Heuristic techniques for the analysis of variability as a dynamic aspect of change

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Abstract

Due to the influence of dynamic systems and microgenetic perspectives, variability is nowadays often seen as an important phenomenon that helps us understand the underlying mechanisms of development. This paper aims at demonstrating several simple techniques that can be used to analyze variability in data of developing (or learning) individuals. These techniques will be illustrated by applying them to a time serial dataset of early child language (to be specific, the emergence of grammatical preposition use). First, we show some descriptive techniques that are essential first steps for generating hypotheses. Also, we propose a measure that expresses qualitative variability. Furthermore, we demonstrate how resampling techniques can be used to test the presence of performance peaks, which may be important because they indicate the emergence of new abilities. Finally, we show the use of a technique that is especially useful for exploring interactions between ordinal variables (the State Space Grid, or SSG). With this illustration, we hope to encourage researchers to take a more exploratory approach to variability in their data and to develop methods directed at analyzing dynamic aspects of change.

Keywords: variability, development, repeated measures, methodology, dynamic systems, microgenetic perspective, language acquisition, prepositions

Técnicas heurísticas para analizar la variabilidad como un aspecto dinámico de cambio

Resumen (Abstract)

Debido a la influencia de los sistemas dinámicos y las perspectivas microgenéticas, hoy en día la variabilidad se vé frecuentemente como un fenómeno importante que nos ayude entender los mecanismos subyacentes de desarrollo. Este artículo tiene como objetivo de demostrar varias técnicas simples que pueden utilizarse para analizar la variabilidad en los datos de individuos en vías de desarrollo (o de aprendizaje). Estas técnicas serán ilustrado aplicándose a un conjunto de datos de tiempo serial del lenguaje infantil temprano (en concreto, la emergencia del uso de preposiciones gramaticales). En primer lugar, mostramos algunas técnicas descriptivas que son los primeros pasos esenciales para generar hipótesis. También, proponemos una medida que expresa la variabilidad cualitativa. Además, vamos a demostrar como técnicas de remeustreo pueden ser utilizados para poner a prueba la presencia de picos en el rendimiento, lo cual puede ser importante porque indican la emergencia de nuevas habilidades. Por último, mostramos la utilización de una técnica que es especialmente útil para explorar interacciones entre variables ordinales (El State Space Grid, o SSG). Con esta ilustración, esperamos incentivar los investigadores a tomar un enfoque más exploratorio a la variabilidad de sus datos y a desarrollar métodos dirigidos a analizar aspectos dinámicos del cambio.

Palabras clave (Key words): variabilidad, desarrollo, medidas repetidas, metodología, sistemas dinámicos, perspectiva microgenética, adquisición del lenguaje, preposiciones.

Note: We thank David van Geert for the Spanish translation of the Abstract

1. Introduction

One of the advantages of time serial data is that they allow us to follow the emergence of new (cognitive) abilities in children. However, when analyzing the results of such studies, especially those with many repeated measurements per individual, a high degree of variability is often more rule than exception. Where at the group level there might be a general increase in competence, at the individual level we observe large moment-to-moment differences. Traditionally, this type of variability is considered as a form of measurement error and is thus predominantly dealt with as a 'methodological problem'. However, due to the influence of dynamic systems and microgenetic perspectives, it is nowadays often seen as an intrinsic property that helps us understand the underlying mechanisms of change (Granott, 1998; Hosenfeld, van der Maas & van der Boom, 1997; Siegler, 1996). What these theoretical perspectives have in common is that variability is viewed as an important developmental characteristic and not as something externally 'added' to the process of development, such as error (Van Geert & van Dijk, 2002). Whereas stability in behavioral patterns indicates that an interaction is organized and consolidated, variability indicates a high degree of context dependency and exploration. According to dynamic systems theory, variability is especially large during a period of rapid development, 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).

Several microgenetic studies have demonstrated that an increase in variability is associated with subsequent learning (e.g. Alibali & Goldin-Meadow, 1993; Siegler, 1995; Graham & Perry, 1993). This way, variability not only co-occurs with change, but is actually one of its causes (Bertenthal, 1998). Variability is not just important because of its prevalence, but also because it can be used to explain and predict change (Granott, 1998). Whereas an increase in variability is associated with a developmental transition, a decrease in variability indicates the presence of an attractor (relatively stable state or stage). Across development, periods with low variability (stable states) alternate with periods of high variability (developmental transitions) in a cyclical fashion (Siegler, 2007). According to the overlapping waves theory (Siegler, 1996), 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.

In spite of the importance of variability as a 'dynamic aspect of change', the standard methodological toolkit of the developmental psychologist is not very well suited to describe and analyze it in a structured fashion. This paper aims to contribute to this toolkit by introducing and demonstrating various simple but powerful techniques to describe and analyze intra-individual variability. In previous publications we have used some of these methods (see for instance Van

Geert & van Dijk, 2003; Van Dijk & van Geert, 2005; Verspoor, Lowie & van Dijk, 2008), and here we want to provide an overview of the possibilities and show what they have to offer in a data set of developing cognitive abilities.

The simple, descriptive techniques we will discuss in the first part of this paper (line graphs and min max graphs) are essential first steps to formulate hypotheses that might be tested later on. In the second part, we propose a measure that expresses qualitative variability and demonstrate how it can be used to describe strategy diversity across development. Third, we show a way of testing the presence of performance peaks. Peaks are important because they indicate functioning under optimal circumstances and thus point at the emergence of new abilities. Finally, we demonstrate the application of a descriptive, topological technique (the State Space Grid, or SSG, see Lewis, Lamey & Douglas, 1999). This technique is especially useful for exploring interactions between ordinal variables (such as qualitatively different strategies). With this demonstration we aim to show that variability is an important characteristic of a developing system, and that using these techniques yields to a more refined description of developmental processes.

2. The case study: a dataset of early language development

The techniques in this paper will be illustrated by applying them to a time serial dataset of early language acquisition. This dataset consists of the repeated observation of the same (cognitive) variable during a period of rapid change. In particular, the study follows the language development of two young children acquiring Dutch as their first language (25 samples between age of 1;6 to 2;6 years). The study analyzed the emergence of different grammatical constructions, and described how they develop and interact. There was a special focus on studying variability in relation to underlying mechanisms of development, such as discontinuities. For the remainder of this illustration, the focus is on the way children learn to verbalize spatial relationships by means of the linguistic category of *prepositions*. Prepositions are those function words that indicate the spatial relationship of an object to the rest of the sentence. In this study, all prepositions that belong to the set of spatial prepositions were selected if the context was spatial. The total set of spatial prepositions consisted of "in", "uit", "op", "af", "voor", "achter", "tussen", "over", "bij", "naar", "onder", "boven", "binnen", "buiten", “door” (approximate translations are: in, out, on, off, before/in front of, after/behind, between, over, near (to)/at, to, under, above, in/inside, out/outside, through). Consequently, these utterances were coded into five mutually exclusive categories, based on the presence of grammatical elements. In order to form a grammatically correct prepositional phrase, the prepositional element needs a noun phrase that functions as the object. For instance, in the sentence “the book is on the shelf”, the prepositional element is ‘on’, and the noun phrase is ‘the shelf’. Without this noun phrase, the prepositional phrase is considered to be ungrammatical (e.g. the sentence “the book is on” is ungrammatical).

Table 1

Coding categories of prepositional phrases

Strategy	**Description**	**Example**
PE-alone (basic)	the utterance contains only a prepositional element	“*in*!”
PE-NP (target)	the utterance contains a noun as the object of the prepositional phrase	“…. *in bed*”/ “ … *in there*”.
PE-X	the utterance contains another noun that is not the noun phrase of the prepositional phrase	*“puppy in”*
PE-V	the utterance contains a preposition and only a verb (no noun phrase)	“*want in*”
PE-uncodable	the utterance contains a prepositional element and something else	*“xx out xx”*

Table 1 shows the categories that were used to code all utterances that contained a preposition. The simplest strategy is the use of a prepositional element only: *PE-alone*. In this case, there are no other words in the utterance. The target strategy is the *NE-NP* form, where the obligatory noun or noun phrase is present in the child’s utterance. Consequently, there are two other strategies in which the obligatory element is missing, but one or two other grammatical components are present. The first is the *PE-X* strategy, involving a noun phrase which is not the object of the prepositional element and second, the *PE-V* strategy, where there are no nouns, but only a verb to compliment the prepositional element. Although these two forms are not totally grammatical, because of the missing obligatory noun, they are already somewhat more grammatical in comparison to the PE-alone strategy. Finally, there is a category for the uncodable utterances.
In the language of a fully competent speaker (virtually) all prepositional phrases are of the PE-NP strategy. In these constructions, there is a prepositional element, a noun phrase that functions as the object of the prepositional phrase, and possibly other grammatical elements such as verbs and other nouns. Prepositions are used from the one word stage on, and soon they are produced in different types of constructions (in combination with or without a verb, in combinations with or without a noun, etc). From the literature we know that children typically start by producing

prepositions that are close to actions (such as going in, out, on, under), and are already present in very early speech (Mandler, Hirsh-Pasek & Golinkoff, 2006; Clarck, 1978; Tomasello, 1987). Children around 2;6 years of age predominantly use prepositional constructions in correct syntactical sequences, including the obligatory NP (Valian, 1986). However, relatively little is known on the emergence of different grammatical propositional phrases across early language acquisition.

3. Analyzing variability in individual trajectories

3. 1. Visual exploration of the quantitative development

Development may take many different types of change, and as a first step we explore the general trends of the developing strategies, at the individual level. For instance, we explore whether there is a gradual increase of decrease, whether there are regressions, etcetera. Also, we question whether the data are relatively smooth or variable, and we compare the different variables. If there are data of more than one participant, a comparison of the individual data aims at describing similarities and differences between participants. Thus, the first step is to inspect the quantitative developmental trajectories and interpret them in qualitative terms. Thus, as a first step to describe the emergence of grammatical preposition use, we start out with simple individual line graphs. Next to the raw data of the observations, a smoothed trajectory is added in order capture the general trends in the trajectories more easily. In these graphs, we show the development of the main categories across time, for each child separately.

For instance, figure 1 shows the trajectories of the major strategies[1] in our case study for Heleen (Fig. 1a) and Lisa (Fig. 1b), as absolute frequencies, including a (Loess) trend line (for an explanation of this type of trend line see Simonoff, 1996). A first observation from this visual inspection is that the two children show striking similarities with regards to the emergence of grammatical prepositional phrases. In both children, the development seems to consist of three consecutive steps. First, there is an initial stage in which the a-grammatical strategy (PE-alone) occurs most frequently and the other constructions hardly occur. Secondly, towards the end of the observed period there is a stage where the target strategy (PE-NP) is used most frequently, and the others occur much less. Here we see a sharp increase in the use of this strategy, accompanied by a clear peak and large fluctuations. Thus, the child develops in the direction of the target adult preposition use, where the PE-NP strategy is used in (almost) all instances. It can also be observed that in between these two stages there appears to be a moment in which all different types are produced at the same time, right between the other two stages (see the arrows). In this third stage, none of the strategies is dominant. For instance the combination of

[1] The category ‘uncodable’ was not included in these figures

preposition and verb (PE-V) or preposition and another noun (PE-X) starts to increase only after the noted decrease of the elementary strategy. In summary, what this visual inspection of the line graphs has brought us is that there are indications for a shift between a-grammatical and grammatical productions, with in between a certain degree of variation in types of constructions.

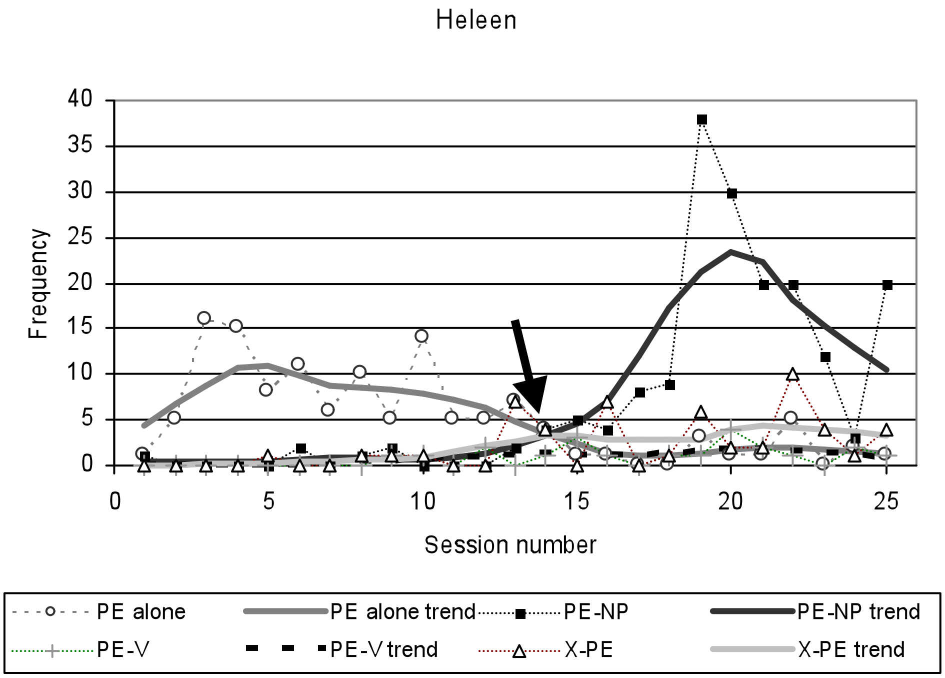

Figure 1a. Grammatical categories of the use of spatial prepositions of Heleen.

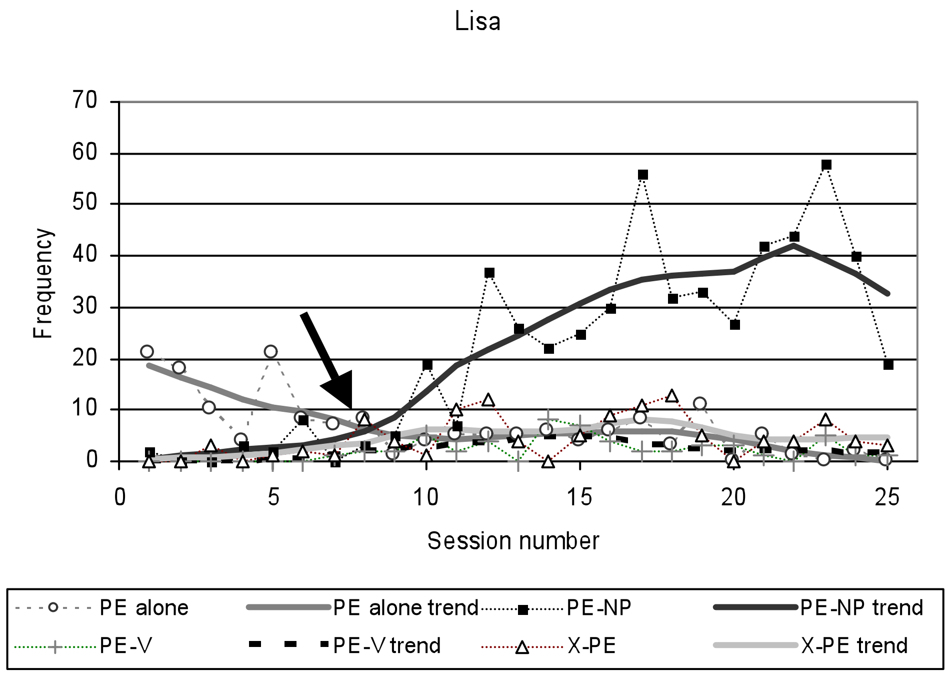

Figure 1b. Grammatical categories of the use of spatial prepositions of Lisa.

There are also some differences between the two children. First of all, the data of Heleen show a clear outlier, at session 19, whereas the data of Lisa contain several smaller outliers. It should also be noted that the total frequencies of the target strategy are much higher for Lisa than they are for Heleen (the highest frequency is 38 for Heleen versus 58 for Lisa). It might therefore be speculated that Lisa's language is somewhat more advanced at this age.

3.2. Variability in strategy diversity

Although a graphical representation of the data is an important first step, there might be changes in the patterns of variability that are not easily discovered by means of visual exploration of the data points alone. As we have seen above, the interpretation of the line graphs of the different strategies might lead to the hypothesis that a shift in the grammatical use of prepositions is preceded by qualitative variability. In other words, we want to find out whether there is an increase in the number of strategies the children use *right before* the emergence of the target grammatical strategy, which is a fairly robust result from other microgenetic studies (e.g. Siegler, 1995). This eventual increase can be used to test the presence of a transition point.

In order to quantify this type of variability, the chi-square can be used as a measure of strategy diversity for each session. This measure is calculated as the difference between the occurrence of each strategy and the probability of each strategy a priori, squared (inverted and scaled relative to the maximum of all chi-square sums). This measure is maximal (equals 1) when all strategies occur in equal frequencies and is minimal (equals zero) when only one of the strategies is used. The resulting measures can be plotted in a simple line graph in order to give an impression of the changing qualitative variability across time.

In our study on the language development of the two children, the a priori probability of each strategy is 0.25, because there are four alternative strategies. We thus calculated the difference between occurrence of each strategy (e.g. .50 if this strategy occurred in 50% of all observation) and the a priori probability of .25, and squared this difference. The resulting values (of each strategy) were summed, inverted and expressed relative to the maximum chi-square sums (in this case 0.75).

Figure 2 gives an illustration of a graphical representation of these values for the language data of the two children in the case study. Here, we have added a Loess trend line in order to make visual inspections of the general tendencies easier.

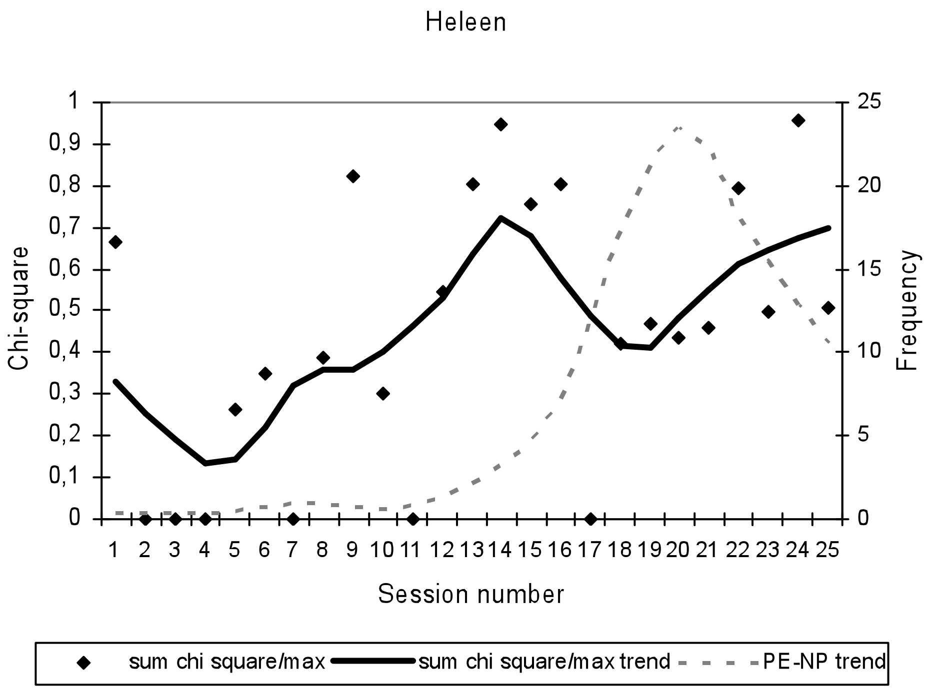

Figure 2a. Smoothed (Loess trendline) chi-square values and smoothed use of the PE NP strategy of Heleen.

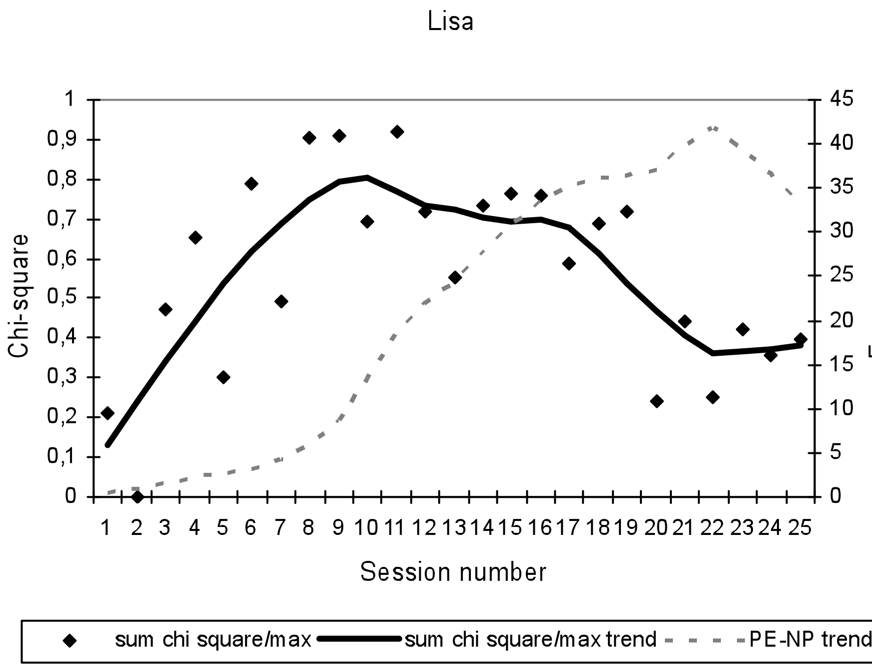

Figure 2b. Smoothed (Loess trendline) chi-square values and smoothed use of the PE NP strategy of Lisa (bottom).

The interpretation is as follows. For Heleen, we observe (see figure 2a) that the biggest increase in the target strategy takes place between session 16 and 19. We would therefore expect that *if* qualitative variability precedes learning, the chi-squares are largest right before this point in time. The figure shows that the chi-squares are largest between session 12 and 16. However, there is also a high frequency at session 9 and approximately session 22-24 (which is after the transition point). Thus, although there is some evidence for an association between qualitative variability and strategy acquisition, there also exist major fluctuations that are not consistent with our expectations. For the second child, Lisa, we have established that the first major increase in the target strategy is situated around session 8-10. In figure 2b, we observe that the chi-square increases relatively gradually up till session 8, and starts to decrease after session 11. Thus, for this second child, our expectations are confirmed, and there seems to be a clear transition point between the use of many different types of strategies and the emergence of the target strategy.

3. 3. Describing patterns of variability as a developing range

By means of simple eyeball statistics on the individual data, we have already obtained a general impression of the large degree of variability. From the literature we know that when learners are acquiring new problem solving abilities, they vary with regard to the level of complexity within a range (Fischer & Granott, 1995). When we focus on the trajectories of the individual variables, the *moving min-max* graph provides an appropriate technique for visually inspecting how the intra-individual variability changes in the course of development. The underlying principle is to display the data as a bandwidth of scores. For this purpose a 'moving window' of observations is used: a time frame that moves up one position for each data point. Therefore, each window largely overlaps the preceding windows, using the same measurement occasions minus the first and plus the next. For instance, for every set of five consecutive measurements we calculate the maximum and the minimum values. This is done by way of a predetermined moving window, such that we obtain the following series:

max(t1..t5), max(t2..t6), max(t3..t7), etc
min(t1..t5), min(t2..t6), min(t3..t7), etc.

For instance, take a fictitious dataset: 1, 1, 2, 1, 4, 8, 2, 3, 3, 2. This would lead to the following values: the min values would be 1, 1, 1, 1, 2, and 2; the max values would be 4, 8, 8, 8, 4, and 3. Now, we plot the original data in combination with the min and max values, and we obtain a bandwidth of scores around each data point. Instead of displaying measurement points as simple dots, the moving min-max graph presents a score range for each measurement occasion, which, can be inspected for changes that occur in the course of development. For instance, we can check whether the bandwidth is relatively stable, or whether there are widenings or narrowings somewhere in this trajectory. Therefore, the application of the min max graph can clarify different patterns of variability in different developmental trajectories.

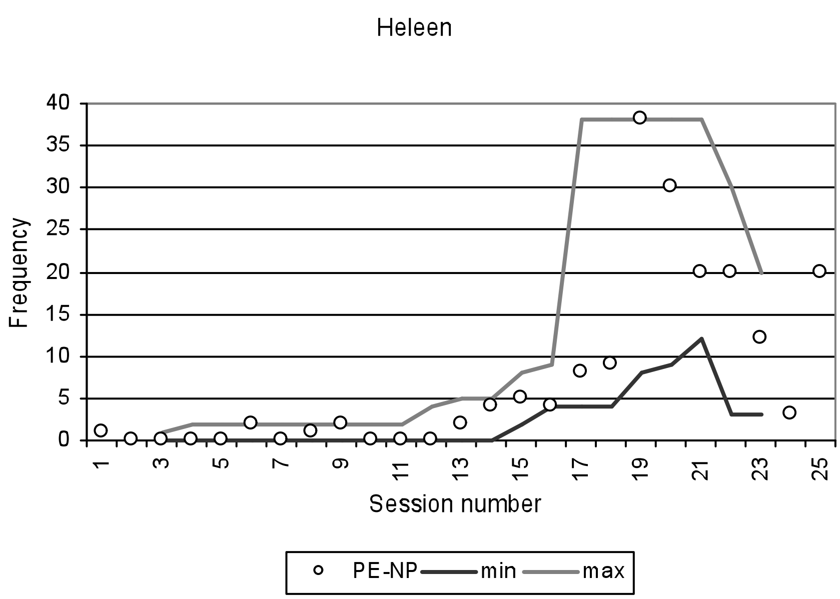

Figure 3a. Min max graphs of the use of the target strategy (NE-NP) for Heleen.

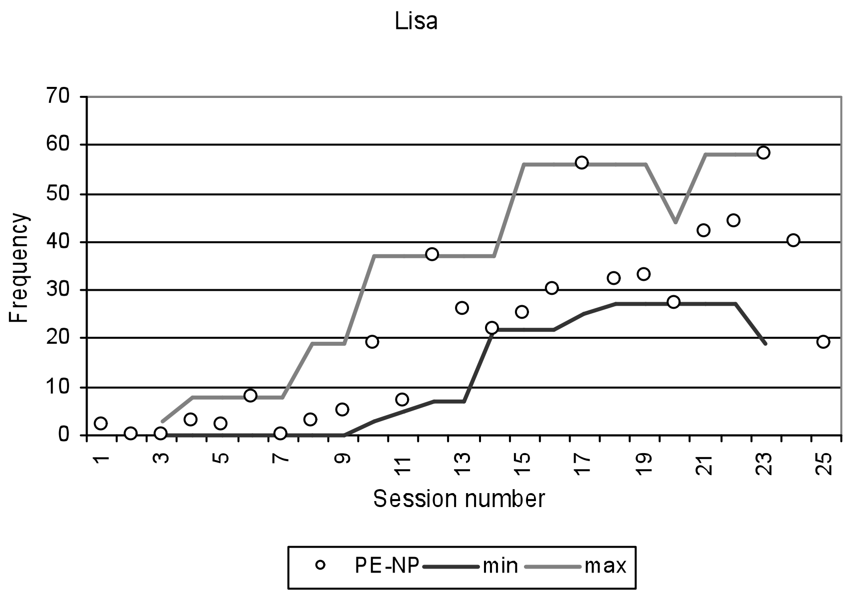

Figure 3b. Min max graphs of the use of the target strategy (NE-NP) for Lisa.

As an illustration, the min-max technique is applied to the children's use of the target strategy (PE-NP) across development (see figure 3). Initially, the range of fluctuations turns out to be small (below 8) in both children. However, after the frequency of the strategy reaches a critical value (between 5 and 10), the variability seems to increase as the frequency of the use of the strategy increases. There are also clear differences between both children. On the one hand, Heleen (Fig. 3a) shows an abrupt 'bulb' in the score range, which is caused by one or two extreme outliers around session 19-20. On the other hand, Lisa's target strategy emerges relatively gradually, with a gradually increasing bandwidth (see Fig. 3b). Thus, whereas Lisa's range of variability increases relatively gradually, that of Heleen seems to consist of two consecutive 'steps' with a much less gradual transition between both[2].

3.4. Testing for statistically significant peaks

In the application of the min max graph, we have seen that the data of the two children contain several outliers, or peaks. From a traditional point of view, outliers are not considered to be informative, because the values are not 'representative' for the performance of the child in a certain period of time. However, from a dynamic systems point of view, these peak performances can represent important characteristics because they might indicate the emergence of new competencies. New behaviors can be used in higher frequencies, because to the child they are

[2] In Van Dijk and van Geert (2006) we have tested the significance of such a two stage model using a resampling procedure.

new and exciting. Peak performances might also reveal the degree of sensitivity to contextual factors, where optimal circumstances lead to high levels of functioning. Peaks can also be caused by contextual factors in which case they illustrate the vulnerability of the system to variation in the context. When development 'settles down' and the new abilities become more consolidated, the system looses this susceptibility and becomes more robust against (subtle) changes in the environment.

Thus, from a dynamic systems point of view, the identification of peaks may be important because they may indicate that the developing system becomes unstable and new competencies emerge in a jump-wise fashion. In each case it has to be tested whether these outliers are 'genuine'. This can be done by the application of so called 'resampling techniques': statistical procedures that are based on estimating probabilities by randomly drawing samples from a data set. Here, the observed result is compared to the result from a resampling procedure. If the probability of finding the observed value in the resampling procedure is very low (e.g. below 5%), the result can be considered to differ 'significantly' from the null hypothesis model.

In our illustration, a resampling procedure is used to test whether an observed peak in the data differs significantly from a model where the peaks are random outliers of an underlying continuous distribution. Here, the first step is to define a *criterion* of what is going to be tested. Secondly, we formulate a resampling model, that is, we define *what* has to be resampled under the null-hypothesis. As a third step, a Monte Carlo Analysis (one per child) can be performed with many simulation steps (e.g. 5000). The analysis can be performed in Poptools (Hood, 2008; For more information on the use of permutation tests, see Good, 1999; Todman & Dugard, 2001). From these results, we can calculate the probability that the peak we observed is the result of random fluctuation on top of a continuous model. Only if the probability is small (in this case below 1%), we can reject the null-hypothesis and conclude that the peak is genuine.

In this illustration, the following steps were taken. First of all, we chose the *maximal distance between two observations* as the testing criterion, and compared the observed value with the one produced by the resampling model. Thus, across all (real and resampled) values the largest distance between data points was defined as the testing criterion. Secondly, in order to remove the immediate fluctuations, the data were smoothed with a simple moving average over 2 observations. The reason for this is that it might be assumed that if there is a real peak, it should be longer than only a single isolated observation. Thus, instead of using the raw data, we performed consequent calculations on the moving averages of each data point.

As a third step, the data were transformed in such a way that the relative peaks were considered, disregarding the underlying general increase in the data. Thus, the data were *detrended and scaled*. This means that the general trend was removed by calculating residuals and these values were rescaled between 0 and 1. This is important because peaks are also related to the average value of a variable. By rescaling the data, the outliers are considered in relation to the level of the surrounding data points. Thus when values are generally smaller, peaks can also be smaller, but significantly larger that what is expected on the basis of chance.

Now, the maximal distance between the values in the real and resampled data set was calculated. This was done by comparing all distances between all data points and selecting the largest distance in the set. In the resampling procedure, we shuffled all data (which means resampling the data with replacement). Thus, in each simulation, a new set is drawn from the original pool, and not all observations are necessarily selected in each simulation. Because we were looking at the individual trajectories, we compared the maximal simulated distance for each subject individually.

Table 2

Results op the resampling procedure of Heleen and Lisa respectively

	Heleen	Lisa
Average	1.125	0.809
Minimum	0.293	0.188
Maximum	2.115	1.503
Perc 0.025	0.551	0.465
Perc 0.975	1.726	1.256
StDev	0.298	0.206
p value	.004	.260

Table 2 shows the results of the resampling procedure of Lisa and Heleen. Here, we see that for Heleen, the resulting p-value was .004, which means that in a small percentage (almost 0,4%) of all simulations, the random model was able to reproduce the peaks in the order of magnitude of those of the observed data. Therefore, the peak we have observed previously in the line graph of Heleen is not likely the result of coincidental fluctuations. However, for Lisa, the random model was easily able to produce peaks such as were observed (in 26% of all simulations). This indicates that for her, the outliers are difficult to distinguish from fluctuations on top of a continuous model.

3.5. Exploring interactions between variables

A further step into analyzing patterns of variability is to look for interactions between the target variables and other relevant variables. According to the dynamic systems perspective, complex

systems consist of many elements that interact during the course of development. These interactions can be different; while some variables have a supportive relation, others are competitive, conditional or neutral. Often, the elements interact in such a way that temporarily stable states selforganize out of the repeated and reciprocal interactions (Lewis, Lamey and Douglas, 1999). All possible combinations of states can be perceived as a 'state space'. The relatively stable states that emerge are also called 'attractors' in the state space. These attractors consequently form the constraints that limit and drive development.
A first impression of the interaction between ordinal variables (such as strategy use) can be obtained by means of a State Space Grid[3] (SSG, Lewis, Douglas & Lamey, 1999). In a SSG, the data are presented topographically on two (or more) dimensions, representing the different variables. Describing the data in an SSG is a very important first step to visually inspect the way your data 'behave' across time. In the grid presented below (figure 4), each data point (dot) represents the classification of one utterance with regard to two dimensions; the lines connect the consecutive dots.

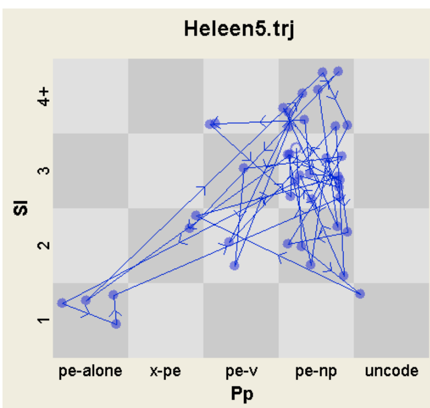

Figure 4. Example of a State Space Grid of the two dimension grammatical strategy of the PP (horizontally) and sentence length (SL, vertically).

In this example, the dimensions (which are the variables) are: the grammatical construction (horizontally), and the number of words in that utterance (vertically)[4] These variables can have the following states; for 'grammatical construction', the options are the different strategies of preposition use (PE-alone, X-PE, PE-V, PE-NP and uncodable), and for 'sentence length', the options are either one- two- three- and more-word utterances. The lines connecting the dots represent the sequence of the utterances within a session. Visual inspection of the resulting

[3] State Space Grids can be constructed by means of the program Gridware (Lamey, Hollenstein, Lewis, & Granic, 2004).
[4] It should be noted that one word utterances are also by definition connected to the PE-alone strategy, since in a one-word utterance contains only one word. The other possibilities (2 and more word sentences and all other strategies) can – by definition- occur in all combinations. The distribution in which they actually occur is, however, an empirical question that is addressed in the grids that are presented.

graph gives a quick and simple impression of how the variables interact with each other, and how these interactions change across time.
In the following, the SSG will be applied to the case study on grammatical strategies in the two children. With regard to the interactions between variables, it might be speculated that there is a meaningful interaction between the grammatical prepositions and sentence length. From the literature we know that -at this age- there is a relation between average sentence length (MLU) and grammatical complexity (Thordardottir & Weismer, 1998). It is argued that children's utterances are short because their utterances reflect their rules (e.g. Brown, 1973, Valian, 1986) and at this stage these rules are relatively simple. On the other hand, longer sentences are a necessary condition for the emergence of grammatical strategies. In the case of the use of the target prepositional phrases strategy, the occurrence of two word sentences might function as a prerequisite for grammaticality to emerge. However, when sentences grow somewhat longer, the relation between the two dimensions may change in the sense that the target strategy competes with the other possible strategies, because the number of words in each sentence is still very limited. However, when utterance length finally increases to above 4 words, the relation between sentence length and grammatical prepositional phrases may again turn into a supportive one, because utterances of this length offer the possibility of realizing more of the linguistic elements. It is important to stress that our expectations are highly speculative. There is some evidence that children with MLUs of 3 and above are able to use correctly ordered and grammatical prepositional phrases, whereas below 3, this is not always the case (Valian, 1986; Howe, 1981). However, the micro-interactions (which are the interaction between these variables from utterance to utterance) between sentence length and grammaticality of prepositional phrases, are still unexplored.

For the simplicity of this illustration, we have used the data of six sessions (and not all 25), two months apart from each other. Based on the hypothesis that variability is characteristic of a developmental transition, we expect the following: a relatively stable period with a-grammatical preposition use, through a period of relative variability, to a new stable phase of grammatical preposition use.
Visual inspection of the SSGs of Heleen across time leads to the following observations. In the first session, all prepositions are non-grammatical (consist of only a prepositional element) and are one word sentences. The second and third grid (two and 4 months later, respectively) show that there is some ‘movement’ across the state space. In the fourth and fifth grid (at 6 and 8 months after the first session) we see that the distribution is much more ‘scattered’, and data points occur across entire the grid. The fifth grid shows that many prepositional phrases are of the target strategy. The final grid is characterized by a highly organized distribution with virtually all observations in the cell that combines the target strategy with long sentences.

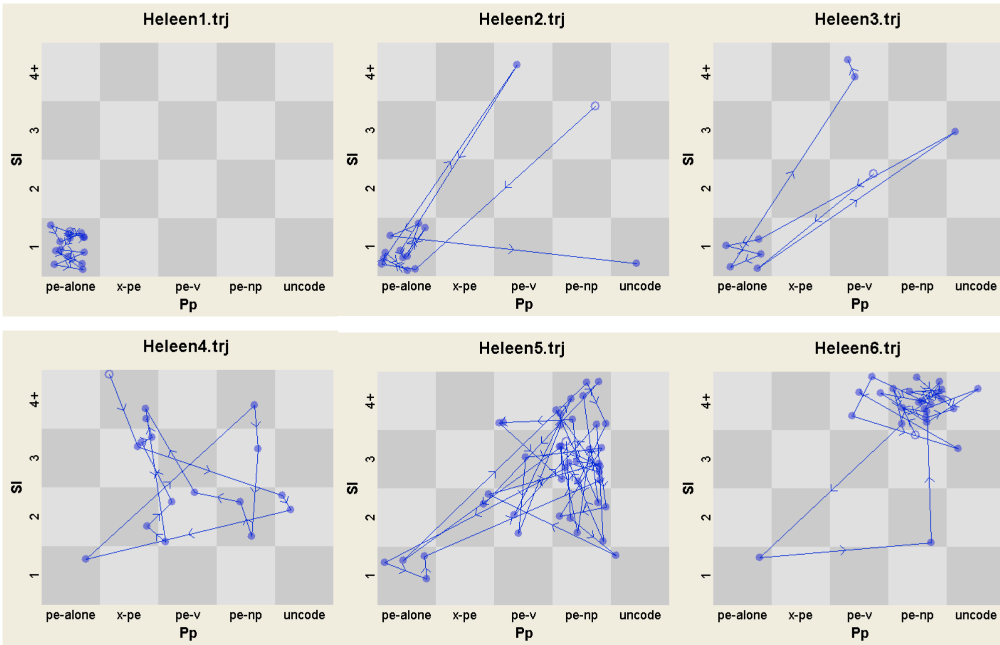

Figure 5. State Space Grids of the strategy of the prepositional phrase (horizontally) and sentence length (vertically) for the six sessions of Heleen.

The data of Lisa show a strikingly similar development (see figure 6). Here we also observe that there are relatively many observations in the one word sentences/prepositional element combination. These are followed by a much more ‘scattered’ distribution in the second, third and fourth grid. In the fifth grid Lisa produces many target constructions, and the distribution with regard to sentence length is also more confined. The final grid shows a fairly organized distribution with again almost all observations in the cell that combines the target strategy with long sentences.

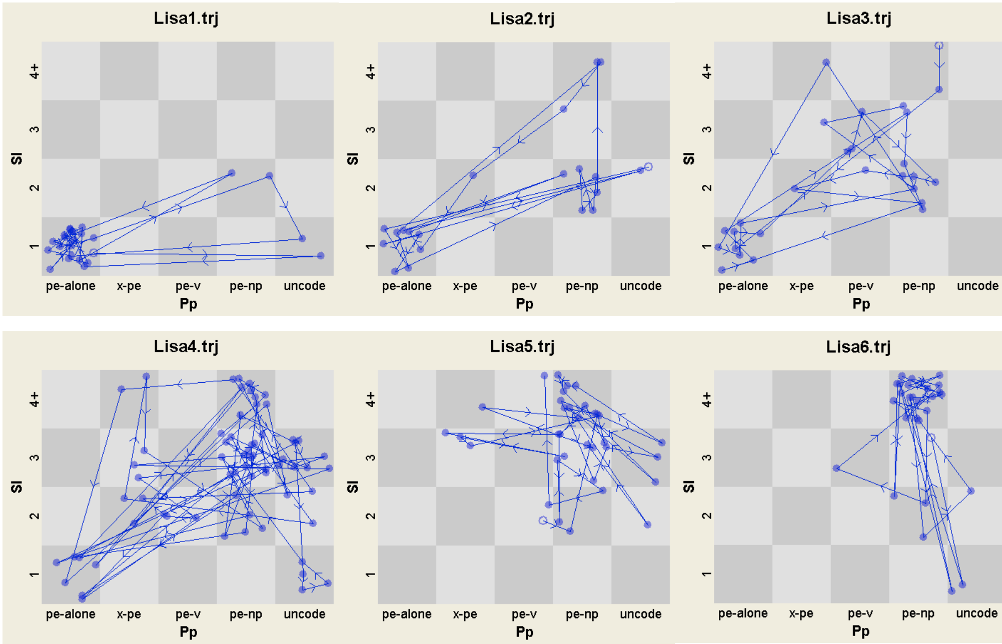

Figure 6. State Space Grids of the strategy of the prepositional phrase (horizontally) and sentence length (vertically) for the six sessions of Lisa.

So far, we have only visually inspected the way the variables seem to interact with each other, and seem to be 'attracted' to certain parts of the state space. The presence of these attractors can also be expressed in several measures, offered by the Gridware software. One of these measures is the *'dispersion'*, a measure of orderliness of the data, across the grid. This measure is calculated as the sum of the squared occasions in all cells corrected for the number of possible cells and inverted so that values range from 0 (no dispersion at all – all behavior in one cell) to 1 (maximum dispersion) (Hollenstein & Lewis, 2006).On the basis of the visual inspection we performed earlier, a classical inverted U-shape can be predicted. Initially, the dispersion is expected to be low, indicating organized behavior preceding a developmental transition. After the occurrence of two word sentences we expect an increase in this measure, referring to the degrees of freedom of the system during a developmental transition. In the final observations we predict to see a decrease in dispersion again, as the system 'settles' into a new relatively stable phase of relatively long target constructions.

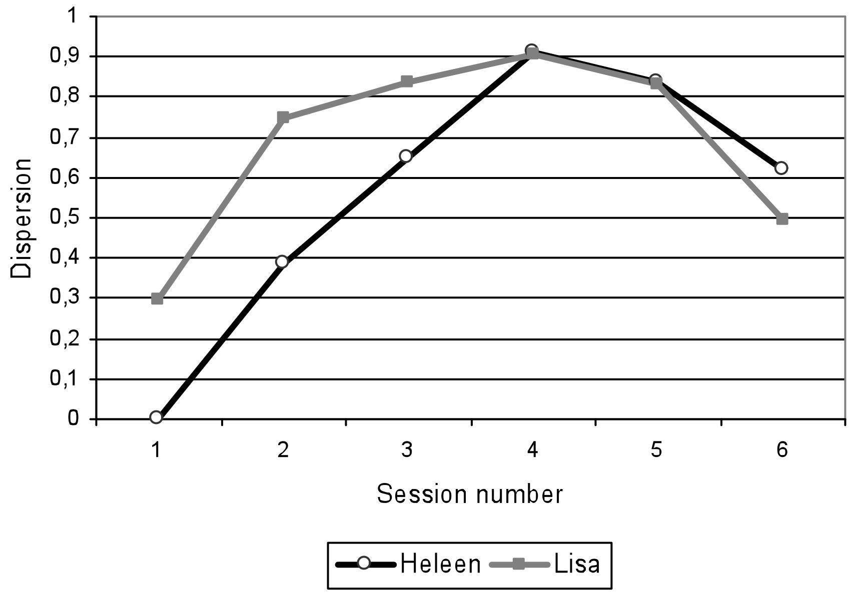

Figure 7. Dispersion across the grid of Heleen and Lisa across time.

Figure 7 shows the resulting dispersions of Heleen and Lisa for the six consecutive sessions as described in the grids. As can be observed, both children show the expected inverted U shaped change. Whereas initially the variability in the interaction between preposition strategy and sentence length is low, this variability first increases and finally decreases again. This indicates that the interaction between these two variables seems to change across development. It should be marked that the SSG is a purely descriptive technique, but that the result can be tested using resampling techniques or other (parametric or non-parametric) tests.

4. Conclusion and discussion

In this paper, a number of simple techniques were demonstrated that are aimed at describing intra-individual variability and the way it changes across development. In analyzing the emergence of new competencies, the starting point of any study should be the visual inspection and the interpretation of individual trajectories of the data. Important questions are: which variables are most frequent and which are less, what are their respective shapes of change, etcetera. This way, a first general impression of the development can be obtained and hypotheses can be generated that can be addressed in consecutive steps. Dependent on the data and theoretical background of the study, these can be directed at the diversity of strategy use, patterns of variability, interactions between variables, etc. In this paper, we have provided several suggestions of techniques that can be used to answer questions such as formulated above. It is important to note that any of these techniques can be used dependent on the specific research questions of the study at hand. However, a thorough description of the real (un-'corrected') developmental trajectories is always a prerequisite for further analysis. It is important to stress the fact that any of the described techniques should start with a thorough description of the data.

The first suggestion we have given addresses a way of quantifying diversity in strategy use. We have shown how the chi-square can be used to explore variability in the relative frequency of strategies compared to what is expected in an equal distribution (that is, each strategy is used in the same frequency). Many studies on cognitive development deal with this concept of strategy diversity. Miller (2002) suggested that transition points correspond with moments during which children are most sensitive to instruction. We have shown that the chi-square can be used as a measure in identifying such moments.

A second possibility is to show variability in a developmental trajectory by means of a moving min-max graph. Here, the observed score is presented in combination with the score range of the corresponding time window. This method is especially useful for obtaining a general impression of the variability pattern. Questions can be addressed such as whether this pattern is generally increasing or decreasing; whether there are changes in the score range, etcetera.

Although most techniques we have described aim at describing variability, we have also illustrated a specific application of a resampling procedure to test a variability-centered hypothesis. We have used such a procedure to demonstrate the identification of 'significant' peaks, performance outbursts which are meaningful indicators of rapid development. Obviously, these analyses are suited to test additional assumptions and null-hypotheses. Essential to this approach is a carefully formulated resampling model adapted to each data set and research question.

As a final possibility, we have shown the use of a simple descriptive technique to explore interactions between variables. Here, we have seen that the SSG offers powerful tools to identify regions of attraction. The measures resulting from this technique can consequently be used in further testing procedures. Here, we refer to the possibilities of employing agent based models for explicating the interaction between variables across time. See for instance Steenbeek and van Geert (2007) for an example of such an approach.

In our case study, the application of the proposed techniques leads to the following synthesis of findings on the development of the use of prepositions in the two children. First of all, the line graphs have shown that in both children, the development of the use of prepositions can be interpreted in terms of three consecutive stages. Initially the most elementary strategy is dominant, then there is a decrease in the use of this strategy accompanied by the increased use of the target strategy, and finally there is a dominant use of the target grammatical strategy. What

we have also seen is that the target grammatical strategy seems to compete with the ungrammatical strategies; once the target grammatical strategy starts to increase, the others remain low in frequency. Secondly, the SSGs have confirmed a possible interaction between strategy use and sentence length in both children. While initially, the relation between strategy use and sentence length is ‘fixed’ to one word utterances and the use of only prepositional elements, this relation changes into an almost random relation as sentence length increases, possibly because the number of words in each sentence is still very limited. However, when utterance length finally increases to above 4 words, the relation between sentence length and grammatical prepositional phrases again turn into a supportive one, probably because longer utterances offer more linguistic possibilities.
With the use of the other techniques, we have also discovered clear individual differences. More specifically, for Lisa, we have discovered (by means of the resampling procedure) that there is a fairly gradual emergence of the target grammatical strategy without statistically significant peaks, while for Heleen we have found a much more abrupt bulb in the pattern of variability, probably caused by a statistically significant peak of the use of the target strategy. Secondly, the chi-square measure has remarked a second clear difference which is that for Lisa, there seems to be a clear transition point with regard to strategy diversity, while for Heleen, the existence of such a relation between target strategy use and variation was much less clear. Thus, although there are clear similarities between the development of grammatical preposition use in two children, there are also remarkable differences that point at the existence of different styles of acquisition. These findings give rise to further research question that are worthwhile to investigate in future studies.

As a final remark, the techniques introduced are also appropriate for exploring variability in cross-sectional data. For instance, the min-max graph can be used to describe the changing competencies of age ranges, and the resampling procedure can be used to mark an extreme ‘outlier’ in a group. Also, the SSG is highly suitable for describing patterns in ordinal inter-individual data. The interpretation of the findings then applies to differences between individuals instead of within. However, when studying development, the primary focus should be on studying change within individual patterns. In our opinion such an approach is essential when describing the process of emergence of new cognitive abilities. In this paper, we have suggested techniques that are useful for analyzing variability, but are by no means exhaustive. With the demonstration of these possibilities we hope to have encouraged researchers to take a more exploratory approach to variability in their data and to develop methods directed at analyzing dynamic aspects of change.

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