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Co-Adaptation Processes of Syntactic Complexity in Real-Time Kindergarten Teacher-Student Interactions

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Abstract: *Under the premise that language learning is bidirectional in nature, this study aimed to investigate syntactic coordination within teacher-student interactions by using cross-recurrence quantification analysis (CRQA). Seven teachers' and a group of their students' interactions were repeatedly measured in the course of an intervention in early science education. Results showed changes in the proportion of recurrent points; in case of simple sentences teachers and students became less coordinated over time, whereas in case of complex sentences teachers and students showed increasing coordination. Results also revealed less rigid (more flexible) syntactic coordination, although there were no changes in the relative contribution of teacher and students to this. In the light of the intervention under investigation this is an important result. This means that teachers and students learn to use more complex language and coordinate their language complexity better in order to co-construct science discourse. The application of CRQA provides new insights and contributes to better understanding of the dynamics of syntactic coordination.*

Key Words: cross-recurrence quantification analysis (CRQA), syntactic coordination, adaptation processes, kindergarten teacher-student interaction, intervention

INTRODUCTION

The bidirectional properties of language learning have been demonstrated in several studies (e.g., Bronfenbrenner & Morris, 2006; Sameroff & MacKenzie, 2003; Van Dijk et al., 2013; Van Geert, Steenbeek, & van Dijk, 2011). In addition, many researchers agree on the importance of social interaction for language development (Dickinson & Porsche, 2011; Powell, Diamond, Burchinal & Koehler, 2010). In classrooms settings, the teacher-student interaction provides a unique entry point for educational interventions in that improving this interaction can be the direct focus of the intervention (Barber & Mourshed, 2007) or that the interaction may be regarded as a contributing factor to successful implementation of an intervention. The intervention that is described in this paper aimed at improving the quality of the teacher-student interaction and

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used coding of real-time observations to evaluate the effectiveness. Therefore, it is important to use novel analysis techniques that allow capturing the complexity of language use in interaction. Traditional evaluation analyses – such as randomized control trials – are often used to study whether an intervention works, but these analyses do not provide information about how and when change occurs at the micro level. In order to gain insight into possible changes in the dynamics of the teacher-student interaction innovative techniques are required.

One of the main reasons why change processes associated with interventions were not widely studied was the lack of appropriate methodology to study them effectively (Granic & Hollenstein, 2003). Recently, more studies have focused on processes of change while taking into account inter- and intra-individual variability (Granic, O'Hara, Pepler, & Lewis, 2007; Lichtwarck-Aschoff, Hasselman, Cox, Pepler, & Granic, 2012; Turner, Christensen, Kackar-Cam, Trucano, & Fulmer, 2014; Van Vondel, Steenbeek, van Dijk, & van Geert, 2016). In part, these studies investigate profiles and pathways of change in the structure of adult-child interactions by quantifying the dynamics within these interactions. The aim of the current paper is to examine the dynamics of language use in real-time teacher-student interactions and to analyze whether this changes in the course of an intervention called "Language as a Tool for Learning Science" (LaT). This intervention is a professionalization training for teachers based on video feedback coaching. The LaT aims to improve the quality of kindergarten science lessons with a specific focus on language interaction since science education both demands and supports complex language (Glass & Oliveira, 2014; Wellington & Osborne, 2001). In this paper, we investigate the *dynamics* of teacher-student interaction – which is measured by sentences of the same syntactic category – and possible changes therein in the course of the intervention.

Complex Dynamic Systems Approach

The complex dynamic systems approach proposes to study evolving patterns within micro-level real-time interactions in educational settings, specifically also focusing on language (Kunnen & van Geert, 2012; Steenbeek & van Geert, 2013; Van Geert, 1994; 2003; Cox & van Dijk, 2013). From a complex dynamic systems point of view, it is argued that the emergence of new patterns or pattern transitions occurs through even small changes of relevant parameters of systems functioning (Heinzel, Tominschek, & Schiepek, 2014). Language, in this context, can be seen as the product of a transactional process between interacting and adapting complex dynamic systems, in this case teachers and students, which is characterized by iterativity, variability, nonlinearity, and self-organization (Cameron & Larsen-Freeman, 2007; Van Geert, 2003; Van Dijk et al., 2013). More coordinated language interactions are expected to be related to more optimal developmental outcomes. The amount and structure of variability in the language interaction is related to the coordination between teacher and students (Menninga, van Dijk, Steenbeek, & van Geert, 2017). Analyzing the patterns of variability by using nonlinear time series techniques provides a window on the coupled dynamics of teacher and students language interaction. Changes in these patterns over time, for instance due to an intervention, can be detected in this way, and can be linked to outcome measures, like intervention effectiveness, and provide clues on the underlying developmental processes (e.g., Heinzel et al., 2014; Lichtwarck-Aschoff et al., 2012).

Coordination of Syntactic Complexity

Language is of great importance in (early) science lessons (Snow, 2014; Wellington & Osborne, 2001). The acquisition of sophisticated forms of language use, including increasing syntactic complexity, is required to appropriately "speak science" (Gee & Green, 1998). This is a process of co-constructing complex science discourse, which entails coordination between teacher and students in a way that enables students to sufficiently understand and contribute to the conversation (Clark, 1996; Garrod & Pickering, 2004; Mercer, 1995). To achieve this contribution, they align their words, grammar and sounds in order to ultimately create mutual understanding (Brown-Schmidt & Tanenhaus, 2008; Pickering & Garrot, 2004).

Many studies have emphasized the crucial role of adaptive processes in language development of children (e.g., Snow, 1972; Van Dijk et al., 2013). Language can be seen as an ordered, coupled and meaningful sequence of utterances of the individual in a specific interactional context (e.g., teacher-student discourse during science lesson). Typically, the utterances of the interaction partners are co-constructed and coordinated, to create meaning and understanding. Both teacher and students adapt their individual utterances to the other, and the probability that certain combinations of utterances will recur within and across multiple interactions increases, creating more predictable patterns of language use. From previous studies, we know that speakers coordinate their language use on various levels; for instance on vocalisations (Goldstein, King, & West, 2003), speech characteristics (Ko, Seidl, Cristia, Reimchen, & Soderstrom, 2015; Reuzel et al., 2013, 2014), verbal expressions (Brennan & Clark, 1996; Garrod & Anderson, 1987; Tamis-LeMonda & Bornstein, 2002), syntactic complexity (Branigan, Pickering, & Cleland, 2000; Dale & Spivey, 2006; Hopkins, Yuill, & Keller, 2016; Van Dijk et al., 2013) but also in gestures, gazes and body posture during conversation (Abney, Warlaumont, Haussman, Ross & Wallot, 2014; de Jonge-Hoekstra, Van der Steen, Van Geert, & Cox, 2016; Golden-Meadow, 1998; Richardson, Dale & Kirkham, 2007; Shockley, Baker, Richardson, Fowler, 2007). Coordination of syntactic complexity in the teacher-student interaction is the focus of the current study. In this paper, coordination is defined as the on-going and (un)intentional process of mutual interpersonal adaptation (Garrod & Pickering, 2009; Van Dijk, Cox, & van Geert, 2016). This means that within an on-going interaction, input as well as (effective) contingent responses of both teachers and students shape their language toward *syntactic coordination* (Dale & Spivey, 2006): teacher and students produce utterances that correspond – regarding syntactic complexity – to those being heard. This process of mutual dependency among relatively independent components derived from two (sub)systems is often referred to as *coupling*.

Both experimental and observational studies provide support that individuals coordinate their syntactic structure while interacting (Branigan et al., 2000; Cox & Van Dijk, 2013; Dale & Spivey, 2006; Sokolov, 1993). In one of our previous studies, we confirmed the existence of transactional relations – which are the mutual influences in interaction, also known as bidirectional relations – regarding syntactic complexity in the context of naturalistic kindergarten science lessons (Menninga et al., 2017). To be more specific, we found that syntactically complex utterances of one speaker were related to complex utterances of the other speaker, pointing towards a bidirectional dependency. The tendency of teachers to imitate the level of complexity of their students' language in immediately consecutive utterances was strongest compared to students imitating the teachers' level of syntactic complexity. This is in contrast with the findings of Dale and Spivey (2006) which showed that older children were more often leaders, whereas the younger children were more guided by adults – in terms of timing – within the process of syntactic coordination. The contribution of the present paper is that we investigate syntactic coordination, which is defined as using sentences of the same syntactic category (no sentence, simple sentence, complex sentence) within lessons and across the course of an intervention. In addition, we aim to get insights into the relative strength and the direction of this coordination process. This relative strength can be interpreted as the symmetry in the dynamics between syntactic complexity of the teacher and syntactic complexity of the students within an interaction. The direction reflects the extent to which syntactic structures of teachers influence – or lead in time – syntactic structures of students, and vice versa.

The Intervention

This paper is based on video observations from the intervention "Language as a Tool" (LaT), which was implemented as a professionalization training for kindergarten teachers in science lessons. The intervention is based on the assumption that kindergarten science lessons provide excellent opportunities to integrate content learning and language learning (Conezio & French, 2002; French, 2004; French & Peterson, 2009; Samarapungavan, Mantzicopoulos, Patrick, & French, 2008). In order to successfully participate in science lessons, students are expected to advance in language and at the same time, science lessons offer opportunities for students to acquire and practice sophisticated language skills. The acquisition of sophisticated language skills is considered a great challenge because children need to express complex thoughts with limited language skills (Snow & Uccelli, 2009). The goal of the intervention was to improve the quality of teachers' science teaching in kindergarten. The intervention was based on video feedback coaching for teachers, which means that teachers received personal coaching based on principles of (school) video interaction guidance (Kennedy, Landor, & Todd, 2011; Van den Heijkant et al., 2006). The professional training combined several components which are important in early science education, which will be introduced briefly.

First, the empirical cycle is introduced as an effective means to structure the thinking process of students during science lessons (de Groot, 1994; Dejonckheere, Van De Keere, & Mestdagh, 2009; Gelman & Brenneman, 2004). This means making continuous use of asking research questions, predicting, testing, observing and analyzing, and drawing conclusions. The empirical cycle was used to facilitate the learning process by encouraging students to verbalize ideas by asking open questions (Chin, 2006; Lee & Kinzie, 2012; Oliveira, 2010).

The second component that was introduced to teachers is how and when to make effective use of open-ended questioning strategies. Open-ended questions are found to be most effective for stimulating children to talk (Oliveira, 2010) and for language development (de Rivera, Giralometto, Greenberg, & Weitzman, 2005; Dickinson, 2001; Mashburn et al., 2008; Peisner-Feinberg et al., 2001). Open-ended questions also provide opportunities for more linguistically and cognitively challenging discourse (de Rivera et al., 2005; Massey, Pence, Justice, & Bowles, 2008; Wasik & Bond, 2001; Wasik, Bond, & Hindman, 2006).

The third – and maybe most important – component of this intervention is to make teachers aware of the important role of complex, sophisticated, and explicit language use during early science education by providing them with information and strategies on modeling and evoking sophisticated language from students. Language is essential to learning science and science lessons provide multiple language learning opportunities (Snow, 2014; Wellington & Osborne, 2001). Engagement in these lessons, in particular in kindergarten, both demands and supports sophisticated science discourse, which brings along sophisticated forms of language use, such as domain-specific vocabulary, dense presentation of information, and complex sentences structures (Schleppegrell, 2001). As the acquisition and advancement of sophisticated forms of language is considered a great challenge, it is important that children are introduced to this register from a young age onwards (Snow, 2010; Snow & Uccelli, 2009; Schleppegrell, 2004) and therefore, kindergarten science education can provide a context for the development of sophisticated language. In order to verbalize complex thoughts, exposure is required to various ways in which sentences can be connected through combining clauses and through the use of conjunctions to express particular relations between clauses.

Previous analyses on the effectiveness of the intervention have demonstrated that in the intervention group, both teachers' and students' language increased in global syntactic complexity and – to a lesser extent – lexical sophistication compared to the control group (Menninga, 2017). The interactions also changed in the sense that the teacher asked more open-ended questions and the students verbalized more observations, predictions and explanations. These results indicate that in the course of the intervention the teacher-student interaction changed from a more teacher-led interaction to a more adaptive interaction. By adaptive, we mean that teachers are sensitive to the abilities, needs and opportunities of students, and that by carefully listening to the students the teachers are expected to be better able to evoke more and complex language from their students. The LaT-intervention has clear explicit learning objectives: teachers aim to learn how to use the empirical cycle, ask open-ended questions and use complex language in order to teach their students to observe, predict and explain the scientific phenomena at hand. However, it may be the case that explicit substantive learning and implicit coordination emerge at the same time, as the result of a process of self-organization (Guastello, 2009). For this reason, we focus on the real-time adaptation processes regarding syntactic complexity. We do this against the background of the previous studies on the effectiveness of the intervention, knowing that co-construction of reasoning had increased and that both teachers and students had shown a marked increase in the (average) syntactic complexity of their language.

Cross-Recurrence Quantification Analysis

In order to investigate the syntactic coordination within real-time teacher-student interactions, *cross-recurrence quantification analysis* (CRQA) (Marwan, Romano, Thiel, & Kurths, 2007; Webber & Zbilut, 2005), is a technique used to quantify the temporal dynamics of these interactions. This technique allows us in particular to study the coupling and attunement within the combined system of language-producing teacher and students. This powerful technique has been applied to studies on language and development to reveal structural and temporal patterns in naturalistic settings (Cox & van Dijk, 2013; Dale & Spivey, 2006; de Graag, Cox, Hasselman, Jansen, & De Weerth, 2012; Lichtwarck-Aschoff et al., 2012; Reuzel et al., 2013; 2014). Recently, additional analyses have been introduced for CRQA on categorical units of measure (e.g., words, sentences structures), which are often encountered in studying development (Cox, Van der Steen, Guevara-Guerrero, de Jonge-Hoekstra, & van Dijk, 2016). CRQA draws on quantitative measures for the extent to which teachers' and students' language use *match* (in a particular way, as will be elaborated on in the method section) across a dialog, also referred to as *cross-matching*. In contrast to more traditional techniques, including lag-sequential analysis (Dale, Warlaumont, & Richardson, 2011), CRQA is not restricted to such cross-recurrences at the same time, or within some fixed time window before or after an event, but it quantifies recurrent patterns across all possible timescales, and, therefore, includes in its analysis matches of all utterances across the entire interaction. In other words, this method quantifies coordination across multiple timescales and reveals global structures and temporal patterns of language interactions between teacher and students, and whether these patterns move toward syntactic coordination.

The Current Study

The goal of this paper is to quantify the relative strength and direction of coordination between teacher and students regarding syntactic complexity, and investigate whether this coordination process changes during an intervention in early science lessons.

The first research question addresses the global effectiveness of the intervention measured by counting frequencies: *Does the use of syntactic* *categories (no sentence, simple sentence, complex sentence) change in the course of the intervention?* The intervention was aimed at raising awareness of the importance of using complex language during science lessons (as will be explained in the method section) and we expected that in the course of the eight lessons, both teachers and students start to use more syntactically complex sentence structures. A general description of these results provides context to the subsequent CRQA.

The second research question is: *What is the relative strength and direction of syntactic coordination between teachers and students, and how does this change in the course of the intervention?* (2a). Studies thus far have demonstrated that speakers coordinate the complexity of their language use in interaction (Branigan, Pickering, & Cleland, 2000; Dale & Spivey, 2006; Van Dijk et al., 2013; Tamis-LeMonda & Bornstein, 2002). This study aims to explore to what degree syntactic structures used by teachers and students during science lessons are coupled, and whether this process of syntactic coordination changes across the course of an intervention aimed at changing language use.

As a next step, we investigated the coupled dynamics within the different syntactic categories in order to answer research question 2b: *What is the relative strength of syntactic coordination for the different syntactic categories, and how does this change in the course of the intervention?* We expected to observe different trends for the respective categories, because the intervention is aimed at increasing the use of more complex sentence structures. This may result in stronger and more stable coupling of teachers' and students' use of complex sentences over time.

METHOD

Participants

Seven (female) teachers with a small group of students (three to six students per teacher) participated voluntarily in this study. In this study, we will refer to these teachers as A, B, C, D, E, F, and G. At the start of the data collection, the teachers were between 30 and 60 years old (M = 44, SD = 13). On average, teachers had 17 years of teaching experience (range = 7-33, SD = 10) and very limited experience in teaching science. The participating students (N = 34) were four and five years of age, and were more or less evenly distributed according to gender (56% boys/ 44% girls). All teachers and students were native speakers of the Dutch language. According to the teachers, none of the participating students had any notable developmental problems.

Material and Measures

Transcription Procedure

The current analyses are based on the transcripts of the video-recorded lessons that were made for investigating the general effectiveness of the LaT intervention (see Menninga, 2017). The lessons were transcribed following the

Table 1. Transcript to Illustrate Coding of Syntactic Complexity.

Speaker	*Original-Dutch / English-Translation*	*Code*
Teacher	Hebben jullie een idee hoe het komt? Have you an idea how it works?	2
Student	Ja. Yes.	0
Teacher	Jij zei dat het door het schilletje kwam, he? You said that it (is) because (of) the skin (..), right?	2
Student	Ja kijk, het schilletje zorgt voor heel veel energie. Yes look, the skin causes a lot of energy.	1
Teacher	Het schilletje zorgt voor energie. The skin causes energy.	1
Teacher	Hoe bedoel je dat? How do you mean (that)?	1
Teacher	Wat is energie? What is energy?	1
Student	Daar word je licht door. That makes you light (..).	1
Teacher	Je bedoelt dat je daar licht door wordt? You mean that it makes you light?	2
Student	Ja. Yes.	0
Student	En zonder schilletje wordt 'ie zwaarder omdat er een gat in zit en dan gaat de lucht eruit. And without skin becomes it heavier, because there is a whole in and then the air goes out.	2
Teacher	O, je hebt het ook al over lucht. O, you are already talking about air.	1
Teacher	Adam, heb jij een idee hoe het zit? Adam, have you an idea how it works?	2
Student	Ja, omdat het rond is en omdat het schilletje eraf is en dat ie lichter gaat worden. Yes, because it is round and because the skin is off and that it becomes lighter.	2
Teacher	Oke, goed. Ok, all right.	0

Codes for Human Analysis of Transcripts (CHAT) conventions (MacWhinney, 2000) by the first author and a trained assistant-researcher. The unit of transcription was the utterance. Utterance boundaries were determined based on turn taking, pauses and on intonation patterns (Brown, 1973). Partly and completely unintelligible utterances were excluded from analysis and only task-related utterances were included in the analysis. All students together were considered "the speaking partner" of the teacher during the small group science activities, and therefore a speaker was marked either as "teacher" or "students" in the transcript. For the current analyses, we only use the middle part (that is the middle 5 minutes) of the transcripts of each lesson.

Coding Syntactic Complexity

The coding scheme – with mutually exclusive and exhaustive categories – was based on the description of syntactic complexity provided in Huttenlocher et al. (2002). We coded each utterance for sentence complexity using the following codes: (0) the utterance contained no clause, (1) the utterance contained one clause (simple sentence), or (2) the utterance contained multiple clauses (complex sentence). This coding procedure is illustrated with a transcript – from a lesson on the floating and sinking of a mandarin with and without its skin – in which the utterances and corresponding codes are presented (see Table 1).

Reliability

The inter-rater reliability for the application of the coding scheme was computed over 20% of the transcripts. Both the inter-observer agreement (88%) and the inter-rater reliability based on Cohen's Kappa (K = .83) were almost perfect (Landis & Koch, 1977).

Procedure

The data were systematically collected (video recorded) in naturalistic classroom situations during science lessons. Teachers were instructed to select three to six students, varying in age, gender and cognitive level. Teachers were recruited from schools in a regional collaboration project about science education but had limited experience with actual teaching science. Teachers and parents of the participating students gave informed consent before the start of the study with these procedures being approved by the local Ethical Committee Psychology of the University of Groningen.

For each teacher-students group, eight lessons were recorded. In these lessons, teachers were instructed to give a science lesson on a subject of their own choice (15-20 minutes). Students were not specifically informed beforehand. After the first two lessons (pre-measurements), all teachers in the intervention group attended an information meeting about the general principles of teaching science as formulated in the Curious Minds program[1]. Teachers were informed about the use of questioning strategies, the empirical cycle and sophisticated language during science education. This information was illustrated by means of video clips from the teachers' own science lessons (pre-measurements) (Seidel, Stürmer, Blomberg, Kobarg, & Schwindt, 2011). After this meeting, teachers specified a personal learning goal that was used as a special point of interest for both teacher and coach in the coaching sessions. This personal learning goal was aimed at stimulating the intrinsic motivation of the teachers and had to be in line with the coaching principles. Examples of teachers' personal learning goals were:

"*I want to learn how to ask questions based on the empirical cycle*" or "*I want to learn to be explicit and avoid terms like 'this' and 'there*.'

In the intervention stage (lesson 3-6), lessons were immediately followed by a coaching session particularly focused on the personal learning goal, the use of the empirical cycle, questioning skills and complex, sophisticated and explicit language use. Coaching was based on the principles of video feedback coaching (Strathie, Strathie, & Kennedy, 2011; Van den Heijkant et al., 2006). The coach selected several moments from the lesson, based on a ratio of three moments that showed successful teacher behavior to one moment that indicated an area for development as a higher positivity ratio is needed for successful behavioral change to occur (Fredrickson, 2013). Coach and teacher discussed and reflected upon these moments to bring the teacher's behavior to a conscious level (Van den Heijkant et al., 2006). The teacher was provided with tools to enhance her skills in the following sessions. An experienced coach (first author of this article) performed the intervention using an extensive manual and, at the same time, adapted the coaching to the authentic teaching situations.

The (video) data collection of the intervention group consisted of eight lessons in total: two pre-intervention lessons, four lessons that were used for coaching purposes, and two post-intervention lessons. Data were collected over three to four months, with sessions every one or two weeks. Post-measurements were collected two to four weeks after the final coaching session.

The current study is based on the data of the intervention group that were collected for the intervention study as a whole (Menninga, 2017), and which were re-coded for the purpose of the current analysis.

Table 2. Overview of Average Length, Minimum Length and Maximum Length of Event Series per Teacher-Student Dyad (Average of Eight Lessons per Dyad), and Average, Minimum and Maximum Length of All Event Series.

	Teacher-Student Dyad							
	A	*B*	*C*	*D*	*E*	*F*	*G*	*Average*
Average Length	129	106	111	133	113	132	132	122
Minimum Length	112	84	68	114	90	119	105	68
Maximum Length	143	140	140	148	156	154	147	156

Analysis

Proportions Complex Sentences

In order to answer research question 1, the average proportion of complex sentences was calculated for the teachers and students on all eight measurements. This proportion was calculated as the number of complex sentences relative to all utterances. In the results section, the minimum and maximum values – which are the lowest and the highest proportion complex sentences per measurement – are also provided (min-max range).

Data Preparation

The video recordings were coded on utterance level, resulting in two event series of consecutive utterances per lesson, one for the teacher and one for the students. Table 2 provides an overview of the event series per teacher-student interaction.

Cross-Recurrence Quantification Analysis

The event series were analyzed by means of *cross-recurrence quantification analysis* (CRQA) to quantify structural and temporal patterns of syntactic coordination between teachers and students. The application of this innovative technique to categorical data is explained in more detail in previous papers (Cox et al., 2016; de Jonge-Hoekstra et al., 2016). The first step was to define recurrence as the matching behavior in the event series of teacher and students. These matching behaviors are the basic unit of the CRQA, and appear as colored points in the CRP (Cross Recurrence Plot). Matching behavior was simply defined as teacher and students using the same syntactic category. This implies that syntactic coordination is based on recurrences where an utterance of a certain syntactic category is matched by a preceding or following utterance of the same syntactic category utterance between the interaction partners. Because of the turn-taking structure in regular dialog, the present study obviously does not contain exact *equal* time language-use matches. This means that the smallest unit (i.e. time scale) of analysis exists of a language-use match between two consecutive utterances. The CRQA procedure included all matching behaviors together (i.e., no sentence-no sentence, simple sentence-simple sentence and complex sentence-complex sentence) for Research Question 2a, and analyzed them separately for Research Question 2b. The CRQA was performed using special-purpose Matlab code.

Secondly, all matching values between a pair of event series were plotted in a cross-recurrence plot (CRP, see Fig. 1), by putting the event series of one speaker along the horizontal axis and that of the other speaker along the vertical axis. When using categorical data most dots in the CRP align to form (vertical and horizontal) rectangular structures. The occurrence of "rectangularity" in the CRP and the extent of its anisotropy (i.e. direction dependence or dissimilarity along the two axes of the plot) reflect multi-stability and asymmetry in the interaction, respectively. These structures indicate instances where a behavior expressed (briefly for a line, and longer for a block) by one subsystem (teacher or students), is accompanied by episodes of lingering in the matching behavior by the other subsystem (students or teacher). From this cross-recurrence plot, several recurrence measures can be derived (see Appendix), which provide information about the shared dynamics of syntactic complexity in the teacher-student interaction, and specifically about the strength and direction of the coupling between the two subsystems (see Cox et al., 2016; see also López Pérez, Leonardi, Niedzwiecka, Radkowska, Raczaszek-Leonardi, & Tomalski, 2017). The direction of the coordination is considered such that *vertical line* structures reflect the extent to which syntactic structures of teachers influence syntactic structures of students, whereas *horizontal line* structures reflect the extent to which the students' syntactic structures influence syntactic structures of teachers.

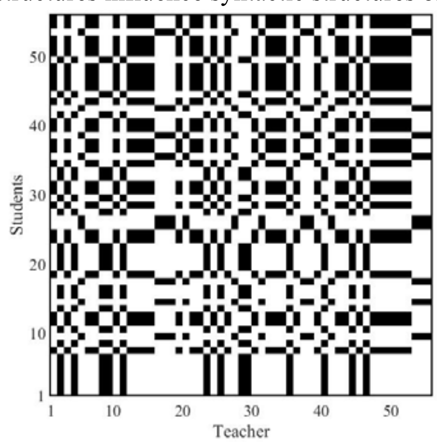

Fig. 1. A CRP produced by the cross-matching procedure, forming the basis for CRQA. In this case matches of categories of syntactic complexity were depicted by black line (and block) structures, together with the non-matching white areas. The data are from teacher F, session 7.

After constructing the CRP, the measures *recurrence rate* (RR), *laminarity* (LAM), *trapping time* (TT) and *maximum line length* (MaxL) were calculated along its two main axes (see Appendix). *Laminarity* indicates the proportion of recurrent points that comprise vertical rectangular structures (LAM_V) and horizontal rectangular structures (LAM_H), and reflect the degree to which each subsystem is "trapped" into expressing matching syntactic categories for all consecutive periods of at least two utterances. TT reflects the average time that one of the subsystems remains in a matching state triggered by the other. In this context, it is the average number of consecutive utterances that either teacher or students produce at the same level of syntactic complexity as the other produced at some point. TT measures are an indication of interactional rigidity (or flexibility). The *length of the maximum (horizontal or vertical) line* or block structure informs about the longest of such episodes, with $MaxL_v$ reflecting the longest consecutive pattern of same syntactic complexity utterances by the teacher, and $MaxL_H$ reflecting the longest pattern of the students. Following de Graag et al. (2012), a decline in these measures reflects an increase in the flexibility of (coupled) use of the three categories of sentences.

In order to detect potential asymmetries in the strength and direction of teacher – students' interaction, vertical and horizontal line structures were first analyzed separately and the resulting measures subsequently combined, following the procedure of *anisotropic* CRQA (Cox et al., 2016). Anisotropy in the CRP was properly quantified by calculating the relative difference between the vertical and horizontal line measures (i.e. $(X_V - X_H) / (X_V + X_H)$). As explained before, the orientation of the rectangular structures (i.e. vertical and horizontal) provides differential and complementary information about the coupling between the two subsystems.

In order to answer Research Question 2b, *chromatic* CRQA (Cox et al., 2016) was performed. This method analyzes several kinds of behavioral matches – in this case matches of the level of syntactic complexity – separately, by tracking them with a color-coding. A straightforward way to implement this is by constructing a cross-recurrence plot, CRP(*color*), for each kind of behavioral match (color). By merging the separate CRP(*color*), all recurrences of the different kinds of behavioral matching can be represented by differently colored dots in a single, multi-colored CRP (see Fig. 2). Using chromatic (i.e. matching-type specific) CRQA, three colored cross-recurrence plots (CRP(*color*)) were analyzed and compared for each teacher-student interaction over the eight measurements.

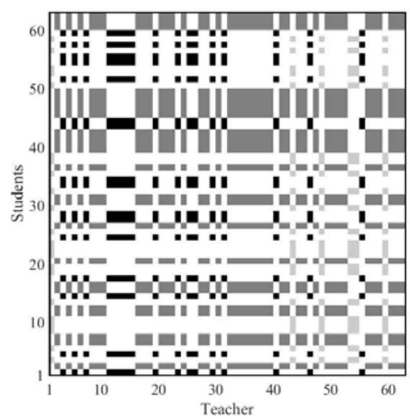

Fig. 2. A multi-colored checkerboard CRP produced by the cross-matching procedure, forming the basis for Chromatic CRQA. Three different matches of categories of syntactic complexity were distinguished, depicted by a light grey (no sentence), dark grey (simple sentence) and black (complex sentence) color code, together with the non-matching white areas. For further details about calculations on the CRP, see text. The data are from teacher D, session 6.

An example of a chromatic CRP is provided in Fig. 2. The first, CRP(*light grey*), only displays matches of the syntactic category *no sentence*, while the second, CRP(*dark grey*), only displays matches of *simple sentences*, and the third, CRP(*black*), displays matches of *complex sentences*. In this way, the recurrence rate of each CRP(*color*), as a basic measure of the coupling between teacher and students, informs about the coordination at a specific syntactic level.

The simplest measure in chromatic CRQA is the *recurrence rate* of a *color* (RR(*color*)), quantifying the density of one kind of behavioral match in this multi-color CRP. This means that the RR(*color*) depicts the proportion of recurrent points – the use of a specific syntactic category by teacher or students, matched by the use of that same syntactic category by the other – across the entire CRP. *RR*, as a basic measure of the coupling between two subsystems, informs us about the syntactic coordination between teacher and students.

Slopes

For both the proportions of complex sentences and for each measure resulting from the CRQA, we tested whether the measures showed an increase or decrease over the eight lessons. We used a non-parametric procedure, called Monte Carlo analysis (Good, 2006), where the linear slope of the empirical CRQA measures (LAM, MaxL, TT) was tested against the slope of randomly shuffled data. First, the slope was calculated over the empirical data, based on an average of all teachers. Second, the columns and rows with empirical data of all teachers are randomly shuffled, after which the slope was calculated again over the shuffled data. This procedure was repeated 10,000 times per test and results in a *p*-value which indicates the probability that the slope of the empirical data stemmed from the distribution of slopes of shuffled data. The Monte Carlo analyses were performed in Microsoft Excel in combination with Poptools (version 3.2)[2]. As significance scores are not directly linked to practical significance (Sullivan & Feinn, 2012), the effect size was calculated using Cohen's *d*. These were computed by taking the average of session 8, subtracting it with the average of session 1, and dividing this value by the pooled standard deviation of the group. Based on Cohen's classification (1992), effect sizes of .20, .50 and .80 (and the negative counterparts of -.20, -.50 and -.80) are small, medium and large, respectively. In order to determine whether the empirical data provided convincing, weak or no support for our hypotheses, we evaluated combinations of *p* values and *d* values. Only when the empirically-found value had a very small probability of being produced under the null-hypothesis – with a *p* value smaller than .05 and an effect size greater than .50 or -.50 – was it understood as convincing evidence supporting that the empirical value was meaningful. Empirical results with a *p* value between .05 and .10 and an effect size greater than .50 or -.50 can be understood as less convincing evidence, providing weak support. Results with relatively small effect sizes (below .50 or above -.50) – whatever the *p* value – or with *p* values above .10 – whatever the effect size – were understood as unconvincing evidence or no support.

RESULTS

Changes in Use of Syntactic Categories

The first research question addressed whether there are global changes in the use of syntactic categories (no sentence, simple sentence, complex sentence) by both teachers and students in the course of the intervention. Figures

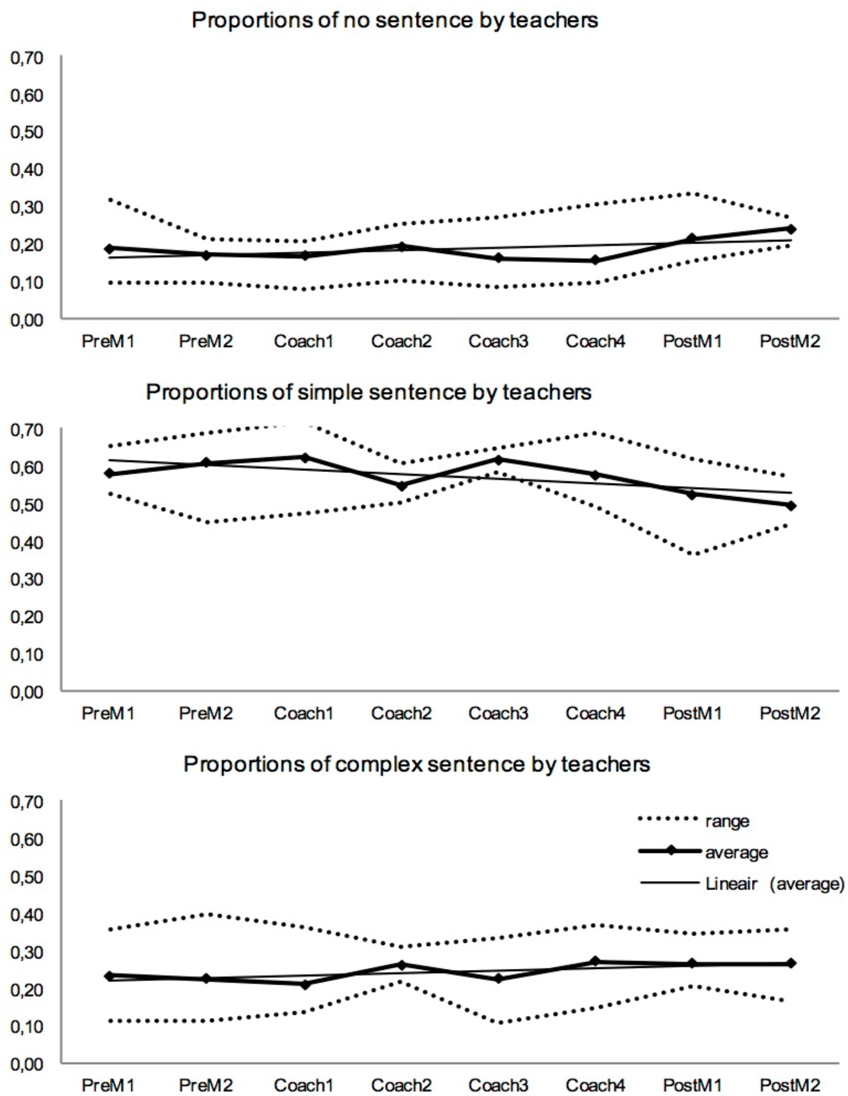

Fig. 3. Teachers' use of syntactic categories (proportions of no sentence, simple sentence, complex sentence) over eight science lessons.

3 and 4 present the use of the different categories over the eight science lessons expressed by the teachers and the students. The teachers' use of the category "no sentence" slightly increased over time (*slope* = .01, p = .10, d = 1.77) providing weak support for a meaningful increase. Teachers started expressing convincingly

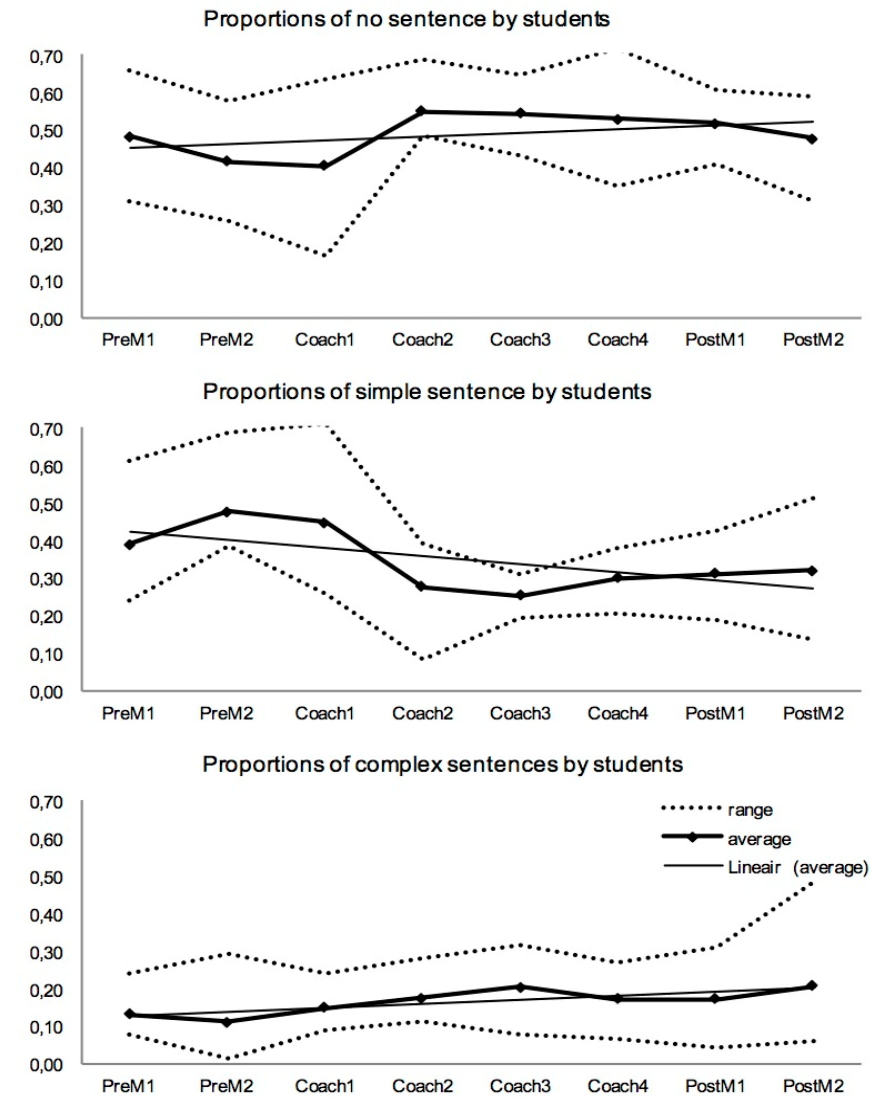

Fig. 4. Students' use of syntactic categories (proportions of no sentence, simple sentence, complex sentence) over eight science lessons.

fewer simple sentences over time (*slope* = -.01, *p* = .03, *d* = -1.83) and convincingly more complex sentences (*slope* = .01, *p* = .03, *d* = 1.31). For the students, use of the category "no sentence" varied between measurements and the slope showed no support for changes over time (*slope* = .01, *p* = .14, *d* = -.09).

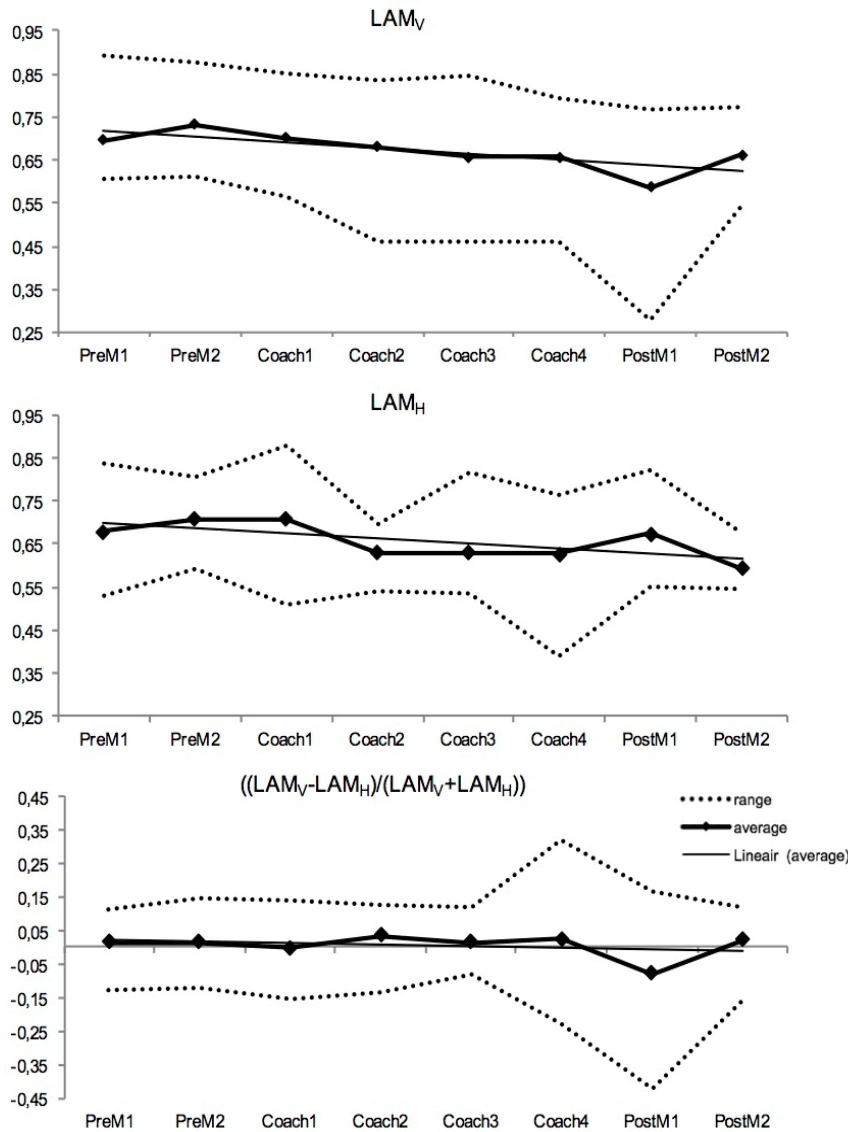

Fig. 5. Average laminarity (LAM_V, LAM_H and $((LAM_V-LAM_H)/(LAM_V+LAM_H))$) over eight science lessons. Solid line indicates average and dotted line indicates the range (minimum and maximum values).

The use of simple sentences convincingly decreased over time (*slope* = -.02, *p* = .05, *d* = -.86) and the use of complex sentences increased convincingly (*slope* =

.01, $p < .01$, $d = 2.34$). In the course of the intervention, both teachers and students tended to use more syntactically complex sentence structures. It is remarkable that we see a pronounced decrease in the proportion simple sentences, which is most evident in the students (Fig. 4), at lesson 4. Despite these general trends, the wide ranges – in particular, in the case of the students – indicate interindividual variability.

Relative Strength and Direction of Syntactic Coordination

An overview of the measures from the CRQA is presented in Figs. 5, 6 and 7. LAM_V convincingly showed a downward trend over the eight lessons (*slope* = -.01, $p = .04$, $d = -.75$). This means that over time there is a decrease in the degree to which the teachers use a syntactic category for some uninterrupted number of utterances, which is imitated by the students at some point. Calculations of the horizontal line structures (LAM_H) revealed that the extent to which students were “trapped” into displaying the same syntactic category as their teacher also decreased convincingly over time (*slope* = -.01, $p = .02$, $d = 2.02$).

Lastly, the slope of the relative difference of LAM_V and LAM_H was significant, but with a negligible small effect size (*slope* < .01, $p < .01$, $d = .19$). This can be interpreted that teacher and students had a similar decrease, and that the influence of teachers on students and of students on teachers, with regard to the syntactic complexity of their sentences, remained the same. Teachers and students became more loosely coupled over time --in terms of being less “stuck” in the same sentence category as the other speaker-- in a way that kept their mutual influence equal over the lessons.

Both TT_V and TT_H values were all around 3 – the average vertical and horizontal lines in the recurrence plot consisted of about 3 recurrent points –, which means that teachers and students ‘trap’ each other into same syntactic categories with average durations around 3 successive utterances. There was no evidence that this pattern changes over time (*slope* TT_V = -.02, $p = .28$, $d = .84$; *slope* TT_H = -.05, $p = .11$, $d = -.88$). In addition, the analysis of the relative difference of TT_V and TT_H did also not provide evidence for any change over time (*slope* < .01, $p = .28$, $d = 1.69$), with average values varying slightly around 0. This means that the analysis of TT provided no indications that teachers and students asymmetrically influenced each other, nor that there were changes over time in the mutual influence, with respect to utterance length in the different categories of syntactic complexity.

The analysis provided only weak support for a decreasing trend of $MaxL_V$ over time (*slope* = -.25, $p = .06$, $d = -2.02$). In other words, the maximum episode that a teacher was “trapped” into a same level of syntactic complexity as students were at some point showed a small downward trend. This means that teachers became less strongly influenced by students. Calculations of the horizontal line structures revealed no support for changes in the $MaxL_H$ over time (*slope* = -.06, $p = .38$, $d = .64$). Last, the relative difference of $MaxL_V$ and $MaxL_H$ was only slightly above zero, indicating no real asymmetry in this respect and did not show any support for change over time (*slope* < .01, $p = .30$, $d = -2.17$).

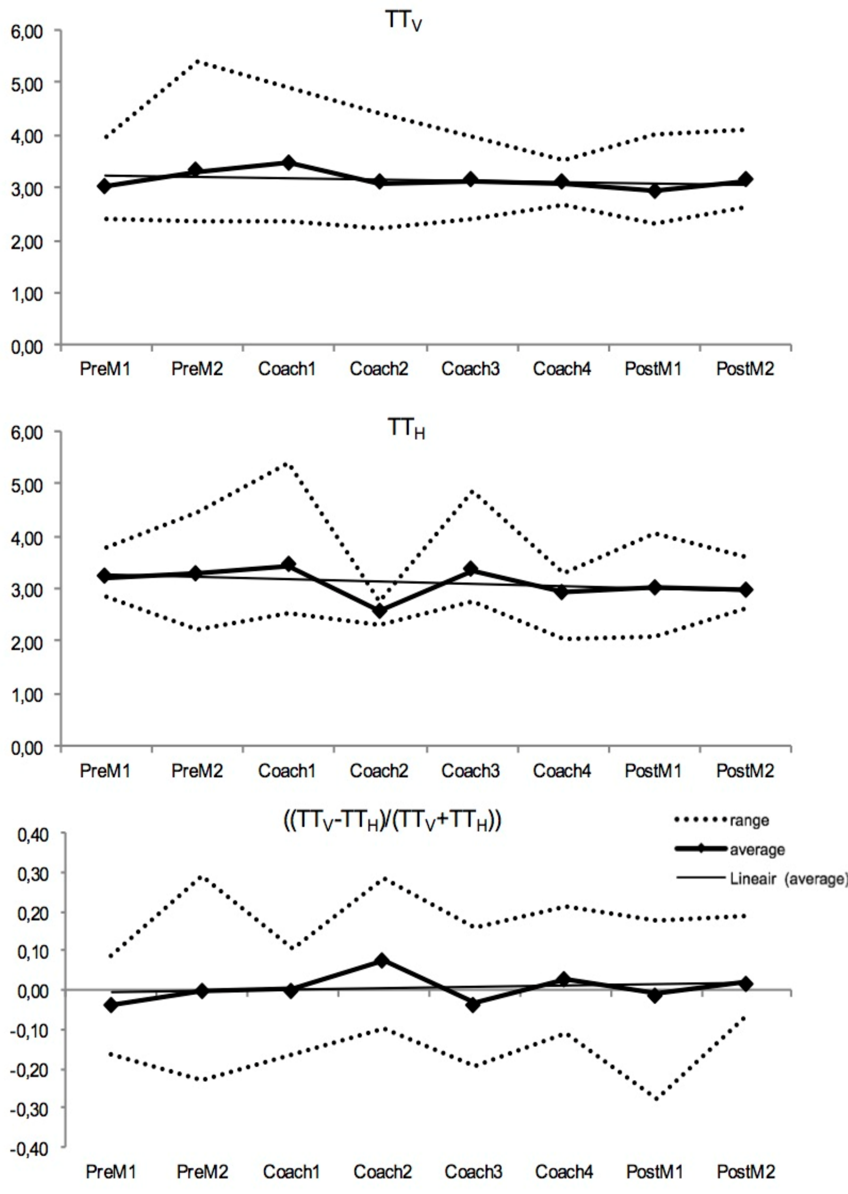

Fig. 6. Average trapping time (TT_V, TT_H and $((TT_V-TT_H)/(TT_V+TT_H))$) over eight science lessons. Solid line indicates average and dotted line indicates the range (minimum and maximum values).

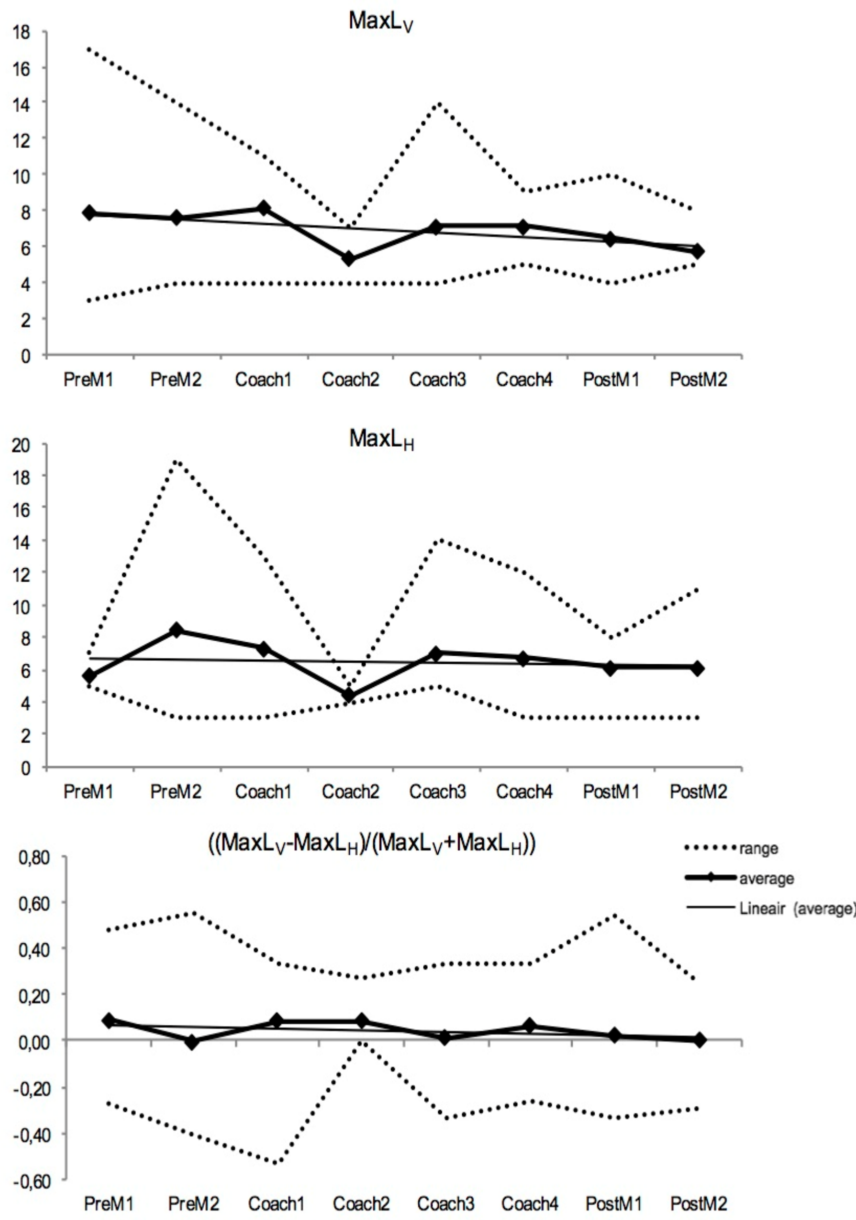

Fig. 7. Average maximum line ($MaxL_V$, $MaxL_H$ and $((MaxL_V-MaxL_H)/(MaxL_V+MaxL_H))$) over eight science lessons. Solid line indicates average of teachers and dotted line indicates the range (minimum and maximum values).

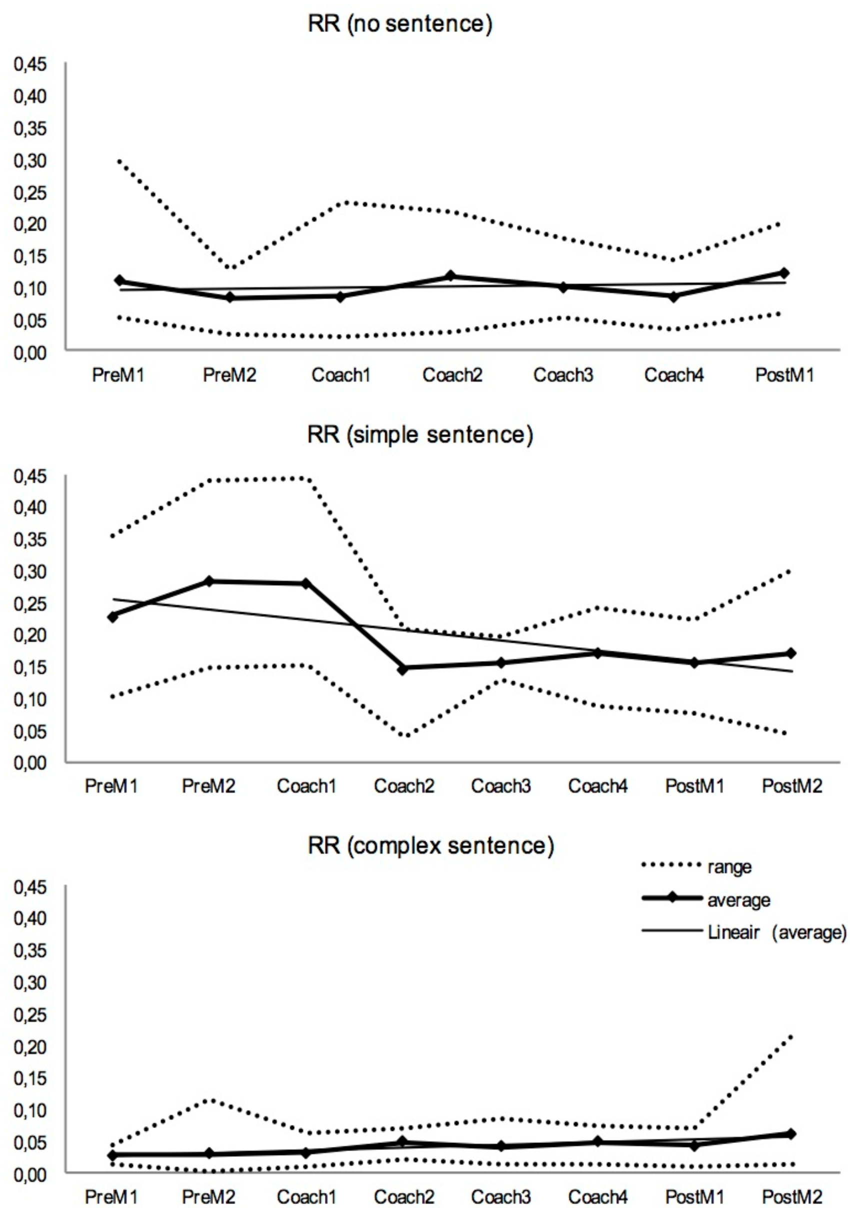

Fig. 8. Overview of recurrence rates per syntactic category (no sentence, simple sentence, complex sentence) over time. Solid line indicates average and dotted line indicates the range (minimum and maximum values).

Relative Strength of Syntactic Coordination for the Different Syntactic Categories

With regard to answering RQ 2b, we first, we plotted the CRP(color) of *no sentence* and calculated the $RR_{no\ utterance}$. The analysis of its slope over the eight lessons did not provide evidence for change over time (*slope* = .002, *p* = .23, *d* = .16). With regard to the simple sentences, $RR_{simple\ sentence}$ showed a convincing (sudden) decrease over time (*slope* = -.02, *p* < .01, *d* = -1.07). From Fig. 8 it is apparent that recurrence of simple sentences changed abruptly after lesson 3. Thirdly, for the category complex sentence the $RR_{complex\ sentence}$ increased convincingly over the eight lessons (*slope* = .004, *p* = .01, *d* = 3.02), which means that complex sentences became more recurrent. These results indicate changes in the coordination of syntactic structures: decreasing coordination for simple sentences and increasing coordination for complex sentences.

DISCUSSION

The contribution of this study has been to provide insight into how syntactic coordination within teacher-students interactions changed during an intervention by applying chromatic and anisotropic CRQA to each of the lessons across the course of an intervention.

One of the main aims of the intervention was to bring about behavioral change among teachers, by changing the interaction, and by raising awareness of the importance of using complex language in science education. This was done by providing teachers with information on effective ways of introducing ("modeling") and evoking more sophisticated language use from their students, which was practiced in the lessons and reflected upon in the video feedback coaching sessions. Previously analyses that were based on a comparison between the intervention group and a control group, had shown that the interactions changed from a more teacher-led interaction to a more adaptive interaction (Menninga, 2017). However, the analyses did not provide any information about *how* these changes are also reflected in the task-related teacher-student language at the micro level of each lesson. For this reason, the current study investigated whether the moment-to-moment syntactic synchronization changed over the course of the intervention period.

The frequency analysis showed that both teachers and students who took part in the intervention started using more complex sentence structures and less simple sentence structures. An important observation was that changes in students' use of simple sentences occurred at lesson 4, which is right after the first coaching session. On the basis of pre- and post-measurements comparisons, we conclude that there *is* change over time with regard to syntactic complexity. Against the background of these global results, chromatic CRQA was used to add a detailed analysis of the temporal structure of syntactic coordination of each lesson, enabling us to inspect for trends over the course of the intervention period. The results of the anisotropic CRQA demonstrated that although the horizontal and vertical line structures remained the same length, there were generally *less* recurrent points that were on these structures over time. Following de Graag et al. (2012), we interpret this as indicating a change over the course of the intervention, with respect to the *coupling* between teachers and students, leading to less rigidity in their use of utterances of similar syntactic complexity. In other words, speakers progressively became less "stuck" in the same sentence category as their conversational partner. With regard to the direction of this coordination (the influence of the teachers onto the students and vice versa), there were no changes over time.

When investigating synchronization within the different sentence categories, the chromatic CRQA revealed two changes that occurred simultaneously: a) the recurrence of the simple sentences decreased and b) the recurrence of the complex sentences increased. This means that in case of simple sentences teachers and students became less coordinated over time, whereas in case of complex sentences teachers and students increasingly coordinated. Combined, the results of the anisotropic and chromatic CRQA showed a global trend towards more flexible (i.e. less rigid) syntactic coordination (in terms of the temporal structure of matching syntactic complexity across sentence categories), and a trend towards more coordination between *complex* sentence utterances.

Earlier studies have shown that speakers tend to align their speech towards syntactic coordination (Branigan, Pickering, & Cleland, 2000; Dale & Spivey, 2006; Van Dijk et al., 2013; Tamis-LeMonda & Bornstein, 2002). Our study investigated syntactic coordination over the course of an intervention and it was found that this coordinative process changed over time. These results are in line with previous studies on changing dynamics during other types of intervention. In the context of psychotherapy for instance, several patterns of change have been identified in relation to intervention effect. For instance, Heinzel et al. (2014) investigated the effect of a therapeutic intervention for OCD and reported that an increase in dynamic complexity of symptoms preceded the reduction in symptom severity. Further studies have demonstrated that nonlinear models (such as the cusp model) often predict change better than linear models do (e.g., Clair, 1998; Byrne, Mazanov, & Gregson, 2001). In addition, Lichtwarck-Ashoff et al. (2012) investigated the effectiveness of a treatment for childhood aggression and found that destabilization of real-time interaction behaviors was associated with better treatment outcomes. These authors argue that this type of destabilization can be described as a period of unpredictability marked by variability in several domains (e.g., affect and behavior). This is consistent with earlier psychotherapy literature in which destabilization is considered to be a precursor for change (Mahoney, 1991). According to a complex dynamic systems viewpoint, the concept of a destabilization period is related to the concept of a phase transition, a sudden reorganization of the system. Such a phase transition is characterized by an increase in the intra-individual variability, followed by a period of re-stabilization (e.g., Gilmore, 1981; Thelen & Smith, 1994). The current study has also demonstrated that the interaction between teacher and students destabilized during the intervention that they organized into a different type of syntactic coordination.

Science lessons provide a highly-suited context for students to become (more) proficient in using complex syntax to express complex ideas, as this requires exposure to various ways in which sentences can be connected through combining clauses and through the use of conjunctions to express particular relations between clauses. The application of CRQA techniques provides new (additional) insights and contributes to a better and unique understanding of the underlying dynamics of syntactic coordination. The CRQA techniques also enable us to tear apart the respective contributions of each of the two contributing subsystems (i.e. teachers and students) to the dynamics.

In the context of language learning, it is important for teachers to be aware of the bidirectional character of language use and the opportunities for advanced language learning of students. By the mutual influences of using increasingly complex language, teachers and students can create an upward spiral of the complexity of their language use. For teachers, this reciprocal adaptation means that they need to learn how to carefully listen to the verbal utterances of their students in order to respond contingently. These contingent teacher responses need to be tailored to the current verbal abilities of students, and they also need to be challenging in order to stimulate students to advance their language skills.

Limitations and Future Research

This paper adopted a relatively novel methodological approach, where data consisted of observations of real-time interactions between teachers and students across the course of an intervention. This kind of data was necessary for analyzing the underlying dynamics of syntactic coordination. Each observation was quantified in order to create event series that formed the input for the CRQA. The number of cases that are used in this study (seven teacher-student dyads) is relatively large for performing such an in-depth analysis of coordination processes, which is possible through the application of CRQA. This is an illustration of the inevitable trade-off between the depth of analysis and the number of cases that can be analyzed. In order to ultimately make generalizations about the real-time processes, we need much more in-depth studies, such as the one described in the current paper.

It is important to note that the analyses were based on existing transcripts of the lessons that were made for different analytical purposes. This leads to several limitations. The first is that the data are event series instead of time series, which implied that the data did not allow us to investigate the contribution of meaningful pauses and other relevant temporal aspects of coordination (e.g., leader-follower dynamics) in the interaction. Mercer and Dawes (2008) argue, for instance, that pauses after posing a question gives students more time to think, which leads to greater learning gains. The structure of a conversation between teacher and students is partially determined by meaningful pauses, and therefore, future studies should be undertaken to explore how these pauses contribute to the underlying dynamics of kindergarten science discourses. The second limitation of using existing transcripts is that it was only possible to include task-related utterances. It might have been interesting, however, to also have considered the changing nature of on and off-task utterances. Switching between on- and off-task talk is related to engagement which may be a factor in coordinated complexity. Specifically, frequent switching may limit the potential for the depth or complexity of the exchanges. As a consequence, the analysis of the current study has only analyzed *one specific dimension* of synchronization between teacher and students during science lessons.

Though the results show a change in complexity dynamics in the course of the intervention, we cannot conclude that this is *caused by* the intervention or by some specific ingredient in the intervention, in a straightforward way. The reason for this is that the analyses were performed on the data of the intervention group only. It may be the case that the observed changes are a result of just becoming more familiar with the content (that is the science lessons) or with the specific context of teaching in these small teaching groups (though teachers and students were already very familiar with each other and working in small teaching groups for other lesson content). It may even be speculated that the results are (partly) caused by simple maturation of the students during the 3-4 months of the intervention. There is also no way of knowing how much of the recurrence is task-related, and how much is affiliation-related or whether task performance precedes synchronization or vice versa. More generally, although the results lead us to conclude that there *is* change over time with regard to syntactic complexity, it is hard to attribute this change to the LaT intervention, or some other factor for that matter. From a complex systems point of view it is much less relevant to attempt to pinpoint that single cause for any change, but conceive of change as resulting from a multi-causal process. In this sense the intervention might (merely) create opportunities for alterations in the coordination dynamics of the teacher-student interaction, which in turn lead to changes in outcomes in a self-organizing way. The causal mechanisms that create the changes at the end of the line are due to a complex interplay between a multitude of factors, however, in which not one thing can be singled out.

Another limitation is that, for the current analyses, the students are considered “the speaking partner” of the teacher during the small group science activities. However, it would have been interesting to include analyses of the contributions of individual students, and interactions between students, and the overall volume of talk between teachers and individual students. The current data did not allow us to investigate the contributions of each of the individual students to the interaction since the CRQA technique requires a continuous data stream. Additional research is necessary in order to shed light on the “influence” that individual children have on this process of syntactic coordination during science lessons, and whether this dynamic relies on only one or two individual students. The question arises whether existing analyses are capable of capturing these complex interaction processes between multiple speakers.

Being limited to small group science activities, the results do not inform us about the temporal and dynamic structure of science conversations during natural whole-classroom situations. The small-group teaching activities were used for two reasons: to optimize the training conditions for teachers and for practical reasons such as visibility and audibility on camera. In this light, additional research is needed in order to investigate syntactic coordination between teachers and students in natural science whole-classroom settings. The current study is a first step towards greater understanding of this process in real-time teacher-student interactions during small group activities. On the other hand, small group teaching activities become an increasingly common form of education because they allow for more intensive interaction.

ACKNOWLEDGEMENT

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APPENDIX

Measure	*Description*	*Formula*
Cross-Recurrence Matrix (CR_{ij})	Matrix of recurrences ('distance matrix') on which the Cross-Recurrence Plot (CRP) is based.	$CR_{ij} = \begin{cases} 1 \; if \; X_i = Y_j \\ 0 \; if \; X_i \neq Y_j \end{cases}$
Recurrence Rate (RR)	Proportion of recurrent points in the CRP.	$RR = \frac{1}{N^2} \sum_{i,j=1}^{N} CR_{ij}$
Laminarity (LAM)	Proportion of recurrent points that form vertical / horizontal lines in the CRP.	$LAM = \frac{\sum_{l=2}^{N} lP(l)}{\sum_{l=1}^{N} lP(l)}$
Trapping Time (TT)	Mean length of the vertical / horizontal lines in the CRP.	$TT = \frac{\sum_{l=2}^{N} lP(l)}{\sum_{l=2}^{N} P(l)}$
Maximum Line Length ($MaxL$)	Length of the longest vertical / horizontal line in the CRP.	$MaxL = \max\left(\{l_i\}_{i=1}^{N_l}\right)$

Note 1: X_i is one of the time series and Y_j is the other, both of length N. $P(l)$ is the distribution of vertical/ horizontal lines of length l. The minimum line length is 2 and N_l is the number of vertical / horizontal lines.

Note 2: All measures can be calculated for each type of recurrence (i.e. 'color') separately.

All measures except RR can be calculated separately for horizontal lines and vertical lines.

ENDNOTES

[1] The basic principles of Curious Minds are that everyone is talented, adults should learn to recognize and stimulate the natural curiosity of children, adults should become talent-experts, adults are the motor behind further

development of children's talent and the best way to achieve this is case-based learning for adults.

[2] To download Poptools: http://www.poptools.org/download

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