A complexity and dynamic systems approach to development:

Measurement, modeling and research

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Understanding mind, brain and education as a complex system

Human development constitutes a complex system. Rocha (1999) defines a complex system as "…any system featuring a large number of interacting components (agents, processes, etc.) … whose aggregate activity is nonlinear (not derivable from the summations of the activity of individual components) … and typically exhibits … self-organization …". In this definition, complexity not only relates to quantitative aspects (large number of components) but also to specific qualitative aspects (non-linearity and self-organization). Our scientific endeavors are directed towards understanding this complexity, which inevitably, implies the reduction of complexity to something that is simple enough for our human minds to understand. Complex systems cannot be understood without taking the complexity into account, which means that, however much we simplify, the core qualitative features of the complex system must be preserved. These qualitative features are central to our understanding of the system.

The standard practice of simplifying the complexity of developmental and growth phenomena is to linearize the phenomena. One standard research method is to take a time span that is short enough to allow for unidirectional and linear causality. For instance, we perform an intervention and then study its immediate aftereffects, in the form of change in some variable of interest. Another method is to measure independent variables over independent subjects, e.g. in cross-sectional research. The subjects are considered representative of an underlying category, e.g. the category "five-year-olds" or "ADHD children". In this design, all variation that does not co-vary with our independent variables must be considered as noise.

By applying this linearization to the developmental phenomena we are able to simplify their complexity and obtain a considerable insight into a great number of relationships that hold in the complex system.

The crucial question is, however, *whether this form of simplification has preserved the core features of the complex and dynamic developmental system*? If it has not, how can we simplify and study the phenomenon in such a way that our approach remains faithful to these core features?

In order to answer these questions we will begin by presenting a short but by no means exhaustive description of what we consider characteristic or core features of complex dynamic systems.

We will then proceed by discussing, first, how these core features or characteristics of complexity affect general aspects of measurement of psychological variables in development and, second, how they affect theory- and model-building and the empirical testing of hypotheses. The discussion of these issues in separate sections is merely a matter of convenience, given that they are intricately linked. The answer to our crucial question will be that, in general, the standard practice of developmental research does not preserve the core features of complexity. However, we intend to show that – and how – it is possible to reconcile our familiar approach to studying development with those features of development that pertain to its dynamic and complex nature.

Characteristic or core features of complex systems

Non-linearity and self-organization

Non-linearity means that effects of variables or forces are not describable as the sum of functions of the causal variables. Self-organization implies that in complex systems, macroscopic order (structure, information, …) increases spontaneously, as a consequence of low-order energy consumption. Self-organization is intimately related to non-linearity, in that self-organization is itself a non-linear effect of the underlying causes (e.g. it may arise suddenly, with no apparent change in the underlying causal factors). Self-organization is the opposite of transmission. For instance, if we conceive of teaching as a form of knowledge transmission, we imply that a structure (the knowledge) present in one location (the teacher) is brought over to another location (the student). Transmission is always subject to natural loss of information (increase of entropy, the second law of thermodynamics). The spontaneous loss of order or information in transmission systems requires that the transmitted information must be over-determined (repeated several times, for instance). Through such over-determination or repetition, the loss of information due to transmission may be repaired. If over-determination is not possible (which is the case in the Chomskyan model of language acquisition) the order, structure or information must be put into the system in advance, for instance in the form of innate modules.

Self-organization on the other hand, implies that certain systems, namely systems that are already highly ordered and structured (for instance a system consisting of students and a teacher, or a language learner in a normal environment), exhibit spontaneous increase of order, structure or information. Thus, in a selforganizing system, transmission of information (as in a teaching process) may lead to the construction of structures that are more complex and more complete than the transmitted information itself (e.g. the learning effect in some of the students exceeds the content of the teaching). Self-organization has now been demonstrated in a large range of developmental phenomena (see for instance Roubertoux and Carlier, 2002; Gottlieb, 1992; Ford and Lerner, 1992).

An important question concerns the empirical indicators of self-organization. The first indicator is the presence of increase of order or structure that goes beyond the order and structure present in the "input". Increase of order and structure is the hallmark of development, but it is not easy to show that such order exceeds the order of the "input" (the teaching and learning environment). Note that in the Chomskyan approach to language development, the "poverty of the stimulus"-argument potentially provides strong support to the idea that language acquisition must in fact be a process of self-organization. Unfortunately, because in the Chomskyan approach, self-organization was no feasible option, the "poverty of the stimulus"-argument has been used to show that the structure of language must be innate. Finally, additional empirical indicators of self-organization are the occurrence of discontinuities in development, stages, temporary regressions, inverse U-shaped growth and so forth.

Superposition

Superposition, the second feature of complexity, means that a phenomenon is characterized by two (apparently) incompatible properties at the same time. The notion of superposition is used, in a formally defined sense, in quantum physics, where it relates to a particular kind of uncertainty, e.g. about the position or energy of a particle. In the context of the complex mind-brain-and-education system, a non-formal version of superposition exists. It often occurs in the context of questions such as "does the brain explain the mind", "is development explained by genes or by the environment, or in part by both", "is learning a matter of transmission or self-organization", "is knowledge a substance (a physical structure in the brain) or is it a process", "should people be (clinically) distinguished on the basis of categories (e.g. as in the psychiatric diagnostic manual) or on the basis of dimensions", and so forth.

These questions can (relatively) easily be answered by linearizing them, for instance by studying the association betweens genes and behavior in a large sample of independent subjects, to name just one issue.

However, these solutions also easily lead to (apparent) paradoxes. For instance, if one compares differences in average intelligence between generations (e.g. the 1900 and the 1950 cohort), the differences are for the greatest part explained by (historical) environmental changes (see for instance the average increase in IQ over generations known as the Flynn effect). However, if one compares differences in intelligence between persons from the same generation, living in an environment that offers easily accessible opportunities for everybody, the differences are for the greatest part explained by genes. Thus, it is possible that for a particular person born in 1950, intelligence is at the same time (almost) completely determined by the environment and (almost) completely determined by genes. The paradoxical nature of this conclusion dwindles as soon as we realize that genes and environment are locked in a complex chain of steps over time and that they cannot be conceived of as variables that make mutually independent contributions to development.

To some extent, the empirical indicators of superposition are indirect. For instance, if certain issues, such as the gene-environment issue, remain over many years of scientific discussion and if the positions swing to and fro, it is likely that the issue entails a superposition that is not captured by the simplifications made in the solutions presented. On a much smaller scale of inquiry, if observers of behavior continue to disagree over certain categorizations that they are supposed to make, irrespective of how well they have been trained as observers, it is likely that the category itself is ambiguous, i.e. that it has properties of both the categories over which the observers cannot agree (see van Geert and van Dijk 2003 for a discussion).

A direct empirical indicator of superposition, particularly in the context of development, are spikes in intra-individual variability. Human behavior and performance is intrinsically variable and fluctuating, but at times these fluctuations peak. Such peaks often indicate transitions from one development state, level or stage, to another and are likely to be caused by the temporal superposition of the two states, levels or stages. The superposition implies that at some moment the child functions on one state or level, and at another moment on another state. Figure 1 gives an example of data from a child's language development (Bassano and van Geert, 2005). Utterances were divided into groups, according to three proposed generating functions, a holophrastic generator producing 1-word sentences, a combinatorial generator producing 2- to 3-word sentences, and a syntactic generator producing 4- and more-word sentences and, by default, also sentences

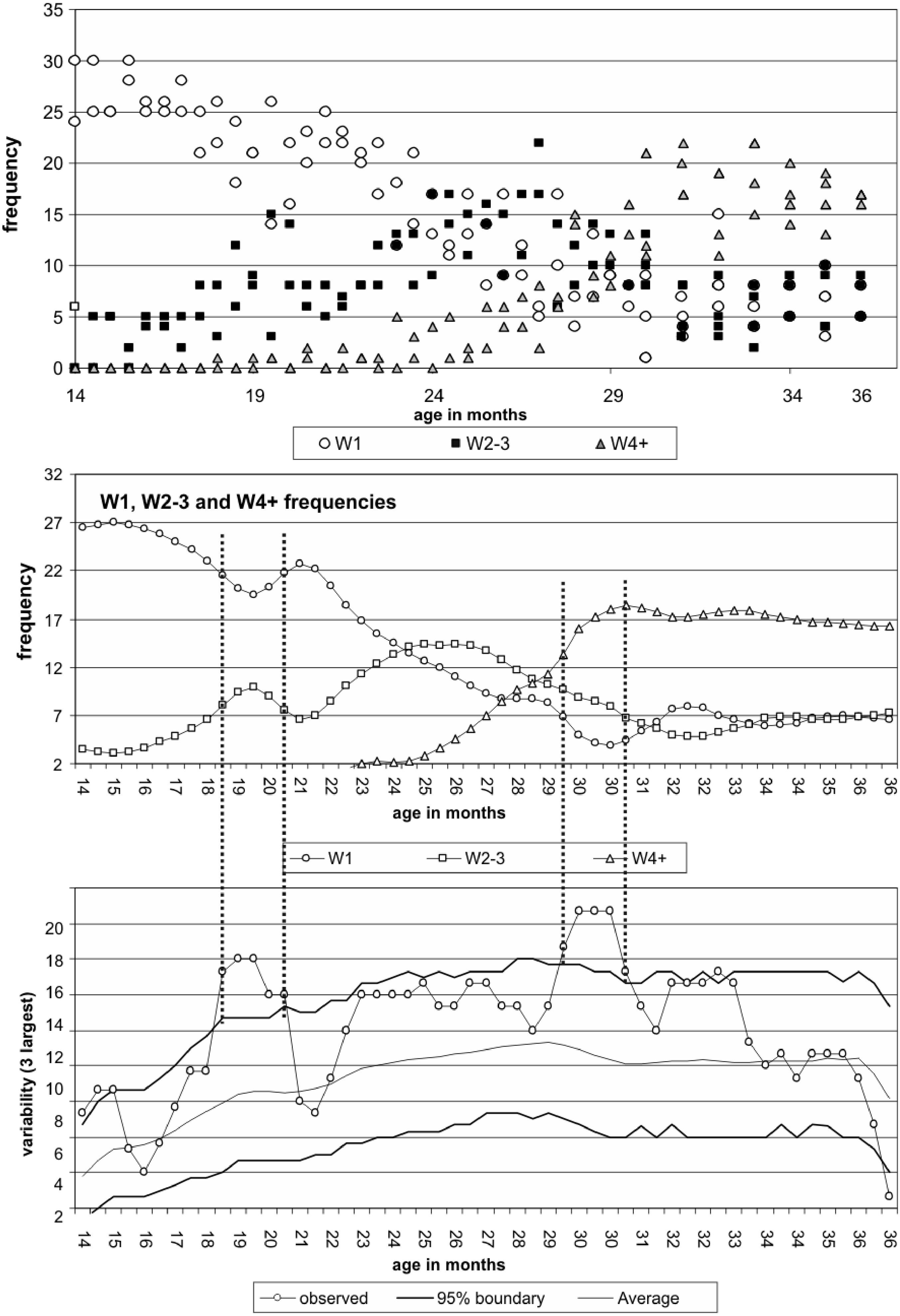
frequency
age in months
W1
W2-3
W4+
W1, W2-3 and W4+ frequencies
frequency
age in months
W1
W2-3
W4+
variability (3 largest)
age in months
observed
95% boundary
Average

Figure 1
Changes in the frequency of 1-word, 2-3 word and 4- and more word utterances in a French-speaking girl between the ages of 14 and 36 months. The utterance groups refer to presumed underlying generators: holophrastic, combinatorial and syntactic.
Figure 1, top: raw data, based on sub-sessions counting 30 utterances each. A complete observation session consisted of either 60 (before month 22) or 120 utterances (after month 22) and was subdivided in sub-sessions of 30 utterances in order to study within-session variability
Figure 1, middle: smoothed frequency curves, based on a Loess smoothing technique, which estimates (changing) central values for the three types of utterances and follows local regressions or other deviations from a main trend
Figure 1, bottom: within-session variability, defined as the average of the three maximal values of within-session variability over a period of 5 consecutive comparisons. Variability peaks around month 19, simultaneous with a temporary regression in 1-word utterances and a temporary peak in the 2- and 3-word sentences. A second peak occurs around month 30, which is the moment of consolidation of 4- and more-word utterances. It is likely that 1- and 2-3-word utterances occurring after month 30 are increasingly generated by the new syntactic generator. The observed variability peaks are compared with a range of variability, estimated on the basis of a multinomial model: since the smoothed frequencies of the three utterance types can be conceived of as multinomial probability functions, the statistically expected variability can be computed, for instance in the form of a 95%-band. The peaks in variability differ significantly from the statistically expected peaks ($p < 0.01$).

consisting of 1 to 3 words. The developmental pattern takes the form of overlapping curves, representing the frequencies of the utterance types. Analysis of the variability patterns showed tow peaks, probably corresponding with the take-over of the holophrastic (1-word) generator by the combinatorial generator, and of the combinatorial generator by the syntactic generator.

Insert figure 1 about here

Substance and process

A third core feature or characteristic of complex dynamic systems is that they are based on the synthesis of substance and process. "Substance" refers to the tangible, physical and permanent existence of physical objects and structures. Process refers to the temporal succession of causally linked changes in substances. Given our human, cognitive structure, it is easier to understand a substance than a process explanation and that is why substance explanations are preferred over the more ephemeral process models. The idea of a brain as a physical substance that contains the causes of behavior in some substance format currently receives major scientific interest. The substance aspect is demonstrated by the search for specific, localizable regions or parts of the brain that are responsible for some specific form of cognitive activity, for instance reading or the manipulation of numbers. However interesting such localization studies are, it should be noted that they do not offer an explanation of the reading process or the thinking with numbers (in the popular press, at least, the finding of a "brain site that does it" is often presented as an ultimate explanation of the process at issue). Moreover, the localized regions are “real” only to a certain extent, since they are the result of a considerable amount of averaging over subjects and occasions, in addition to the fact that they refer only to regions of increased activity and not to unique places where the task at issue is performed without the help of less active regions (see for instance Mazoyer and Tzouriou-Mazoyer, 2002; Beaulieu, 2000, Uttal, 2001).

Thelen and Smith’s dynamic systems theory (Thelen and Smith, 1994) makes a very strong case against the substance interpretation of knowledge. They argue strongly against interpreting knowledge and concepts as some fixed “machine” in the brain that produces the behavior in which this knowledge and behavior are expressed. In their view, knowledge, concepts, skills and so forth are processes. They view these things as soft-assembled, i.e. local and temporal entities that have no existence outside the process in which they emerge. However, it is a characteristic of the complexity of human cognition, that knowledge and concepts are at the same time substance and process, that they are at the same time transient and “soft-assembled” on the one hand and causal and conditional entities of the mind on the other hand. Note that this fact is closely related to the property of superposition explained in the preceding paragraph. This relationship illustrates a more general point, namely that the properties of complexity are in fact *all* related to one another.

Are there any empirical indicators for this superposition of substance and process? An important indicator is intra-individual variability itself (note that, in the section on superposition, we focused on *peaks* in intra-individual variability as a main empirical indicator). If psychological phenomena, such as knowledge or skills, are at the same time “hard-wired” (in the brain) and the product of processes that necessarily involve contexts and environments, for any person in particular they will fluctuate or vary in characteristic ways. The amount of variability determines whether a phenomenon can be more reliably described as substance (if variability is low) or process (if variability is high).

The multi-layered and multi-scaled nature of causality

The fourth core feature or characteristic of a complex dynamic system is that it consists of many layers and many time-scales, for instance the layers of the individual, group, society, culture, species and the scales of micro-genetic, ontogenetic, historical and evolutionary time. It is clear that many problems relating to the study of development can be tackled by isolating a particular layer or scale, but many others will require explicitly accounting for the interactions between the layers or scales. One of the cornerstones of the Vygotskyan program, for instance, which was formulated about 80 years ago, was the study of the interrelationships between the historical development of society and the ontogenesis of the individual (Vygotsky, 1976). The relationships between these layers of organization and between the corresponding time scales are inherently mutual.

The principle of mutual or reciprocal causality is explicitly accounted for in dynamic growth models (van Geert, 1991, 1994, 1998; Fischer and Bidell, 1997). They conceive of development as a web of interacting components that entertain supportive, competitive and conditional relationships. The relationships are reciprocal but not necessarily symmetrical. For instance, it is likely that an earlier linguistic strategy bears a supportive relationship to a later, more complex linguistic strategy. The latter, however, may have a competitive relationship with its predecessor (see Bassano and van Geert, 2005). By modeling such webs of reciprocal action, it is possible to understand the emergence of stages, temporary regressions, inverse U-shaped growth and so forth.

The multi-layered nature of developmental causality is also expressed in the fact that properties of complex systems are (often) distributed over many components. Things such as “concepts” or “knowledge” are definitely properties of persons. If we think about them, we cannot see them but as internal properties. However, the complexity of the task that such properties have to serve, for instance of moving about in a real world or solving a math problem, far exceeds the possibilities of an internally represented knowledge base. Hence, our knowledge and concepts heavily rely on the properties of the outside world, and in that sense, our knowledge is a so-called distributed and situated property (Clark, 1999). It is situated not only in the physical but also in the social context (e.g. computers and human collaborators). The external tools that are created to improve cognition and action, are not just external appendages that in themselves do not affect the internal processes that they support. Over the long run – and it is the long run that counts in developmental and historical processes – they will shape the form of the internal processes themselves, for instance by selecting for those internal skills that improve the use of the external tools. For instance, in the history of writing, written signs were originally just external mnemonic aids, but since then they have evolved into an entirely new kind of cognitive skill, evolutionarily speaking, namely reading and writing.

These skills have been "adopted" by regions of our brains that could handle them (see Dehaene, this volume, and Wolf, this volume). However, it is highly likely that the evolution of reading and writing itself has been shaped by the properties of the brain functions by which these skills were adopted.

What are the empirical indicators of the multi-layered and multi-scaled nature of development? A direct indicator is the finding of a difference between the mechanisms that govern the short-term evolution of a process and those that govern its long-term change. Another indicator is the finding of a difference between structures found by analyzing differences *between* individuals in a population (e.g. the factor structure of personality or intelligence) and structures found by analyzing differences *within* an individual (for instance as a result of a dynamic factor analysis of repeated measures in a single individual, see Molenaar, 2004). The problem is that there is only so little research on individual trajectories and thus that the evidence on such differences is scarce (an exception is the study on perceived control and academic performance by Musher-Eizenman et al (2002)).

We have now reviewed four core features or characteristics of complex dynamic systems, namely non-linearity and self-organization, superposition, substance and process and finally, the multi-layered and multi-scaled nature of causality. We have suggested empirical indicators, i.e. properties that indicate the presence of these features in a process or phenomenon. We will now apply these features or characteristics to an important aspect of developmental research, namely the measurement of development.

Aspects of complexity in developmental measurement

Fuzziness and ambiguity versus uncertainty

Most of the phenomena that we are interested in – a child's cognitive level, reading ability, social cognition, and so forth – are in themselves complex variables, i.e. variables that inherit all or many of the properties of the complex systems in which they feature. We already mentioned an interesting group of empirical indicators of complexity, which was primarily related to the characteristic of superposition, namely ambiguity and apparent paradoxicalness. These characteristics are directly related to the issue of developmental measurement.

For instance, if we score emotional expressions during an interaction between children, we will often be confronted with the fuzzy or even ambiguous nature of such emotions, which we solve by imposing simplifying assumptions upon them, such as reducing them to a one-dimensional variation from negative to positive expressions (see for instance Steenbeek and van Geert, 2002). Another example is the interpretation of syntactic categories in early child language, such as prepositions and verbs. In general, there exists no sharp boundary between a word that is and one that is not yet a preposition, for instance (van Dijk and van Geert, 2005, van Geert and van Dijk, 2002, 2003). The fact that, in this example, a word is something in-between a verb and a preposition, is an example of fuzziness: a categorical distinction that seems to involve mutual exclusiveness (a word is either a preposition or not a preposition) involves gradualness (there is a gradual transition between a non-preposition and a preposition). This gradual transition can be quantified, i.e. fuzziness can be accounted of in a formal way (van Geert and van Dijk, 2003). The gradual transition between categories creates ambiguity, e.g. if a word represents something between a verb and a preposition, it is both a verb and a preposition and at the same time it is neither one. Thus, the word is ambiguous in terms of syntactic categorization.

The fuzziness and ambiguity of variables is often interpreted as the result of a lack of information. In this view, the phenomenon is clearly determined, it is either this or that, but the observer still lacks the information (or the skill) to determine which of the two it is. Put differently, fuzziness and ambiguity are nothing else but uncertainty. It is clear that there are many instances where fuzziness and ambiguity, resulting for instance in disagreement among observers, is indeed caused by insufficient information or lack of expertise in the observers and can be solved by obtaining more information or by further observer training. However, if fuzziness and ambiguity are part of the very nature of the phenomena that we study, we must try to make a distinction between observations where fuzziness is real and observations where it indeed amounts to a lack of information. In situations where fuzziness is real, we must try to objectify it by trying to quantify it (in the same way as uncertainty is quantified by specifying a confidence interval). For instance, instead of using inter-rater disagreement as an indicator of measurement error (the more disagreement, the more error), the disagreement among well-informed and trained observers that share the same set of criteria and rating skills can be used as quantifiable information about the intrinsic ambiguity and fuzziness of the categories they have to rate (see van Geert and van Dijk, 2003, for an application in the field of language development).

In clinical assessment, uncertainty – we would however call it real fuzziness – is often an issue, for instance uncertainty about a child "having" or "not having" ADHD. Would the uncertainty – or the fuzziness, for that matter – be solved if the behavioral indicators can be linked with objective ones, such as particular regions of the brain that are more active in "real" ADHD children, for instance? In our discussion of the third characteristic of complex dynamic systems, the superposition of substance and process, we have already argued that the identification of a substance property, such as a particular region of the brain, does not solve the problem of what ADHD – for instance – really is, how it develops, how it differs among persons and how it varies over the life span. Knowledge of the brain adds another piece to the complexity puzzle and will thus contribute to solving the puzzle; it does not replace the puzzle by the real picture.

Dynamic aspects of psychological variables.

In our discussion of the fourth characteristic of complex dynamic systems, the multi-layered and multi-scaled nature of such systems, we have seen that whatever we measure as a variable, e.g. the child's developmental level on a cognitive reasoning task, in fact results from the dynamic interplay between person abilities and context affordances (see Thelen and Smith, 1994; Fischer et al., 1993, van Geert, 2002; Clark, 1999). Although it is statistically possible to separate context- and person-aspects, such separation requires the assumption of independence of persons and contexts. This assumption is untenable under a dynamic interpretation of performance. On a short time scale, context affordances and person abilities result from the real-time interaction between the two and are, therefore, inherently dependent on one another. On a longer time scale, persons tend to actively select and manipulate the contexts in which they function, whereas contexts on their turn help shape the person's characteristics and abilities. Given a person's characteristic internal features and also given the person's range of characteristic contexts (which are different for a child and an adult, for instance), the person's scores on the variable in question will show a characteristic dynamic. It is this characteristic dynamic that should be the target of psychological measurement. In order to capture the properties of that dynamic, measurement must comply with the following requirements.

First, measurement must be repeated with such frequency (intervals between the measurements) that the characteristic variability of a person can be observed, i.e. the characteristic range within which the person's scores will vary. This range is the product of the person's characteristic context variation, but also of the inherent variability of internal conditions (see for instance De Weerth, Hoitink and van Geert, 1998; de Weerth and van Geert, 2002a, 2002b, Li et al. 2001, 2004, Granic et al. 2003, Eizenman et al. 1997; Schmitz and Skinner, 1993; Kernis et al. 1993; Butler et al. 1994; Rabbit et al. 2001; Alibali, 1999; Bassano and van Geert, 2005). Research on developmental discontinuities – for instance the sudden emergence of a new cognitive principle such as conservation – has also strongly focused on the meaning of increasing variability as a predictor of the coming discontinuity (van der Maas and Molenaar, 1992; van der Maas, 1993; Hosenfeld, van der Maas and van den Boom, 1997ab; Jansen and van der Maas, 2002; Wimmers, 1996). Secondly, the measured variable is distributed across the person and the person's characteristic contexts (a property that we have discussed in the section on the multi-layered nature of complex systems). The distributed nature often coincides with the person functioning in characteristic modes. Thus, measurement implies that the characteristic modes of operation are explored, in the form of multiple testing in various (characteristic) contexts. Examples are the functional and optimal mode resulting from Fischer's testing with and without support, support or cooperation with more competent others being one of the characteristic contexts of cognitive operation, especially in developmental and educational contexts (Fischer et al. 1993). Other examples relate to states in the vicinity of a discontinuous shift, e.g. between different types of language production (Bassano and van Geret, 2005), from non-conservation to conservation understanding (van der Maas and Molenaar, 1992) or when discontinuous stages are represented by means of distinct modes of operation (e.g. verbal and nonverbal modes, see Goldin-Meadow et al.1993). The brain of a person who (eventually temporarily) operates in these two distinct modes shows an example of superposition. It is a brain that features both on a developmental level A and a developmental level B, for instance. This superposition does not amount to a logical paradox. It is possible because the brain in question functions in a complex system – and is itself a complex system.

Aspects of complexity in developmental theory building and hypothesis testing: a case study

What are the consequences of the features of complexity for the way we do research on developmental processes? How can we capture aspects such as non-linearity and self-organization, superposition and the multi-layered nature of causality? Can we understand the course of processes if we do not actually follow these processes in real time? It seems that the adoption of a complexity and dynamic systems approach requires an entirely new developmental methodology. Does it mean that our current methods are not suitable for understanding the dynamic and complexity aspects of development? In this section, we will argue that the standard methodology and standard designs of developmental psychology allow us to capture at least a significant part of the complex and dynamic nature if we are prepared to take a slightly different look on our data. In order to illustrate how this can be done we present an example of one of our own research projects.

The relationship between properties of interaction and sociometric status

Already at the age of six to seven years, children show specific preferences for their classmates. By means of sociometric techniques, it is possible to divide children from the same school class in various sociometric statuses, for instance popular, average and rejected. Earlier research has shown that in social interaction with peers, popular children show a higher amount of positive emotional expressions and more directedness toward peers than children from other statuses (Black and Logan, 1995; Rubin et al. 1998). In a longitudinal research project at the University of Utrecht, children of popular and rejected status were put together with a child of average status and then videotaped during a pretend play session with various sets of toys, lasting for ten minutes. The results did not confirm the earlier findings of a positive linear association between status and positive emotional expression (de Koeijer, 2001; Gerrits and Goudena, 2003). The problem is, however, that the finding of an association between variables in a sample or population – and eventually the inability to replicate such findings – tells us nothing about the causal process that relates features of sociometric statuses in children with their actual expression of positive emotions and interactions with other children.

A dynamic model of emotional expression and interaction

General properties of the model

In our own study, we started from a dynamic model of emotional expression and directedness in social interaction (*directness* is all activity that is directed towards another person, if it is responded to by the other person we call it *coherence*; Steenbeek and van Geert, 2003; Steenbeek and van Geert, 2004). The model of social interaction is based on a general, highly simplified model of human action in general and is strongly inspired by the functional theory of emotions, introduced among others by Frijda (1986) and Campos et al. (1994). We speculated that action – and behavior in general – is based on two components. One component refers to the person's *concerns*, i.e. the "interests" that the person tries to realize. The other component that we call *reciprocity*, refers to the inherently adaptive nature of social exchange, which means that people will tend to reflect each other's behavior. If applied to a play situation involving two children, the concerns are reduced to two basic concerns. One is an interest in Involvement (the class of actions of playing together, including all actions directed towards the other person with the intention of trying to involve that person in the interaction). The other is an interest in Autonomy (the class of actions of playing alone, without interchange with the other person). Emotions are evaluations of the degree to which concerns are realized, i.e. satisfied. For instance a positive emotional expression communicated to the play partner signals both to the child himself and to the play partner that the current situation satisfies the child's involvement concern (see figure 2 for a graphical representation of the model).

Insert figure 2 about here

A play session, like any other form of social interaction, is a structure of iterative actions. That is, an action (such as verbally directing oneself to the other person) is answered, in some way or another, by the other person, and this response of the other is again followed by an action from the person, and so on (see figure 2, at the bottom). This iterative or recursive aspect is an explicit part of the model. It implies, among others, that the interacting persons constitute each other's interaction context. Moreover, it is a context that is partly created by the child himself and partly by the play partner. In this sense, the context is not an added, static frame that can be conceived of as an "independent" variable that can be freely varied over individuals. The rules of the actions and responses in a particular context are defined by the concern aspect and by the reciprocity aspect.

Sociometric status is incorporated into the model in the following way. First, we assume that the child's concern for Involvement is higher if the play partner has a higher sociometric status. Second, the literature

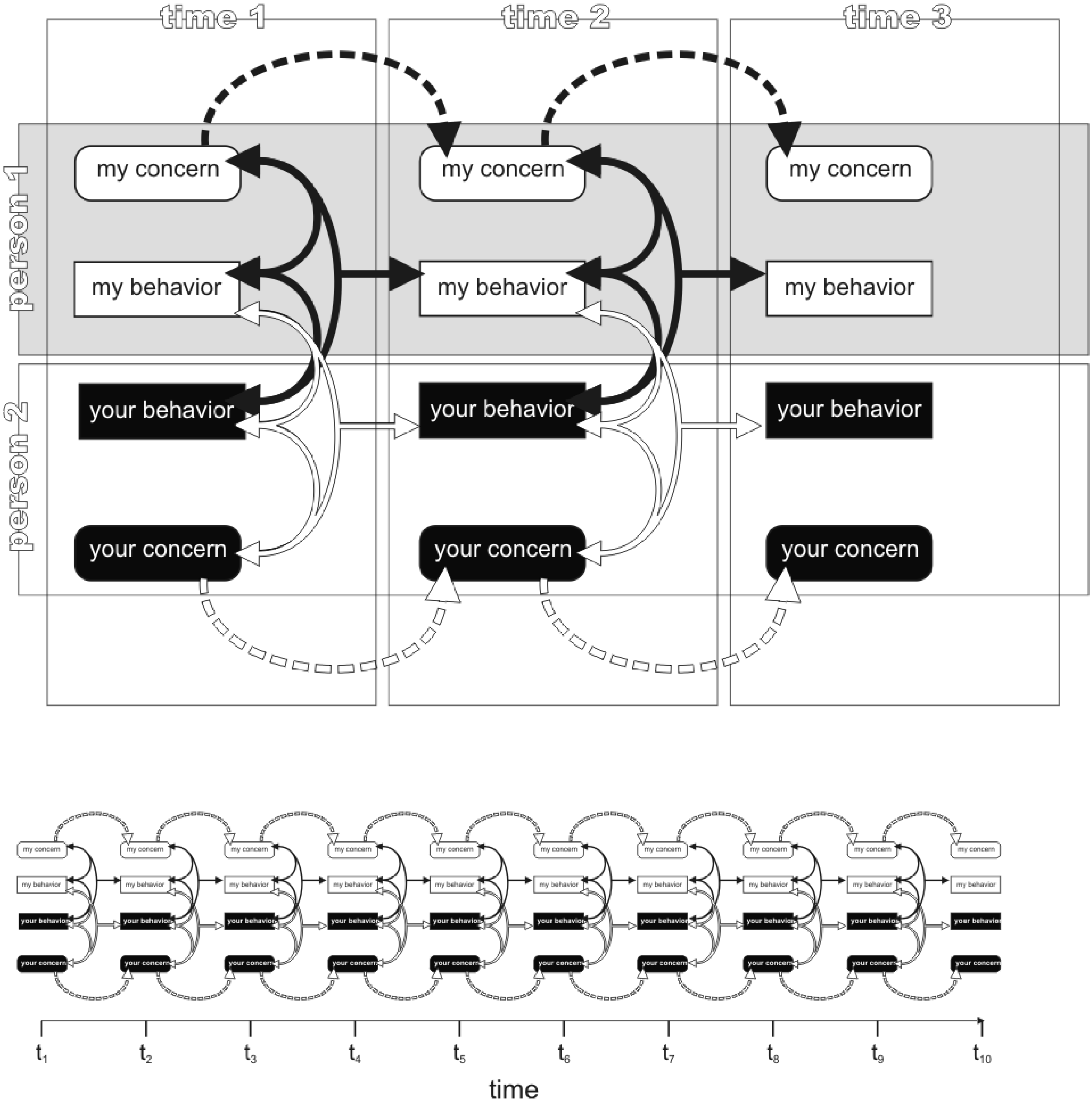

Figure 2
A basic model of behavioral short-term change in a social interaction situation. Both persons (e.g. two children) have a concern regarding doing things together or alone (playing together or playing alone). Mathematically, the concern takes the form of a preferred ratio of playing together over playing alone. The next level in a person's behavior (e.g. at time 2) is based on an evaluation of the difference between the person's own behavior (either playing together or playing alone), the other person's behavior and the person's concern. The model is symmetrical for both persons. In this simplified model, concerns are not adapted over the short term (dashed arrows represent the fact that the concerns remain the same over time). Whereas the figure at the top represents only three time steps, the figure at the bottom provides a better idea of the iterative character of the process.

suggests that popular children are more socially effective than their non-popular peers: they have a higher impact on the behavior of their peers and they are better able to discriminate between situations in which action is effective and situations in which it is not (effectiveness is defined in function of the realization of their concerns).

This basic conceptual model has been transformed into two kinds of dynamic models. The first is a so-called agent model, which models the interaction process in a more detailed way (see Steenbeek and van Geert, 2004). The second is a highly simplified mathematical formulation of the above-mentioned interaction principles, captured in the form of a pair of coupled differential equations. This model was used to calculate predictions regarding directedness and emotional expressions in children of popular and rejected sociometric status playing with a peer of average status. The predictions did not pertain to the actual course of the interaction process, but concerned only global measures such as average amounts and intensities of expressions over the entire interaction course. Before discussing these predictions and their empirical testing, we will first address the question of how the current procedure of starting from a dynamic model is consistent with the complexity approach discussed in this chapter.

Aspects of complexity in the simple dynamic interaction model

Instead of using a model of linear associations between variables over independent subjects, we used a dynamic model that specifies the interaction properties as a result of a process in real time. The dynamic model is used to specify predictions about global, average properties of interaction sessions and can thus be tested by means of a standard cross-sectional design, based on independent cases (the dyads). The model also specifies the simplest possible case of self-organization: for each set of parameter values, it stabilizes onto a fixed value. Thus, the amount of positive emotions and directedness of the children towards each other is not conceived of as the product of a certain internal and relatively static tendency of a child towards positive emotions. It is modeled as the outcome of a dynamic interaction process and thus incorporates aspects of the subject(s) and of the context. In this sense, the levels of emotion and directedness are the result of a distributed process, i.e. a process distributed over the participants of the interaction.

The property of superposition, characteristic of complex systems, clearly features in the way the notions of context and subject are defined. In view of the iterative nature of the interaction, the context, namely the play partner's actions and properties, is at the same time a product of the child's own action and a cause of those actions. Similarly, the properties of the child are to a considerable extent determined by the context (e.g. the child's concerns). Thus, although context and subject can be separated at any time, the subject is the creator of the context and the context is the creator of the subject. This form of superposition is not vague or metaphorical: it is entirely defined by the equations specified in the model.

The aspect of substance and process takes the form of an explicit choice between those parts of the model that are conceived of as "fixed" internal properties, for instance the social effectiveness of the child, and those parts that result from the processes that the model describes (the concerns, the emotions, etc.). The choice for a "substance" or fixed aspect (a property of the person, for instance) does not entail a generalizable claim about the nature of the fixed aspect as "fixed". In a model that tries to explain this aspect, e.g. the social effectiveness, it is likely that the fixed aspect takes the form of a process.

However, the current model still falls short in a final aspect of complex dynamic systems, namely the multi-layered and multi-scaled nature of processes. The model specifies the short-term dynamics of social interaction, corresponding with a play session of ten minutes, for instance. It should be complemented by a model of the long-term dynamics of social interaction, explaining how and why the parameters distinguished in the model change in the course of development, partly as a consequence of social interaction itself.

Testing dynamic systems hypotheses in a standard sample design

Subjects, procedure and predictions

Grade 1 pupils with mean age of 6.5 years, with an upper limit of 8.8 years and a lower limit of 5.8 years participated in this study. From a group of 83 children (47 boys and 36 girls), 24 dyads were selected on the basis of their sociometric status, determined by means of a rating test, Ssrat (Maassen, Akkermans & van der Linden, 1996). The dyads were videotaped three times, with intervals of approximately one and a half month. An interaction consisted of a ten-minute play session. Changes in expressiveness and responsiveness of each videotaped child separately were coded for every one-tenth of a second (event sampling).

Model predictions were generated by calculating all possible outcomes for a parameter space corresponding with the postulated properties of rejected and popular children, in terms of their hypothesized concerns and hypothesized effectiveness. The predictions that the model made were as follows. In his own dyad, the popular child will show less directedness towards the play partner than the rejected child and also show less positive emotional expressions. In the popular child, the positive emotions will be more effectively distributed; the popular child will also show more negative emotions than the rejected child. Irrespective of the differences between dyads, we expect more similarity between the child and his play partner than should be expected on the basis of chance. The model predicted that the involvement of the play partner of a popular child would not differ from the involvement of the play partner of a rejected child. The play partner of the rejected child will show more negative expressions than the play partner of the popular child. Finally, the model predicts less shared involvement in the popular-average dyad than in the rejected-average dyad. No differences are expected between popular dyads and rejected dyads in the amount of shared negative expressions. Note that these predictions, based on a dynamic model of real-time interaction, are crucially different from the prediction made on the basis of earlier research that found a positive association between popularity, positive emotions and directedness.

The fact that the numbers of popular and rejected children are small and also given the labor-intensive scoring procedure, resulted in small samples of rejected-average, average-average and popular-average dyads (13, 14 and 14 respectively). For this reason and also because we have no idea about the expected distribution of the variables on the population level, we applied a non-parametric random permutation test (see Manly, 1997; Good, 1999; Toddman and Dugard, 2001) for each operational variable. A major advantage of this statistical procedure is that virtually any prediction can be tested, as long as the null hypothesis is clearly formulated and the test can take the form of a statistical simulation.

Finally, what is characteristic of a group, e.g. of rejected children, is not necessarily something that occurs in all the members of the group and not even in the majority of the group members. Thus, it is likely that differences between groups occur in the extremes and not necessarily in the averages, or that the differences in the averages are in fact due to differences in extremes. For this reason, we not only tested differences in terms of group averages, but also inspected the properties of the extremes (in fact the upper or lower 20% of the group).

Results and discussion

In short, our data confirmed almost all our predictions. In particular, rejected children are inclined to show an *overflow* with regard to positive expressions, in the sense that they show many positive expressions that are not reflected by reactions of the play partner. It is likely that this overflow is a consequence of their hypothesized high concern for Involvement, in this particular context of playing with a child of a higher status. The overflow is also an indicator of their relative lack of effectiveness, in the sense that much of their effort is not shared.

The positive expressions shown by the popular children, which, as predicted, were less frequent than with rejected children, are more often accompanied by a positive expression of the play partner. This association suggests that popular children are more effective than rejected children in establishing an intersubjective framework. In addition, popular children are effective in their interaction, in the sense that they invest less effort and nevertheless generate high levels of effort in the play partner. This effort is demonstrated by the play partner's many initial verbal and nonverbal turns. The differences we found between average-status play partners, whether playing with a rejected or with a popular child, were not statistically significant, (and this absence of difference was predicted). There was one exception, namely if a play partner of a rejected child expresses a negative emotion, this emotion is more intense.

In addition, besides examining differences between status groups, we also looked at differences between child and play partner of each dyad separately. In both types of dyads a process of adjustment emerges, i.e. child and play partner develop a characteristic level of concordance. This concordance is demonstrated among others by the fact that the play partner of the rejected dyad is remarkably positive, both in directedness and positive expressions.

Visual inspection of the data suggests that in most variables, the lower part of the distributions of the status groups is similar, whereas differences appear in the upper part, including the extremes, of the distribution. In some variables, we found differences in extremes that were not found in the analyses of the averages.

Aspects of complexity

Our data illustrate the fact that behavior must not be treated as a fixed property of a person, but as the result of adaptive action in a context that is partly the product of the person's action itself. The data also illustrate non-linearity in that the association between a property and a sociometric status is not linearly distributed across the status group or sample. Differences are often due to a characteristic subgroup that represents the "typical" patterns on the basis of which the groups or statuses are identified but that not necessarily represent the majority in the group. Moreover, the characteristic patterns found in rejected and popular dyads show a superposition of (apparently) contradictory properties: the child has a rejected status but nevertheless shows high-intensity interaction and positive emotions that are shared by the play partner. Thus, the complexity of being popular or rejected in a group is related to the diverse ways in which interaction among children can occur and the fact that action is functional, i.e. geared towards realizing concerns.

Finally, the fact that our findings so strongly supported our predictions, lends additional credibility to the dynamic systems model from which the predictions were inferred.

Conclusion: Simplifying the reality of development must preserve its complexity

In this chapter, we discussed four core features of complex dynamic systems that directly apply to human development. Human development cannot be properly understood if these features are not taken into account. Unfortunately, in its quest for necessary reduction and simplification of the object of study, much of the current methodology discards those properties and by doing so creates an inadequate image of the fundamental aspects of human development. In our discussion of psychological measurement, we have attempted to show that features such as ambiguity, fuzziness, variability and context specificity should be put at the heart of the measurement process, instead of being abandoned as mere measurement error. In an example of a study on the relationship between sociometric status, emotional expression and directedness in social interaction, we have tried to demonstrate that with relatively little alterations, a standard research design can provide interesting insights into the complexity and dynamics of the behavior of young children.

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