Scientific understanding of students in the picture

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Chapter 1

General introduction

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The following example, originating from the dataset of this dissertation, is an illustration of how students co-construct scientific understanding together with the teacher during an inquiry-based learning situation.

Egg in a bottle

A raw egg is soft and a boiled egg is firm. The boiled egg cannot just go through the small opening of a bottle.

The teacher asks: ‘what do you think? Can you get a boiled egg into a bottle [without destroying it]?’ Most 10-year-olds agree that the egg cannot get inside the bottle: ‘the bottleneck is just too small, right!?’ However, some students are in doubt. Although they do not come up with a valid explanation they reason ‘why perform this experiment if nothing is going to happen’. Then burning matches are put into the bottle and the egg is placed on the bottleneck. After several cries of astonishment, the students conclude that ‘the whole egg can get into the bottle!’ The teacher asks a crucial question: ‘how is it possible that, contrary to most of our predictions, the egg did get into the bottle?’ One student says: ‘The egg starts to sweat!’ Now, the teacher is surprised. To gain insight into the student’s complexity level of scientific understanding, he decides to follow this line of reasoning by asking ‘why do you think that?’ The student comes up with a reasonable explanation for his statement: ‘the fire of the matches makes the egg warm. Through this, the egg starts to sweat and therefore it slips easily into the bottle’. This explanation is the starting point for a spontaneous teachable science moment in which the question for all students is ‘can an egg sweat?’ Together they conclude that the egg cannot sweat. The alternative, correct explanation they come up with is that the difference in air pressure within and outside the bottle, due to temperature differences within the bottle, has caused the egg to end up in the bottle.

This example demonstrates some important characteristics of science and technology education. First, an inquiry-based hands-on activity is used to spark students' curiosity (Gibson & Chase, 2002). Second, students' enthusiasm and curiosity is used as a starting point to actively engage students in science and technology education (Bryson & Hand, 2007; Laevers, 2005). Third, questions of the teacher are used as a means to structure the activity (White & Fredriksen, 1998) as well as to elicit and deepen students' scientific understanding (e.g. Oliveira, 2010; Van der Steen, Steenbeek, Van Dijk & Van Geert, 2014). Fourth, students' naïve perceptions of scientific phenomena are used as an opportunity to engage students in the co-construction of scientific understanding (Hyun & Marshall, 2003).

Cognitive aspects, i.e. scientific understanding, as well as non-cognitive aspects, i.e. curiosity and engagement, constitute students' learning processes (Dai & Sternberg, 2004). The importance of social interaction in such learning processes is stressed in sociocultural theories (Vygotsky, 1986). However, little is known about how such interrelated skills develop during actual teaching-learning situations (Howe & Abedin, 2013) and how teachers can stimulate students' scientific understanding in naturalistic classroom settings. We aim to contribute to our knowledge of, on the one hand, the development of students' (9-12 years old) scientific understanding in interaction with the teacher, and, on the other hand, of how to successfully intervene in this development, by means of studying the effects of the Video Feedback Coaching for upper grade teachers (VFCt).

This general introduction first discusses the motivation of the current research. Secondly, we present a short outline of the research program this study is part of, the Curious Minds program. Thirdly, the complex dynamic systems theory will be discussed as foundation for the design of the VFCt professionalization intervention, and as the theoretical framework for studying effects of the VFCt. Finally, the four empirical studies that were conducted in order to answer the main research question are briefly described, and how they are related to one other.

Motivation of current research

Scientific understanding is considered increasingly important for science performance and for future citizens to be able to fully participate in society (Esmeijer & Van der Plas, 2012; Silva, 2009). The need for better scientific understanding in the population is stressed both from an individual perspective — concerning the individual's life span development — and a collective perspective, such as a country's economy (Bybee & Fuchs, 2006; CITO, 2010; Jorde & Dillon, 2013; National Research Council, 2011). An important reason is that more technical and scientific scholars are needed to meet society's current and future challenges and innovations. However, international concern is raised about the limited numbers of students that pursue science and technological careers (Jorde & Dillon, 2013, p. 7-8). This concern is nourished by the fact that students' natural curiosity, an important characteristic for science and technology, decreases during elementary education (Engel, 2006). More specifically, especially around the transition from elementary to secondary education a significant drop takes place in students' interest in and enjoyment of science and technology (Murphy & Beggs, 2005). On a political level, this concern is reflected in the acknowledgment that science and technology should be a part of the curriculum from an early age on (Jorde & Dillon, 2013, p. 10). In the Netherlands, from 2020 onwards, science and technology should be structurally provided as a subject in primary education (Techniekpact2020, 2016). However, teachers view science and technology education often as highly challenging (Jarvis & Pell, 2004; Van Aalderen-Smeets, Walma van der Molen & Asma, 2012; Wetzels, Steenbeek & Van Geert, 2015). As a consequence science and technology education is currently hardly embedded in national curricula. Students are therefore not sufficiently familiarized with the basic principles of and skills related to science and technology. The lack of knowledge makes it hard for students to develop and articulate their potential interests in these fields[1]. The introduction of science and technology education in elementary education is important to evoke students' natural curiosity, for the development of positive attitudes, and increased understanding (Eshach & Fried, 2005). At present, many teachers still lack the adequate pedagogical-didactical skills for introducing their students to the world of science. For this reason, professionalization of teachers in the field of science and technology education is needed.

Curious Minds

This need for professionalization, among others, prompted the initiation of the nationwide research program Curious Minds in the Netherlands (in Dutch: TalentenKracht, founded in 2006 by Van Benthem, Dijkgraaf, & De Lange, 2005). Researchers from seven universities (6 Dutch and 1 Belgian) cooperated to study young children's talents for science and technology. The resulting scientific insights are translated into pedagogical-didactical strategies for teachers and parents to optimize educational settings in order to provide children with opportunities to excel in science and technology. The department of developmental psychology at the University of Groningen, which is one of the participants of the Curious Minds research program, has theoretically grounded its Curious Minds projects in complex dynamic systems theory (see 1.4 Complex dynamic systems theory; Steenbeek, van Geert, & Van Dijk, 2011). The projects range from more fundamental research (Guevara Guerrero, 2015; Meindertsma, Van Dijk, Steenbeek, & Van Geert, 2014; Van der Steen, Steenbeek, Van Dijk, & Van Geert, 2014) to research in applied settings (Geveke, Steenbeek, Doornenbal, & Van Geert, 2016; Menninga, Van Dijk, Cox, Steenbeek, & Van Geert, 2016; Wetzels, 2015). All projects have in common that students' scientific understanding is understood as a non-linear process that develops in dynamic interaction with the material and social context.

An important starting point of the Curious Minds program in general and the Video Feedback Coaching for teachers in particular, is that each child is naturally

[1] Though, National Platform Science & Technology (Platform Beta Techniek) reports that at the end of 2015 due to several initiatives in the past few years a positive change is visible; the number of influx of students into beta technical studies increases. See also OECD (2015).

curious (Steenbeek & Uittenbogaard, 2009). The assumption is that every child is talented and can develop his/her talents in interaction with his or her environment. Another important assumption is that the talent should be defined in an iterative way, i.e. talented, high quality performance of the individual child in comparison to that particular child's unsupported or baseline performance. Talent is not primarily seen in the comparative way (some children are real talents others are not), and excellence is defined relative to the individual child's own baseline or unsupported performance, and not relative to other children per se. Van Geert and Steenbeek (2007) defined talent as a child's capacity to reach a high level of performance in a specific domain. Several characteristics of talent are mentioned: a high learning potential, in-depth processing of domain-specific information, the ability to elicit high-quality support from the (social) environment, creativity, belief in one's own competence, enthusiasm, and strong intrinsic motivation to learn. What is important is that teachers need to observe, recognize and act according to these student characteristics. By doing so, teachers can enhance the quality of students' scientific understanding by establishing a series of inspiring teachable science moments (Bentley, 1995; Hyun & Marshall, 2003). These are moments that are understood as opportunities to learn that arises when students are excited, engaged and primed to learn and the teacher seizes those moments to optimize scientific understanding.

The results of several research projects have contributed to the development of the Video Feedback Coaching for lower grade teachers (VFCt; Wetzels, Steenbeek, & Fraiquin, 2011). Wetzels and colleagues (2011) bridged research and practice by designing the Video Feedback Coaching program for lower grade teachers. This pedagogical-didactical intervention was developed to evoke change in teacher's practice during science and technology lessons in order to stimulate student's scientific understanding (Wetzels, 2015; appendix C). The intervention was based on principles of talent development, inquiry-based learning and teaching, and behavioral change in the context of science and technology education (Wetzels, 2015; appendix C). Video feedback coaching (Fukkink, 2005) was used as a means to alert teachers on students' talented behaviors and to focus on interactional sequences of high quality during their own lessons. These lessons were videotaped and immediately discussed with them, which is an effective means of supporting teachers to create more of those high-quality moments in order to stimulate students' scientific understanding (e.g. Mortenson & Witt, 1998; Seidel, Stürmer, Blomberg, Kobarg, & Schwindt, 2011). The study showed that the Video Feedback Coaching for lower grade teachers is an effective and efficient way to change teacher's practice. The results are promising in that teachers used more scientific understanding eliciting questions during the coaching-period and the pupils showed an increase in their level of understanding (Wetzels, Steenbeek, & Van Geert, 2015).

Teachers were supported to implement inquiry-based learning as a means to evoke more teachable science moments. Inquiry-based teaching is a frequently used approach in science and technology education in which students' active participation in both scientific experimentation skills and display of scientific understanding is facilitated (Gibson & Chase, 2002). Predictions and explanations have been used as measures for students' scientific understanding (Henrichs & Leseman, 2014; Treagust & Tsui, 2014). Students who are actively engaged in the learning process through scientific investigations show increased scientific understanding (Minner, Levy, & Century, 2010). Although big strides have been made in recent years in the field of understanding students' behavior during science and technology tasks (e.g. Meindertsma, Van Dijk, Steenbeek, & Van Geert, 2012; Oliveira, 2010; Van der Steen, Steenbeek, Van Dijk, & Van Geert, 2014; Van Schijndel, Franse, & Raijmakers, 2010), it remains an open question as to how teachers can stimulate scientific understanding in whole class settings with upper grade students, and how upper grade students construct scientific understanding.

The current study

This dissertation aims to contribute to answering this open question, by reporting about an adaptation of the Video Feedback Coaching for teachers to the upper grade level. The *Video Feedback Coaching for upper grade teachers (VFCt)* was implemented to improve students' scientific understanding in the upper grades of elementary education by supporting teachers with theory, practical pedagogical-didactical strategies, and immediate video feedback[2]. More specifically, teachers were encouraged to change their practice towards the use of open and stimulating questions to elicit and deepen students' scientific understanding. The question of this dissertation is: what are the effects of working with VFCt on teacher's practice and how does this relate with cognitive and non-cognitive aspects of students' learning of science and technology?

That is, we examine whether an increase in students' scientific understanding can be brought about by improving teacher's practice. Teachers' practice is operationalized as teachers' use of pedagogical-didactical skills such as the use of the empirical cycle, scaffolding, and use of questions that elicit students' scientific understanding. Cognitive aspects of students' learning science and technology are operationalized as students' scientific understanding and students' non-cognitive aspects related to learning are operationalized as students' engagement and attitude towards science and technology. The study was implemented in an authentic, ecologically valid context. Recent research has shown that positive adult-child interactions best predict student outcomes (in educational setting, Mashburn et al., 2008; in parental practice, Zaslow et al., 2006), lending support for improving learning by improving the quality of teacher-student interactions (Barber & Mourshed, 2007) and the use of observational techniques to achieve (Fukkink, 2005) and assess (Boelhouwer, 2013) such changes. The potential of a realistic setting was a premise for this study as the authentic setting is critical to gain insight into whether and how teachers can be professionalized in such a way that it yields changes in teacher's practice and students' learning in daily practice. However, as changing practice often yields changes on other related aspects we also examined teachers' and students'

[2] For an elaborate description the reader is referred to appendix C.

attitudes towards science and technology. Coburn (2003) stresses that the depth of change should be assessed by focusing on multiple outcomes by paying attention to beliefs, norms, and pedagogical principles.

The VFCt consisted of an introductory session and four individual coaching sessions. These four coaching session took place immediately after a science and technology lesson. Video feedback coaching was used during the individual coaching sessions to support teachers to change or optimize their repertoire of pedagogical-didactical strategies. Teachers formulated personal learning goals that were used to supply customized support. For research purposes, the coaching sessions were supplemented with premeasures and post-measures. The premeasures were used as baseline measures and the post-measures were regarded as representative for long-term changes. The post-measures allowed investigating whether or not and how teachers sustained the intervention when the coach was no longer present.

Twenty nine upper grade classes of Dutch elementary education participated in this study. Six classes took part in the pilot-study (chapter 2). The effect-study consisted of eleven classes in the intervention condition, i.e. classes who participated in VFCt, and twelve classes in a control condition (chapters 3 to 6). Two types of data were collected; questionnaires and video recordings. Questionnaires were considered as static measures, whereas video recordings of the science and technology lessons were considered as process measures. All students filled out a test about scientific knowledge and teachers and students completed questionnaires regarding their attitude towards science and technology at premeasure and post-measure. In addition to the questionnaires, the classes of the intervention condition were videotaped during eight science and technology lessons, and the classes of the control condition were videotaped during four science and technology lessons (premeasures and post-measures). Data consists of teacher-student interactions recorded in whole class settings.

Complex Dynamic Systems theory

The complex dynamic system view on teaching-learning processes has served as the main overarching theoretical background for this dissertation (as will be discussed in chapter 2), as a theoretical framework for the design and implementation of the VFCt intervention (Wetzels, Steenbeek, & Van Geert, 2016), and as framework for the analysis conducted in the empirical studies (chapters 3 to 6). Next, these three applications will be shortly introduced.

The complex dynamic systems approach views learning as a nonlinear process that emerges in person-in-context interactions over time (Fischer & Bidell, 2006; Van Geert, 2003). In other words, the competence of a student is unfolding in the individual – e.g. based on previous experiences, interest, and enthusiasm - while simultaneously modifying and being modified by the changing behavior of the teacher (Fogel, 2009; Steenbeek & Van Geert, 2013). The theory of co-construction is an operationalization of how complex dynamic systems might emerge in practice (Sorsana, 2008). The major assumption of this theory is that, as students construct scientific understanding about a specific problem, they do so together with an adult or another student. That is, co-construction refers to the process of reciprocal influence (Thelen & Smith, 1994; Van Geert, 1994), which in the case of classroom practices mainly concerns the behavior of a student that influences the reaction of a teacher and vice versa. The best way to study these teaching-learning processes of co-construction is to study it in authentic situations, by observing and analyzing the dynamics of this co-construction process in for instance the classroom.

An important characteristic of complex dynamic systems thinking is that change occurs over multiple (nested) time scales (Lewis, 2002; Thelen & Smith, 1994). This means that learning takes place on a macro-level timescale (over weeks, months or years) and students' performance typically occurs on a micro-level timescale (during an actual lesson). These timescales are nested in that the macro-level learning constrains the behaviors at the micro-level, whereas at the same time the behaviors at the micro-level shape the learning at the macro-level. Teacher-student interactions, i.e. micro-level, during actual lessons are considered to be building blocks by which learning, i.e. increased scientific understanding, emerges and stabilizes over several lessons (Steenbeek & Van Geert, 2013). This refers to the process of self-organization by which global patterns of behaviour arise from the interactions of simpler parts (Fischer & Bidell, 2006; Thelen & Smith, 1994). The processes of teaching and learning are not just the result of putting together a number of properties, such as the teacher's practice and the student's behavioural properties. Instead, teaching and learning are complex, intertwined and self-organizing processes of interactions between many components in the teacher, the student and the school environment (Pennings, Van Tartwijk, Wubbels, Claessens, Van der Want, & Brekelmans, 2014; Steenbeek & Van Geert, 2013; Van Geert, 2009; Van Geert & Steenbeek, 2005; Van Geert & Fischer, 2009).

This perspective has shaped the design of the current project. An intervention that aims to change teacher's practice can be regarded as a 'perturbation' of the complex dynamic system in which the teacher-student system functions on a daily basis (Wetzels et al., 2016). As each teacher-student system is unique, this VFCt took the idiosyncratic processes of learning into account. In fact the implementation of the intervention can be seen as an emergent process in which many components — including the written intervention protocol, the coach's capacities, the unique circumstances of the school and the time and effort invested by the teachers — are dynamically intertwined. Other researchers coin the term process-oriented interventions (Ritzema, 2015) in which the contextual fit of the program is stressed. In the present study, this fit between the VFCt with a specific coach and a teacher is taken into account by adapting the VFCt to the needs and possibilities of each teacher. A consequence of the goal to study the complexity of teaching-learning processes and the focus on the individual is that observational methods, i.e. video recordings, are considered essential to be able to capture the developments on real-time (micro) timescales and to preserve the complexity of the process of learning and change under influence of an intervention.

The complexity of educational settings and the complexity of evaluating the effects of educational interventions in particular pose challenges for researchers. Several properties of learning that eventually result from an intervention such as the VFCt — for example change, nonlinearity, iteration and self-organization, and variability — must be taken into account in order to be able to assess the quality of change during the intervention. These characteristics are, however, hard to capture by using traditional methodology or traditional methods (such as surveys, large-scale studies, and pre-posttest designs). The complex dynamic systems approach, however, offers tools for understanding how interventions or specific teacher's practice yield effects during teaching-learning processes, and for examining how classroom processes unfold in time it is important. To conclude, these considerations are in this dissertation reflected by focusing on individual change in classroom practices by means of time serial analysis. This is important as it provides opportunities to make educational research relevant for the real context of schools.

Overview of the dissertation

The main purpose of this dissertation is to examine, on the one hand, the development of students' scientific understanding in interaction with the teacher, and, on the other hand, how to successfully intervene in this development, by means of studying the effects of the VFCt. Before the main research question about the effects of the VFCt can be answered we consider it essential to first answer the question: which methods can be used to examine the effects of VFCt? This question, which is of a methodological as well as a theoretical nature, will be answered in chapter 2. Chapters 3 to 6 focus on answering the main empirical research question from a multidimensional perspective.

Theoretical and methodological considerations

Chapter 2 is theoretical and methodological in nature. The time serial progress of individual students or the change in micro dynamics in combination with longitudinal data of teacher's practice as a result of an intervention is hardly reflected in effect studies. Often the conclusions of large-scale effect studies are based on surface-level changes such as changes in material or curriculum or an average student outcome measure. Note that this dissertation does not intend to criticize this approach. It does provide important information, for instance if a policy maker has the goal to know which curriculum works best in enhancing students' performances. However, we argue that characteristics of complex dynamic systems methodology provide avenues to more comprehensively understand the properties of the change *process* due to educational interventions on students' scientific understanding and teacher's practice.

To assess the effectiveness of interventions several guidelines are frequently used (Veerman & Van Yperen, 2007). In this chapter we build upon Boelhouwer's taxonomy (2013) — which is grounded in the complex dynamic systems approach — which stresses the importance of using process measures to assess the effects (and depth) of an intervention. An important goal of this chapter is to find ways to gain insight into the properties of teaching-learning processes in individual teacher-student pairs that help understand the effects of the VFCt. Data from the pilot study are used to illustrate the surplus value of using characteristics of a complex dynamic system approach, i.e. a process-based approach, to assess the effectiveness of VFCt on student's scientific understanding. This chapter aims to serve as a theoretical background of the dissertation, and the taxonomy, presented in this chapter, is used as a reference and methodological framework for the analyses in the next chapters.

Empirical studies[3]

Chapters 3 to 6 focus on answering the main research question: what are the effects of working with VFCt, focusing on improving teaching-learning processes, on teacher's practice and how does this relates with cognitive and non-cognitive aspects of students' learning science and technology? Table 1.1 provides an overview of the chapters in terms of variables and type of measurements. Chapters 3 to 6 are based on the data collected during the effect-study. We stated that both cognitive and non-cognitive aspects related to learning are important aspects in teaching-learning processes, and that the depth of an intervention should be assessed by focusing on several aspects that might be influenced by the VFCt. Therefore, the remainder of the dissertation is organized as follows: chapter 3 and 4 focus on cognitive aspects of learning processes (i.e. scientific understanding), while chapter 5 and 6 focus on non-cognitive aspects of learning, i.e. engagement and attitude. Regarding these two aspects of learning, subsequently the first chapters mainly focuses on the static measures (chapter 3 and 5, respectively) while the other chapters specifically focus on the process measures (chapter 4 and 6, respectively). In other words, the latter adds important insights by focusing the intervention assessment on the actual process of change in students' scientific understanding during teaching-learning processes. Each study's primary goal is to establish the effects of the intervention, i.e. answer the main research question. However, at the same time each chapter adds to our understanding about how the particular type of assessment of the intervention addressed in the chapter at issue, can provide insight into the complexity of the evaluation of intervention studies.

Chapter 3 focuses on change in students' scientific understanding during pre- and post-tests to provide information about the global effect of the intervention for the group average of the students. For this study, both static and process measures are used to measure, respectively gains in students' scientific knowledge and students' scientific understanding as constructed in teacher-student interaction. By focusing only on pre- and post-measure and only on student outcomes, a gap remained in our understanding about how change occurs — in interaction with the context during the VFCt — and how this relates to individual learning gains.

[3] The studies presented in this dissertation examined the same intervention. Since we wanted the chapters to be readable in isolation, overlap in terms of background and content of the intervention was deliberately built in.

Therefore, in chapter 4 analyses are based on process measures, i.e. video-observations are used to assess the process of co-constructing scientific understanding in student-teacher interactions. The decision to focus on the occurrence of co-constructive behavior rather than overall student outcome (as in chapter 3) helps to identify which teacher strategies co-determined increased complexity levels of scientific understanding, and vice versa, to see whether the students' scientific understanding had an effect on the teacher strategies. Analyses are carried out using State Space Grid analyses (Hollenstein, 2013). This method of analysis enables to focus on joint states of students' level of scientific understanding and teachers' extent of stimulation in their reactions.

Chapter 5 takes a static perspective on non-cognitive aspects of teaching-learning processes, this time focusing on the change in students' and teachers' attitudes towards science and technology education. Teachers' and students' attitudes are assessed using a questionnaire in a pre- and post-intervention schedule. Again, by focusing only on a static premeasure and post-measure, a gap remained in our understanding about how change occurs and whether the reported attitudes are an accurate reflection of the processes on the behavioral level.

Chapter 6 adds insight by focusing on micro level changes in non-cognitive aspect of learning processes, namely students' engagement. We are interested in how students' scientific understanding and engagement dynamically interact and how the person-context dynamics shape this learning process. A case study approach is used, based on one class that, according to the micro-level analysis in chapter 4, effectively profited from the intervention. The case study enables us to investigate intra-individual change in the teacher-student system, with the aim of finding evidence for the mutual influence between teacher and students, if such form of influence actually exists. The focus is on teacher's openness, students' scientific understanding and students' engagement.

Finally, in chapter 7 conclusions about the effectiveness of the intervention will be drawn by taking the results together. In addition, the implications of this project will be discussed, supplemented with recommendation for educational practice and future research.

Table 1.1 Overview of the chapters

Chapter	Variable	N classes	Goal	Data
2	S. Scientific understanding T. extent of stimulation	6 of pilot study	This study aims to demonstrate how properties of a complex dynamic systems approach can help gain insight into change in teaching-learning processes due to educational interventions.	Process measures
3	S. Scientific understanding	23 of effect study 11 intervention 12 control	This study aims to examine to what extent students' performance changes under influence of the VFCt, and how this compares to changes in the control condition.	Static measures Process measures
4	S. Scientific understanding T. extent of stimulation*		This study examines the characteristics of the process of co-construction of scientific understanding during regular science and technology lessons. The focus is on change in teacher-students interactional patterns in the classes of the VFCt condition, and how this compares to changes in the control condition.	Process measures
5	T. attitude S. attitude		This study aims to examine to what extent the attitude changes under influence of the VFCt, and how this compares to changes in the control condition.	Static measures
6	S. Scientific understanding S. Engagement T. openness*	1 of intervention	This case study describes the time serial relation between engagement and scientific understanding, and teacher-students interactional patterns in terms of engagement and openness during the VFCt.	Process measures

S: Student; T: Teacher. * Teacher openness refers to all teacher utterances and teacher extent of stimulation refers to reactions only (see appendix B).