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Foreign language learning as a complex dynamic process: A microgenetic case study of a Chinese child's English learning trajectory

He Sun [a,*], Rasmus Steinkrauss [b], Steffie van der Steen [c], Ralf Cox [d,**], Kees de Bot [b]

[a] The Education and Cognitive Development Lab, National Institute of Education, Nanyang Technological University, Singapore
[b] Department of Applied Linguistics, University of Groningen (RUG), Oude Kijk in't Jatstraat 26, 9712 EK Groningen, The Netherlands
[c] Department of Orthopedagogy, University of Groningen (RUG), Grote Rozenstraat 38, 9712 TJ Groningen, The Netherlands
[d] Department of Developmental Psychology, University of Groningen (RUG), Grote Kruisstraat 2/1, 9712 TS Groningen, The Netherlands

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ABSTRACT

The current study focuses on one child's (male, 3 years old) learning behaviors in an English as a Foreign Language classroom, and explores the coordination and developmental patterns of his nonverbal (gestures and body language) and verbal (verbal repetition and verbal responses) learning behaviors over time. Guided by the principles of the theory of Complex Dynamical Systems, the child's learning behaviors were analyzed over the course of four months, using (Cross) Recurrence Quantification Analysis and Monte Carlo permutation tests. The results show that the coordination between the child's nonverbal and verbal behaviors exhibited a rigid pattern at the beginning but got loosened over time, allowing the child to respond more flexibly to the teachers' instructions and to alternate more freely between his verbal and nonverbal learning behaviors. When focusing on the child's verbal learning behaviors only, we found that patterns of the verbal responses seemed to be more predictable than those of verbal repetitions, which suggests the varied influence of internal and external factors on these verbal learning behaviors.

1. Introduction

In recent years, we have seen a substantial increase in the number of very young foreign language (FL) learners worldwide (Nikolov & Mihaljevic Djigunovic, 2011). These children, who are in their early childhood (2–7 years old as defined by Philp, Oliver, & Mackey, 2008; 3–6 years old as defined by Nikolov & Mihaljevic Djigunovic, 2011), receive FL instruction at bilingual schools or at private language institutes. In China, for example, 210 million children are taking English courses in >50.000 private English institutes (Li, 2013). Research on this growing number of young learners and the development of their language skills is, however, still rare (Zhou & McBride-Chang, 2009).

Young FL learners' initial classroom experiences could have a lasting effect on their learning motivation and outcomes on the long term (Nikolov, 2001), and the development of their learning behaviors therefore deserves special attention. Studying the development of a child's learning behaviors is not an easy task, as these behaviors vary from moment to moment in complex interactions with the child's (proximal) environment (cf. Van Geert & Van Dijk, 2002). The most common way of analyzing the development (of e.g., language skills) is, therefore, to average the measurements taken from groups of children. This, however, comes at a cost. By definition, the average learning trajectory does not apply to the individual learner (cf. Molenaar, 2008), because development is a real-time idiosyncratic process (Molenaar, 2013; Molenaar & Campbell, 2009; Van Geert & Steenbeek, 2005) driven by bidirectional interactions with the environment. This is why researchers from the paradigm of Complex Dynamical Systems (CDS) have developed and used (non-linear) time series techniques to study developmental phenomena and the person-environment interactions from which they emerge (e.g., Cheshire, Muldoon, Francis, Lewis, & Ball, 2007; Cox & Van Dijk, 2013; Thelen & Smith, 1994; Van Geert, 1994; Van Geert & Steenbeek, 2005).

From a CDS perspective, development can be seen as a self-organizing process, in which the state of a system (for example, the child's language system) is shaped by multiple interactions (e.g., other children in class, the teacher, the child's motivation). Over time, the behavior of a system may evolve from fluctuating and unstable toward more adaptive stable behavioral states (i.e., attractor states) (e.g., Thelen & Smith, 1994). The term self-organizing process refers to a series of patterns that emerge from the successive interaction of all the subcomponents

* Corresponding author.
** Correspondence to: R. Cox, Faculty of Behavioral and Social Sciences, Developmental Psychology, Grote Kruisstraat 2/1, 9712 TS Groningen, The Netherlands.
E-mail addresses: he.sun@nie.edu.sg (H. Sun), r.g.a.steinkrauss@rug.nl (R. Steinkrauss), s.van.der.steen@rug.nl (S. van der Steen), r.f.a.cox@rug.nl (R. Cox), c.l.j.de.bot@rug.nl (K. de Bot).

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of a developing system at every level, characterized by fluctuation (i.e., variability) and stability. Before moving into a new stable state, the system usually demonstrates variable behaviors, making variability an indication of developmental change.

Despite the growing number of CDS techniques available, they have not yet been applied to early FL learning. The current paper therefore focuses on one three-year-old Chinese child during his first half year of English learning in a private language institute. The relationship between his verbal and nonverbal learning behaviors, as well as the developmental patterns of his verbal behaviors are explored in the context of an early childhood FL learning program. A (Cross) Recurrence Quantification Analysis, a non-linear time series technique, is used to study the coordination between several learning behaviors over time, allowing us to obtain an in-depth understanding of the tangible patterns in the child's learning behaviors, as well as their couplings.

1.1. Early stages of very young children's foreign language development

Sun, de Bot, and Steinkrauss (2015) followed a group of very young English as a Foreign Language (EFL) learners (three years old) for their initial five months of learning English, and found three general stages. During the first stage (the first two months), most children kept silent and relied on body language to respond to their teachers' instructions. During the second stage (the third month), the frequency of using English repetitions surpassed the frequency of using body language. Children repeated single words and formulaic language after their teachers as they became familiar with English pronunciation and the learning environment. In the third stage (in the fourth and fifth month), the average use of English responses and mixed use of English and Chinese grew steadily. In this stage, children tended to use single words or simple phrases to initiate or answer questions, and expressed themselves with more confidence and ease in English. At the same time, they seemed to be more aware of their limitations in English, and used more Chinese to express their thoughts as well.

It is worth noting that although the authors named the stages according to their most distinctive behaviors (in terms of frequency) that occurred, all of these behaviors occurred at each stage (cf. Siegler, 2000). For instance, English repetition was seen throughout these five months, only reaching its peak in the third month. It's also worthy of attention that body language plays an important role in children's language development. Children often combine gestures and speech during the early stages of first language production, several months before they produce combinations of words (Goldin-Meadow, 2015). One reason for this might be that when children have a restricted vocabulary, body language offers them "a way to extend their communicative range" (p. 2). Children's body language indicates that they are ready to learn new words, allowing adults to read their intentions clearly and to provide finely tuned language support in time (Goldin-Meadow, Goodrich, Sauer, & Iverson, 2007; Vygotsky, 1986). Therefore, body language bestows children great flexibility for meaning delivery and better adaptation to different learning environments.

Researchers such as Goldin-Meadow (2015) view body language and speech as an integrated synergestic system, since they share some underlying cognitive components, such as memory and attention (Wijnants, Cox, Hasselman, Bosman & Van Orden, 2012). During communication, there is a synchronization between body language and speech (McNeill, 1992), reflecting the self-organization of these shared cognitive mechanisms. If communication goes smoothly, this synchronization should be quite stable, and we could characterize this as an attractor state. However, if a person is exposed to a new or challenging context, such as a foreign language learning environment, the synchronization between gestures and verbal behavior could be greatly affected, forcing the synergy of verbal and nonverbal behaviors into great fluctuation.

Not only the relationship between verbal and nonverbal learning behaviors deserves our attention, but also the development of different categories of verbal learning behaviors, which serve an important function in early EFL language development. Verbal repetition, for example, is one of the most pervasive behaviors during the initial period of early EFL learning (Duff, 2000; Bennett-Kastor, 1994). From a cognitive and linguistic perspective, verbal repetition helps young EFL learners to memorize, recite and decompose the new language at their own speed, and to gradually integrate the information into their linguistic repertoire (Duff, 2000; Rydland & Aukrust, 2005). From a socio-cultural perspective, verbal repetition indicates that something is internalized by the learner, allowing for social, intellectual and discursive cohesion during interactions (Duff, 2000; Cekaite & Aronsson, 2004).

1.2. Complex dynamical systems in EFL learning

In sum, both verbal and nonverbal learning behaviors are crucial for a child's early language learning (Goldin-Meadow, 2014, 2015). Previous studies, such as the one conducted by Sun et al. (2014), propose a general outline of children's initial EFL learning behaviors. However, it remains unclear how these behaviors evolve over time and how they interact with each other. Studying these interactions from a CDS perspective would extend our knowledge on the mechanisms of EFL learning that goes beyond these stage descriptions. This requires the use of microanalyses, allowing researchers to examine these behaviors for individual children in detail, and from moment to moment (Wallbott, 2003). Ultimately, combining this idiographic micro-approach with more general, nomothetic models of L2 language development allows researchers to construct models that are applicable to the individual level (cf. Nesselroade, 2001).

The theory of Complex Dynamical Systems (CDS) provides us with the theoretical framework and methods to analyze micro processes. It has not widely caught the attention of researchers of second language acquisition until recent years (e.g., de Bot, 2008; Larsen-Freeman, 2007; De Bot, Lowie, Thorne, & Verspoor, 2013). From a CDS perspective, EFL development should be considered an open system, consisting of a series of subsystems (e.g., different learning behaviors) undergoing continuous, as well as abrupt changes over time due to internal and external constraints (de Bot & Larsen-Freeman, 2011; Larsen-Freeman, 2007; Larsen-Freeman & Cameron, 2008). CDS assumes that an open dynamic language system has nine basic characteristics, including a dependence on initial conditions, complete interconnectedness, non-linearity, internal reorganization and environment interaction, internal and external resources, attractor states, iteration, variation and emergent properties (for details, see de Bot & Larsen-Freeman, 2011).

When introducing CDS to EFL studies, the research focus shifts. Instead of asking research questions that center around a unidirectional (linear) causal relationship between variables, the interconnectedness and non-linear development of different learning components are the central focus. CDS emphasizes the changes within a system over time, driven by the interactions between the system's internal process of self-organization and the external environment (cf. Vallacher, Van Geert, & Nowak, 2015). These interactions result in individual non-ergodic processes of change (Molenaar, 2013; Molenaar & Campbell, 2009). The term 'internal process' refers to dynamic (i.e. changing) variables within the learning individual, such as learning capacity and adaptability. The external environmental resources refer to dynamic variables outside the learner, such as EFL input of the teacher, in terms of both quantity and quality (De Bot & Larsen-Freeman, 2011). Under the realm of CDS, analytical approaches could inform us about the recurrence of certain behavioral states from the time series, revealing the stability and variability of the system. This goes beyond the power of a linear analysis, because we can assess non-stationary and non-linear development in a complicated situation, such as early EFL development.

1.3. (Cross) Recurrence Quantification Analysis

Combining the previous discussion on EFL learning with the CDS principles introduced above, we can deduce that a child's initial EFL learning emerges from the child's bi-directional interactions with his/her learning environment. In the current study, we specifically focus on verbal (verbal repetitions and responses) and nonverbal learning behaviors (nonverbal repetitions and responses) that can be observed in the EFL classroom. Together, these behaviors represent the interactive learning repertoire of a young child in this learning environment. Importantly, from a CDS perspective, these learning behaviors are continuously active (to varying extents) and mutually constraining. As a result of a child's altering language competence and constant mutual adaptation to the instructional setting, the dynamic balance (i.e. coordination) within and between the verbal and nonverbal learning behaviors changes. This changing balance is reflected by observable differences in the patterns of learning behaviors over time. This study particularly focuses on the coordination of these learning behaviors, their development (within a single child), and their relation to the instructional setting. In other words, we focus on the temporal patterns of the child's learning behaviors, to understand the dynamics of early EFL learning.

A useful method to detect differences in the temporal patterns of learning behaviors over time is RQA, "a particular type of non-linear time series analysis based on the registration of whether a system's state at each and every point during an observation recurs, that is, repeatedly occurs" (Reuzel et al., 2013, p. 288). It has been widely used in physiology and life sciences, and has been introduced to developmental psychology and children's language learning in recent years (e.g., Cox & van Dijk, 2013; De Graag, Cox, Hasselman, Jansen, & de Weerth, 2012; Dale & Spivey, 2006; Wijnants, Hasselman, Cox, Bosman, & Van Orden, 2012). The advantage of RQA is that it offers valuable and unique information about the behavior of complex dynamical systems. Recurrent behavioral states, and especially their stability, regularity and flexibility form an important property of dynamic systems. By using RQA, measures of interest in a dynamic analysis of the behavior of a system, such as stability, regularity, and complexity can be retrieved. In the current study, RQA has been adopted to investigate the developmental patterns of different verbal behaviors (i.e., verbal repetition and verbal response). For more details about this approach, see Marwan, Romano, Thiel, and Kurths (2007), see also Cox, Van der Steen, De Jonge-Hoekstra, Guevara, and Van Dijk (2016).

Cross recurrence quantification analysis (CRQA) is an approach based on RQA, which is used to assess the attunement of *two* interacting systems (Shockley, Butwill, Zbilut, & Webber, 2002). This approach has proven to be effective in the study of the coordination (i.e. shared dynamics) of verbal and nonverbal behavior in dyadic interactions, e.g., during a conversation (Reuzel et al., 2013, 2014). In such cases, recurrence reflects that the behavioral state of one system (e.g., activation of the verbal response subsystem) is matched by the other system (e.g., activation of the nonverbal response subsystem) across all possible timescales, from the sample rate to the duration of the observation. That is, these matches are not only detected if they occur at the same time, but also earlier or later in time (for more details on this approach, see Dale & Spivey, 2006 and Reuzel et al., 2013, 2014). In the current study, CRQA has been used to explore the coordination of verbal and nonverbal learning behaviors.

To elaborate, in the case of a CRQA on the verbal and nonverbal behavioral time series, all instances of matches between verbal and nonverbal behaviors are registered as black dots in a two-dimensional grid, called the recurrence plot (see Fig. 1). In our study, a black dot in a CRQA recurrence plot shows how one of the verbal learning behaviors of the child at some point in time is matched with a nonverbal learning behavior at the same, or any other point in time during the observation. The recurrence plot therefore informs us about the temporal attunement of these verbal and nonverbal learning behaviors across all possible time scales within a session. Changes in the patterns, as they appear in the recurrence plots across the sessions, provide information about the changing dynamics of the verbal and nonverbal learning behaviors.

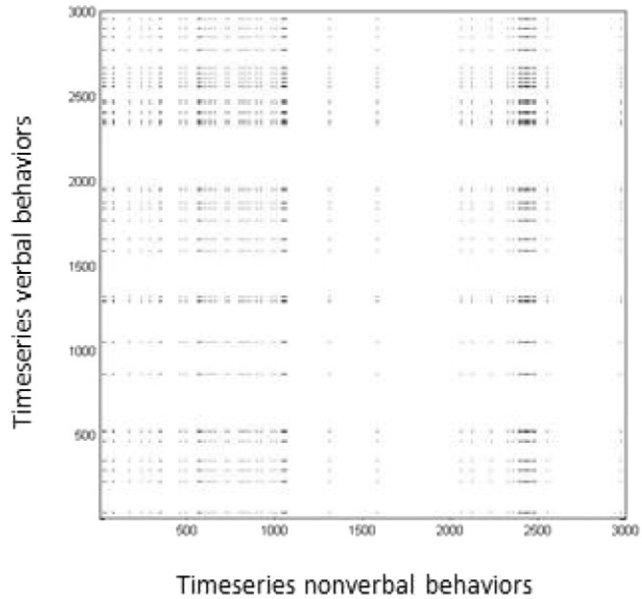

Fig. 1. An example of a CRQA recurrence plot. A black dot in the plot represents an instance where a nonverbal behavior matches a verbal behavior.

In the case of the *RQA* on the verbal behavioral time series, the recurrence plot informs us about the patterns of only the verbal learning behaviors (verbal repetitions and verbal responses) during a session. For verbal repetition, as an example, the black dots in the recurrence plot would represent how repetition is used repeatedly during a session, with (possibly) some delay between their occurrences.

Table 1
Explanations of the (Cross) Recurrence Analysis measures.

Measure	Description
Recurrence Rate (RR)	RR is the *proportion of recurrent (i.e. matching) points in the recurrence plot*. Values can range from 0 (a completely empty recurrence plot) to 1 (completely filled). RR reflects to what extent the behaviors of the nonverbal system are matched by the behaviors of the verbal system (CRQA), or to what extent the behaviors of the verbal system are matched by the same system (RQA), at each point during the observation.
Laminarity (LAM)	LAM is defined as *the proportion (ranging from 0 to 1) of recurrent points that form vertical line structures* in the recurrence plot (i.e. a pattern of two adjacent black dots or more). LAM reveals the extent to which learning behaviors are 'trapped' into expressing a single specific level repeatedly for some time. In these instances the same state is repeated consecutively (point attractor state).
Trapping Time (TT)	TT is calculated as *the average length of all vertical lines* in the recurrence plot, measured in units of time (here 0.5 s). TT expresses the average duration of trapped learning behaviors, in other words, the mean time that a system will stay in a specific point attractor state, reflecting the rigidity of the system.
Maximal Length of the Vertical Lines (MaxVL)	MaxVL is *the length of the longest vertical line* in the recurrence plot, measured in units of time (here 0.5 s). MaxVL provides the maximal duration of 'entrapment' in a point attractor state. A MaxVL of 20 means a 10-s duration of the longest period within this attractor state.

(C)RQA is essentially a method to quantify the patterns that are present in the recurrence plot (see Fig. 1). Several measures can be derived from the basic recurrences (i.e. black dots in the plots), which quantify the dynamic organization of the system under study. These measures can reveal the global structural patterns in the learning behaviors, and the dynamic relationship between the learning behaviors. In this case, “global” refers to “general quantitative measures, with minimal dependence on statistical assumptions” (Dale & Spivey, 2006, p. 394). The measures that are relevant to the current study are explained in Table 1. LAM reflects how much of the recurrence plot consists of vertical line structures, also called ‘laminar states’, whereas TT and MaxVL reflect the average and maximal duration of these structures, respectively, indicating behavioral regularity and rigidity (Cox & Van Dijk, 2013; De Graag et al., 2012). More specifically, LAM (Laminarity) reveals the extent to which learning behaviors are trapped into expressing a single specific level, repeatedly, for some time, (usually) with varying duration. TT (Trapping Time) expresses, in units of time (0.5 s), the average duration of such ‘trapped’ learning behaviors. MaxVL (Maximal Vertical Line) measures the duration of the longest of such expressions (in units of 0.5 s). If TT and MaxVL are high, it indicates stronger attraction of laminar states in the system. In the current study, the CRQA measures LAM, TT and MaxVL inform about the rigidity of the coordination between the verbal and nonverbal learning behaviors, while the corresponding RQA measures are used to explore the regularity of the verbal learning behaviors repetition and verbal response.

1.4. Research questions and hypotheses

This study follows one three-year-old male Chinese EFL learner during his first months of English language learning. The in-class interactions between the child and the teacher were coded in monthly intervals at 4 measurement times (Month 2–Month 5), resulting in a time series of these interactions. Two research questions have been formulated.

1) How can we characterize the coordination between the boy's nonverbal learning behaviors (gestures and body language) and verbal learning behaviors (repetition and verbal response), and how does this coordination change over time? We expect that the coordination between the child's nonverbal and verbal behaviors gets more flexible over time, because the boy's gradual adaptation to the English learning environment allows him to flexibly shift between learning behaviors. To answer this question, we performed a CRQA analysis on the verbal and nonverbal learning behaviors. If the values of LAM, TT, and MaxVL decrease over time, this would indicate that the coupled dynamics of the verbal and nonverbal learning behaviors (i.e. their coordination) becomes less rigid over time.

2) How do the verbal learning behaviors (verbal repetition and verbal response) develop over time, and do we see a difference in their rigidity (or flexibility) over time? We expect that the pattern of verbal repetition is less rigid than that of verbal response, because the former might be more influenced by other interlocutors (teachers in particular), and the latter might be more influenced by the child's own language competence. To verify this hypothesis, we performed a RQA analysis on the verbal learning behaviors repetition and verbal response. If this hypothesis can be confirmed, the values of RR, LAM, TT and MaxVL for repetition should be more fluctuated than those for verbal response, with less regularity over time.

2. Method

2.1. Participant information

A three-year-old boy, here called Jimmy, who had no formal English education before the current project, was followed during his first months of English learning in one of the largest English initiation schools in southeast China, targeting 3–12 years old EFL learners. The goal of this learning program is to increase students' interest in English, acquaint them with English pronunciation, and help them understand and produce simple English words and phrases. The Total Physical Response (TPR) method is used to ensure children's active participation in class (Asher, 1996). In TPR, physical movement is used to enhance the comprehension of verbal input, aiming at motivating students to participate in language activities and reducing their participation anxiety. This teaching method is widely used in child EFL learning settings (Pinter, 2009; Ortega Calle & Peña Ortega, 2011) and is believed to effectively promote meaningful interactions in the foreign language at early stage (Sun et al., 2014). Every child is required to visit the educational facility twice a week, for approximately 2 h in total, once for the main course taught by an American teacher and a Chinese teaching assistant together, and the other time for an activity class taught by the Chinese teaching assistant only. Due to unforeseen circumstances, Jimmy's Chinese teaching assistant was replaced in Month 5.

The aim of the main course is to teach new words and songs, whereas the activity class is used to review what children learned in the preceding main course. The current study only used data from the main course, because these sessions are similar in content and duration. Each of these 35-minute sessions starts with a greeting, and then a video of a song or a mini-dialogue displayed on an interactive whiteboard. After watching the video, children are asked to stand up to sing and dance, mimicking their teachers and using gestures. This is followed by the introduction of new words with pictures, props or body language. Subsequently, these words are practiced in songs and games. The words and phrases that are taught can be described as “child-friendly”, depicting colors, numbers and greetings.

2.2. Data collection and coding

Before launching the project in class, Jimmy's parents were asked for consent and to fill out a questionnaire about Jimmy's background, such as his age and English learning history. To confirm that Jimmy knew little English, he was tested with 20 simple words from the MacArthur-Bates Communicative Development Inventories (MCDI; Fenson, Marchman, Thal, Dale, & Bates, 2007). The 20 words were selected after consulting the teachers, making sure these words are taught early during children's English education. Ten words were used to measure his production[1] of English, and ten to measure his comprehension.[2] After seeing a picture, Jimmy was expected to verbalize the depicted image in English, or to choose a target word from four images. The results of the inventory showed that he could comprehend one word and produce none before the sessions started. Jimmy was then videotaped in class for 20 weeks from September 2012 to January 2013. During these five months, all main course sessions were recorded, with some exceptions in the first month due to technical problems. Because Jimmy was present each second week of the first five months (except the first month), we selected these four sessions with balanced intervals for further analysis.

To explore Jimmy's English learning in class, his nonverbal and verbal learning behaviors, as well as other relevant actions (being silent, murmuring) were coded in two steps using the computer program MediaCoder (Bos & Steenbeek, 2007). The first step of the coding procedure was to determine the exact points in time when an utterance or nonverbal behavior started and ended (event sampling). The boundaries of the utterances were based on intonation contour and pause duration, and the boundaries of nonverbal behaviors were decided by focusing on changes in movement. The second step was to classify the utterances and nonverbal behaviors into several categories, as Table 2 demonstrates.

[1] Production words used: banana, fish, shoe, hand, table, ice-cream, dance, listen, read, write.

[2] Comprehension words used: book, pink, five, hair, cat, father, cherry, square, ice-cream, sofa.

Table 2
Explanations and examples of the categories.

Category	Sub-category	Description	Example
Nonverbal behaviors	Nonverbal repetition	Copies the teacher's action or gesture	**Teacher:** Run, run, run (says "run" while running). **Jimmy:** Runs, mimicking the teacher (no utterance).
	Nonverbal response	Comprehends the teacher's question by demonstrating it with an action	**Teacher:** Who wants to try? **Jimmy:** Raises his hand (no utterance).
Verbal behaviors	English repetition	Repeats (part of) the teacher's English utterance	**Teacher:** Sit down nicely. **Jimmy:** Sit nicely.
	English response (verbal response)	Uses English to answer the teacher's questions or requests	**Teacher:** Ok, what's this? **Jimmy:** Eraser.
	Mixed use of English and Chinese (verbal response)	Either uses Chinese only in the utterance, or code- switches between English and Chinese	**Teacher:** Red (demonstrates "red" with a picture). **Jimmy:** 老师,他没说 red ("Teacher, he didn't say red").
Other	Other	Keeps silent or acts/murmurs seemingly without learning purpose	

Note. The bold words indicate the speaker. Contextual information and utterance translations (when applicable) are in parentheses.

The percentage of inter-rater agreement (based on double-coding one video) was 81.3% ($p < 0.001$). The p-value was calculated by comparing this percentage to the inter-rater agreement based on chance. For this, the agreement between the observations of one observer and the shuffled observations of the other observer was repeatedly calculated (5000 times) using a Monte Carlo procedure (see below). The average agreement based on chance was 23.9% (SD 0.07).

2.3. Data analysis

The coding contained all information regarding the moment a learning behavior occurred, the duration of behaviors, and the time in between subsequent behaviors. For the purpose of applying recurrence procedures, the codes were transformed to a discrete-time sampling at a frequency of 2 Hz. The duration of most verbal and nonverbal behaviors was between half a second and one second. The sampling rate of 2 Hz can, therefore, adequately capture the dynamic nature of the learning behaviors, without overestimating relatively stable or noisy periods (cf. Van Der Steen, Steenbeek, Van Dijk, & Van Geert, 2014). The time series consisted of 4208, 3612, 3900 and 3881 data points for M2, M3, M4 and M5, respectively.

2.3.1. Linear analysis

The relative proportion of the frequency and duration of the verbal and nonverbal behaviors, and of the verbal repetitions and verbal responses were calculated (for example, the frequency of the verbal behaviors divided by the total frequency of behaviors; and the duration of the verbal behaviors divided by the total duration of the session). These measures provided us with a global overview of Jimmy's learning behaviors.

2.3.2. Recurrence analyses

To find the developmental patterns and coordination of different learning behaviors, recurrence quantification analysis (RQA) and cross recurrence quantification analysis (CRQA) were performed on the time series. A special-purpose MATLAB routine was used to perform CRQA and RQA on the time series of the verbal and nonverbal learning behaviors. For calculating the distribution of vertical line structures, the functions "dl" and "tt" from Marwan's (2009) CRP Toolbox were used, respectively.

In the results section we mostly focus on changes in the measures LAM, TT, and MaxVL. These indicate a change (increase or decrease) in the amount and length of vertical line structures (i.e. laminar states) in the recurrence plot (see Introduction Section). Laminar states correspond to repeated patterns of identical learning behaviors, of shorter and longer duration. When LAM is high, there are many laminar states. When TT and MaxVL are high, these laminar states are relatively long. Hence, a combination of high LAM, TT and MaxVL means that there are relatively extended periods where the learning behavior settles (or gets trapped) into a single specific state, which repeatedly occurs. Likewise, when these measures are low, this means there are less of such episodes where the system gets trapped into one kind of behavior.

2.3.3. Monte Carlo permutation tests

All MATLAB output was further analyzed using Monte Carlo (MC) permutation tests performed in Excel. Because the current study only focused on one child, MC is considered appropriate because it has no required minimal sample size and no underlying assumptions (Todman & Dugard, 2001; Van der Steen, 2014). Taking the data distribution into consideration, MC measures the probability that a difference (e.g., a decrease in verbal repetition from M2 to M5) is caused by chance.

To check whether the temporal patterns as quantified by the (C)RQA measures were significantly different from a random, unstructured and uncoupled pattern, the empirical time series were randomly redistributed. This means that each point in the measured time series received a randomly assigned new temporal location, which effectively destroyed any deterministic pattern present in the original data. Then the empirical data and the shuffled data of the (C)RQA were compared using MC, to check whether the patterns found in the (C)RQA were above chance level, and to confirm the developmental trend of the verbal learning behaviors and the trend of the coordination between the verbal and nonverbal learning behaviors. When the empirically found measures significantly differed from the shuffled measures ($p < 0.05$), the result was considered statistically significant. A summary of the analytical approaches is presented below (see Fig. 2).

3. 3. Results

3.1. The coordination between verbal and nonverbal behavior

3.1.1. Linear analysis

Fig. 3a and b show the relative distribution of the duration and frequency of the verbal and nonverbal behaviors from Month 2 to Month 5. Both graphs reveal that at the beginning Jimmy had more distinct instances of nonverbal behaviors (approximately 70%) than verbal behaviors (approximately 30%). However, as time goes by, the use of verbal behaviors surpassed the use of nonverbal behaviors in both frequency and total time. For instance, by Month 5, the verbal behaviors encompassed approximately 63% of the total duration of Jimmy's behaviors, and the nonverbal behaviors <37%. MC tests were used to examine whether the changes between two months were significant. In terms of the frequency of using verbal and nonverbal behaviors, only the changes between Month 2 and Month 3 were approaching significance (verbal: $p = 0.08$; nonverbal: $p = 0.06$). For the duration verbal

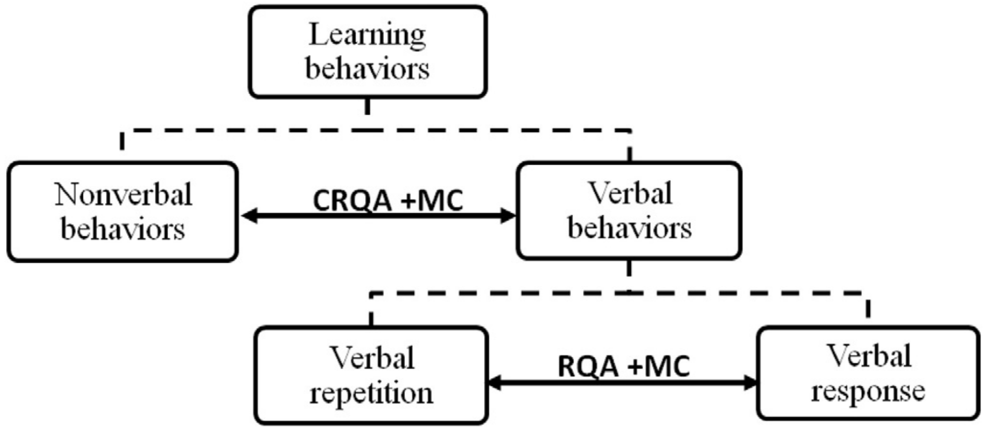

Fig. 2. Behavior categories in the current study and the analytical approaches.

and nonverbal behaviors, the changes between Month 2 and Month 5 were approaching significance (verbal: $p = 0.09$; nonverbal: $p = 0.09$).

3.1.2. CRQA on verbal and nonverbal behavior

Fig. 4a, b, c and d present the general pattern of the coordination of the verbal and nonverbal learning behaviors over time. The CRQA measures fluctuated throughout the four months with a decreasing trend. The first two months witnessed little change, however, from Month 3 to Month 4, a sharp decrease appeared, with declines in RR from 0.8% to 0.1%, LAM from 0.97 to 0.88, TT from 3.8 to 3.2, and MaxVL from 13 to 7. MC tests reveal that the decreases of LAM and TT are significant ($p < 0.001$) and that the decrease of RR is approaching significance ($p = 0.08$). This signifies that the degree of coordination between verbal and nonverbal behavior decreases (RR), and that the learning behaviors become less predictable, with fewer laminar states (LAM) in the recurrence plot. To be more specific, the learning patterns become somewhat more flexible (a decrease in TT), with a reduced tendency to remain in a similar behavioral state (attractor) for a longer period (a decrease in MaxVL). This signifies that Jimmy performs more flexibly over time, relying less on coupling body language and verbal production to deliver meaning. From the fourth to the fifth month, however, we see a somewhat unexpected increase in these measures. This could be due to the fact that the Chinese teaching assistant was replaced around that time, and this shift might have had an influence on Jimmy's learning.

To confirm the decrease of the laminar states and other trends found, the empirical data were compared to the shuffled data. Fig. 4a, b, c and d show that the values of LAM, TT and MaxVL were well above those of the shuffled (random) data, and hence, above the level of chance. MC tests confirmed that this difference between the shuffled and empirical data was significant ($p < 0.001$). The general decreasing tendency of the CRQA behaviors was also significant ($p < 0.001$), confirming the decrease in the coordination between the verbal and nonverbal behaviors. Overall, the results imply that Jimmy's EFL learning behaviors reorganize over the course of the study: The coupling of verbal and nonverbal behaviors becomes more flexible. When the learning environment is perturbed, viz., by the change of teacher, the coupling between his verbal and nonverbal learning behaviors seems to become more rigid, as reflected by the increases in the CRQA measures between Month 4 and 5. This latter increase, however, was not statistically significant.

3.2. The developmental patterns of verbal repetition and verbal response

3.2.1. Linear analysis

Fig. 5a and b present the relative proportion of using verbal repetition and verbal response by Jimmy over the four months (frequency and duration). The two graphs show that Jimmy used a similar amount of verbal repetition and verbal response in Month 2. However, verbal response was used consistently more (in terms of both frequency and duration) than verbal repetition throughout the remainder of the months, which is probably related to Jimmy's improved command of the English language over time (cf. Sun et al., 2014). MC tests were used to examine whether the changes between two months were significant. In terms of the frequency of using repetition and verbal response, the changes between Month 2 and Month 3 approached significance (repetition: $p = 0.08$; verbal response: $p = 0.08$). For the total time of using these two behaviors, the change between Month 2 and Month 5 is significant for repetition ($p < 0.01$) and approaching significance for verbal response ($p = 0.08$).

3.2.2. RQA on verbal repetition and verbal response

The developmental patterns and dynamics of verbal repetition and verbal response are derived from the RQA. The details for RR, LAM, TT and MaxVL are presented in Fig. 6a, b, c and d. Overall, only a few recurrent points were found. For repetition, LAM, TT and MaxVL all reveal different patterns. The laminar states of repetition decrease from Month 2

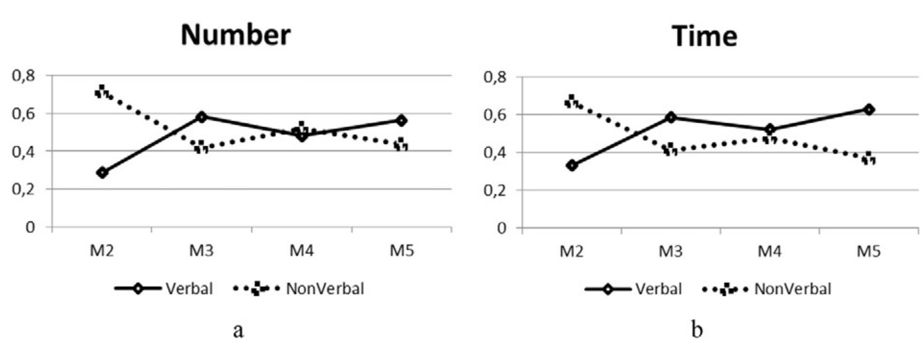

Fig. 3. a and b. Line graphs of Jimmy's use of verbal (solid lines) and nonverbal (dotted lines) behaviors. Panel a refers to the relative proportion of frequency (number of instances) and panel b refers to the relative proportion of duration (total time).

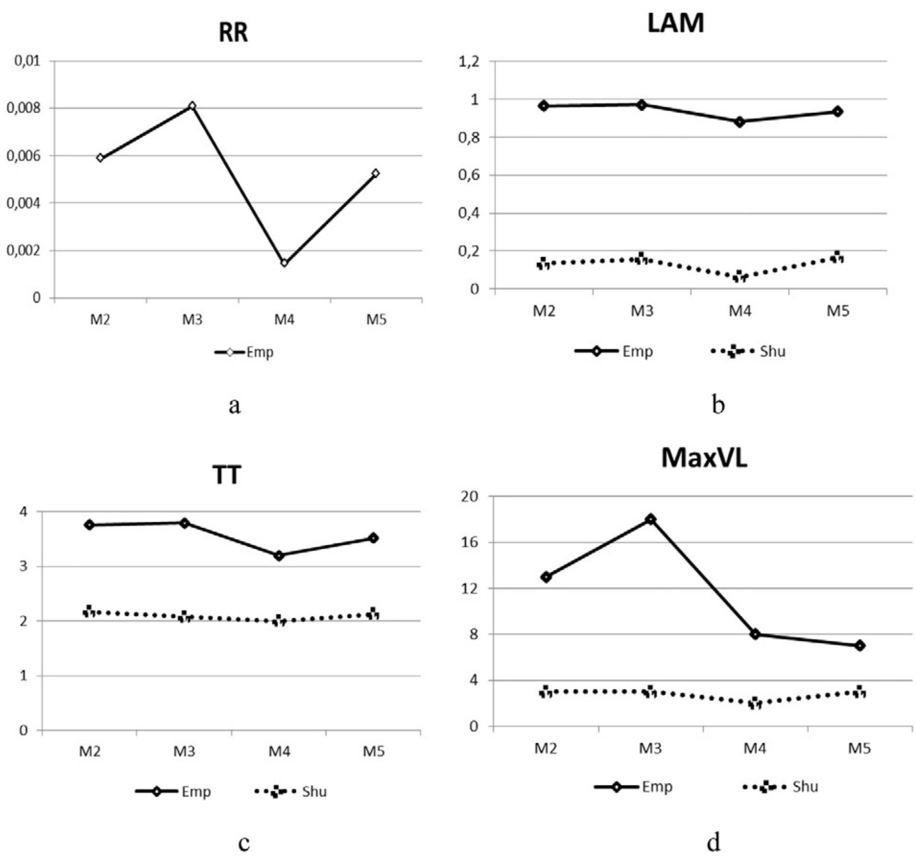

Fig. 4. a, b, c and d. Recurrence Rate (RR; panel a), Laminarity (LAM; panel b), Trapping Time (TT; panel c) and Maximum Vertical Line (MaxVL; panel d) for the coordination between Jimmy's verbal and nonverbal behaviors, as retrieved from the CRQA analysis. The solid lines refer to the empirical data and the dotted lines refer to the shuffled data.

to Month 4, reflecting a decrease in rigidity, that is, we see a decrease in *repeatedly* using verbal repetition in class. In Month 5, an increase is observed in LAM from 0.8 to 0.93, returning to the level reached in Month 2. TT fluctuates around a value of 3.3, with a maximum value of 4 and a minimum value of 2.5, indicating that the average duration of the laminar states is rather stable. MaxVL experiences a sharp increase at the beginning, but decreases in the following three months, implying a stronger reliance on English repetition at the beginning, but greater flexibility in its use over time.

In contrast, the patterns of verbal response, as indicated by its LAM, TT and MaxVL values are clearer. All measures show a non-linear decrease over time: LAM from 0.98 to 0.95, TT from 4.4 to 3.5 and MaxVL from 13 to 7. These results demonstrate a decrease in the amount of laminar states (decrease in LAM). The average duration of these laminar states decreases, indicating that patterns of using verbal response become more flexible (decrease in TT), with a reduced tendency to remain in a similar behavioral state (point attractor state) for a longer period of time (decrease in MaxVL). The results indicate that Jimmy becomes more flexible in producing English and Chinese in class.

MC tests demonstrate that the changes between Month 3 and 4 show some statistical significance. For repetition, the changes of RR and TT are significant ($p < 0.001$). For verbal response, the change of RR is significant ($p < 0.001$), and that of LAM is approaching significance ($p = 0.07$). Overall, verbal response appears to be more predictable than verbal repetition, with higher values of LAM and TT across time.

MC tests were also used to confirm the developmental trends of verbal repetition and verbal response found by the RQA. First, the values of the empirical data were well above the shuffled (randomized) data (the black line vs. the grey lines of graphs b, c and d in Fig. 6) and the differences were significant (for all tests, $p < 0.001$). This indicates that the patterns of verbal repetition and verbal response are different from a random, unstructured pattern.

In terms of the general developmental trend of verbal repetition, only the slope of MaxVL was found to significantly decrease

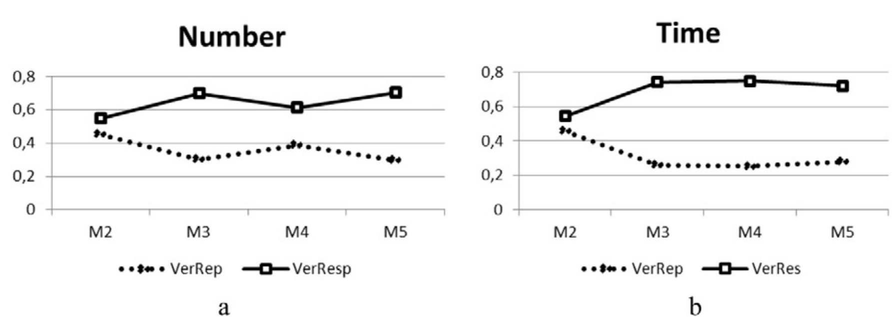

Fig. 5. a and b. Line graphs of Jimmy's use of verbal repetition (the dotted lines) and verbal response (the solid lines). The left graph (panel a) refers to the relative proportion of frequency (number of instances), and the right graph (panel b) refers to the relative proportion of the two categories in terms of duration.

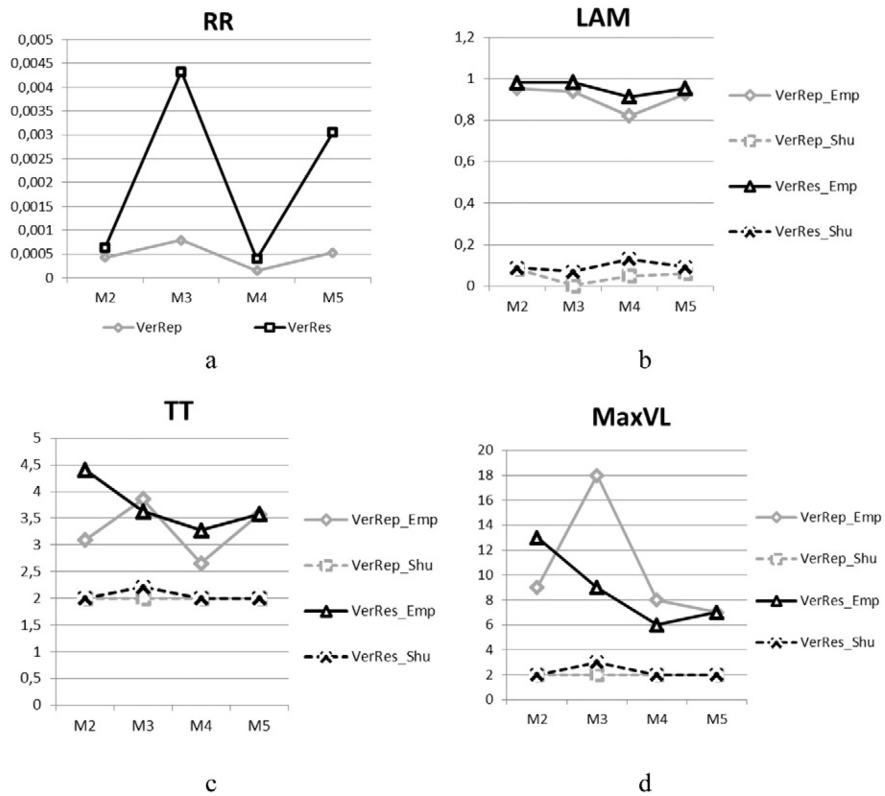

Fig. 6. a, b, c and d. Recurrence Rate (RR; panel a), Laminarity (LAM; panel b), Trapping Time (TT; panel c) and MaximumVertical Line (MaxVL; panel d) for the developmental pattern of verbal repetition (the grey lines) and verbal response (the black lines). In graphs LAM, TT and MaxVL, the solid lines represent empirical data and the dotted lines represent shuffled data.

($p < 0.001$). This indicates a reduced tendency to remain in a similar behavioral state (attractor) for a longer period. Regarding the general decreasing trend of verbal response measures, all slopes differed significantly from chance (slope of TT: $p < 0.001$; slope of MaxVL, $p < 0.001$) or approached significance (slope of LAM, $p = 0.072$).

4. Conclusion and discussion

The current study explored developmental patterns of Jimmy's early EFL nonverbal and verbal (repetition and response) learning behaviors. While a linear analysis showed that Jimmy mostly relied on nonverbal behaviors at the beginning of the course, which were later surpassed by his verbal learning behaviors (cf. Sun et al., 2014), the non-linear time series techniques gave more information on the underlying dynamics and coordination of these learning behaviors. These techniques focus on recurrent behavioral states, and especially their stability, regularity and flexibility.

In the current study, we first focused on the coordination of verbal and nonverbal learning behaviors over time using CRQA, to obtain an in-depth understanding of the coordination of these learning behaviors. We found that over time, Jimmy's learning behaviors became more flexible, with a reduced tendency to remain in a similar behavioral state (attractor) for a longer period of time. This means that over time, Jimmy relied less on a rigid coupling of body language and verbal production to deliver meaning, allowing Jimmy to alternate more flexibly between his verbal and nonverbal behaviors. These findings indicate that, first of all, nonverbal behaviors were strongly coupled to verbal production at the beginning, possibly facilitating Jimmy's EFL learning when his verbal language skills were still quite limited. As Goldin-Meadow (2014, 2015) discussed, when children lack fundamental vocabulary, gestures and body language might help them maintain interaction momentum. From our qualitative observations, we can see that Jimmy used nonverbal behaviors in class to emphasize what he said, to attract the teachers' attention, and to strengthen his verbal behavior (to provide a more complete picture of what he is attempting to communicate). Over time, the coordination between verbal and nonverbal behaviors became more flexible for Jimmy, which might indicate a better adaptation to the new environment. Note that Jimmy shifted to a slightly more rigid pattern (albeit not statistically significant) when the Chinese teaching assistant was replaced, indicating the influence (perturbation) of an external factor on the learning system.

With regard to the learning verbal behaviors, Jimmy's use of verbal response tended to become increasingly more flexible over time, visible in the overall decrease of TT and MaxVL in Fig. 6. For verbal repetition however, most RQA measures showed no significant positive or negative trend over the four months (apart from MaxVL, indicating a reduced tendency to remain in a similar behavioral state for a longer period). These different degrees of predictability of verbal repetition and verbal response might be related to the varied influence of internal and external factors on different learning behaviors. Jimmy repeated after people (primarily his teachers), mostly to confirm what they said (cf. Rydland & Aukrust, 2005). Thus, the extent of using repetition depended on the behavior of the teachers in this specific learning environment (cf. Duff, 2000). In other words, patterns of Jimmy's verbal repetition were heavily influenced by external factors, such as the frequency of the teacher's repetitions and intentional pauses, which changed from moment to moment. This might have caused his developmental pattern of verbal repetition to fluctuate. In contrast, the patterns in Jimmy's developmental trajectory of verbal responses, such as using English responses and code-switching, became less rigid over time. This could mean that these behaviors are primarily influenced by his own language competence and willingness to communicate. Over time, Jimmy might have become more familiar with English, and more comfortable using verbal language in this environment. In turn, his gradually improving language competence might have caused the developmental trajectory of his verbal response to become more flexible.

4.1. Limitations and implications

As a case in point, this study demonstrates the context sensitivity of EFL learning and the 'information richness' of the time series of learning behaviors. It gives us a first idea of the organization and coordination of verbal and nonverbal learning behaviors. Note that the fluctuations in CRQA measures are not a limitation of the study design, but should be taken as a fundamental and informative part of developmental systems (e.g. Van Geert & Van Dijk, 2002; Van Dijk & Van Geert, 2007). However, to achieve a more general and detailed description of Jimmy's attractor dynamics, including the underlying processes, denser and longer measurements are needed. In addition, it would be interesting to investigate other children's learning trajectories using these methods, to explore meaningful differences in patterns of learning behaviors.

Despite these limitations, the current study represents the potential of combining a microgenetic approach with non-linear time series methods in exploring the dynamic relationships between the developmental trajectories of subcomponents (verbal and nonverbal behaviors) of a learning system over time (cf. Cox & Van Dijk, 2013). Non-linear techniques provide more information on the dynamic coupling of students' learning behaviors, by revealing that learning is complex and consists of many interacting components. Compared to the linear measures that were presented, the non-linear measures reflect the learning process in greater detail, highlighting dynamical aspects of the behavior, such as changes in flexibility and stability. Non-linear time-series techniques are still new to social science, and even more so to early EFL learning studies. However, as Cox and Van Dijk (2013) claimed, "the ongoing improvements of techniques and the appearance of powerful new measures based on recurrence analysis, especially for categorical time series, will make this approach increasingly important and appealing for the study of developmental processes" (p. 314).

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