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# Using the Dynamics of a Person-Context System to Describe Children's Understanding of Air Pressure

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Additional information is available at the end of the chapter

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## 1. Introduction

Understanding refers to “the ability to understand”, which means “to comprehend, to apprehend the meaning or import of, or to grasp the idea of [something]” (Oxford English Dictionary, 1989). Understanding is a key concept within all fields of study concerning learning and development, such as cognitive psychology, pedagogy, educational sciences, and developmental psychology. Within these fields of study, understanding has been studied for different domains, such as scientific reasoning (e.g., Grotzer, 2004; Inhelder & Piaget, 1958/2001; Rappolt-Schlichtmann, Tenenbaum, Koepke, & Fischer, 2007), social development (e.g., Blijd-Hogeweys, 2008), mathematics (e.g., Dehaene, 1997; Gilmore & Bryant, 2008), and many more. In the field of education, children's understanding is especially important, as understanding involves deep knowledge of concepts, and the active manipulation of this knowledge in the form of explaining, predicting, applying, and generalizing (Perkins & Blythe, 1994). A model of understanding can give guidance to both researchers and educators dealing with children's understanding and the development of their understanding. In this chapter, we will present such a model, based on dynamic Systems and Skill Theory principles. The model is illustrated throughout this chapter with examples of children's understanding of scientific concepts, or more specifically, children's understanding of air flow and air pressure during a syringe task, which is described below. The syringes task is designed to let children explore how air flows through a system, and to introduce them to the relationship between pressure and volume, as well as the way in which pressure can exert forces on objects (see also De Berg, 1995). Although there are some basic questions the researcher asks every child during the administration of the task, most of the interaction between the boy and the researcher emerges in real-time, i.e. during the task itself.

Between three and seven years of age, important changes in children's conceptual understanding of scientific concepts take place (Van Geert & Steenbeek, 2008), in addition to changes in curiosity and exploration tendencies (Simonton, 1999), which are probably related to important changes in children's lives. That is, they go through a major transition when they enter first grade, and start learning to read, write, and to do arithmetic (Carrière, 2009). During this age period children's learning behavior gets shape, attitudes toward school are formed, and first interactions with peers and teachers in a school setting emerge, which are the building blocks of academic performance at a later age.

Moreover, this is also the age at which important cognitive developmental transitions take place. From the work of Piaget (1947/2001) we know that children between three and seven years old are in the pre-operational stage of development, which is characterized by the forming of concepts, and the use of symbols to think about the world, but also by centrism, i.e., focusing on a single aspect instead of more aspects while children reason or solve problems. More recently, research using Skill Theory, which is inspired by Piaget's theory, illustrated that the highest skill (understanding) level that children first reach between 3 and 7 years of age develops from single representations (understandings that go beyond specific actions on objects) to representational systems (linking several of these representations that define the object or concept at hand – see also section 3) (Fischer & Bidell, 2006). However, this research also showed that children vary enormously in their skills across context, tasks, and within short periods of time. This variation is due to the fact that context dynamically contributes to the deployment of skills in the form of a real-time activity. That is, thinking or understanding takes place in the form of action. How does the process of understanding occur in action, taking into account the real-time interactions that constitute this process in a teaching environment, and taking into account the vast amount of intra-individual variability?

Based on our ongoing longitudinal research project, we will illustrate how short term “building blocks” of understanding give rise to various long-term patterns of understanding. In order to fully understand these short-term building blocks, we have selected one particular problem domain for this chapter, namely air flow and air pressure, because it provides a domain that is both limited and rich enough to study. Zooming in on these short-term interactive processes gives us important information to understand the development and transformations of understanding on the long term (Steenbeek, 2006; Thelen & Smith, 1994).

During the ongoing longitudinal research project, a researcher repeatedly visits 32 young children (3 to 6-years old) as part of an ongoing longitudinal study on children's understanding of scientific concepts, such as the flow of air and air pressure. During one visit, the researcher presents each child with two empty medical syringes without a needle, which are joined together by a small transparent tube. One of the syringes' pistons is pulled out. “What do you think will happen if I push this [piston] in?” is one of the questions the researcher asks. This question triggers a variety of answers from the children. Some children think nothing happens, others say the tube will pop out, whereas others even think the

material will explode. Some children say they don't know and others predict that the piston of the other syringe comes out, which is the right answer in this case. After the researcher demonstrates what happens, researcher and child discuss about possible explanations for this phenomenon. Again, multiple answers are given. Some children simply say they don't know. A few mention batteries or electricity as a causal explanation, whereas others say that water flows through the syringes and causes the piston to move upwards. Some children emphasize the tube that connects the syringes, and others understand that air flows through the tube and syringes.

What accounts for the differences in young children's understanding of scientific concepts, and what is the role of the environment, i.e., the teacher in supporting and promoting this understanding? To answer this question, a model of children's scientific understanding should take the complexity and dynamic nature of this into account, as well as the complex interactions with the environment on which the understanding of children is often based (Fischer & Bidell, 2006). This chapter aims at explaining how children's understanding of scientific concepts can be studied using a model based on properties derived from dynamic systems Theory (e.g. Van Geert, 1994) and Skill Theory (Fischer, 1980; Fischer & Bidell, 2006).

## 2. Dynamic systems and understanding

A dynamic systems approach describes how one condition changes into another, and how different time scales are interrelated (Van Geert, 1994; Van Geert, 1998; Van Geert & Steenbeek, 2005, 2008; see also the theory of embedded-embodied cognition of Thelen & Smith, 1994). Research in the dynamic systems paradigm investigates real-time processes and captures development as it unfolds through multiple interactions between a child and the environment (Van Geert & Fischer, 2009). Such development can be viewed as a self-organizing process, since the state of the system organizes from the multiple interactions among the elements (e.g. the child and environment). Over time, the system's state may emerge toward certain stable states, or attractors (e.g., Thelen & Smith, 1994). Dynamic systems theory has so far proven to be a valuable framework for studying human development, including reflexes (Smith & Thelen, 2003), parent-child interactions (Fogel & Garvey, 2007), language development (van Dijk & Van Geert, 2007), scaffolding in teaching-learning situations (Van Geert & Steenbeek, 2005), dyadic play interactions (Steenbeek, 2006), identity development (Lichtwarck-Aschoff, Van Geert, Bosma, & Kunnen, 2008), and cognitive development (Fischer, 1980; Fischer & Bidell, 2006). The approach makes use of methods to investigate time-serial processes, and test dynamical relations between these processes (Cheshire, Muldoon, Francis, Lewis, & Ball, 2007; Lichtwarck-Aschoff, et al., 2008; Van Geert & Steenbeek, 2005; 2007; Steenbeek & Van Geert, 2005). For example, Van Geert and Steenbeek (2005; 2007) present mathematical models to predict patterns and variations in combinations of variables over time. Other authors used time series to describe relationships between variables (van Dijk & Van Geert, 2007) or state space grids (Hollenstein, 2007) to investigate interactions between dyads; as opposed to probabilistic approaches which rely on deviations from the mean and group differences.

Applying a dynamic approach to the study of understanding scientific concepts means that several properties of this approach have to be taken into account. Below, four properties (intertwining person-context dynamics, iterativeness, interconnected time scales, and micro-genetical variability)<sup>1</sup> and examples of their application to the study of understanding (of e.g., scientific concepts) will be discussed. In section 5, the properties will be illustrated in light of an empirical example, in combination with Skill Theory's framework to measure the complexity level of understanding (Fischer & Rose, 1999).

## 2.1. Intertwining person-context dynamics

Vygotsky (1934/1986) already pointed out that children develop understanding in close cooperation with their teachers and the material. His concept of the zone of proximal development is a dynamically changing concept, in which teacher and child co-construct the child's development. This means that the child's skills and understanding are constructed by a series of actions guided by the educator, instructions and tool-use, which are then internalized and personalized (cf., Van Geert, 1998; Van Geert & Steenbeek, 2005).

From a dynamic systems perspective, understanding is seen as a process of intertwining person-context dynamics (Thelen & Smith, 1994), meaning that the social (e.g., the science teacher) and material environment (e.g., materials used in science class) play an active part in the process and cannot be viewed separately, or merely as an outside-based influence. In fact, these elements are intertwined across time, in a continuous person-environment loop: at any moment in time, one component (e.g., the child) affects the other (e.g., the teacher) and the other affects the first, thus creating the conditions under which both components will operate during the next moment in time (Steenbeek, 2006). For example, interactions between a child, a researcher, and the syringes-task will organize toward certain distributed patterns of understanding at that moment (in real time), which eventually evolve toward stable attractors on a longer time scale (Thelen, 1989; Halley & Winkler, 2008). Hence, understanding is an active process of what the child constructs in interaction with (not just within) a specific environment, in which each individual contribution is virtually meaningless if not viewed in light of the interaction (Van Geert & Fischer, 2009). Merged together, person and context become what Fogel and Garvey (2007) call a "cooperative unit", in which both components not only contribute to the process of development, but are highly intertwined and form an unique process together.

Representationalists, such as Fodor (1981) hold the idea that understanding takes the form of internal structures (representations) within the child's mind. A child's scientific understanding thus consists of a collection of these internal structures which represent scientific facts and concepts, which are activated and used to coordinate our behavior toward the current environment (Haselager, de Groot, & van Rappard, 2003). In this case, a

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<sup>1</sup> Actually, the dynamic systems approach has many more properties or "tools" (Howe & Lewis, 2005) to study development. However, we highlighted these four specific properties to illustrate how this approach sheds new light on the study of understanding scientific concepts.



concept or representing model of the air pressure task would be represented in the child's mind, and this representation would guide the child's behavior as he or she is working on the actual air pressure task.

Terms such as "concept" or "representation" are actually more or less undefined, and derive their meaning from a particular theoretical framework. From a representationalist (or information-processing) view, these words refer to internal entities responsible for our thinking or actions toward the environment. From a dynamic view, however, these words refer to processes, perception and action structures, that emerge within a specific environment (Van Geert & Fischer, 2009). Perceiving, acting and thinking are conscious processes that take a particular shape in the stream of consciousness of the participants, such as a child and the researcher (van Gelder, 1995; 1998). This shape is governed by the participants' actions on the objects, such as the syringes, or on physical representations of the syringes, such as prints or drawings, within their current context, and should not be identified with a retrieval of internally stored representations (Van Geert, 2011). We can construct much of this stream of consciousness by carefully watching the ongoing interaction between child and environment in terms of the intertwining of various forms of verbal and non-verbal behavior, such as eye and head movements, gestures, pointing, verbal descriptions, manipulations of the materials, etcetera. The child's current understanding of the concept at issue (for instance, the flow of air through two syringes connected by a tube), is the child's continuously changing state of mind, or stream of consciousness, as he picks up and reacts to whatever goes on in the current dynamic interaction. Thus, despite the fact that the process of constructing an understanding is a distributed process, involving the intertwining of person and context, understanding can still be specified as an individual and "internal" process corresponding with the individual child's ongoing state of mind, but only as a changing state that unfolds in this active process (Van Geert, 2011). Hence, representations are structures that emerge during a specific interaction in a specific environment, and are not internal symbolic structures which guide behavior.

## 2.2. Iterativeness

Within the process that results from an intertwining between person and context, understanding emerges through iteration, that is, every step in understanding is based on the previous one and embedded in the current context. More precisely, iterativeness (sometimes referred to as recursiveness) involves a series of computational operations, in which the input of the next operation is the output of the previous one. For instance, if a child determines that an empty syringe contains air, he can build on this knowledge by trying out what happens if he joins two of these syringes together by using a tube. Understanding changes through repeated interactions, instead of being the retrieval of a complete representation that is already there in memory. During a teaching interaction, each previous action of the child has an influence on the subsequent (re-)action. In other words, the existing understanding is the basis for the emergence of the next understanding as it develops in the interaction.

In its simplest possible form, a dynamic systems model specifies the change in a variable ( $L$ ) over time ( $t$ ) as a function of the current level of the variable:  $L_{t+1} = f(L_t)$ . The function  $f$  refers here to the change in 'understanding', but can specify any sort of influence or mechanism of change (Steenbeek, 2006). Understanding does not consist of particular moments within the interaction (e.g. when the child answers), but is in fact the whole iterative process itself, and every interaction unit is a component of this holistic understanding process during a particular problem solving event. Even though understanding consists of the whole iterative process, the child's answers are a reflection of the child's ongoing state of mind within that process and reveal his or her understanding at that very moment in time.

As Howe and Lewis (2005) point out, the iterative nature of the process of understanding can also explain some of the differences between children. When children's understanding depends on interactions, and each interaction is based on the previous one, small differences between children's initial states of understanding can grow bigger over several interactions. This is particularly so if the process takes the form of a positive feedback loop amplifying idiosyncratic properties of the answers, i.e. properties that are typical of a particular child. For example, if the child focuses on only one syringe and the researcher's follow-up questions center on that syringe as well, the difference between this child and another child who focuses on both syringes grows bigger. However, if the process takes the form of a negative feedback loop reducing the idiosyncrasies, small differences in initial states will most likely remain small over the course of the problem-solving process. This would be the case if the researcher switches the focus of her follow-up questions to the other syringe, thereby scaffolding the child towards a more complete picture of the task. The difference between this child and the child who initially focused on two syringes then becomes smaller.

### 2.3. Time scales

The property of interconnected time scales entails that the dynamics of long-term development of understanding are intrinsically related to the dynamics of short-term processes of understanding (Thelen & Smith, 1994; Lewis, 2000). That is, in order to get a grip on long-term changes in understanding of children, it is worthwhile to focus on the short-term (micro-genetic) process, and examine properties of that process, such as variability (Granott, Fischer, & Parziale, 2002; Steenbeek, 2006).

Iterativeness occurs on the short term as well as on the long term, meaning that on the short term (e.g. during one interaction between child and teacher in science class), each step in understanding is based on the previous step in understanding, while on the long term each interaction builds on the preceding interaction (e.g. the interaction during last week's science class). In this way, the same mechanisms are sculpting the development of understanding over a shorter and longer period. Thelen and Corbetta (2002) indicate that the general principles underlying behavioral change work at multiple time scales. The short-

and long-term scales interact, in that repeated (iterative) processes on the short term time scale influence processes on the long-term time scale (Lewis, 2000). In addition, the emergence of large-scale patterns also influences what happens on the short-term time scale, by shaping the structure and function of the interaction on the short term (Lewis & Granic, 2000; Smith & Thelen, 2003; Van Geert & Steenbeek, 2005; Steenbeek, 2006). The underlying idea is that all levels of the developing system interact with each other in a self-organizing way, and consist of nested processes that unfold over many time scales, from milliseconds to years (Thelen & Smith, 1994; Lewis, 2000).

## 2.4. Micro-genetical variability

As a result of the iterative organization of the components and the intertwining between child and context that mark the process of children's understanding, we can observe micro-genetical variability. This means that the complexity of children's understanding fluctuates within very short periods of time, e.g. during one task. While studying the processes of developmental change, it is crucial to take many observations (adopting a microgenetic research method) to detect the subtle changes that constitute understanding and its development (Siegler & Crowley, 1991; Kuhn, 1995). Researchers note that, driven by bi-directional interactions with the environment, the complexity of children's understanding can increase during a task, but also temporally decrease, for example when the task difficulty increases, when the teacher's support decreases, or when children encounter something unexpected while working on a task. Understanding can change gradually or abruptly in a stage-like pattern in a short timeframe, even during a single task (Yan & Fischer, 2007; Siegler & Crowley, 1991).

Researchers have suggested that this variation is an important factor in development, since an increase in variability may be related to the ability to reach higher levels of skill (Howe & Lewis, 2005; Thelen, 1989), or, more generally, to a transition to another pattern of behavior (i.e., attractor) (e.g., Thelen & Smith, 1994; Van Geert, 1994). The variability on the short-term (e.g. during the syringes-task or during a science lesson) can therefore yield important information about how the developmental pathways of understanding will be shaped on the long term.

In order to capture the complexity of understanding and variations in complexity over a short and longer time periods, we can use Skill Theory's framework of cognitive development (Fischer, 1980; Fischer & Bidell, 2006). This framework can be used on both the long- and short-term time scale and is compatible with a dynamic systems approach. Even more so, Skill Theory could be considered as a specific dynamic system's theory applied to human skill development, since it assumes skills are built in an iterative and hierarchical way, i.e. each skill level builds on the previously obtained skill level. Moreover, skills are highly context-dependent and fluctuate over time, that is, they depend on the constraints and affordances of the context in which they are mastered (Fischer & Bidell, 2006).



### 3. Skill theory and understanding

Skill Theory focuses on the complexity and variability of children's skills, which consist of actions and thinking abilities, and the way these are constructed (Fischer, 1980; Fischer & Bidell, 2006). Since skills are thinking structures mastered in a specific context, such as a science class, they hold both person-related as well as context-related characteristics (Parziale & Fischer, 1998). An example of a skill is a child's ability to understand how air pressure works while manipulating the syringes-task. This understanding is reformulated when the student works on a similar task in another environment (e.g. with different materials or without the help of the researcher). Skills are thus highly influenced by the possibilities and constraints of the situation in which the skill is used.

Skill Theory explains both long- and short-term development of skills by measuring these on the same hierarchical complexity scale. This complexity scale consists of 10 levels, grouped into 3 tiers, which are sensorimotor, representational or abstract by nature. The scale can be applied to different cognitive (Fischer & Granott, 1995; Schwartz & Fischer, 2005), social (Fischer & Bidell, 2006) and language domains (Fischer & Corrigan, 1981), as it focuses on hierarchical complexity rather than content. This makes Skill Theory especially suitable to describe differences between children, as well as differences between skills in different domains for the same child (Parziale & Fischer, 1998).

A child's understanding within a domain, as an emergent process in real-time, can be viewed along two dimensions: the first being the dimension of content (the subject), the second of complexity (the complicatedness). In order to evaluate children's understanding (of, for example, air pressure), we need a fair ruler to determine how elaborate their understanding is, and to evaluate whether they need extra help in some areas. One of the most powerful characteristics of Skill Theory (Fischer, 1980) is that it extracts complexity from content, resulting in a content-independent ruler of understanding. Because of the content-independent nature of the way Skill Theory approaches understanding (or other skills), it enables researchers to compare understanding across multiple time points, contexts, persons, and for different age ranges.

According to Fischer (1980) and Fischer and Bidell (2006), development in a particular domain goes through 10 levels of skills hierarchically grouped into three tiers that develop between 3 months and adulthood. The first tier consists of sensorimotor skills: simple connections of perceptions to actions or utterances. An example is a statement that two syringes are attached to a tube. Sensorimotor skills form the basis of the skills in the two subsequent tiers, i.e. they are the building blocks of the higher levels. The second tier constitutes of representational skills, these are understandings that go beyond current simple perception-action couplings, but are still based on them. Hence, the term representation refers to the coordination of several sensorimotor skills at the same time, not to an internal symbolic structure (Fischer, 1980). Within the context of the air pressure task for example, the child can predict what will happen if the piston is pushed in without literally touching or manipulating the syringe. Nonetheless, what he or she predicts depends on the material context, and on the sensorimotor skills that he or she mastered

before. The third tier consists of abstractions, which are general nonconcrete rules that also apply in other situations (Schwartz & Fischer, 2005). This would be an explanation about the relationship between pressure and volume inside a syringe.

Within each tier, three levels can be distinguished<sup>2</sup>, each one more complex than the previous one. The first one can be characterized as a single set, meaning a single action (or a single representation, or a single abstraction). The second level is a relation between two of these sets, which is referred to as a mapping. The third level is a system of sets, which is a relation between two mappings, in which each mapping consists of a relation between single sets. After this level, a new tier starts, which is divided in single sets, mappings and systems as well (Fischer & Bidell, 2006). For the emergence of each level, evidence of discontinuities and differences between levels has been demonstrated using analysis methods based on Rasch scaling (Schwartz & Fischer, 2005).

Fischer and colleagues (Fischer, 1980; Fischer & Bidell, 2006; Yan & Fischer, 2002; Schwartz & Fischer, 2005; Granott & Parziale, 2002) showed that Skill Theory can not only describe and explain the development of skills on the long term, but also describe the micro-genesis of problem solving. When facing a new task or problem within a domain, even high-skilled adults go through the same cycles of development. That is, at the beginning they show skill levels that are mostly sensorimotor, which build up to more elaborate levels during the course of the task. During a task (and also during the long-term development of skills), people do not go through the skill cycles in a linear fashion. Instead, they repeatedly build up skill levels and show collapse before they obtain their highest possible level, something Yan and Fischer (2002) call "scaloping". During a task, people vary constantly within a bandwidth between their highest and lowest possible complexity levels, which is also known as the developmental range. The highest levels within the bandwidth are only reachable when the environment provides sufficient support (Fischer & Bidell, 2006; see also Yan & Fischer, 2002).

Skill theory also accounts for inter-individual differences in understanding and is therefore especially suitable for describing individual developmental pathways (Fischer, Rose & Rose, 2007). Yan and Fischer (2002) showed that adults' performance on a computer task can move through a variety of pathways, each one showing nonlinear fluctuations. Of all participants, novices showed the most frequent and rapid fluctuations in performance. Experts however fluctuated less frequent in their performance, meaning that variations followed on each other in a slower fashion.

In sum, a model of understanding needs some kind of ruler to determine the complexity of understanding levels children show. Skill Theory (Fischer, 1980; Fischer & Bidell, 2006) provides a content-independent ruler for understanding, which can be applied to different

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<sup>2</sup> After the 3 levels of the abstraction tier, a higher complexity level emerges, also known as 'single principles', which is the 10<sup>th</sup> level of the scale. Additionally, people function on the few highest levels usually in early adulthood, but only for their domains of expertise. For most other domains, people function on a lower complexity level.

time scales of development, and takes both the role of context, as well as inter- and intra-individual variability into account.

#### 4. A model of understanding

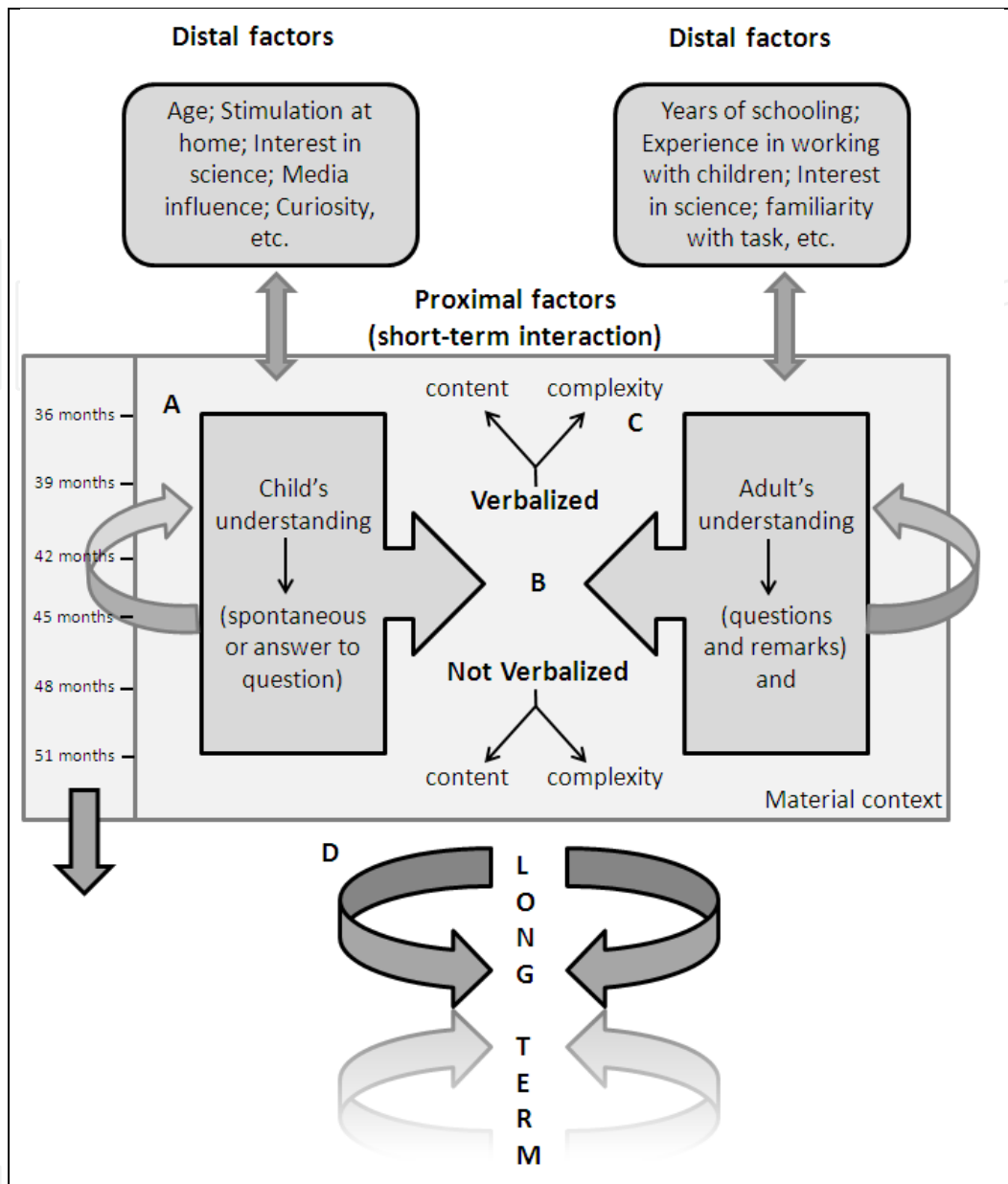
Using the four properties from the dynamic systems paradigm and Skill Theory's ruler, we can construct a model of understanding to guide research and practice in education, but also in other areas that require the evaluation of cognitive growth. The general model of understanding here is that it is an active process, distributed across people involved, and that it is dynamic, i.e., it continuously changes, and self-organizes through iteration. It is important to keep in mind that, even though the four properties describe distinct mechanisms, they all work at the same time while the process of understanding unfolds. Below, we will present the model and briefly highlight its components, after which we discuss these in more detail by using an empirical example.

As Figure 1 shows, children construct levels of understanding during short-term interactions with the environment, such as during a task they are working on together with an adult. Both child and adult are characterized by specific distal factors (e.g. years of schooling) that influence their behaviour. However, those distal factors are not what we focus on, since the figure can be characterized as an action model, that is, it focuses on understandings which are constructed during an interaction by means of a process that is distributed across the child, the adult, and the material context with which they interact or which they manipulate. This means that during an interaction, there is a bidirectional influence between the child's answers and the adult's questions within the material context. This is illustrated in the big square (part A) of figure 1.

Moreover, the process is iterative, meaning that it changes through repeated interactions, instead of being the retrieval of a complete representation that is already there in memory. During a teaching interaction, each previous action of the child has an influence on the subsequent (re-)action. This is illustrated by the big arrows between adult and child (part B of figure 1) and the small arrows on the side of the boxes indicating the child and adult.

Each task-related utterance has two dimensions: a specific content and a complexity level. During interactions, we can observe the complexity level of understanding, as it comes forward in the child's distinct utterances, which are often reactions to what the adult is saying, or are part of the ongoing discussion between an adult and a child. This complexity level, measured by Skill Theory (Fischer, 1980), will vary between different children, and will fluctuate over time within the same child. This is illustrated by part C in figure 1.

Lastly, the long-term development of children's understanding unfolds through several of these short-term interactions. As an example, figure 1 displays the sessions with 3-month intervals we used in our study of young children's understanding of scientific concepts. The link between short- and long-term development is indicated in part D of figure 1.



**Figure 1.** A conceptual (action) model of understanding based on principles derived from dynamic systems theory and Skill Theory

## 5. An empirical example and illustration of the model

In the next sections, we illustrate the model and the four properties by using an example (see table 1) derived from our empirical study focusing on the long-term development of understanding air pressure (and other scientific concepts, such as gravity) in three to seven year old children. Table 1 is an excerpt of a transcribed session in which a boy (4 years, 6 months) and a researcher explore the syringes task mentioned in the introduction. The transcript starts right after the point in which the researcher and the boy explored the exterior of the syringes. That is, they compared them in size and examined the numbers written on the outside.

Person	Content: verbal ( <i>gestures, manipulations, gaze directions</i> )	Complexity	Nr
Researcher	(Attaches the two syringes by a small transparent tube, gives one syringe to the boy) "I attached the tube to these. What do you think will happen if I push mine in?"		1
Boy	(Looks at his own syringe) "I don't know"	No level	2
Researcher	"But what do you think?"		3
Boy	(Looks from the researcher to his syringe) "Uhm..."	No level	4
Researcher	(Pauses) "You said they are the same. I pulled this piston out ( <i>Touches the piston</i> ), and pushed the other piston in ( <i>Points down to the other piston</i> ). Then I attached the tube. What do you think will happen if I push this one in?" ( <i>Gestures as if she is pushing down</i> )		5
Boy	"Then this one will go up like this." ( <i>Holds his syringe in one hand, while his other hand pushes the end of the piston on the table, then he moves his hands up</i> )	Single representation (prediction)	6
Researcher	(Points to this syringe the boy holds) "Is that one going up?"		7
Boy	"Yes, and then that one is going down" ( <i>Points at the piston of the syringe the researcher is holding</i> )	Single representation	8
Researcher	"Really? Why does that happen?"		9
Boy	"Because we attached the tube." ( <i>Follows the tube with his finger to the tip of his syringe</i> )	Sensorimotor system	10
Researcher	"I see... If we would take away the tube, it wouldn't work?"		11
Boy	(Shakes his head) "No".		12
Researcher	(Pushes her piston in, pauses) "Were you right?"		13
Boy	(Watches his own syringe as the piston pulls out) "Yes"		14
Researcher	"Can you do it as well?" ( <i>Holds her syringe up</i> )		15
Boy	(Looks at both syringes, pushes the piston of his syringe in)		16
Researcher	"How is this possible? You're pushing it over there ( <i>Points at the piston of the boy's syringe</i> ) and then this one goes backwards!"		17
Boy	(Pushes piston in and pulls it out) "I don't know"	No level, zero	18
Researcher	"OK, but it has something to do with the tube, you said. What do you think is inside the syringes and tube?"		19
Boy	(Pauses for a long time, looks around) "I don't know"	No level, zero	20
Researcher	"I think there's no water in it" ( <i>Shakes her syringe</i> )		21
Boy	"No" ( <i>Starts shaking the syringe</i> )		22



Person	Content: verbal ( <i>gestures, manipulations, gaze directions</i> )	Complexity	Nr
Researcher	"But then, what is in it? And how is it possible that we can move one by pushing the other?"		23
Boy	"Because this is attached ( <i>Touches the end of the tube</i> ) and then it can move out" ( <i>Pulls the piston out</i> )	Sensorimotor system	24
Researcher	"You know what; we can also attach a longer tube! ( <i>Gets a longer tube</i> ) "What do you think will happen then?"		25
Boy	( <i>Gets the end of the tube and attaches it to his syringe</i> ) "I think still the same."	Single representation (prediction)	26
Researcher	"Even with a longer tube?"		27
Boy	"Yes" ( <i>Looks at his syringe</i> )		28
Researcher	( <i>Pushes her piston in, it works</i> ) "So now it works as well"		29
Boy	( <i>Pauses, pushes the piston of his syringe in, then pulls it out</i> )		30
Researcher	"So it has to do with the tube or something like that..."		31
Boy	"Yes, because the tube is attached to this one ( <i>Looks at syringe while he pushes the piston back in</i> ), and it is attached to here ( <i>Points at the point where syringe and tube are connected</i> ), and then goes ( <i>Makes a gesture for pushing the piston in</i> ) this ( <i>Points at the tip of the syringe</i> ), it goes like this" ( <i>Follows the tube from the tip until he is halfway</i> )	Single representation	32
Researcher	"I see...what do you mean when you say 'this'?"		33
Boy	( <i>Keeps on following the tube with his finger, can't reach for the last bit, so follows it in the air</i> ) "The tube, it goes like this"	Single representation	34
Researcher	( <i>Follows the last bit of the tube with her finger</i> ) "Yes, but what is going through the tube?"		35
Boy	"That... ( <i>Pauses and looks at the tip of his syringe</i> ) "The sigh is going through the tube ( <i>Gestures for pushing the piston in</i> ) "And then it goes, like this, and this, and this" ( <i>Follows the tube until halfway</i> )	Single representation /representational mapping	36
Researcher	"The sigh is going through the tube and flows to mine?"		37
Boy	"Yes" ( <i>Pulls the piston of his syringe out</i> )		38

**Table 1.** Excerpt of a session from our longitudinal project in which a boy (4 years, 6 months) explores the syringes task together with a researcher.

### 5.1.1. Person-context dynamics – social construction

An important part of these context dynamics is the social part of the context, meaning the people around the child. Thus, the development of the child's understanding occurs in

interaction with the social environment (e.g. the teacher), and it is this interaction that drives the process of understanding, enabling the student to receive adaptive assistance and make progress step by step (Hirsch-Pasek, Golinkoff, Berk, & Singer, 2009; Van Geert & Steenbeek, 2005). In our example (see table 1), the child constructs his answers together with the researcher. The researcher's questions are guided by, and on their turn guide, the child's answers. An illustration of this can be seen in fragments 2 to 6 of table 1. After the boy answers he does not know what happens with the syringe he is holding if the researcher pushes the piston of the other one in, the researcher asks him "What do you think?" In this way, she is trying to get the boy to make predictions, encouraging him to hypothesize. In response, the boy looks around and does not answer the question. The researcher, in turn, helps him getting started by summarizing what he said before and by a verbal repetition of her actions with the task material. After having heard the adult's repetition of her actions, the boy starts to construct an answer on a higher complexity level than before. In terms of Skill Theory, this answer can be classified as a single representation, as he makes a prediction that goes beyond simpler perception-action couplings (skill levels, when applicable, are indicated the right column of table 1).

Two things are important here. First, the researcher is responding to the boy in this way, because he did not know the answer. Had the boy given the answer, she may had pushed the piston in, or asked him to elaborate on his answer. Because the boy does not know the answer, she needs an approach to determine whether he really has no idea, and if so, how she can help him to make a prediction based on what he knows about the syringes. In order to do this, she tries out two different approaches. First, she asks him what he thinks, which can be a starting point for further elaboration on his side. When the boy does not reply, she decides to help him to get started by giving some information about what they have done and seen before. The boy now hypothesizes what happens if the piston of one of the syringes is pushed in. The answer to the question "What do you think will happen?" (see fragment 1 of table 1) is therefore the product of the interaction between the boy and researcher. In her reactions to the boy's "I don't know" the researcher is trying to guide his understanding. In turn, after hearing the researcher's summary, the boy constructs his understanding. What happens with regard to the boy's understanding during the interaction with the researcher is not mere retrieval of earlier gathered knowledge, or a reaction to a trigger (whether it be the syringe itself or the questions), but a (re)construction of knowledge through a constellation of interactions with researcher and material. If we look at understanding while it occurs in real time, we can only study the person-context aggregation that results from this interactive process and cannot distinguish the unique contribution of the individual components (Van Geert & Fischer, 2009). Even though one can describe what the child does in answer to a specific action or expression of the adult; it is not possible to distinguish the adult's or child's contribution to the (variance in) understanding during the task.

Parallels can be drawn with other teacher-student interactions, such as in scaffolding during instructions in arithmetic lessons. In their model of scaffolding, Van Geert and Steenbeek (2005) model the process of scaffolding during an arithmetic class taking a dynamic systems

approach. Scaffolding is an interactive process in which the student makes progress using the help of a teacher, which scaffold-level should be adapted to the student's level in order to have the right effect. One of the most interesting properties of this dynamic model is that it accounts for transactions between teacher and student, and that it portrays a dynamic, real-time combination of both the student's performance level and the scaffold-level of the teacher. One of the parameters in the model is the *optimal scaffolding distance*, a bandwidth which differs among individuals and contexts, within which help stimulates learning. Within that bandwidth, the optimal scaffolding distance is the distance between the pupil's level and the level of help or scaffolding for which the learning effect is maximal. Just like in our model of understanding, the actions of student and teacher form a unique process built of bi-directional relationships (Fogel & Garvey, 2007).

### 5.1.2. Person-context dynamics – the material context

In addition to the social context, the material context (such as the syringes) also plays an important role in the process of understanding. The syringes should not be conceived of as fixed or monolithic things, but are instead part of the emerging dynamics. Even an unmovable material object is dynamic in terms of its effect on the child, in the sense that the child continuously changes his angle of vision towards the object and thus sees different parts of the object. The dynamic and intertwining nature of the material context is even more strongly illustrated by the syringes task, in which the child or the adult manipulate the syringe, and are thus changing the nature of the object in line with their activities.

In the example (table 1), the syringes and tube are frequently touched by the boy and the researcher to emphasize or guide their verbal expressions (see fragments 5, 6, and 10). The best illustration of this, however, can be found in fragments 32 to 36. In this fragment, the boy uses the material extensively, after which a higher level of complexity emerges: he transitions from a sensorimotor systems level to a single representation/representational mappings level. Note how the boy substitutes words for gestures and pointing in fragments 32 and 34, following the process of what happens with his hands. Parallels can be drawn with fragment 5, in which the researcher is talking the boy through what happened before. In fragments 32 and 34, however, the boy uses the material instead of the researcher's words to construct his understanding. Before fragment 32, he predicted that one piston comes out when you push the piston of the other syringe in. However, so far, he was not able to explain why. Now, using his hands to examine the syringe, he is able to represent the process, and concludes that "it" is going through the tube. Eventually, guided by the researcher's question "But what is going through the tube?" which seems to suggest that he is on the right track, he is able to replace the word "this" in his explanation for "sigh".

## 5.2. Second property: Understanding is an iterative process

In figure 1, the iterative character of the understanding dynamics between student and researcher is shown in that each previous action of the student has an influence on the subsequent (re-)action of the researcher, and vice versa. Over time, each session has an influence on the subsequent session of this student-researcher pair, which implies that the

influences between the child and environment are bidirectional, meaning that not only the action of the researcher influences the next (re)action of the student, but also that the previous interaction influences the next interaction. Iterativeness is thus the form in which the cyclical or reciprocal character of causality occurs.

In our example (table 1), the iterative nature of the process is not only illustrated by how the researcher and child react to what has been said previously throughout the whole transcript, but also by how the child's understanding develops during the interaction. With regard to the prediction he makes in the first half of the interaction, the child goes from "I don't know" (fragments 2 and 4; no skill level) to "This one goes up like this" (fragment 6; single representation). This change in understanding is constructed in reaction to what the researcher said right before in fragment 5. With regard to the explanation of the boy why this happens, his understanding goes from "Because this [the tube] is attached" (fragment 24; sensorimotor system), to "Something goes like this [through the tube]" (fragment 32; sensorimotor system/single representation), to "The sigh is going through the tube" (fragment 36; single representation/representational mapping)." The statement that the tube is attached, which the researcher repeats and emphasizes in fragments 19 and 31, leads to the conclusion that there must be something flowing inside the tube. Since there is no water in the tube fragments 21 and 22), or anything else visible for that matter, it must be "sigh" (fragment 36).

This step-wise refining of the boy's understanding, in which each previous step is the beginning of the next step, illustrates the iterative nature of the process nicely. Not only does iterativeness occur on the conversation level (what the child says depends on what the researcher said previously and vice versa), it also occurs on the complexity level of understanding (each understanding of the child depends on the previous understanding). Finally, the iterative nature of the process can also be seen over sessions, meaning that previous sessions influence subsequent sessions.

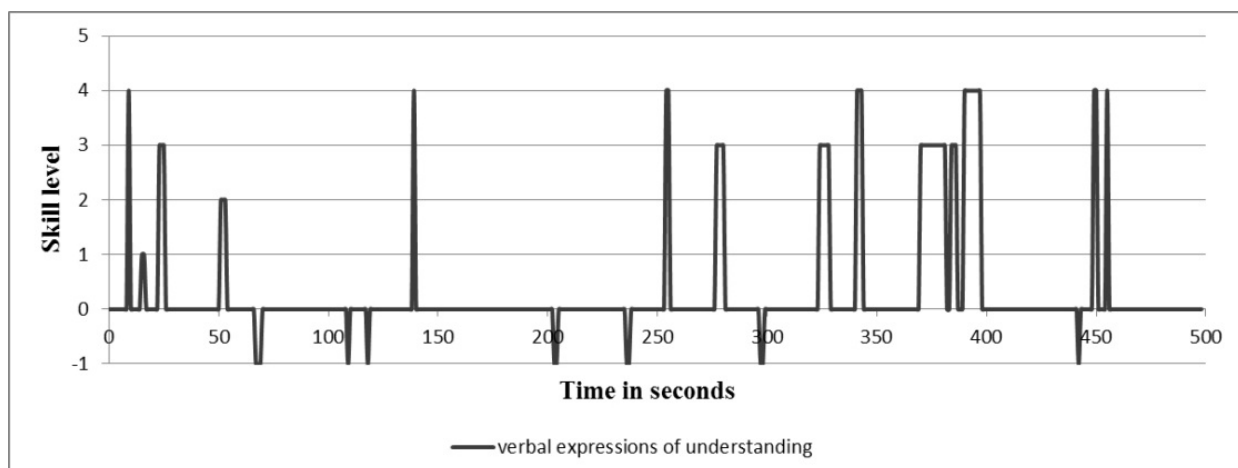
### 5.3. Understanding is micro-genetically variable

In our example (see table 1), micro-genetical variability is seen in the child's understanding of how the material works. First, in fragment 10 the boy names a single cause for what happens: "Because we attached the tube". This is an answer on a sensorimotor system level; he gives a single, observable causal explanation for the phenomenon, not taking the volume of the syringes or the air into account (see also the third column of table 1). Over the course of the interaction, he briefly regresses to "I don't know" (fragments 18 and 20; no skill level), and restores his previously gained skill level again in fragment 24: "Because this [the tube] is attached". From there, he further constructs his understanding, and eventually reaches a higher level in fragment 36: "The sigh is going through the tube", for which he needs a representation of the role of air in the system.

In Figure 2 a time-serial illustration of the fluctuations in the boy's answer levels during the air pressure task is depicted. The graph shows how the understanding of the boy fluctuates over time. While Skill Theory's level 4 (single representation) is mostly observed during the interaction, the boy also regularly shows understandings at level 3 (sensorimotor system).

Even though his understanding seems to increase in complexity over time (on average the boy reaches level 4 more often in the second half of the interaction), his understanding often regresses to level 3 and to incorrect/irrelevant understandings. Hence, understanding is not a fixed entity, but varies over time, even within a single task.

The short-term intra-individual variability influences the variations in development we can see on the long term (Fischer & Bidell, 2006; Van Geert & Fischer, 2009). If micro-genetical variability is associated with reaching higher-level skills (Howe & Lewis, 2005; Thelen, 1989), long-term trajectories of understanding may differ between children showing more periods of variability versus children showing little periods of variability within short-term interactions. This also makes sense in combination with the property *Iterativeness*, as a short-term interaction showing a broad range of skill levels makes it more likely that skill levels subsequently move toward a higher level (cf., a phase transition), compared to a previous interaction showing a narrow range of skill levels. After all, the interaction with a broad range of skill levels yields more possibilities for the next interaction than an interaction with a narrow range. In conclusion, as Howe and Lewis (2005) mention, understanding gets form over various instances and in turn, drives long-term developmental change. This connection between the short- and long-term scale of development brings us to the next property, that of interconnected timescales.



**Figure 2.** Time-serial illustration of the variability in the boy's understanding during the air pressure task, measured by using Skill Theory (Fischer, 1980). For this boy, levels on the y-axis range from 1 (single sensorimotor set) to 4 (single representation). A -1 score represents an incorrect or irrelevant answer.

#### 5.4. Fourth property: Interconnected timescales

Three months later, the researcher returns with the syringes and the tube. The researcher starts by asking "Do you remember what we had to do with this?" In response, the boy immediately grasps the material and attaches the tube to the syringes. Then he replies: "Yes, when you push this one in, the air will go over here". He doesn't need more time to think about the process in a stepwise fashion: That it works like this because the tube is attached,



that there must be something going through that tube, etcetera. Based on the previous interaction, he now knows that air is going through the tube and makes the pistons move. Note, however, that this is not a mere retrieval from memory. The boy first attaches the syringes to the tube, and answers afterwards. Moreover, the question of the researcher is phrased in a way that encourages him to think about what they did before. Even though the researcher's role is not as prominent as it was in the previous interaction, the social context still plays a role in the construction of understanding. However, three months earlier, the understanding was clearly a co-construction between child and researcher. Now the child can directly introduce this understanding to the interaction, triggered by the researcher's question and the material, but without further interference.

## 6. Discussion

From a theoretical point of view, we discussed a number of dynamic properties in combination with Skill Theory's ruler of cognitive development. We argued that using these properties and ruler give both educators and researchers important means to get a grip on how children's understanding of scientific concepts builds up over time. More specifically, it helps to understand how children organize their knowledge in concordance with the context, i.e. the teacher, and highlights the importance of being aware of teachers' accounts in conversations with children, for example during a science lesson.

There are many different types of knowledge generation processes, one of which is the socially situated process between adult, child and task that we are discussing here. When a child is assessed or diagnosed, a different process of knowledge generation occurs. In these instances, the child is asked to construct knowledge without the help of an adult, but usually in interaction with a particular symbolic substrate, such as a piece of paper to draw on, or the structure of language that the child is using to describe knowledge. It is however wrong to think that only the latter process (in which the child works without help) is a reflection of the child's "real" knowledge. In fact, both the co-constructed as well as the individually constructed knowledge reflect the child's "real" understanding. Variations in complexity levels within one type of knowledge generation, but also between different types of knowledge generation, illustrate the intrinsic variation of understanding as such.

The model we proposed helps in re-conceptualizing the process of understanding in individual children, and the underlying mechanisms of change in their understanding. The latter is especially important, since "Developmental psychologists are not simply interested in the stable states achieved by individuals along their lifespan, but also about the mechanisms of change that lead from one state to the next." (Howe & Lewis, 2005, p.248). The advantage of a dynamic systems approach to the study of understanding is that it makes the development of understanding more transparent and no longer limited to an invisible process inside the individual learner (Van Geert & Fischer, 2009). Instead, it enables us to closely monitor interactions between child and environment to determine how the outcome (a form of understanding at some point) is constructed in real time.

In an applied sense, it is of great importance for parents, (science) teachers, and other practitioners to have knowledge about how children grasp varied concepts and how their understanding develops over time. By having this knowledge, they will be able to challenge children in their current level of understanding in order to promote children's optimal developmental trajectories with regard to cognitive understanding, and by doing so, promote children's optimal development in a broader sense. Departing from the idea of understanding as a process of change in which the child and the (social and material) context intertwine, the ways and complexity levels at which educators interact with their pupils have an important influence on the development of understanding. With regard to iterativeness, it is important for educators to acknowledge that how understanding changes at one moment in time depends on the understanding at a previous time point. That is, from a dynamic systems perspective, there are no internal operations on representations of knowledge that cause intellectual growth. Understanding organizes on the spot, and gets internalized over time through multiple interactions with the environment. Regarding micro-genetical variability, it is important for educators to understand that the highest complexity level on which children operate (e.g. when they learn about scientific concepts) can change rapidly during short-term interactions, not only when the environment or the amount of support visibly changes. Finally, a better understanding of the temporal stream of understanding will help educators to become aware of their own role in the long-term learning process, and may help them to change their actions when necessary or wanted. Students who are engaged in (scientific discovery) learning need adequate support to construct their knowledge (Alfieri, Brooks, Aldrich, & Tenenbaum, 2010). We claim that teachers' awareness of their own role is an important indicator for the quality of their support, which is a crucial factor in improving children's learning (McKinsey, 2007).

We need to work further on completing the empirical picture of possible trajectories of understanding that can emerge in individual children and investigate how these are related to processes on the short-term time scale. This will help us to differentiate components that build up to children's successful and unsuccessful learning trajectories with regard to scientific understanding. This knowledge will also help science educators to teach children to successfully master scientific concepts, as children's understanding of scientific concepts is not always accurate (Grotzer, 2004). When children have more expertise in science, feel confident about this, and enjoy science lessons, this may eventually boost the current number of young people pursuing a scientific academic career. In order to maintain economic growth, people with a scientific education who can ensure continuous technical capability of the highest standards in all fields of expertise are very much needed.

An important next step in the study of the development of children's understanding of scientific concepts as a dynamic system is to try to map individual learning trajectories and build a dynamic simulation model, based on a general theory of action or agent behavior on interacting time scales, and a general theory of mechanisms of change (see van Geert, 1994; Van Geert & Steenbeek, 2008; Steenbeek, 2006). With the help of such a simulation model, the important role of the (science) educator in the emergence of understanding can be unravelled. As a result, such a simulation model will have an important educational value,

by making the dynamic principles that play a crucial role in the development of understanding accessible for a broader public of educators. Based on the short-term interaction patterns we see emerge, and the implications this has for the long term, we can eventually construct adaptive teaching programs, lessons and materials for science education, which are better adapted to children's current levels of understanding and how this understanding develops in interaction.

An example of an adaptive educational and assessment (computer) program is Mathgarden (van der Maas, Klinkenberg, & Straatemeier, 2010), an educational computer game with a wide range of sums children that can play at school or at home. Children's responses (the short-term child-computer interactions) are frequently analyzed and reported to their teachers by means of error analyses, individual growth curves, and comparisons between the particular child and his classmates (or the broader population of peers). The program itself uses the child's data by varying the complexity of the sums adaptively, depending on the percentage of right answers, but also on the child's reaction time. Moreover, using the responses and reaction times of all individual children, the items of Mathgarden are arranged (and get frequently re-arranged) in terms of complexity. This program shows how multiple short-term interactions provide information about the individual's long-term development and how this information can inform educational practice. These kinds of adaptive teaching and assessment programs translate dynamic principles into concrete materials that help children to develop their understanding in an optimal way.

In conclusion, as Vygotsky (1934/1986) already noted: "To devise successful methods of instructing the schoolchild in systematic knowledge, it is necessary to understand the development of scientific concepts in the child's mind. No less important than this practical aspect of the problem is its theoretical significance for psychological science." (p. 146). We think that by studying the development of children's understanding of scientific concepts using a model based on properties derived from dynamic systems theory and Skill Theory an important contribution to both this applied and scientific goal is made.

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