

The Nature and Meaning of Intraindividual Variability in Development in the Early Life Span

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--in press--

Handbook of Intraindividual Variability across the life span

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1. Introduction

In the last two decades, more and more studies take a process perspective and look at *how* young children are developing over time. This process approach is dependent on the collection of (many) repeated measurements with the same individuals. However, when we start observing the changes in behavior across time, we are struck with large differences from measurement to measurement. As Thelen and Smith (1994) have pointed out in their seminal publication, it is important to distinguish stability and variability on two time scales. The first time scale is the ‘view from above’, where we observe global structure across ‘developmental time’. For instance, when learning to communicate verbally, infants display roughly the same behaviors. They most often start with expressive vocalizations, and go through a ‘babbling’ stage. The second time scale views development ‘from below’, and measures the changes that occur from moment to moment. From here, a much more irregular – almost chaotic – picture emerges. In real time, development turns out to be variable and changes from moment to moment. We see, for instance, that not all infants use the same type of vocalizations, and there is large variability in vocalization and communication from day to day. Thus, though development might seem to be ordered at a macroscopic time scale, the microscopic time scales reveals large differences between and within individuals.

In a previous publication, we have defined intraindividual variability as “differences in behavior within the same individuals, at different points in time” (van Geert & van Dijk, 2002, p. 341). Though variability may exist at all possible time scales, the term is most often used for fluctuations on a relatively short time frame (between weeks, days or even smaller units of time), corresponding to the ‘view from below’ (Thelen & Smith, 1994) as described before. The aim of this chapter is to provide a general orientation on intraindividual variability as an important phenomenon in early child development. In the first part, we will

review the traditional theoretical interpretations of intraindividual variability in early development. The second part of the chapter describes more current theoretical developments and discusses the reasons why studying variability in early development is important. After this, a review will be given of empirical work on variability. Here the most common patterns of variability in early development will be described. We limit ourselves mainly to the domain of early interaction behavior, ranging from emotional expressions in very young infants, to language acquisition in toddlerhood (for examples on motor or cognitive development, we refer to other chapters in this volume). After this, various methodological advances to study intraindividual variability will be reviewed. After discussing future challenges and limitations, we end this chapter with a general summary and conclusion.

2. Traditional views on variability

It has long been acknowledged that individual development is almost never smooth, but that it shows many irregularities. Though intraindividual variability seems to be a rather universal finding, its importance has not always been recognized. Traditionally, the most common theoretical explanations are: (1) That variability is a result of context changes; or (2) that variability is caused by measurement error.

The first explanation is that intraindividual variability is nothing else than the expression of the fact that behavior is adaptive and reactive to variable circumstances. For instance, a child might be crying in response to hunger, and thus variation in crying is a consequence of variation in hunger; or cry in response to threat, hence variations in threat cause variations in crying. Many different influences may take place at the same time and are additive; the sum of these lead to variations in crying. Intraindividual variability is thus a stable characteristic of any (developing) behavior, in the sense that it is an expression of sensitivity to internal and external influences. However, the underlying model is that there is a

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direct relation between changes in the environment and the changes in behavior. This way, the variability in the dependent variable (the behavior) is a result of changes in the independent variable (the context). These relations may be linear or non-linear, but in essence it is assumed that all variability in behavior can be explained by changes in context.

The second explanation is that variability is caused by measurement error. This interpretation originates from true score theory (Cronbach, 1960; Lord & Novick, 1968; Nunnally, 1970), that states that each observed score is the result of both a true psychological score plus an error term. This error term consists of all circumstances that lead to a difference between the performance (or behavior) of a child and its underlying competence. For instance, a young child may have acquired a certain linguistic competence (e.g. making combinatory utterances), but this is not always expressed in a specific measurement occasion (for instance because the time frame is too short, the child is tired, etc.). Variability is considered to be externally 'added' to the underlying psychological process. The measurement error hypothesis considers fluctuating developmental levels to be the results of random error, and deals with it as a methodological problem. Because these errors are --by definition-- independent of the true developmental level, observed data points are often averaged out by using central tendency measures or data smoothing. The observed variability is thus a surface phenomenon, accidental variation superimposed on an underlying property that is virtually constant at the time scale of the observed variation. Behavior may be variable, but the underlying latent factors (the psychological variables) are considered more or less constant. This viewpoint largely overlaps with the previous viewpoint of sensitivity to context, but the difference is that the measurement error concept is more focused on the problem of psychological measurement of latent variables, and thus it is translated into a measurement problem needing a methodological solution.

These classical views have been --and to a certain extent still are-- the dominant perspectives on variability in developmental psychology. As a result, most studies have focused --or are still focusing-- on general trends of development or on revealing differences between individuals or conditions, and most studies take a limited number of observations per individual.

3. Theoretical developments

In the early 1990s, a new theoretical framework called *dynamic systems theory* (DST) initiated a departure from the more classical approaches to variability as described in the previous section. According to this theory, variability should be seen as an intrinsic property of development and thus as an important characteristic that should be a focus of further investigation itself (Lewis, 2000; Thelen & Smith, 1994; van Geert, 1994). DST provides a meta-theoretical framework, using principles of self-organization to explain how novelty can emerge without predetermination (Lewis, 2000). Development is seen as the result of many non-linearly interacting components in a system. In physical, chemical and biological systems, self-organization refers to the mechanism that causes the spontaneous emergence of order. When these systems are far from equilibrium, the flow of energy links their energy into orderly arrangements and gives rise to an increased organization and complexity (Prigogine & Stengers, 1984). The framework of DST was first and most extensively applied to human development in the domain of motor coordination (by authors such as Thelen, Ulrich, and Smith), followed by cognitive and language development (by authors such as van Geert, Fischer, Case, and Granott,) and more recently by emotional/social development (by for instance Fogel, Granic, and Lewis).

The assumption that variability is a genuine property of behavior is not limited to child development. Variability is a characteristic of all behavior, including mature behavior and

immature behavior. Similar conditions can cause different reactions, or a reaction or behavior varies in spite of the fact that the context does not change. The individual is not a passive recipient of changes in the context, but an agent who creates his own variability (this explanation fits with the concept of 'ordinary variability;' see Fogel & Garvey, 2007). However, the essence of the DST explanation is that of a circular causation: Variability and context create each other and this interaction is a driving force of development.

In the previous sections, we have described different viewpoints on the phenomenon of intraindividual variability. In all of these, the context in which the developing behavior takes place has an important position. The biggest difference between these explanations is whether the developing behavior is seen as a dependent variable of context or whether it has a causal role in creating the context and, thus, a causal role in development. In other words, the main question is whether variability is a *reactive* or *causal* phenomenon. The latter view is defended by the theoretical framework of DST which advocates that variability has a central role in the process of self-organization in development.

There are two important strands of reasoning on why variability is important for developmental psychology. These strands are: First, variability is a *source of information* to gain insight into developmental transitions or the interactions between different developmental variables. Second, variability is *functional* for development. These explanations are not independent from each other, but they stem from the same theoretical background of DST.

Let us first address the idea that intraindividual variability is a source of information. From this viewpoint, the existence of a relatively unstable period --or periods of increased variability-- is seen as a sign that a system is changing. Whereas stability in behavioral patterns indicates that an interaction is organized and consolidated, variability indicates a high

degree of context dependency and exploration (Thelen & Smith, 1994). One of the central concepts of DST is that human development occurs within embedded time scales (Lewis, 2011): (1) It emerges in the real-time microscopic changes of the system in a specific context and (2) these micro-level changes constrain developmental change in the long term (Fogel, 2011). Within a dynamical system, global reorganizations occur at *transition points*, periods of instability where old patterns break down and new ones emerge (Lewis, 2000). Around these transition points, systems are extremely susceptible to small changes in context. Some transitions are discontinuous in the sense that abrupt changes occur, and some transitions are more gradual. Variability is important because its presence can be used to detect transition points and, thus, can be used to explain and predict change (Granott, Fischer & Parziale, 2002). Whereas an increase in variability is associated with a developmental transition, a decrease in variability indicates a higher degree of organization in a system. According to DST, variability is especially large during or right before a period of reorganization, because at that time there exists a particularly high level of exploration of adaptive strategies (Thelen & Smith, 1994). From a more formal perspective, systems have to become 'unstable' before they can change (Hosenfeld, van der Maas & van der Boom, 1997). This phenomenon that increased variability is associated with a developmental transition has been empirically validated in several domains. Examples of studies will be described in the next section.

Stability and variability in development can be explained by means of the concept of a *state space continuum*, which can be described as the abstract representation of all (combinations of) possible states in a certain system. In such a state space, *attractors* emerge, which are relatively stable states to which the system gravitates (Granott, Fischer & Parziale, 2002).

A state space is often described by means of a landscape of peaks and valleys (Granic & Hollenstein, 2006). Here, a time series of development is traceable as a trajectory, for instance as the path of a ball that moves around in this landscape, going in and out several attractor valleys. An example of this representation can be seen in Figure 1.

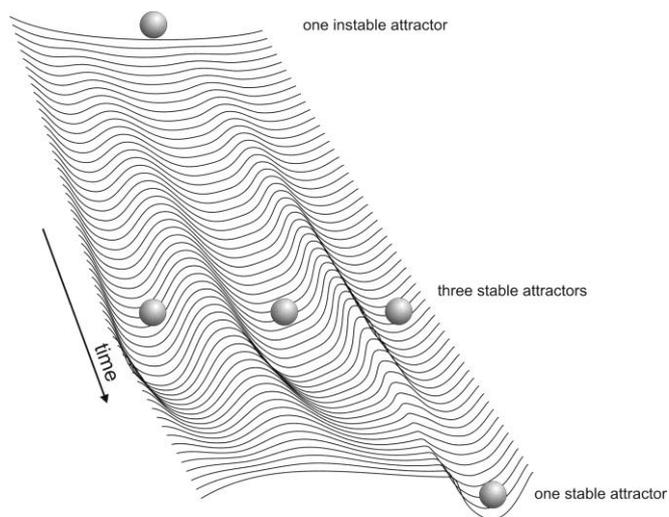


Figure 1. Graphical representation of an attractor landscape with five attractors (Source: van Geert, 2009)

The width and depth of these valleys correspond to the strength of the attractor on the behavior in development. The stable use of certain strategies, the occurrence of certain interaction patterns, etc. can be represented as attractor states. A strong attractor is deep or wide; a weaker attractor is shallower or less deep. The depth of an attractor describes the strength of the ‘gravitation’ on behavior that leads to relative stability. The width of the attractor refers to the range of initial conditions that lead the system to the same attractor point. In Figure 1, the initial attractor on top of the figure is wide and shallow, meaning that all initial conditions, for instance different contexts, will lead to the same attractor, but since this attractor is very shallow, the system will show a high degree of spontaneous variability and a high degree of sensitivity to accidental events in the context. In the middle, the system

is characterized by three attractors, which means that it will randomly alternate between these three attractor states. Wider and less deep attractors lead to more intraindividual variability in behavior. The behavior is most variable when it is at a *transition point* between attractors, or when it is in a wide and shallow attractor valley.

In order to understand these transition points better, a group of DST inspired researchers took a special interest in *catastrophe theory*. This theory is predominantly used to conceptualize discontinuities in behavioral variables as functions of continuous variation in control variables (Fischer & Paré-Blagojev, 2000). Thom (1975) described seven typical catastrophes, and one of these --the cusp-- became the focus of attention for a group of developmental psychologists (see Figure 2 for a graphical representation of the cusp catastrophe).

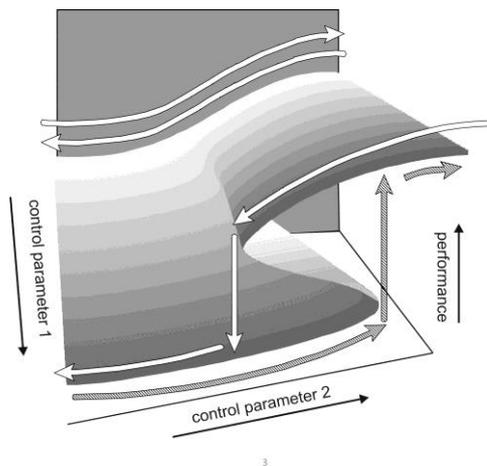


Figure 2. Graphical representation of a cusp catastrophe (phase transition with 2 control parameters).

A central feature of a cusp is that a *bifurcation* emerges at the point of phase transition (which is the point of the ‘fold’ in the graph). To detect cusp catastrophes in developmental data, a set of empirical ‘flags’ can be applied (Ruhland & van Geert, 1998; van der Maas &

Molenaar, 1992). One of these flags is called ‘anomalous variance,’ referring to an enlarged amount and/or different pattern of variability in the vicinity of a transition. According to this criterion, variable behavior may be used to predict a discontinuity. Another indicator of a cusp catastrophe is ‘bimodality,’ implying that an individual can switch between two ‘modes’ of behavior, dependent on the control parameters (i.e., the context). The notion that people function at different levels of development during a particular point on the developmental time scale leads to behavioral variability. Thus, in conclusion, the presence of intraindividual variability is informative; it can be an indicator of a period of rapid development, either in the form of a more gradual transition or a more discontinuous type of change, such as the cusp.

The second reason why variability is important for developmental psychology is that it is *functional* for development. Variability can be a driving force of change. It is clear that Thelen (1985) placed great importance on behavioral variability as a precursor of a new behavioral repertoire. She argued that variability offers flexibility and room for exploration, which promotes development following the Darwinian principles of variation and selection. Formulated in this way, it is highly reminiscent of Campbell's (1960) classic theory that creativity and discovery depend on ‘blind variation and selective retention’ (BVSR). Here the central assumption is that an individual varies on a given idea in many different ways, eventually selecting the best variants. The process is repeated until an adequately creative solution is reached. In this theory, a specific type of variability is a precondition for the emergence of true discovery. For an overview of the BVSR, we refer to Simonton (2007).

One of the underlying driving mechanisms of these Darwinian principles is the theorem of operant conditioning by Skinner (1937), stating that learning is dependent on the consequences of the individual's actions. According to this theory, the basis for learning is the variation and selection of a behavioral repertoire. This operant behavior must show a

particular bandwidth of variability in order for selection, based on reinforcement of successful behaviors, to occur. In this sense, variability is a precondition for development because it enables the individual to adapt to new situations. Variability, therefore, does not only co-occur with change, but is also one of its causes.

Applied to the domain of cognitive development in childhood, Siegler (1996, 2006) argued that variability is one of the core mechanisms that cause the evolution of new strategies in children's problem solving behavior. In this particular case, variability is the expression of an increased degree of exploration, which offers the possibility for differential reinforcement of successful strategies (many examples are reviewed in Siegler, 2006). Siegler formulated the *overlapping waves theory*, which states that the analysis of cognitive change occurs along five dimensions: Path, rate, breadth, source, and variability. The latter concerns how individual children apply fluctuating sets of strategies, or more specifically, how a child's behavior varies across tasks within a specific domain. Across development, periods with low variability (i.e., stable states) alternate with periods of high variability (i.e., developmental transitions) in a cyclical fashion (Siegler, 2006). Although the overlapping waves model was originally proposed as a theory of cognitive development, it actually offers a framework for thinking about developmental changes in general.

An overlapping waves model is easily understood when relating it to the concept of connected growers (van Geert, 1994). Here, a less-advanced grower (this can be a strategy or interaction pattern, etc.) is a precursor for a more complex grower and has a supportive relation to its growth. Thus, the less advanced grower stimulates the increase of the more advanced grower. However, when the more advanced grower has a competitive relation to the less advanced grower, then the less advanced grower gets used less and less often, and eventually dies out. The result of this simple asymmetric relation between variables is the

presentation of development as a series of overlapping waves with less advanced types of behavior overlapping with more advanced ones (see Figure 3 for an example). In conclusion, the reason why variability is important is that it is a prerequisite for the selective reinforcement of more complex behaviors.

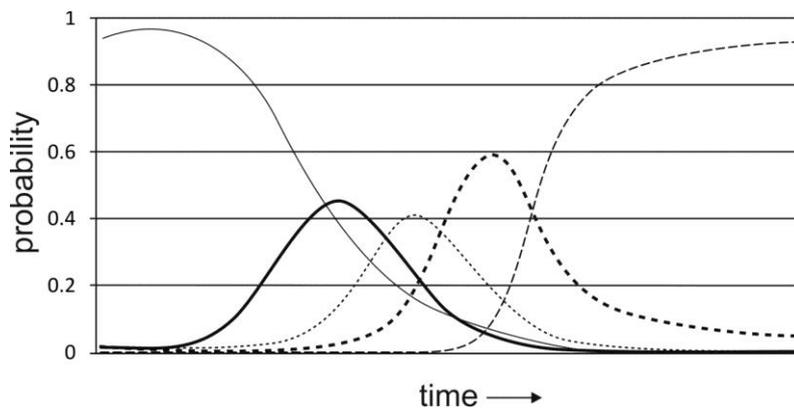


Figure 3. Overlapping waves model of skill development

Behavioral variability can also be functional in the sense that it serves an adaptive function in itself, especially in infancy. De Weerth and van Geert (2002a), for instance, have suggested that an increased level variability may lead to a higher degree of maternal attention and responsiveness. According to these authors, this finding points at a possible adaptive strategy of infants. Intraindividual variability, they claim, ensures the infant of maternal care because fluctuations in the behavior of the infant will address different parental demands. The authors argue that it might be a natural goal for mothers to obtain homeostasis in their relationship with the infant (in this case, a certain stability in interaction). At the same time, the infant's rapid development during the first year of life will diminish the chances of attaining long-lasting and unchanging periods of homeostasis. Periods with greater short-term variability attract a high level of parental involvement and variety of parenting behaviors, increasing the infant's chances of survival.

4. Review of current research

In the previous paragraph, we have discussed two theoretical reasons why it is important to study variability in early development. In this paragraph, we will review examples of current research on studies that have focused explicitly on common patterns of variability and will describe their findings.

Common patterns of variability

When reviewing the literature on early development, it becomes clear that variability is prominent in various domains, such as sleep patterns (e.g. Jenni, Deboer & Acherman, 2006), infant temperament (e.g. Crockenberg & Smith, 1982; Peters-Martin & Wachs, 1984; Worobey & Blajda, 1989), emotion behavior (e.g. Bornstein & Tamis-LeMonda, 1990), crying (e.g. Rebelsky & Black, 1972; Barr, 1990), play behavior (Tamis-LeMonda & Bornstein, 1991), and motor and mental development (e.g. Freedland & Bertenthal, 1994; McCall, Eichorn, & Hogarty, 1977). However, in many other studies the description of variability is not focus of attention. Instead, the analysis of behavior is mostly performed in terms of global trends (smoothed data) or averages within age groups.

As we described before, intraindividual variability is a natural phenomenon of human behavior, which may be a constant across development.¹ However, in many other cases, the amount of variability is not stable across time. Those studies that do pay explicit attention to changes in variability across development, generally report one of three typical patterns. These patterns are: (1) A general decrease of variability; (2) a general increase of variability; or (3) a peak of variability, that is an increase followed by a decrease (this can also be a cyclical pattern where peaks and stable periods alternate).

¹ This is also supported by empirical research. For instance, Jenni, Deboer and Acherman (2006) report that in the first few months of life, sleep patterns exhibit a rather monotonic increase to a greater degree of regulation, but with rather stable fluctuations across the trend

In the case of a *decrease* of variability, we initially observe unpredictable behavior with a general stabilization when development proceeds. We described this pattern in our own study on feeding during the introduction to solid food around the age of 6 months (van Dijk, Hunnius & van Geert, 2009). In this context, the mealtime success (measured as the food intake, meal duration, feeding efficiency, and food acceptance) exhibits considerable short-term variability, which is largest right after the introduction of solids. When zooming in on the interaction behaviors of infants and caretakers (van Dijk, Hunnius & van Geert, 2012), the same pattern is found: Initially the interaction is rather unstable, with both effective and non-effective strategies alternating each other, but after a few weeks, the smooth interactions predominate, and the give-and-take actions show a much higher degree of ‘automaticity’.

Figure 4 provides an illustration of this pattern among the 20 participating dyads.

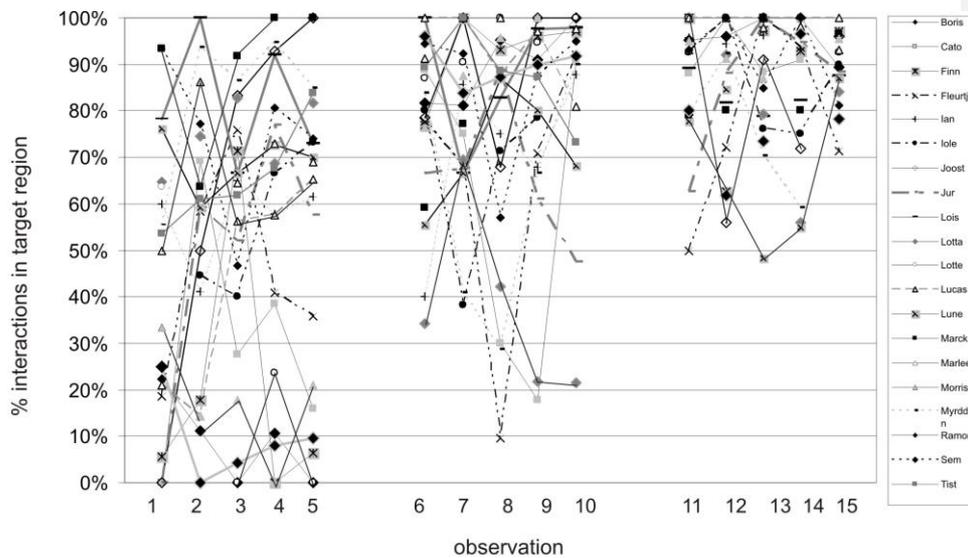


Figure 4. Percentage of smooth feeding interactions during the introduction of solid foods (20 infants) (Source: van Dijk, Hunnius, & van Geert, 2012).

In Figure 4, the percentage of smooth interactions (y-axis) is plotted across time (x-axis) (for details on the measurement design and coding, see van Dijk, Hunnius & van Geert,

2012). The Figure shows a clear decrease of variability, though clear individual differences also exist. This pattern can be linked to the emergence of a greater degree of co-regulation of the caretaker-infant system. Co-regulation (Fogel, 1993) is described as a continuous process by which individuals mutually adjust their actions to the actual and anticipated actions of the social partner. It plays an important role in constraining the behavior of children and caretakers, and in limiting variability in a certain context.

This pattern of decreased variability has also been reported in the domain of crying in infancy. A study of De Weerth, van Geert and Hoijsink (1999) showed that the first months after birth are characterized by a high degree of day-to-day fluctuations in crying: Some days, the infant cries a lot, whereas other days, the amount of crying is rather low. However, from the age of 10 months onwards, these behaviors were shown to stabilize. Thus, in this case, the average crying decreases, but this is only caused by the fact that the short-term variability has decreased (the crying peak-days disappear). A similar pattern of a general decrease in variability was also reported for the amount of body contact, though the decrease appeared to be slightly less pronounced. It also corresponds with data on the development of cortisol across the first year of life (Tollenaar, Jansen, Beijers, Riksen-Walraven & de Weerth, 2010). A stable decrease of basal cortisol was found from 6 weeks to 5 months and to 1 year. However, the degree of intraindividual variability decreased much steeper (quadratic instead of linear) towards the end of the first year. Initially, the degree of variability turns out to be so large that basal cortisol cannot be used as a reliable measure (De Weerth & van Geert, 2002b).

The same pattern of a general decrease of variability is also prevalent in other developmental domains. For instance, it has previously been observed in early motor

development; young infants lack coordination of the different body parts but this variability reduces over time (Piek, 2002; Thelen, Skala & Keslo, 1987).

The second common pattern is that of a general *increase* of variability across time, when children start out with a rather limited behavioral repertoire, which grows as they develop. For instance, in van Dijk and van Geert (2011a), we reported that between ages of 1;6 to 2;6 years, children show an increasing range of intraindividual variability in their mean length of utterance (MLU). Initially, their production ranges are relatively small, and they only increase after a certain minimal value has been achieved (i.e., MLU is greater than 2). With regard to this relation between child speech and the child-directed speech of the parent, it seems as if the range of variability of the child ‘grows into the range of variability of the parents’ language (see Figure 5 for an example of a single child). The same pattern is found in the distribution of utterances across sessions (1-word utterances, 2/3-word utterances and 4+-word utterances; see van Dijk & van Geert, 2011a).

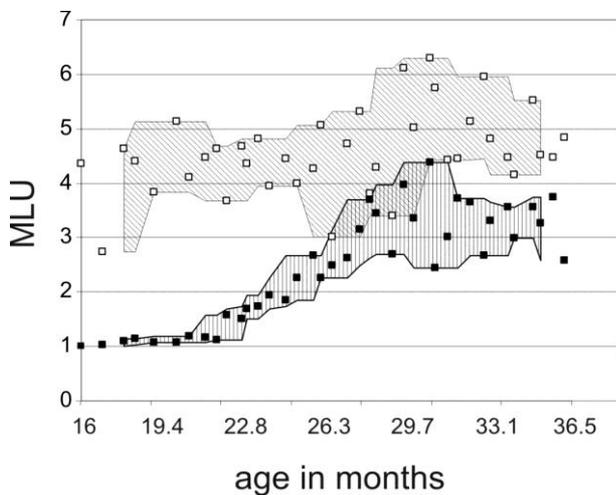


Figure 5. Range (min/max representation) of the MLU of Jessica (solid squares) and her parents (open squares). (Source: van Dijk & van Geert, 2011a)

In another study, the development of the use of spatial prepositions showed an even steeper, and in some cases more discontinuous, increase of variability across time. This was probably due to the fact that the use of a lexical category is a less global linguistic measure than utterance length (see van Dijk & van Geert, 2007).

Taken together, these examples are illustrative for many other acquisition processes in development, but serve to specifically illustrate processes in language acquisition. In these cases, children acquire a greater repertoire of behavior, offering them a larger degree of flexibility, richness to express nuances, and adaptability to a variety of circumstances.

In the case of ‘*peak variability*,’ we see an initial increase of variability followed by a decrease of variability. This type has also been called ‘cyclical’ (Siegler, 2006), indicating that a single developmental grower can show multiple phases of increased and decreased variability. There are indications that these patterns exist—for instance—in problem solving in early toddlerhood (Chen & Siegler, 2000) and in patterns of infants’ attention and emotion during early face-to-face communication (Lavelli & Fogel, 2005).

Several studies have corroborated the idea that variability is relatively high in the vicinity of a developmental ‘jump.’ For instance Courage, Edison and Howe (2004), who reported longitudinal data on the development of self-recognition in infancy, show that 9 out of 10 children in their sample showed a phase in which they displayed a high degree of variability. This phase was positioned between constant sequences of either successful or unsuccessful behaviors.² In other cases, a local increase of variability is associated with peak performances or discontinuities at the same moment in time. In a microgenetic study by Amsterlaw and Wellman (2006) on the development of ‘false belief’ in preschoolers, all

² However, it should be remarked that in this case, the behavior was coded dichotomously, meaning that the variability may also be an expression of an underlying gradual development.

improving children also showed variability in performance in the sense that they failed tasks they had previously passed. Fluctuations were especially prevalent right before children's mastery of the tasks provides evidence of a transitional period in children's theory of mind development.

There are also examples from the area of language development. In van Dijk and van Geert (2011b), for example, we aimed at studying qualitative combinations of the length of prepositional phrases with the grammatical constructions that were used. The sample consisted of longitudinal data of two children. Here, we found that initially, the relation between prepositional phrase use and sentence length was rather 'fixed' to one-word utterances and the use of only single prepositional elements. However, large variability in strategies emerged when sentences became longer. When utterance length finally increased to above 4 words (i.e., indicating more advanced grammatical development), the strategy use stabilized again (into the target construction).

The study by Bassano and van Geert (2007) --which was also based on two cases-- also reported periods of increased intraindividual variability in the development of utterance length. All results converged on the conclusion that an increase in variability was no statistical artifact but that it was related to meaningful local transitions, in this case accelerations of more advanced strategies and decelerations of less advanced strategies. In fact, this study represents a clear example of the application of the overlapping waves model as described before, where a less advanced grower stimulates the increase of the more advanced grower. In Figure 6, the peaks of within session variability (of a single child) are expressed as those instances at which the variability exceeded the 95% bandwidth of variability around the observed values.

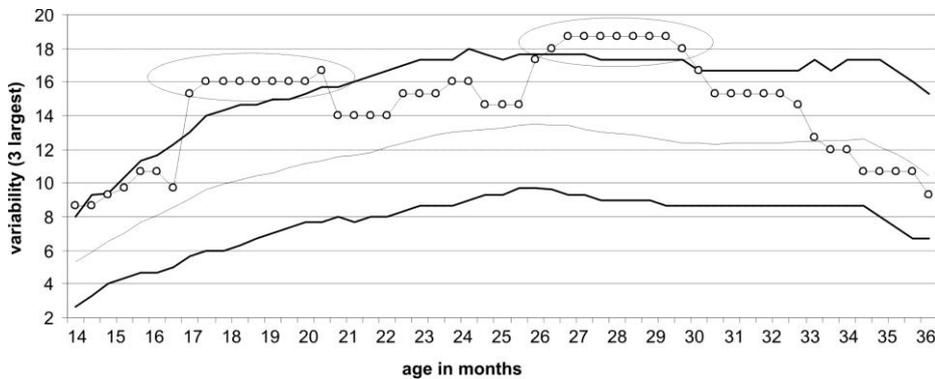


Figure 6. Peaks in the within session variability of Pauline's 1-word utterances (Source: Bassano & van Geert, 2007).

In one of her seminal publications, Thelen (1985) argued that variability is a precursor for structural change in early motor development. In a study on the supine kicks of infants between the ages of 2 weeks and 10 months (see also Thelen & Smith, 1994), one of the motor behaviors studied was the coordination between kicks. During the first few months, kicks were predominately alternating. However, this period is followed by a period with high levels of variability. This instability led to new forms of coordination between legs, for instance, simultaneous kicking of both legs. Thelen argued that it appears that the infants must 'free themselves' from the stable patterns of the newborn period before they can assemble new behavioral modes. Structural change is thus preceded by increased variability.

This phenomenon that increased variability is associated with a developmental transition has been empirically validated in several domains. We already listed some examples in the previous section of the chapter (Amsterlaw & Wellman, 2006; Bassano & van Geert, 2007; Courage, Edison & Howe, 2004; van Dijk & van Geert, 2011a;), but there are other examples from the field of socio-emotional behaviors of toddlers (Lewis & Cook, 2007), language (Alibali & Goldin-Meadow, 1993; Ruhland & van Geert, 1998) and cognitive development (Siegler, 1995; Graham & Perry, 1993).

Some studies report that increased fluctuations in one developmental domain sometimes correspond to fluctuations in another domain. For example, Robertson, Bacher and Huntington (2001) have demonstrated that movement variability in 3-month-old infants is inversely related to variability in visual inspection. According to the authors, this indicates that the motor and visual attention systems are coupled at that age. This suggests that patterns of variability can be used to reveal interactions within a developing system. Hsu and Porter (2004), for instance, have related intraindividual variability to spurts in neurological development. In their study on infant behavior around the 2-month transition, they argue that changes in the infant's reactivity to mild perturbation may be a function of underlying neurobiological shifts. Variability in one factor is related to changes in another factor and thus indicates how different variables are coupled during development.

Another example is provided by Bacher and Robertson (2001) who suggest that variability in motor activity in early infancy may regulate visual attention. They present evidence that the ability to visually disengage from objects appears to be coupled with rates of change in motor behavior. The authors refer to studies by Hoffmann (1983) and Farnsworth and Beecham (1999) to argue that randomness has advantages in search behavior in young infants. Irregular fluctuations may result in unpredictable perturbation of perceptual and cognitive processes that depend on attention.

In summary, we have seen that variability is not necessarily stable across early development. We have distinguished three meaningful patterns of variability: A general increase, a general decrease, and a peak (or cyclical) pattern. However, it should be noted that not all individuals show identical patterns and that these differences might have many causes. Some researchers speculate that these differences can relate to differences in temperament or reactivity (seen as vulnerability to mild perturbations). For instance Wachs, Creed-Kanashiro

and Gurkas (2008) have investigated whether or not the degree in which infants show behavioral fluctuations is a stable trait (i.e., related to the construct of temperament). The results confirm that there are positive associations between the variability at the age of 3 months and the age of 12 months, but the effects are only of moderate size. This indicates that the degree of intraindividual behavioral variability is not a stable trait, but that it changes across development. Individual differences may also be a reflection of different learning styles or different styles of adaptation (van Dijk, Hunnius & van Geert, 2012; van Dijk, van Geert, Korecky-Kroell, Maillochon, Laaha, Dressler & Bassano, 2013). For instance, in van Dijk and van Geert (2011a) we found large differences in the use of noun determiners in the three participating children across development. Though two children showed a relatively long phase (10 months or longer) with large variability in determiner/filler use, there was one child who had a much more abrupt switch between determiner omission and determiner use (and in which the variable period was limited to just a few months). Whereas the global change in the first two children suggests a rather gradual acquisition, the same process in the latter child seems to fit more with the idea of a discontinuous development.

Methodological Developments

Intraindividual variability always exposes itself *within* a specific measurement design. For instance, a design consisting of three consecutive measurements will provide an entirely different pattern of variability than a design consisting of 30 such measurements made over the same time span (only in the hypothetical case that there is *no* real variability, e.g. when the pattern is entirely smooth or linear, both designs will reveal the same pattern). If it occurs, the observed variability is thus critically dependent on that specific design and measurement level. Every developing behavior has a real time dimension, which is a sequence of actions in a specific context. The different time scales at which variability reveals itself are not natural

scales, but instead are a matter of measurement unit within a certain research design (see chapter by Ram & Diehl). For instance, when behavior is scored in a dichotomous way, the variability can only express itself in consecutive 0/1 shifts. When behavior is averaged over sessions or time intervals, this limits the description of variability at smaller time scales and compresses the total amount of variability. Thus in order to study intraindividual variability, the time scale of measurement (coding, data processing) must be sufficiently short and the measurement frequency must be sufficiently high to capture the real-time behaviors.

A highly suitable way to study developmental processes is by means of the *microgenetic method* (Flynn & Siegler, 2007; Lavelli, Pantoja, Hsu, Messinger, & Fogel, 2006). Within this method, short-term development is studied by means of dense observations of learning behavior. The center of attention is the process of change at a rather microscopic level; fine-grained information of real-time behavior is considered to be essential for grasping macro-level change processes (Lavelli et al., 2006). The dense observations before, during, and after a developmental transition reveal how variability changes across time and what its structure is (Siegler, 1995; Lavelli, et al, 2006). Around the early 90s (and partly inspired by DS theoretical viewpoints), the microgenetic research design was developed for the analysis of cognitive development (Siegler, 1995, 1996, 2006). According to Siegler (2006) –who is one of the leading researchers promoting this research design–, examinations of variability are significant in identifying mechanisms of development. He argues that microgenetic designs enable researchers to investigate how children’s novel behaviors evolve, a fundamental issue relative for learning (for a review of the microgenetic framework and a review of research findings, we refer to Siegler, 2006). Though the method was originally designed to study learning, it is currently also used to study other developmental processes, such as self-awareness (Fogel & DeKoeyer-Laros, 2007; Trevarthen, 1993), emotional development

(Fogel & Garvey, 2007), and infant attention and emotion (Lavelli & Fogel, 2005).

Specifically interesting is the fact that several microgenetic studies have demonstrated that averaging over individual participants' developmental jumps, gives a smoothed presentation of their actual development and evens out much of the variability (Benigno, Byrd, McNamara, Berg, & Farrar, 2011). The microgenetic method enables us to track individual pathways of change and to analyze patterns of intraindividual variability.

Variability is always both qualitative and quantitative, but the way it becomes visible is dependent on the way the developmental variables are operationalized. Children may show qualitative variability in the sense that they exhibit categorically different behaviors within a certain time frame. The variability may thus be scored nominally. But variability may also be expressed in a certain fluctuating 'frequency' or 'level' of behavior across time. In most cases, qualitative variability can be translated into quantitative variability. In some cases, data can be recoded into a more microscopic level of analysis. For instance, if the category "eating" is redefined as a particular succession of categories like "opening mouth," "actual food intake," "munching," "swallowing," "spitting out" and so forth, the action of "eating" can vary from scoop to scoop. In other cases, the occurrence of particular nominal categories may be counted and a statistical association between frequencies of such categories can be analyzed. And vice versa, by collapsing quantitative data into sets of meaningful patterns, qualitatively different patterns can be constructed. However, in all these cases, the way the behavior is measured remains a determinant of how the patterns are exposed and can be analyzed.

It should be stressed that intraindividual variability occurs and should be approached at the individual level,³ and in order to get a valid description of its development across time, many repeated measurements and reports are required. A crucial first step is to express variability in a *measure* to describe how it changes over time for each individual. In the next section, we will discuss several of these measures that can be used for this purpose. The initial focus should not be on the correlates of variability, but on its structure across time. In van Geert and van Dijk (2002) and van Dijk and van Geert (2007), we suggested some simple descriptive techniques that can be applied to time series of a single behavior, such as the moving min/max graph (for an example of this technique, see Figure 5), the skewness-analysis and peak analysis. Other measures describe the interaction of variable behaviors. For instance, Lewis and colleagues (Hollenstein, 2013; Lewis, Lamey, & Douglas, 1999) developed the *State Space Grids* (SSG) method to depict the sequential structure of nominal or ordinal behaviors in the way they interact in two dimensions. An SSG is a graphical representation of the interaction between ordinal variables on two axes. The cells represent all possible combinations of behaviors, each cell represents a specific combination. An example of such a graph can be seen in Figure 7.

³ Note that we use the term "individual" as a generic term, referring to an individual unit of analysis, which can indeed be a specific individual person such as infant x, but also a specific dyad, such as infant x and mother y.

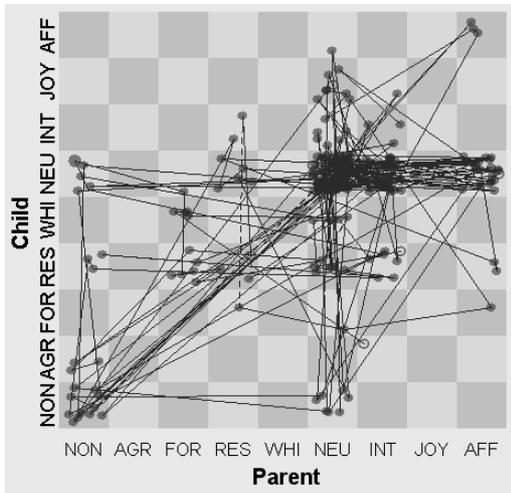


Figure 7. State space grid of affective parent-child interactions ($n = 5$) during a single play session (the abbreviations stand for: no-interaction, aggression, force, resistance, whining, neutral, interest, joy and affection) (Source: van Dijk, 2012).

In this Figure, each dot represents a single moment in time (in this example, a 10-sec time frame) at which the behavior of the parent and the behavior of a child are coded along an affective/emotional dimension. The lines connecting the dots show the progression through time (the open dot is the starting point). In this example, the interactions show moments of stability (see the concentration of dots in the NEU-NEU/INT cells, suggesting 'neutral' or 'interested' dialogical interactions to be most frequent) and moments of increased variability (movements across many states).

SSGs are very easy to plot and describe the stability and variability of the interactions between variables, which makes it easy to compare variability within and between individuals. Some measures concern the movements across the entire grid (across all combinations) whereas others represent a selected region of the grid or individual cells (i.e., a specific cluster of combinations). Examples of whole grid measures are 'dispersion,' which is the sum of the squared proportional durations across cells, which is a measure of total grid

variability, and ‘visits’, which is the number of cells in each trajectory. A measure that can be used to analyze only a preselected part of the grid is the ‘return time,’ which is the mean time for an individual to return to a preselected region or individual cell. In recent years, the state space grid technique is becoming increasingly popular in the field of parent-child interactions, (see for instance Dishion, Nelson, Winter, & Bullock, 2004; Granic & Lamey, 2002; Hollenstein, Granic, Stoolmiller, & Snyder, 2004; Hollenstein & Lewis, 2006; Lewis, Granic, & Lamm, 2006; Lunkenheimer, Olson, Hollenstein, Sameroff, & Winter, 2011; van Dijk, Hunnius & van Geert, 2012) but also in a broader domain, such as teacher-child interaction (Mainhart, Pennings, Wubbels, & Brekelmans, 2012), young children’s peer relationships (Martin, Fabes, Hanisch, & Hollenstein, 2005), peer interaction during sport (Murphy-Mills, Bruner, Erickson, & Côté, 2011), and narrative in psychotherapy (Ribeiro, Bento, Salgado, Stiles, & Gonçalves, 2011).

One of the most promising advances in the analysis of individual variability patterns is offered by *Recurrence Quantification Analysis* (RQA), which also has a DS-theoretical background. RQA is a non-linear toolbox to analyze recurrence plots, plots that visualize the recurrence of states in a phase space (Marwan, 2008; Webber & Zbilut, 2005). Figure 8 shows an example of such a recurrence plot in the field of infant emotional expressions.

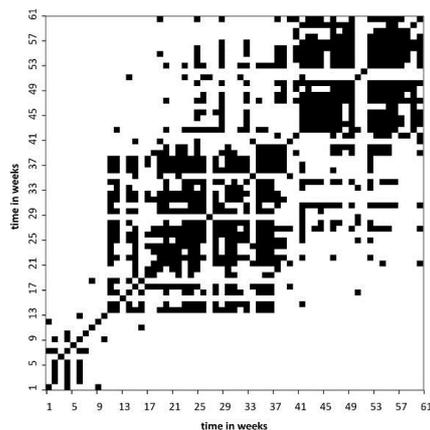


Figure 8. Example of a recurrence plot of infant behavior. Multivariate time series of a boy for whom weekly observations of five variables are represented: Body contact, crying duration, fretting, smiling and crying frequency. (Source: de Weerth & van Geert, 2012)

RQA is a technique to exploit the temporal structure of a time series (i.e., the temporal variability pattern) to quantify the dynamic organization of a system. This is helpful, for instance, to detect transitions in the system dynamics of time series (Marwan, Romano, Thiel, & Kurths, 2007). RQA-measures include recurrence (i.e., the percentage of points in phase space occupied by recurrent points), determinism (i.e., the percentage of recurrent points that form diagonal line segments), and maxline (i.e., attractor strength). All these measures express the degree of determinism or order in a single time series. Nowadays, RQA is mostly applied to life sciences, including psychology and neuroscience, earth sciences, and engineering (Marwan, 2008). Though the application to the field of human development is rather new, the technique is successfully applied to study variability in human development, such as the field of syntactic coordination during language development (Dale & Spivey, 2006), parent-child conversations (Lichtwarck-Aschoff, Hasselman, Cox, Pepler & Granic, 2012, Cox & van Dijk, 2013) and mother-infant synchrony (De Graag, Cox, Hasselman, Jansen, & De Weerth, 2012), reading in developmental dyslexia (Wijnants, Hasselman, Cox, Bosman & Van Orden, 2012), and motor control (Wijnants, Bosman, Hasselman, Cox, & Van Orden, 2009).

The measures of variability we described above can be used in traditional uni- and multivariate statistics, such as repeated measures ANOVA's and t-tests.⁴ However, due to advances in computing and software, some non-linear multivariate techniques that are better

⁴ e.g. the studies of Martin et al (2005) and Lunkenheimer et al (2011) combine SSG-measures of variability with traditional statistics, such as t-tests, correlations and structural equation modeling

suited for the hierarchical structure and variable nature of time serial data sets have recently become available. These methods are not suited to measure or describe (patterns of) individual variability, but incorporate patterns of short-term individual/dyadic variability in a multivariate analysis.

An example of such a statistical tool is *multilevel survival analysis* (Stoolmiller & Snyder, 2006), which is a technique for studying real time interaction processes between dyads and relating it to developmental outcomes. An example of a research question that can be answered with this method is “How do children respond affectively to their parents and how do these response tendencies differ according to the level of antisocial child behavior?”⁵ The central variable in this analysis is the real-time affective interaction, which by definition shows variability from moment to moment. Instead of averaging or summing over these moment-to-moment changes, the analysis is performed on the original time series and thus leaves the variability pattern intact. Multilevel survival analysis is a variant of sequential analysis and includes estimation of multilevel random effects. The method focuses on the hazard rate, which is the rate at which an event occurs at a particular moment in time (for more information, see Stoolmiller & Snyder, 2006).

Other statistical tools suited to analyze transactional processes are *hidden Markov modeling* (Rovine, Sinclair, & Stifter, 2010) and *latent differential equation modeling* (Nicholson, Deboeck, Farris, Boker, & Borkowski, 2011). Hidden Markov models are based on a simple Bayesian network and give information about the sequence of latent states in terms of probabilities. This method works with multivariate categorical and continuous variables based on time serial data. Latent differential equation models aim at expressing the relationships between current states of individuals and how individuals are changing over

⁵ The example is taken from the study of Stoolmiller and Snyder (2006).

time. In both methods, models with different specifications that describe the dynamic interactions are compared to one-another using measures of fit (AIC, BIC, etc). What these methods have in common is that they are able to answer multivariate questions for processes that are *dynamic* and *variable* in nature. In doing so, they move beyond discrete time analysis and models of linear change. These methods are suited to analyze transactional, dynamic relations (couplings) between variables at different time points, but they aim at providing a model to explain variance in group data instead of describing (changing) patterns of variability and the role it plays in development.

Though these methods have an important added value to many studies in developmental psychology, we argue that researchers should not too easily shy away from analyzing their data at the individual level by moving to multivariate techniques aiming at explaining population variance. Instead they should explore the richness of their observations by performing a critical and thorough exploration of the individual time series, by means of the visualization and descriptive techniques, for instance as the ones discussed above (also see van Geert, 2011) for more elaborate discussion of individual versus multivariate data analysis).

5. Future Work and Challenges

In this chapter we have described how dynamic systems theory and microgenetic methods have radically changed the perspective on intraindividual variability. There are many examples of studies that have adopted this new perspective and have focused on variability and real-time interactions as important developmental indicators in early childhood. Already in 1994, Thelen and Smith urged researchers to treat intraindividual variability as data and to use it in their analyses, instead of averaging it out by means of smoothing techniques. Two decades later, we can assess that many researchers --from various domains-- have

implemented this recommendation. Rapid developments in computation and software have clearly been a catalyst in this process. Many innovative methods have been developed with regard to data analyses and description, which are a prerequisite for the labor-intensive study of variability. The application of these new descriptive and statistical methods to a wide variety of topics in early child development is a clear direction in future work on intraindividual variability.

A practical challenge for many variability-centered studies may be the composition of a study's sample. Analyzing patterns of variability requires the collection of many repeated measurements that can be a time consuming matter. Because in the average research project the time dedicated to data collection is limited, it can be difficult to find an optimal balance between the number of measurements and the number of participants (van Geert, 2011). It may be expected that developments with regard to data collection and processing, such as automated video-recording, coding and transcription, will play an important role in determining this optimum.

The study of intraindividual variability also leads to challenges of a more fundamental nature. Probably the most prominent finding in studies with many repeated measurements is that developmental patterns turn out to be highly idiosyncratic. In all the studies described in Section 4 of this chapter (with regard to feeding, crying, talking), inter-individual differences in intraindividual variability patterns clearly existed: Some individuals stabilized more quickly than others, some individuals developed more gradually, whereas others developed more discontinuously. Crucial questions are: "How can any description of the process provide a valid representation of all these unique trajectories?" and more fundamentally "How do we generalize from these idiosyncratic patterns to more general knowledge about the developmental process under investigation?" Multivariate techniques --such as the techniques

described in Section 4-- are typically suited to answer these questions, but they encounter a similar problem. As an example, with regard to the application of hidden Markov models (though the problem applies to the other measures and statistical techniques as well) Rovine et al. (2010) already mentioned that the model with the best fit offers a solution (a common model that is used to define the states) that should fit all individuals, because individuals can differ only in the sequence of and duration of time spent in these states. These authors offers two alternative approaches: The first one is to estimate a separate model for each individual (which --according to them-- has the drawback of hindering direct comparison between individuals) and the second one is to attempt to find subgroups for which a common set of state definitions would be adequate. Thus, instead of aiming to construct a model that describes or explains the development for all cases, these authors suggest that one can start with the identification of groups of individuals that share certain similarities.⁶ This leads to a more nuanced type of generalization and does better justice to both inter- and intraindividual variability.

A few critical remarks are also in order. First, we argue that the individual is the level where the developmental processes take place and should therefore be the primary focus of attention when studying these processes (see van Geert, 2011). Variability, which is an important property of development, also takes place at the individual level, implying that patterns of variability should also be analyzed at this level. Because of the ergodicity principle (e.g. Molenaar & Campbell, 2009), there is no reason to assume that developmental models based on aggregated group data have any logical relation with individual processes. Therefore, individual development can (almost) never be adequately modeled by a generic trajectory model based on sample information. Secondly, we should reconsider the meaning

⁶ An example of such an approach can be found in van Dijk, Hunnius, and van Geert (2012).

of the concept of ‘generalization.’ Currently, most empirical work in developmental psychology is based on sample-based explanations of variance and generalization is predominantly viewed in terms of ‘sample generalization’ (see van Geert, 2011). In many cases, it boils down to whether a distribution of properties in a sample carries information about the distribution of those properties in the population or how much of the variance between individuals are explained by a single model. However, generalizability should also be viewed in terms of how individual development relates to an underlying theory of development (van Geert, 2011). The identification of subsets of similar individuals can be an important step in achieving a more legitimate generalization to a certain population (Rovine et al., 2010, Molenaar & Campbell, 2009).

6. Conclusion

In summary, we have shown that intraindividual variability is a prominent feature in (early) child development. Several theoretical conceptions of the causes of this phenomenon have been reviewed. In the early 1990s, dynamic systems theorists put forward the view that variability is an important characteristic of self-organization in development. Finally, influenced by the DST viewpoint, we have argued that variability is important for developmental research because it can be used to detect and predict developmental transitions and also to detect interactions between domains of a developing system. There are also indications that variability is an adaptive and functional feature of human development.

Empirical studies have shown that different forms of variability exist (i.e., increasing, decreasing and peak variability) and that these forms can be related to the underlying state space dynamics of the changing variable at hand. However, the way variability is revealed is critically dependent on the way development is measured. The measurement should be detailed enough to capture the real-time behavior in its context. Microgenetic designs offer

optimal possibilities for the study of variability in development. In recent years, a variety of new methods have been developed to measure variability, to describe its patterns, and to incorporate variability in multivariate analyses. The application of these methods to the various topics in early child development is one of the greatest challenges for future research on intraindividual variability.

It should be noted that the first few years of life are characterized by a high degree of interconnectedness of developmental domains. Moreover, all major developmental transitions in early childhood occur in a dynamic interaction between the child, the social environment, and the context. Young children acquire skills and knowledge about the world through social and material interactions, while at the same time actively shaping their environments. Variability and stability play a central role in this process. Developing behavior is adaptive and reactive in nature. For instance, when an infant cries, this is always in response to the internal or external context (e.g. hunger, cold). However, we have seen that it is also a way to select and create situations, and thus aims at creating a certain degree of stability. This way, development always shows elements of both variability and stability, which are related to the dynamic interaction between the child and the environment.

References

- Alibali, M. W. & Goldin-Meadow, S. (1993). Gesture-speech mismatch and mechanisms of learning: What the hands reveal about a child's state of mind. *Cognitive Psychology*, 25, 468-523. doi:10.1006/cogp.1993.1012.
- Amsterlaw, J., & Wellman, H. M. (2006). Theories of mind in transition: a microgenetic study of the development of false belief understanding. *Journal of Cognition and Development*, 7, 139-172. doi:10.1207/s15327647jcd0702_1
- Bacher, L. F., & Robertson, S. S. (2001). Stability of coupled fluctuations in movement and visual attention in infants. *Developmental Psychobiology*, 39, 99-106. doi:10.1002/dev.1034
- Barr, R.G.(1990), The normal crying curve: What do we really know? *Developmental Medicine & Child Neurology*, 32, 356-362. doi:10.1111/j.1469-8749.1990.tb16949.x.
- Bassano, D., & van Geert, P. (2007). Modeling continuity and discontinuity in utterance length: A quantitative approach to changes, transitions, and intra- individual variability in early grammatical development. *Developmental Science*, 10, 588–612. doi:10.1111/j.1467-7687.2006.00629.x
- Benigno, J. P., Byrd, D. L, McNamara, J. P., Berg, W K., & Farrar, M. J. (2011). Talking through transitions: Microgenetic changes in preschoolers' private speech and executive functioning. *Child Language Teaching and Therapy*, 27, 269–285. doi:10.1177/0265659010394385
- Bornstein, M. H. & Tamis-LeMonda, C. S. (1990). Activities and interactions of mothers and their firstborn infants in the first six months of life: Covariation, stability, continuity, correspondence, and prediction. *Child Development*, 61, 1206-1217. doi:10.2307/1130888.

- Campbell, D. T. (1960). Blind variation and selective retention in creative thought as in other knowledge processes. *Psychological Review*, *67*, 380–400.
doi:10.1037/h0040373
- Chen, Z., & Siegler, R. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development*, *65*, v-96. doi:10.1111/1540-5834.00072
- Courage, M. L., Edison, S. C., & Howe M. L. (2004). Variability in the early development of visual self-recognition. *Infant Behavior and Development*, *27*, 509–532. doi:10.1016/j.infbeh.2004.06.001
- Cox, R. F. A., & van Dijk, M. (2013). Micro-development in parent-child conversations: From global changes to flexibility. *Ecological Psychology*, *25*, 304-315. . doi:10.1080/10407413.2013.810095
- Crockenberg, S. B. & Smith, P. (1982). Antecedents of mother–infant interaction and infant irritability in the first three months of life. *Infant Behavior & Development*, *5*, 105-119. doi:10.1016/S0163-6383(82)80021-0.
- Cronbach, L. J. (1960). *The essentials of psychological testing*. New York, NY: Harper & Brothers.
- Dale, R., & Spivey, M. J. (2006). Unraveling the dyad: Using recurrence analysis to explore patterns of syntactic coordination between children and caregivers in conversation. *Language Learning*, *56*, 391-430. doi:10.1111/j.1467-9922.2006.00372.x
- De Graag, J. A., Cox, R. F. A., Hasselman, F., Jansen, J., & de Weerth, C. (2012). Functioning within a relationship: Mother–infant synchrony and infant sleep. *Infant Behavior and Development*, *35*, 252-263. doi:10.1016/j.infbeh.2011.12.006

- De Weerth, C., & van Geert, P. (2002a). Changing patterns of infant behavior and mother-infant interaction: Intra- and interindividual variability. *Infant Behavior and Development*, *24*, 347-371. doi:10.1016/S0163-6383(02)00083-8
- De Weerth, C., & van Geert, P. (2002b). A longitudinal study of basal cortisol in infants: Intraindividual variability, circadian rhythm and developmental trends. *Infant Behavior and Development*, *25*, 340-374. doi:10.1016/S0163-6383(02)00141-8
- De Weerth, C., & van Geert, P. (2012). *RQA of emotion relation behavior in one infant*. Unpublished data. University of Groningen, The Netherlands.
- De Weerth, C., van Geert, P., & Hoijtink, H. (1999). Intraindividual variability in infant behavior. *Developmental Psychology*, *35*, 1102-1112. doi:10.1037/0012-1649.35.4.1102
- Dishion, T. J., Nelson, S. E., Winter, C., & Bullock, B. (2004). Adolescent friendship as a dynamic system: Entropy and deviance in the etiology and course of male antisocial behavior. *Journal of Abnormal Child Psychology*, *32*, 651-663. doi:10.1023/B:JACP.0000047213.31812.21
- Farnsworth, K. D., & Beecham, J. A. (1999). How do grazers achieve their distribution? A continuum of models from random diffusion to the ideal free distribution using biased random walks. *American Naturalist*, *153*, 509-526. doi:10.1086/303192
- Fischer, K. W., & Paré-Blagojev, J. (2000). From individual differences to dynamic pathways of development. *Child Development*, *71*, 850-853. doi:10.1111/1467-8624.00192

- Flynn, E., & Siegler, R. (2007). Measuring change: Current trends and future directions in microgenetic research. *Infant and Child Development, 16*, 135-149. doi:10.1002/icd.502
- Fogel, A. (1993). *Development through relationships*. Chicago, IL: The University of Chicago Press.
- Fogel, A. (2011). Theoretical and applied dynamic systems research in developmental science. *Child Development Perspectives, 5*, 267–272. doi:10.1111/j.1750-8606.2011.00174.x
- Fogel, A., & DeKoeper-Laros, I. (2007). The developmental transition to secondary intersubjectivity in the second half year: A microgenetic case study. *Journal of Developmental Processes, 2*, 63-90.
- Fogel, A., & Garvey, A. (2007). Alive communication. *Infant Behavior and Development, 30*, 251-257. doi:10.1016/j.infbeh.2007.02.007
- Freedland, R. L. & Bertenthal, B. I. (1994). Developmental changes in interlimb coordination: Transition to hands-and-knees crawling. *Psychological Science, 5*, 26-32. doi:10.1111/j.1467-9280.1994.tb00609.x.
- Graham, T. & Perry, M. (1993). Indexing transitional knowledge. *Developmental Psychology, 29*, 779-788. doi:10.1037/0012-1649.29.4.779.
- Granic, I., & Hollenstein, T. (2006). A survey of dynamic systems methods for developmental psychopathology. In D. Cicchetti & D. J. Cohen (Eds.), *Developmental psychopathology* (2nd ed., Vol. 1, pp. 889-930). Hoboken, NJ: Wiley.
- Granic, I., & Lamey, A.V. (2002). Combining dynamic-systems and multivariate analyses to compare the mother–child interactions of externalizing subtypes. *Journal of Abnormal Child Psychology, 30*, 265–283. doi:10.1023/A:1015106913866

- Granott, N., Fischer, K. W., & Parziale, J. (2002). Bridging to the unknown: A transition mechanism in learning and development. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 1–28). New York, NY: Cambridge University Press.
- Hoffmann, G. (1983). The random elements in the systematic search behavior of the desert isopod *Hemilepistus reaumuri*. *Behavioral Ecology and Sociobiology*, *13*, 81–92. doi:10.1007/BF00293798
- Hollenstein, T. (2013). *State space grids: Depicting dynamics across development*. New York, NY: Springer.
- Hollenstein, T., & Lewis, M.D. (2006). A state space analysis of emotion and flexibility in parent-child interactions. *Emotion*, *6*, 663–669. doi:10.1037/1528-3542.6.4.656
- Hollenstein, T., Granic, I., Stoolmiller, M., & Snyder, J. (2004). Rigidity in parent-child interactions and the development of externalizing and internalizing behavior in early childhood. *Journal of Abnormal Child Psychology*, *32*, 595–607. doi:10.1023/B:JACP.0000047209.37650.41
- Hosenfeld, B., van der Maas, H. L. J., & van der Boom, D. C. (1997). Detecting bimodality in the analogical reasoning performance of elementary schoolchildren. *International Journal of Behavioral Development*, *20*, 529–547. doi:10.1080/016502597385261
- Hsu, H. C., & Porter, C. L. (2004). Young infants' behavioral reactivity to mild perturbations: Developmental continuity, stability and organization. *Infancy*, *6*, 95–120. doi:10.1207/s15327078in0601_5

- Jenni, O. G., Deboer, T., & Achermann, P. (2006). Development of the 24-h rest-activity pattern in human infants. *Infant Behavior and Development*, *29*, 143-152. doi:10.1016/j.infbeh.2005.11.001
- Lavelli M., & Fogel, A. (2005). Developmental changes in the relationship between the infant's attention and emotion during early face-to-face communication: The 2-month transition. *Developmental Psychology*, *41*, 265–280. doi:10.1037/0012-1649.41.1.265
- Lavelli, M., Pantoja, A. P. F., Hsu, H., Messinger, D., & Fogel, A. (2006). Using microgenetic designs to study change processes. In D. M. Teti (Ed.), *Handbook of research methods in developmental science* (pp. 40-65). Malden, MA: Blackwell Publishing.
- Lewis, M. D. (2000). The promise of dynamic systems approaches for an integrated account of human development. *Child Development*, *71*, 36-43. doi:10.1111/1467-8624.00116
- Lewis, M. D. (2011). Dynamic systems approaches: Cool enough? Hot enough? *Child Development Perspectives*, *5*, 279–285. doi:10.1111/j.1750-8606.2011.00190.x
- Lewis, M. D., & Cook, M. L. (2007). Changing habits of emotion regulation at transition points in infancy: A dynamic systems analysis. *Journal of Developmental Processes*, *3*, 67-89.
- Lewis, M. D., Granic, I., & Lamm, C. (2006). Behavioral differences in aggressive children linked with neural mechanisms of emotion regulation. *Annals of the New York Academy of Sciences*, *1094*, 164–17. doi:10.1196/annals.1376.017

- Lewis, M. D., Lamey, A. V., & Douglas, L. (1999). A new dynamic systems method for the analysis of early socioemotional development. *Developmental Science*, 2, 458-476. doi:10.1111/1467-7687.00090
- Lichtwarck-Aschoff A., Hasselman, F., Cox, R. Pepler, D., & Granic, I. (2012). Characteristic destabilization profile in parent-child interactions associated with treatment efficacy for aggressive children. *Nonlinear Dynamics, Psychology, and Life Sciences*, 16, 353-379.
- Lord, F. M., & Novick, R. (1968). *Statistical theories of mental test scores*. Reading, MA: Addison-Wesley.
- Lunkenheimer, E. S., Olson, S. L., Hollenstein, T., Sameroff, A. J., & Winter, C. (2011). Dyadic flexibility and positive affect in parent, child coregulation and the development of child behavior problems. *Development and Psychopathology*, 23, 577-591. doi:10.1017/S095457941100006X
- Mainhard, M. T., Pennings, H. J. M., Wubbels, T., & Brekelmans, M. (2012). Mapping control and affiliation in teacher–student interaction with state space grids. *Teaching and Teacher Education*, 28, 1027-1037. doi:10.1016/j.tate.2012.04.008
- Martin, C. L., Fabes, R. A., Hanish, L. D., & Hollenstein (2005). Social dynamics in the preschool. *Developmental Review*, 25, 299–327. doi:10.1016/j.dr.2005.10.001
- Marwan, N. (2008). A historical review of recurrence plots. *European Physical Journal*, 164, 3–12. doi:10.1140/epjst/e2008-00829-1
- Marwan, N., Romano, M. C., Thiel, M., & Kurths, J. (2007). Recurrence plots for the analysis of complex systems. *Physics Reports*, 438, 237–329. doi:10.1016/j.physrep.2006.11.001

- McCall, R. B., Eichorn, D. H. & Hogarty, P. S. (1977). Transitions in early mental development. *Monographs of the Society for Research in Child Development*, 42, 108. doi:10.2307/1165992.
- Molenaar, P. M., & Campbell, C. G. (2009). The new person-specific paradigm in psychology. *Current Directions in Psychological Science*, 18, 112-117. doi:10.1111/j.1467-8721.2009.01619.x
- Murphy-Mills, J., Bruner, M. W. Erickson, K., & Côté, J. (2011). The utility of the state space grid method for studying peer interactions in youth sport. *Journal of Applied Sport Psychology*, 23, 159-174. doi:10.1080/10413200.2010.545101
- Nicholson, J. S., Deboeck, P. R., Farris, J. R., Boker, S. M., & Borkowski, J. G. (2011). Maternal depressive symptomatology and child behavior: Transactional relationship with simultaneous bidirectional coupling. *Developmental Psychology*, 47, 1312–1323. doi:10.1037/a0023912
- Nunnally, J. C. (1970). *Introduction to psychological measurement*. New York, NY: McGraw-Hill.
- Peters-Martin, P. & Wachs, T. D.(1984). A longitudinal study of temperament and its correlates in the first 12 months. *Infant Behavior & Development*, 7, 285-298. doi:10.1016/S0163-6383(84)80044-2.
- Piek, J. P. (2002). The role of variability in early motor development. *Infant Behavior and Development*, 25, 452-465. doi:10.1016/S0163-6383(02)00145-5
- Prigogine, I., & Stengers, I. (1984). *Order out of chaos*. New York, NY: Bantam.
- Rebelsky, F. & Black, R. (1972). Crying in infancy. *The Journal of Genetic Psychology: Research and Theory on Human Development*, 121, 49-57.

- Ribeiro, A., Bento, T., Salgado, J., Stiles, W.B., & Gonçalves, M.M. (2011). A dynamic look at narrative change in psychotherapy: A case study tracking innovative moments and protonarratives using state space grids. *Psychotherapy Research, 21*, 54-69. doi:10.1080/10503307.2010.504241
- Robertson, S. S., Bacher, L. F., & Huntington, N. L. (2001). Structure and irregularity in the spontaneous behavior of young infants. *Behavioral Neuroscience, 115*, 758-763. doi:10.1037/0735-7044.115.4.758
- Rovine, M. J., Sinclair, K. O., & Stifter, C. A. (2010). Modeling mother-infant interactions using hidden Markov models. In K. Newell & P. C. M. Molenaar (Eds.), *Individual pathways of change in learning and development* (pp. 51-67). Washington, DC: American Psychological Association.
- Ruhland, R., & van Geert, P. (1998). Jumping into syntax: transitions in the development of closed class words. *British Journal of Developmental Psychology, 16*, 65-95. doi:10.1111/j.2044-835X.1998.tb00750.x
- Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology, 25*, 225–273. doi:10.1006/cogp.1995.1006
- Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. New York, NY: Oxford University Press.
- Siegler, R. S. (2006). Microgenetic analyses of learning. In W. Damon & R. M. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Volume 2: Cognition, perception, and language* (6th ed., pp. 464–510). Hoboken, NJ: Wiley.

- Simonton, D. K. (2007). The creative process in Picasso's Guernica sketches: Monotonic improvements versus nonmonotonic variants. *Creativity Research Journal*, *19*, 329–344. doi:10.1080/10400410701753291
- Skinner, B. F. (1937). Two types of conditioned reflex: A reply to Konorski and Miller. *Journal of General Psychology*, *16*, 272-279. doi:10.1080/00221309.1937.9917951
- Stoolmiller, M. & Snyder, J. (2006). Modeling heterogeneity in social interaction processes using multilevel survival analysis. *Psychological Methods*, *11*, 164-177. doi:10.1037/1082-989X.11.2.164
- Tamis-LeMonda, C. S. & Bornstein, M. H. (1991). Individual variation, correspondence, stability, and change in mother and toddler play. *Infant Behavior & Development*, *14*, 143-162. doi:10.1016/0163-6383(91)90002-A.
- Thelen, E. (1985). Developmental origins of motor coordination: Leg movements in human infants. *Developmental Psychobiology*, *18*, 1-22. doi:10.1002/dev.420180102
- Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT-Press.
- Thelen, E., Skala, K. D., & Kelso, J. A. S. (1987). The dynamic nature of early coordination: Evidence from bilateral leg movements in young infants. *Developmental Psychology*, *23*, 179-186. doi:10.1037/0012-1649.23.2.179
- Thom, R. (1975). *Structural stability and morphogenesis: An outline of a general theory of models*. Reading, MA: Benjamin.
- Tollenaar, M. S., Jansen, J., Beijers, R., J. Riksen-Walraven, M. & de Weerth, C. (2010). Cortisol in the first year of life: Normative values and intraindividual

variability. *Early Human Development*, 86, 13–16.

doi:10.1016/j.earlhumdev.2009.12.003

- Trevarthen, C. (1993). The self born in intersubjectivity: An infant communicating. In U. Neisser (Ed.), *The perceived self: Ecological and interpersonal sources of self-knowledge* (pp. 121–173). New York, NY: Cambridge University Press.
- Van der Maas, H. L. J., & Molenaar, P. C. M. (1992). Stages of cognitive development: An application of catastrophe theory. *Psychological Review*, 99, 393–417. doi:10.1037/0033-295X.99.3.395
- Van Dijk, M. (2012). *SSG of parent child interaction*. Unpublished data. University of Groningen.
- Van Dijk, M., & van Geert, P. (2011a). Exploring patterns of adaptation in child directed speech during the process of early grammaticalization of child language. *Language, Interaction and Acquisition*, 2, 61–81. doi:10.1075/lia.2.1.03dij
- Van Dijk, M., & van Geert, P. (2007). Wobbles, humps and sudden jumps: A case study of continuity, discontinuity, and variability in early language development. *Infant and Child Development*, 16, 7–33. doi:10.1002/icd.506
- Van Dijk, M., & van Geert, P. (2011b). Heuristic techniques for the analysis of variability as a dynamic aspect of change. *Infancia y Aprendizaje*, 34, 151–168. doi:10.1174/021037011795377557
- Van Dijk, M., Hunnius, S., & van Geert, P. (2009). Variability in eating behavior throughout the weaning period. *Appetite*, 52, 766–770. doi:10.1016/j.appet.2009.02.001

- Van Dijk, M., Hunnius, S., & van Geert, P. (2012). The dynamics of feeding during the introduction to solid food. *Infant Behavior and Development*, *35*, 226-239. doi:10.1016/j.infbeh.2012.01.001
- Van Dijk, M., van Geert, P., Korecky-Kroell, K., Maillochon, I., Laaha, S., Dressler W. U., & Bassano, D. (2013). Dynamic adaptation in child–adult language interaction. *Language Learning*, *63*, 214-270. doi:10.1111/lang.12002
- Van Geert, P. (1994). *Dynamic systems of development: Change between complexity and chaos*. New York, NY: Harvester Wheatsheaf.
- Van Geert, P. (2011). The contribution of complex dynamic systems to development. *Child Development Perspectives*, *5*, 273-278. doi:10.1111/j.1750-8606.2011.00197.x
- Van Geert, P. L. C. (2009). A comprehensive dynamic systems theory of language development. In K. de Bot & R.W. Schrauf (Eds.), *Language development over the life span* (pp. 60-104). New York, NY: Routledge.
- Van Geert, P., & van Dijk, M. (2002). Focus on variability: New tools to study intraindividual variability in developmental data. *Infant Behavior and Development*, *25*, 340-374. Doi:10.1016/S0163-6383(02)00140-6
- Wachs, T. D., Creed-Kanashiro, H., & Gurkas, P. (2008). Intraindividual variability in infancy: Structure, stability, and nutritional correlates. *Developmental Psychobiology*, *50*, 217-231. doi:10.1002/dev.20284
- Webber Jr., C. L., & Zbilut, J. P. (2005). Recurrence quantification analysis of nonlinear dynamical systems. In M. A. Riley & G. C. Van Orden (Eds.), *Tutorials in contemporary nonlinear methods for the behavioral sciences* (pp. 26-94). Washington, DC: National Science Foundation.

- Wijnants, M. L., Bosman, A. M. T., Hasselman, F., Cox, R. F. A., & Van Orden, G. C. (2009). 1/f scaling in movement time changes with practice in precision aiming. *Nonlinear Dynamics, Psychology, and Life Sciences*, *13*, 79-98.
- Wijnants, M. L., Hasselman, F., Cox, R. F. A., Bosman, A. M. T., & Van Orden, G. C. (2012). An interaction-dominant perspective on reading fluency and dyslexia. *Annals of Dyslexia*, *62*, 100-119. doi:10.1007/s11881-012-0067-3
- Worobey, J. & Blajda, V. M. (1989). Temperament ratings at 2 weeks, 2 months, and 1 year: Differential stability of activity and emotionality. *Developmental Psychology*, *25*, 257-263. doi:10.1037/0012-1649.25.2.257.