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Transitions and non-linear dynamics in developmental psychology

One of the central ideas behind the notion of development is that of a natural, spontaneous and self-determined increase in order or complexity. In a living being, development is a natural and spontaneously occurring phenomenon. That is, it does not just sit there and wait until its development is triggered by some external condition. To the contrary, development often occurs in spite of counteracting and even malign forces. It is also a self-determined increase in order and complexity, in that the changes that specify development are based on mechanisms and processes that reside inside the system or organism. It goes without saying that development also depends on the external resources and conditions to which it is subjected, but it incorporates these resources and conditions into its own, internal organization. The later implies that developmental processes are often of a non-linear character. That is to say, the effect of some external (or, for that matter, internal) variable onto a developmental process is neither fixed nor proportional. That is, a similar value of that variable — say the visible properties of some observable object — does not always have the same effect on the system (non-fixed). Second, effects are not always proportional to the magnitude of a variable, more precisely, to its magnitude of change. For instance, if we confront a child with a series of problems that gradually increase in difficulty, the effect of any fixed increase depends both on the level of difficulty and on the characteristics of the problem solver. It is interesting to note that such non-linearities are non-fixed themselves. That is, they may come and go during development and their appearance or disappearance may signalize specific stages, states or transitions in development.

Perhaps the best known phenomenon of nonlinear dynamics is deterministic chaos. Simple deterministic, but nonlinear, systems can show unpredictable behavior. Their long-term behavior is sensitive to very small differences in initial conditions. Theoretically, or philosophically, this phenomenon is of great importance: Even a deterministic world is unpredictable in the long term (see figure 1). The application of chaos theory, however, is not straightforward. Distinguishing chaos from noise turns out to be more difficult than expected. The estimation of the embedded dimension of a chaotic time series requires many data points, and is seriously hampered by the presence of measurement error or stochastic parts of the system involved. Especially in developmental psychology, where time-series often consist of 4 to 64 data points (where there should be thousands), application of chaos theory is completely out of scope.

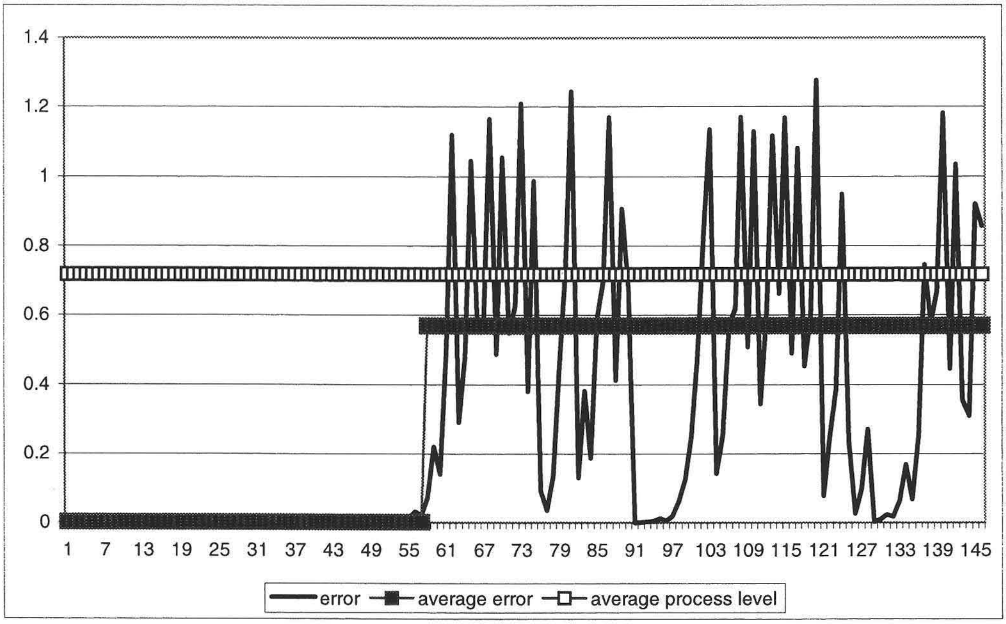

Fig. 1. Non-linear increase of prediction error in a stepwise chaotic process, based on an initial state difference of 1E-15 percent of the starting level. The prediction error suddenly increases around step 60. The average prediction error suddenly grows to about 80% of the average process level.

Saltatory change, e.g. a discontinuous jump in behavior because of small continuous changes in control variables, is another important phenomenon in nonlinear dynamic models. In contrast to linear models, certain non-linear models allow for non-trivial discontinuities. Discontinuities are of special interest because they may indicate self-organization in the system, that is a spontaneous organization from a lower to a higher level of order by means of a phase transition. Although self-organization is not as well understood and defined as chaos and bifurcations, it is nevertheless one of the most promising aspects of non-linear dynamical system theory. It has been demonstrated in various chemical and biological examples and can be simulated with cellular automata on a computer (Serra & Zanarini, 1990).

Self-organization is a central property of what we have now become used to call complex systems. A complex system is just what the word says it is: it is complex. It typically consists of many components that interact with one another and with the system's environment. The interactions serve to maintain the system's integrity by producing a structural equilibrium or a process of dynamic structural transformations that specify the system's dynamic identity. Complex systems are often if not always characterized by the fact that they develop and that their way of maintaining their identity is one of becoming, not mere being.

After introducing the concepts of non-linearity, dynamics, complexity and discontinuity, we must ask ourselves how they relate to the notion of (behavioral and mental) development. After discussing this relationship, we shall proceed to the central issue of this book, which is the study of discontinuous change and its relation to development and developmental theory.

Development in non-linear, self-organizing complex systems

The classic view of development

Etymologically, development means the unwrapping or unfolding of some essence or property that is already there but that is still concealed and needs to be brought out by some form of action. In this classic view, development may lead to surprises — such as when the final unwrapping reveals something that we hadn't hoped for — but they are nevertheless the expression of a deep, underlying continuity. One cannot get out what's not already in. This classic view, which is still endorsed by a considerable number of students of language development, also implies that what comes out of development is not only the result of what is already there but also of what is brought in from outside, e.g. as a result of learning. In this classic view, therefore, there is no room for novelty (no new things can emerge as a result of the developmental process alone, which can only uncover what is present or assimilate what is given). In addition, there is also no room for discontinuity. Even if a change seems pretty discontinuous at the surface, as when a child suddenly starts to use two-word instead of one-word sentences, that discontinuity is only apparent, because it is the expression of a pre-wired phenomenon that has only waited to become manifest.

Transitions in the 'genuine' developmental view

This classic view of the unfolding stands in stark contrast to what one might call the 'genuine' developmental view. The latter found its first modern defender in Piaget. Irrespective of whether and where Piaget got it right, his theory is one of the best examples of a view on development that prominently features properties such as novelty, structure, dynamic equilibrium, self-organization and discontinuity.

What is the role of transitions in this view on development? The notion of transition implies the existence of states that last long enough to be recognized as temporarily stable properties of a system. Whatever occurs between one temporarily stable state and another is a transition. By definition, then, a transition cannot be a stable state itself but must be characterized by change or instability of everything that characterizes the states as states. By terminological convention, one may call all states that are relatively stable and between which transitions can occur *stages* or *phases*. The notion of stage has a notorious history in developmental psychology. It has been criticized both as a descriptive and as an explanative concept (Brainerd, 1978). The criticisms mostly addressed the Piagetian stage concept, which is supposed to specify the entire developmental state of a subject at a particular moment in time (although one may doubt whether this was actually what Piaget intended, see Chapman, 1988).

However, there is no reason why the concept of stage or phase should be so specific (Levin, 1986). Thus, we can apply the notion of stage (or phase) to any specific type of content, skill or knowledge as it functions during a particular stretch of time in a developing subject as long as it is characterized by certain detectable stable properties (of whatever kind) and as long as the system runs through a history of changing stages, which are then characterized by transitions between one stage and another.

All-encompasing stages of the Piagetian type are just one very particular, macroscopic example of stages or phases. The notion of stability as the hallmark of a stage or phase requires some further explanation. Stability is developmentally interesting only if it is the result of an internal process that actively maintains the stability, among others by compensating for external perturbations. If a system is stable only because its environment is stable and does not produce any external cause for change, we should not say that the stability characterizes a stage or phase in the developmentally relevant sense of that word. Therefore, instead of characterizing a state by some form of stability, we should characterize it by *equilibrium*. Equilibrium can be defined as a state of stability that is actively maintained by the system, in the face of external perturbations.

Assuming that we agree on this very general definition of stages as periods characterized by some form of equilibrium, we must ask what definition of *transition* we should endorse. Under this definition, a transition must be characterized by *dis-equilibrium* of those properties that are in equilibrium during the stages linked by the transition (note that stages and transitions may be characterized by both stable and unstable properties, but that the stages are specified by a subset of those properties that are actively stabilized, that is, kept in equilibrium). What forms of disequilibrium are there? To give just two examples, the transition may, first, consist of a mixture of the properties that are characteristic for both stages linked by the transition. Second, the transition may be characterized by either a continuous or a discontinuous change in the properties that characterized the equilibrium states. In the next paragraph, we shall discuss forms of transitory disequilibrium based on notions derived from catastrophe theory. Before proceeding to catastrophe theory, however, there are two additional issues that must be addressed. The first concerns the question whether or not development is identical to the process of stages (in the broad definition) and transitions. The second issue deals with the distinction between discontinuity in the general and in the restricted sense.

Is development necessarily a stage-wise process?

The emphasis that we have put on stages and transitions could easily suggest that they are the necessary and maybe also the only interesting characteristic features of development to the extent that, if stages do not occur in a process, that process cannot be developmental. This conclusion is not warranted, however. First, given our broad definition, stages could easily occur on an almost 'microscopic' scale, that is, confined to highly limited temporal and content ranges. If development occurs in the form of such small-scale stages and transitions, the overall image could be one of continuous and gradual change. Second, development is a process that occurs in complex systems. Complex systems often display complex behavior (although that relationship is not of a necessary nature).

The complexity of development is expressed by the fact that consists of many different kinds of processes that exist alongside one another and that affect and influence one another in a variety of ways. Thus, the occurrence of stage-wise development does not rule out the simultaneous occurrence of gradual change, linear processes and so forth. The image of development as only-this or only-that is certainly not warranted in light of the empirical evidence on the variety of processes that actually occur. Nevertheless, stages and transitions, in the broad sense, are very significant properties in that, if they occur in a process, that process is most likely of a self-organizational and developmental nature. That is, they are very important and reliable *indicators* of development. This point of view — of transitions as indicator phenomena — has inspired a considerable amount of the research that is presented in this volume. To put it differently, stages and transitions are extremely important to development, even if they constitute only a small part of what actually occurs during a developmental process. We should caution, however, against the possible misunderstanding that self-organizing, dynamic processes produce stages, discontinuities and transitions only and that continuous processes are based on linear, external mechanisms. In fact, non-linear dynamics covers a wide range of phenomena and processes, which encompasses continuous, gradual as well as discontinuous and non-gradual events. The advantage of non-linear dynamics is that they explain such a wide scope of phenomena on the basis of a relatively small number of simple principles. In addition, we have argued that non-linear dynamics are amazingly consistent with many older approaches in developmental psychology (van der Maas, 1995, van Geert, 1996) whereas Thelen and Smith (1994) claim that the new metaphor leads to a new developmental theory.

Continuity and discontinuity

We have been using the notion of discontinuity a number of times without really defining what it means. The problem with this notion is that it can be dealt with in a qualitative as well as in a quantitative way and that it conceptually relates to equally interesting but complex notions such as identity and integrity (in the sense of being integral, wholeness). We can define a discontinuity in the most general sense by identifying it with any stage transition. That is, if a stage is replaced by another stage, in the sense of consecutive sets of different equilibria, a discontinuity has occurred. It is very well possible, however, that during the transition each of the variables that specifies the first equilibrium is continuously transformed into a variable or value that specifies the second equilibrium. This is a process that could occur in growth models where clusters of mutually dependent 'growers' change their levels and settle into a new, temporary equilibrium. In this particular case, we could speak about a stage discontinuity with a continuous transition.

Discontinuity in the restricted sense of the term occurs if the transition itself is discontinuous, that is, if the replacement of equilibria occurs suddenly. In the case of the continuous transition, all states are stable in principle, or, to put it differently, the system can eventually stabilize anywhere, depending on the conditions that govern the changes. In a growth process, for instance, the states that lead from the initial state to the point attractor (if any occurs) are transient, but can nevertheless be transformed into stable attractors (depending on the resources that govern the growth process, for instance). In the case of a discontinuous transition, states between the consecutive equilibria can eventually occur, but they are unstable. For instance, any randomly occurring effect, of whatever (small) magnitude, will push the system's state back to one of the equilibrium states. Or, to put it differently, there is no (practically realizable) way to keep the system in one of the unstable positions that occur in the range between the effective equilibria. This form of strict discontinuity (that is, in the transition itself) is a strong indicator of self-organization in dynamic processes (though the opposite, again, does not necessarily hold, that is, it is not so that self-organizing dynamic processes must produce strict discontinuity). The search for such strict discontinuities in various fields of infancy development has been the topic of several of the investigations that are presented in this volume.

Catastrophe theory and the detection of phase transitions

Indirectly, phase transitions indicate self-organizing processes. Furthermore, discontinuity in itself has been an important subject of discussion in developmental psychology. With the decline in interest for Piaget's stage theory transition and discontinuity have become impopular concepts. From a methodological point of view it has been doubted that stage-like changes can be detectable in any developmental process (Brainerd, 1978).

Here lies a fruitful application of dynamic systems theory. At least one part of this theory, catastrophe theory, provides concrete models and criteria for discontinuities (Thom, 1975).

Catastrophe theory studies singularities in the equilibrium behavior of a large class of nonlinear dynamical systems. These systems are locally described by a single smooth potential function of which the first derivative defines the equilibria. If also the second (and possibly higher order) derivatives are zero, singularities exists. Then discontinuities can occur as a result of smooth continuous changes in control or independent variables can occur. Figure 2 shows an example.

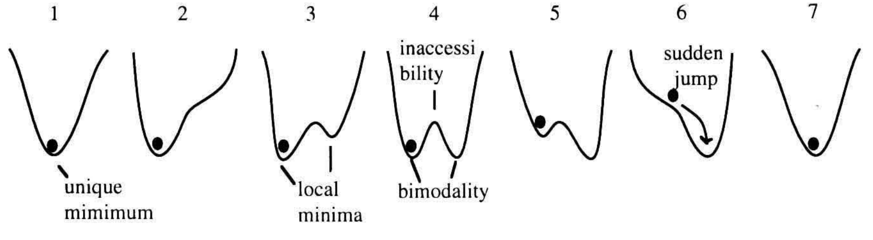

Fig. 2. The form of the potential function changes as the control variable changes (from 1 to 7). The equilibria are the minima and maxima of these functions. A little ball is used to illustrate the equilibrium characteristics of this system. Jumps occur when the little ball is forced to leave its minimum and drops into the other minimum. Note that if we go from right to left the jump will take place at position 2. This dependence of the location of the jump on the direction of change of the control variable is called hysteresis.

Catastrophe theory classifies singularities in seven elementary forms (for a limited number of variables). The most widely applied one is the cusp, which has two control variables and one behavioral variable (figure 3). The cusp is a 3-dimensional model, folded at the front and smooth at the back; x and y are control variables, z is the behavioral variable. Jumps can occur when the system passes the boundary of the bifurcation set for which two behavioral states exist. Path A and B illustrate a discontinuous and a continuous change, respectively.

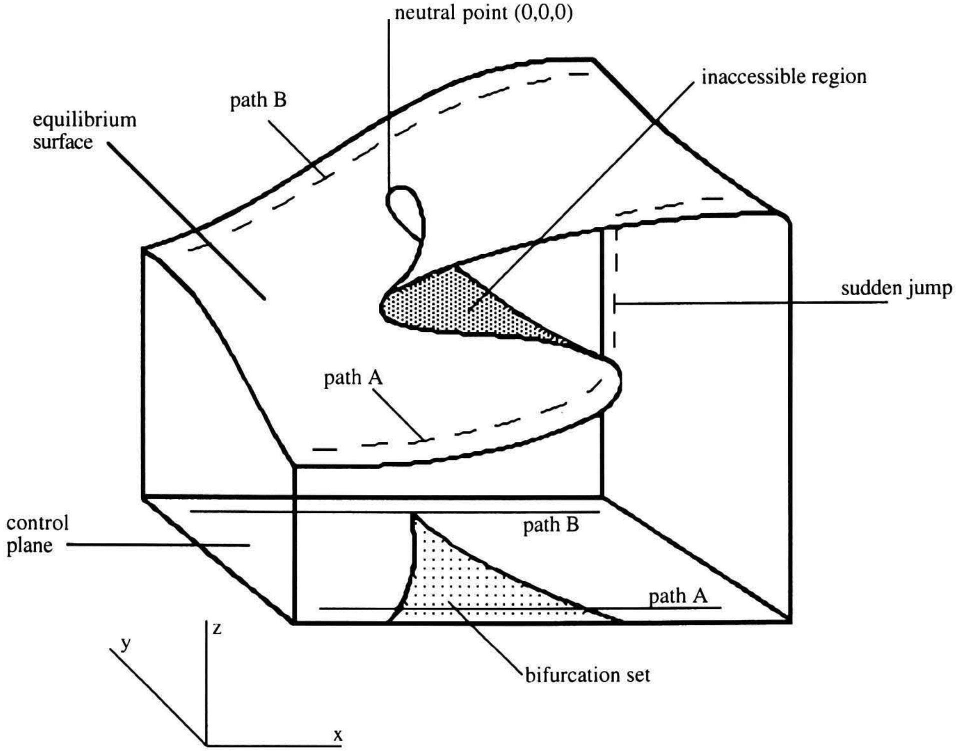

Fig. 3. The cusp model. x and y are independent or control variables. z is the behavioral variable for which the equilibria are plotted (equilibrium surface). Path A and B illustrate a discontinuous and a continuous process of change. Discontinuities occur in the bifurcation set.

The cusp model can be fitted to data consisting of measurements for x, y and z by the method of Cobb (Cobb & Zacks, 1984). This maximum likelihood approach works with a stochastic equivalent of the cusp model (see the paper of Hartelman, this volume). Another way of testing this model makes use of the special characteristics of the cusp model, which are the so-called catastrophe flags (Gilmore, 1981):

1. the change must be sudden (sudden jump)
2. from one mode to another (multimodality)
3. jumping across impossible modes (inaccessibility)

4. at a level depending on the direction of change (hysteresis)
5. critically dependent on initial conditions (divergence)
6. inducing increased behavioral variance near the jump (anomalous variance)
7. with large oscillations after perturbation (divergence of linear response)
8. with delayed recovery of equilibrium behavior after perturbation (critical slowing down)

Figure 4 presents a visual explanation of the flags.

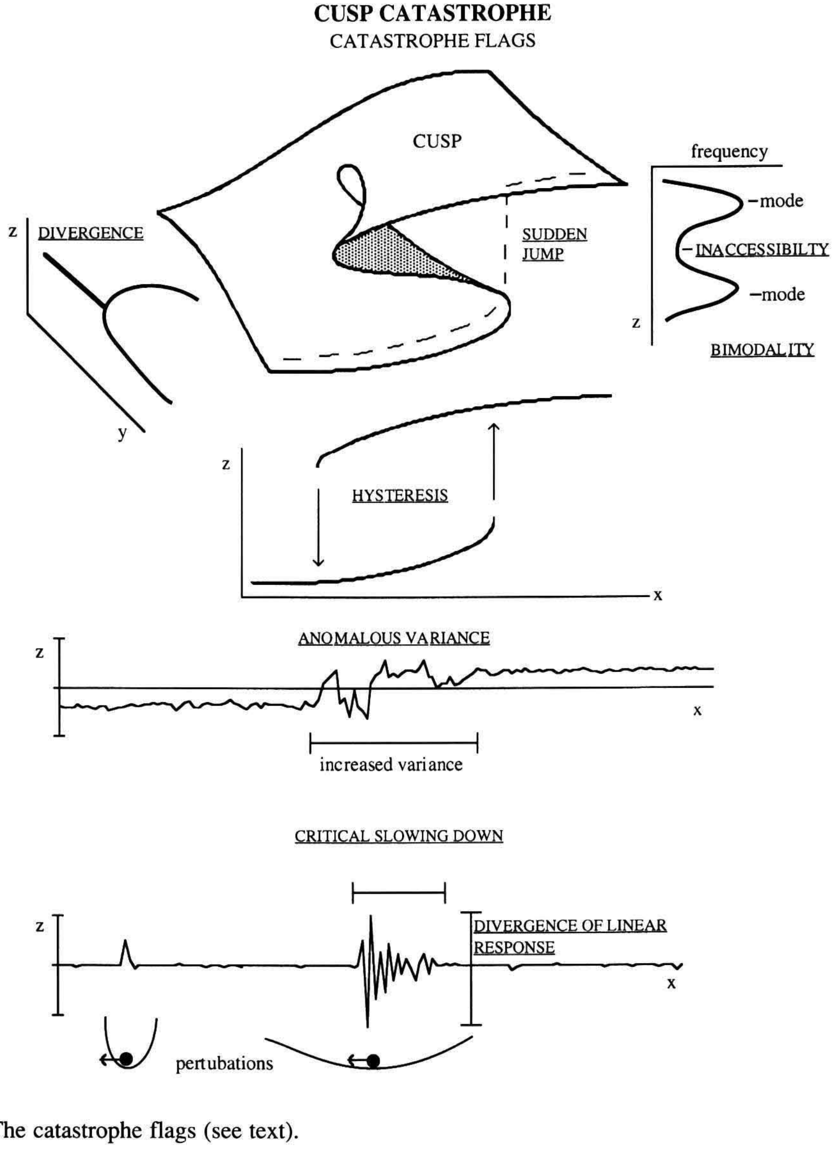

Fig. 4. The catastrophe flags (see text).

If all the flags are identified in a particular process, that process is, almost without doubt, an instantiation of a cusp catastrophe. That is, the process amounts to a discontinuous phase transition and is therefore a strong indicator of the presence of self-organization.

The theory of catastrophe flags potentially leads to a developmental research program with highly specific testable hypotheses. For instance, if we expect that a process is a real discontinuous phase shift, we may predict that all the flags can be observed. 'Flag hunting' can be done based on existing, for instance observational, studies but also requires new studies to be carried out. For instance, the detection of hysteresis requires that a suspected control variable be varied in two different ways, one in a descending and another in an ascending order. Divergence of linear response requires that perturbation studies be carried out. That is, if a discontinuous phase shift is suspected, the system should be perturbed, which means that some inhibiting factor is introduced that the system has to compensate for. Examples of studies that have employed catastrophe flag predictions in infancy development can be found elsewhere in this volume. An application and explanation of the critical slowing down flag can be found in the chapter by van der Maas and Raijmakers (this volume).

Summary

Development is a process that occurs in complex systems. It typically involves properties such as self-organization, dynamic interactions, non-linearity, discontinuity, equilibria and transitions. The theory of dynamic systems provides a new framework for the study of developmental processes. It not only suggests new concepts and ways of explaining, but also new ways for theory- and model building, the design of experiments and the use of statistical methods. The current volume contains, among others, reports from a number of studies that have addressed the question of discontinuous phase shifts in infancy development. Discontinuous phase shifts are certainly not the only phenomenon in development that is worth studying and also they are not necessarily the most common and obvious form of development. On the other hand, if such discontinuities can be found, they are strong indicators of the occurrence of underlying self-organizational dynamic processes that belong to the most fascinating aspects of the developmental scenery.

References

Brainerd, C.J. (1978). The Stage Question in Cognitive-Developmental Theory. *The Behavioral and Brain Sciences*, **2**, 173-213.
Chapman, M. (1988). *Constructive evolution*. New York: Cambridge University Press.
Cobb, L., and S. Zacks, (1985). Applications of Catastrophe Theory for Statistical Modeling in the Biosciences. *Journal of the American Statistical Association*, **80**(392), 793-802.
Gardiner, C.W. (1994). *Handbook of stochastic methods for physics, chemistry and the natural sciences, second edition*. Berlin: Springer-Verlag.
Gilmore, R. (1981). *Catastrophe Theory for Scientists and Engineers*. New York: John Wiley and Sons.

Levin, I. (1986). *Stage and structure: Reopening the debate.* Norwood (NJ): Ablex.
Serra, R. and G. Zanarini, (1990). *Complex systems and cognitive processes.* Berlin: Springer-Verlag.
Thelen, E., and L.B. Smith, (1994). *A Dynamic Systems Approach to the Development of Cognition and Action.* Cambridge, MA: MIT press.
Thom, R. (1975). *Structural Stability and Morphogenesis.* Reading, Mass.: Benjamin.
Van der Maas, H.L.J. (1995). Beyond the metaphor? *Cognitive development*, **10**, 621-642.
Van Geert, P.L.C. (1995). The dynamics of Father Brown. *Human Development*, **38**, 111-222