a dynamic person-context transaction, known as the goodness-of-fit hypothesis.

A third theme that is of particular importance for early social and emotional development is the development of *attachment*. Around 6 to 8 months, infants begin to develop a strong affectional bond with familiar people, the mother or primary caretaker in the first place. This strong tie serves as a source of emotions, such as comfort and joy while the object of attachment is present and sadness or discomfort when he or she is absent. Attachment thus serves as a basic model for the emotionally close relationships that will develop and last throughout life. As with temperament, attachment shows a certain stability across short-term fluctuations in contexts, and a partitioning into characteristic patterns. About 2/3ds of the infants show a pattern of secure attachment; other infants show avoidant, resistant or disorganized patterns of attachment. In a dynamic systems framework, these patterns should be interpreted as short-term attractor states, showing a gradual long-term development, with considerable individual differences in the amount of displacement over the developmental state space [342].

Childhood (5 to 12 Years)

Cognitive Development A characteristic feature of cognitive development during this phase is that it makes a transition to a new mode of thought, concrete operational thinking, a term stemming from the work of Piaget (as do most of the basic terms used for stages or phases as represented in the major handbooks). A major feature of this type of cognition is that it shows reversibility, a notion that is similar to the notion of inverse operations in mathematical groups. Hence, for every action the child can think of, it automatically knows there is an imaginable operation that undoes the effect of the first. The emergence of a property such as reversibility amounts to an increase in the complexity of the cognitive system.

From a dynamic point of view, such formal properties must be given a concrete temporal meaning, for instance in the form of a pattern of reasoning about a possible inverse operation that is not explicitly given in perception.

Neo-Piagetian theorists such as Fischer and Case have postulated comparable qualitative extensions of the child's cognitive system. In Fischer's theory, for instance, the cognitive system which is able to represent relations between elements (e. g. a relationship is-a-brother between me and my brother) is transformed into one which can represent relationships between relationships; see for instance [103].

As regards the theoretical interpretation of what such increases in or extensions of complexity of the cognitive system actually mean, various considerations should be taken into account. The first is that properties such as reversibility and comparable formal properties of the cognitive system refer to action potentialities of a system that is based on or consists of an embodied neural network in a concrete, spatiotemporal world. Hence, the generative cause of child's actions and reasoning is the system consisting of a concrete context or niche on the one hand and the child – as embodied and organic neural-network on the other hand [350]. This generative cause generates a stream of action to which certain formal properties can be ascribed, such as reversibility (and comparable properties). Second, a major feature of dynamic theories is that they view this generative cause as a dynamic interdependence of many factors (memory, perception, action, changes brought about by action in the context, recent experiences, long-term effects of experiences and so forth) on many levels (from the micro-level of neuronal activity via the meso-level of bodily activity to the macro-level of physical-cultural environments). There is no single factor that can be held responsible for an emergent phenomenon such as reversibility of cognitive representations [19,103,271,293,368].

Examples of developmental acquisitions typical of this phase are conservation, classification, and seriation. Conservation, for instance, is the child's ability to understand that physical properties, such as the amount of liquid in a glass, are conserved under certain operations, such as pouring the liquid into another glass. The emergence of conservation understanding is a typical example of a discontinuous development, i. e. it tends to occur in an all-or-none fashion and can be described as a bifurcation or cusp catastrophe [325,327]. However, the developmental emergence of a phenomenon such as conservation is characterized by a considerable intra- and inter-individual variability. That is, children tend to dramatically fluctuate in their type of conservation answer (yes or no) over test occasions during the period of transition. Moreover, children also tend to differ considerably from each other in terms of the path they take towards conservation understanding. The emergence of conservation forms an interesting example of a phenomenon of development that resembles the phenomenon of phase transition in physics.

During childhood, an important aspect of the development of information processing concerns the development of executive functions, functions that critically depend on the frontal lobe. Important skills related to executive functions are inhibitory control (resisting habits, temptations, or distractions), working memory (mentally holding and using information), and cognitive flexibility (adjusting to change). These skills are of crucial importance for and to a considerable extent dependent on scholarly learning during childhood [79,84]. They are closely related to issues of time management (when to do what, how long to retain information), adaptability and goal-and-desire structures (how to focus on which goals and when). The dynamic manipulation of goals and tools (physical and symbolic) and the patterning that emerges as a consequence of this process is a characteristic feature of dynamic accounts of cognition and cognitive development [19,322]. By "patterning" I understand the unique structure of components and relationships in a child's ability repertoire as witnessed through context-specific and context-supported actions. This ability repertoire greatly extends during childhood, as the child goes to school and acquires skills in major domains such as math, reading and writing, conceptual knowledge and so forth. These new domains of thought and symbolic action were prepared and prefigured during the preceding developmental stage (see for instance the discussion on core knowledge), but show an explosive development in (schoolgoing) children during this developmental stage. The acquisition of these fundamental domains of skill and knowledge requires massive recruitments of brain regions [298].

Social Cognition In this section I shall concentrate on an interesting aspect of social cognition which nicely illustrates the complexities of development and which is also increasingly accepted as being of applied and clinical importance, namely Theory-of-Mind. Theory-of-Mind (ToM) is the ability to attribute mental states to oneself and others and to use these attributions in understanding, predicting and explaining behavior of oneself and others [19,214] or the book 'Autism: mind and brain' [111]. A typical aspect of ToM is the ability to entertain first-order beliefs, i. e. beliefs about the beliefs (thoughts, knowledge, ...) of other persons, which typically develops around the age of 4.

There is supportive but indirect evidence of two 'approaches' to ToM: an intuitive (or automatic) and a reflective (or controlled) route [196]. Indirect evidence for an intuitive, neurophysiologically-based understanding of ToM-related properties of other persons comes from the rapidly growing literature on the neuronal systems that underlie the spontaneous understanding of human actions and psychological states of others. An example of such systems is the mirror neuron system (for the relationship between the mirror neuron system and autism, see for instance [113,135,153,183,232,371] but see [81] for critical remarks). There is neuropsychological evidence that specific parts of the brain, such as the medial prefrontal cortex and the temporal-parietal junction are involved in the processing of ToM-related information [110,174,196,266].

In a dynamic systems framework, the ability as described under the definition of ToM above does not emerge from an internal symbolic structure, generating prescriptions for acting under certain conditions (e. g. a false belief experiment). ToM, as it is actually expressed, in real time, emerges out of a coordination of many components, including perceived similarities in bodily appearance and action between the child and other persons, goals and emotions, inhibitions of associations (e. g. between what I know and what another person eventually knows), automatic simulations of actions and emotions perceived in others, language and linguistic terms for expressions of states of mind and so forth. This ability grows throughout childhood, until it entails abilities such as the ability to think about how other people think you think (second-order beliefs).

Other aspects of social and socio-cognitive development that are worth mentioning in this regard are the views children develop on their own person in relation to others. These views concern the child's self-concept, the sense of competence and self efficacy, gender- and gender-role concepts and so forth. From a dynamic standpoint, these concepts are relatively stable and adaptive patterns of action and emotional evaluation featuring in situations or events that elicit self-referential aspects are in general self-sustaining (e. g. when confronted with a math assignment, a child must ask himself "will I be able to solve that assignment", "will it require little or great effort", etc.). In a social interaction the child may react with intense negative emotion when confronted with statements about his capacities, lack of fit with the gender stereotype and so forth. For examples of the interdependence between short- and long-term time scales in this particular domain, see [301,303].

Self-referential emotions and concerns play an important role in the dynamics of group relationships among peers. Children in this particular age range tend to form patterns of social interaction, creating particular interaction positions such as popular versus rejected children. These so-called sociometric structures (because they formed the subject of an approach to children's social interactions known as sociometry) tend to self-organize as a result of interactions driven by concerns, emotions and perceptions of actions of other children in the group (for an explicit dynamic model of this process, see [208,300,302,303]).

Adolescence

Biological Maturation and the Problem of Timing Puberty and adolescence are ages of accelerated change and development. A major aspect concerns sexual maturity during puberty, which involves major changes in primary sexual development (the person becomes biologically capable of reproduction) and secondary sexual development (the person develops bodily features characteristic of one's sex). These biological changes are related to a spurt in bodily growth, the functioning of the endocrine system and changes in brain development [29,78]. Biological changes are directly related to social changes in terms of interaction, interaction forms and preferences, and changes in cultural expectations.

The structure of interactions between biological, social and cultural changes provides an interesting example of the importance of timing (the temporal ordering of related events). Sexual maturation is an extremely important event. From the point of view of the evolutionary time scale, it must occur at the "right" time, which means that it must run parallel with the timing, i. e. the temporal sequencing, of additional events, required for successful reproduction. The timing is a result of events that preceded it, and on the other hand timing provides a condition for later events. For instance, pubertal timing is responsive to ecological conditions earlier in life, which might be beneficiary as well as adverse. Such conditions may lead to either inhibiting or accelerating onset of puberty. The effects of earlier or later puberty, on the other hand, are non-linear, being most notable in the extremes (both positive and negative [43,95,97]. Differences in the timing of biological maturation are gender specific and occur mostly with girls [207]. The problematic or beneficiary effects of early or late timing of onset or puberty are not a matter of a linear ordering of events. For instance, it is not the eventually early menarche itself that leads girls to experience adverse effects on other variables, such as psychosocial adaptation or birth weight of the first offspring. What matters is that such timing issues cause a problematic (or beneficiary) coordination, that is, mutual ordering, of different time lines or event sequences. Examples of such event sequences are timing of romantic dating and first sexual intercourse, the nature of the partners and potential providers who may or may not be able to support the offspring, and so forth. From the point of view of the participants, i. e. the people who are actually involved in these issues, timing relates to the subjective order of meaningful life-events in their own life and in the life of other persons with whom they are intimately connected (educators, parents, peers, romantic friends,...; see for instance [206]). In short, biological maturation during puberty provides an excellent example of timing problems in a complex dynamic system.

Autonomy, Identity and Connectedness The processes of biological and social development described in the preceding section are related to a renegotiation of the person's place in the familial, social and peer network. According to the historically important and psycho-analytically inspired theory of Erik Erikson (1902–1994), the main challenge during adolescence is to develop a personal identity (see [41,42] for an overview). For Erikson,"At times, identity refers to a structure or a configuration, at other points it refers to a process. Still on other occasions identity is viewed as both a conscious subjective experience as well as an unconscious entity" [179]. Erikson himself saw the conscious feeling of having a personal identity as "... based on two simultaneous observations: the perception of the selfsameness and continuity of one's one existence in time and space and the perception of the fact that others recognize one's sameness and continuity" [100]. Self-sameness means the existence of invariant properties over change that is both developmental (long-term) and actional (short-term). Erikson's view of identity is an example of an approach that respects the complex nature of the phenomenon under study and by doing so accepts the superposition of its features (it is both a process and an entity, it is an invariant defined by change, it is of the person but only insofar as it is also of other persons, and so on; see Sect. "A Working Definition of Complexity"). Although the concept of identity is an essential feature of the study of adolescent development, its complexity and in particular the acceptance of its complexity is a constant source of unease among researchers. Lichtwarck-Aschoff et al. [193] suggested a description – and the associated empirical study – of identity as a concept distributed across a two dimensional, categorical state space. One dimension concerns the distinction between dynamic and static approaches to phenomena, the other concerns the distinction between short- and long-term processes.

Identity development is closely related to the tension between autonomy and connectedness, both in terms of the short-term dynamics of action and social interaction and the long-term dynamics of development. As children become sexually mature they renegotiate their relationship with their parents by claiming a greater level of personal autonomy and self-determination. Meanwhile, if the relationship with the parents is positive, they do not want to loose the connectedness they feel with their parents, and these opposite tendencies create an interesting developmental dynamics. Lichtwarck-Aschoff et al. [193] have used this tension as the basic component of a long-term dynamic growth model of autonomy and connectedness, in order to account for the classical phenomenon of parent-child conflict during adolescence and for the considerable inter-individual variation in the form and outcome of this process (see also Sect. Development and Resource-Dependent Competition-Support Systems" for an explanation of the model; for comparable models see [180]).

Future Directions

Although human development is a prime example of a complex dynamic system, the theory of complex dynamic systems is not the mainstream approach to studying development. Human development is an example of one such system in which the observer – the researcher, the parent, the educator, ... – are part and parcel of the complex system itself, thus leading to the epistemological and conceptual complexities and entanglements that are characteristic of systems in which the observer is an essential agent, in one way or another. Maybe it is because of this entanglement and epistemological complexity that psychology, and the study of development for that matter, still adheres to an approach of linearizing processes and disentangling causal contributions from identifiable factors. Changes are observable, for instance in the form of theories and approaches that focus on developmental systems, holistic interactions, dynamic systems, and so forth. Unfortunately, these approaches are still mainly theoretical: their contribution to changing the habits of empirical research and theory formation are at best very modest. The statistical sophistication that is required from most manuscripts that are submitted for publication in developmental journals stands in a glaring contrast to the almost complete lack of requirements regarding theoretical depth and reflection. In a book review, the philosopher and psychologist Harré referred to the situation as follows:

> It is a remarkable feature of mainstream academic psychology that, alone among the sciences, it should be almost wholly immune to critical appraisal as an enterprise. Methods that have long been shown to be ineffective or worse are still used on a routine basis by hundreds, perhaps thousands of people. Conceptual muddles long exposed to view are evident in almost every issue of standard psychology journals. ([138], p. 1303)

The blessing of our being so closely involved in the processes of development and education (all persons living have gone through a process of bio-psycho-social development themselves and cannot be but daily witnesses of ongoing developmental processes in others) is maybe also its curse. In order to study the process scientifically we probably feel obliged to discard all the intuitive knowledge and models we use in daily life and by doing so surrender to approaches that are critically incompatible with the complexity and dynamics of the phenomenon that we wish to understand. This problem is not easy to solve and will continue to be a very hard problem for the coming decades.

Meanwhile, it is the firm belief of the current author that progress can be made by reformulating the questions and methods on the basis of an approach of complex adaptive systems. The first steps that scholars in this field will have to take will most likely appear utterly naïve and limited to scholars studying other fields where conceptual and mathematical theory building has gone hand in hand with the development of rigorous empirical methods. Students of development will have to invest much more time and intellectual energy in the descriptive and exploratory study of individual developmental trajectories, studied with an intensity that is sufficient to capture the nature of the underlying process and with a thorough understanding of the fact that their focusing on the individual alone is in itself an important factor in the development of that individual. In addition, researchers should not be afraid – and in fact should promote the use – of so-called toy models that are highly simplified representations of the assumed, basic dynamics of some sort of phenomenon. It should not be expected that these toy models will provide us with stunning empirical fits with great data sets (but model fitting in itself is not the primary goal of scientific research, see [126]). However, if we ever wish to understand the intricacies of even relatively simple dynamic processes, we will have to study them in ways that can be made conceptually transparent, and this means, among others, taking toy models serious, as long as they are based on good theoretical considerations. An important consideration for a model is that it should be descriptively adequate, that is, that it captures the "essential" features of the phenomenon it addresses (the term descriptive adequacy stems from Chomskyan linguistics [61]). Since it is difficult to agree on what the essential features of some sort of phenomenon are, it is easier to define a model as not descriptively adequate if it leaves out or is incompatible with at least one feature of the phenomenon that is generally accepted as "essential". A descriptively adequate approach to human development and education should be one that is deeply compatible with the major features of development, namely its complexity and its dynamic nature.

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Development, Evolution, and the Emergence of Novel Behavior

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Article Outline

Glossary

Heterochrony an evolutionary change in the timing of individual developmental events.

Plasticity the ability of individuals to respond flexibly in biologically or behaviorally adaptive ways to changes in the enviroment.

Developmental Systems Theory the idea that development unfolds via the bidirectional interaction of genes and enviroment at all levels of the developmental system, including genetic, cellular, structural, behavioral, and cultural.

Epigenesis an emergent process by which an organism's structure and function chage from relatively undifferentiated states to increasingly specialized, differentiated forms throughout ontogeny.

Epigenetic inheritance the non-genetic transfer of information from one generation to another.

Definition of the Subject

Ontogeny, or individual development, results from the bidirectional interactions of genes and environment. It is this interaction that allows inherited traits to become expressed in the phenotypes of adult organisms. While each individual will develop along its own unique trajectory, most members of a species are very much the same because they all inherit a species-typical genotype and a species-typical environment. When this enviroment changes, individuals must adopt or they will fail to survive. Individuals with enough plasticity to respond to new environments by developing novel phenotypes will be more likely to survive than those without such resilience. In this way, developmental change can have substantial impact on evolution by providing the grist upon which natural selection acts. Successful developmental systems will be selected and inherited, and evolution may thus be seen as a series of ontogenies.

Introduction

There has been a resurgence of interest in evolution among psychologists and other students of behavior. Darwin's great insight that not only morphology but also behavior and "mind" have evolutionary histories has captured the attention of a myriad of scholars in disciplines from anthropology through zoology. An important issue in evolutionary psychology concerns how evolved, inherited characteristics become expressed in the phenotypes of adults. It seems obvious to some that such characteristics do not appear fully formed in the adult but emerge during *ontogeny* (the development of the individual), requiring a developmental analysis (e. g., [11,40,99]). On the flip side, developmental analyzes can be used to provide insights into the processes of evolution. *Phylogeny* (the development of the species) can be viewed as a series of ontogenies: The many ancestors of extant creatures each themselves developed, and it was changes during the course of these ontogenies that produced evolutionary change. In the words of West-Eberhard (p. 89 in [124]), "The evolution of the phenotype is synonymous with the evolution of development". Natural selection has had as much or more of an impact on the early stages of development as it has had on the adult, and as a result modifications during the fetal, infant, or juvenile periods establish new contexts for further selection and thus the evolution of the species. From this perspective, the influences of both genetic and environmental mechanisms are expressed through the process of development, yielding phenotypic variation that selection might then act upon.