Chapter 1

General Introduction

From the behaviors in real time to the understanding of their underlying processes
1. From the behaviors in real time to the understanding of their underlying processes

Consider the following example of two dyads of 5-year olds playing different games. Think of one dyad playing to build a marble track with the goal of making a marble to roll into a basket. The children explore the use of marbles of different sizes and weights; as well as the use of different wooden columns to adjust the height of the ramp. Also, let’s think in another dyad of children playing with a mechanism of tubes and valves. The children can open and close the valves, as well to connect a pump to the mechanism in order to inflate a balloon. In both situations, children try out different configurations of the materials, reaching sometimes the goal and other times not. While playing, the children of each dyad interact with each other in different ways. At some times they work independently from each other or take turns using the materials; other times they replicate the actions of their peer, or collaborate to attain the goal. In these situations the children’s behaviors involve cognitive and social skills. The children are engaged in the task while interacting with their peers and using complex scientific reasoning skills that are related to their exploration of the task.

At first sight, the children’s behaviors may seem chaotic, a matter of trial, error and changing from time to time. But in fact their behavior is creative. Upon close inspection— beyond the success and failure of their performances— it is possible to discover patterns, not only in their actions with the tasks but also in their interactions with each other. Children are spontaneous learners with a ‘curious mind’. In daily activities, children do not only learn by themselves, but also with others. As ‘little scientists’, they explore and learn about the world by conducting experiments, establishing causal relations and elaborating explanations about it. In the last three decades, psychological studies have shown the striking skills of children’s minds from early development onwards (Gopnik, 2012). The cognitive skills capacities not only emerge individually, but also as part of social interactions (Melander, 2012). These cognitive abilities (exploring, experimenting, describing, predicting and explaining) are part of what is considered “scientific reasoning” and are cognitive tools that constitute the basis of the learning process (Khun, 2004; Zimmerman, 2007). Scientific reasoning skills are present in daily life every time a child solves a problem. It applies not only to complex reasoning in order to solve an equation, but also on everyday situations (Dierking, Falk, Rennie, Anderson & Ellenbogen, 2003; NRC, 2009) for instance when anticipating the plot of a movie, predicting and explaining a rainbow, or finding how to fix a bike.
With the challenges of our modern society, one of the interests of education is focusing more on the academic disciplines of Science, Technology, Engineering and Mathematics (STEM). On the bases of observation that children have the spontaneous ability to explore and discover the world, many educational programs aim to encourage scientific reasoning from the early years of life (NRC, 2007, 2012; Osborne, 2013; Klahr, Zimmerman & Jirout, 2011). An example of this effort can be seen in the Netherlands, with a research program – financed by the Dutch government – called “Curious Minds”¹ (Talentenkracht in Dutch) in which seven universities develop research and interventions to promote early science talent and science education.

Traditional research on scientific reasoning can be characterized by the use of relatively big data samples – (generally collected in the controlled situation of lab contexts), the use of single measurements, and the analysis of outcomes in terms of success or failure. Although these studies on scientific reasoning have covered diverse domains and populations, the focus is much less on the process of reasoning than the more natural context of interaction. However, from the viewpoint of a complex dynamic systems approach, reasoning should also be studied as a process, in order to understand the mechanisms of change in short-term and long-term development. Initially, the focus was mostly on what changes in development; nowadays the focus is more on how changes take place (Spencer, Perone and Buss, 2011). From the 1990s onwards, the framework of complex dynamic systems (Thelen & Smith, 1994; van Geert, 2011, 2014; Schöner, 2009) has generated a change in the way psychologist conceived and studied development. In the last two decades, the contributions of the complex dynamic systems have been demonstrated by the translation of their conceptual bases into methodological procedures that reveal the underlying process of development (Spencer, Perone and Buss, 2011). As a result, this approach has changed from the epistemic view of an ideal subject to the idea of a real subject developing in real-time, in a particular context (Kloos & van Orden, 2009; Overton, 2014; van der Steen, Steenbeek & van Geert, 2012).

The core idea about a complex dynamic system (see Thelen & Smith, 1994; van Geert, 2008) lies in their self-organized process in which the interconnected components enable the emergence of novel behaviors (Kunnen & van Geert, 2011). Below we give a brief description of the central concepts that define a dynamic system:

¹ For more information visit the website www.talentenkracht.nl
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(1) *The formation of attractors*: behaviors are the result of a self-organized system that evolves towards states of equilibrium that can be evidenced in the presence of patterns (regularities) in variability.

(2) *Non-linearity*: behaviors emerge over time as variable trajectories with structured patterns and not as gradual, progressive or cumulative trajectories. The nonlinearity of the behaviors is not seen as the result of a random effect but as the natural attribute development.

(3) *Multi-causality*: behaviors are the result of complex underlying processes that are interdependent from each other

(4) *Recurrence*: behaviors take place as a continuous loop of individual-context, as an iterative process that can be relatively stable in particular states of the system (attractors)

(5) *Nested time-scales*: behaviors changes in short- and long- term, revealing the interconnection of microdevelopmental processes on long term processes.

Nowadays, we often call this approach a 'complex dynamic systems' which has been applied to diverse research topics in psychology, such as interactions (e.g. Ensing, van der Aalsvoort & van Geert, 2012; Granic & Lamey, 2002; Steenbeek & van Geert, 2005), language development (e.g. Ellis & Larsen-Freeman, 2009; van Dijk, et al., 2013), learning processes (e.g. Fischer & Granot, 1995) and scientific reasoning (e.g. Meindertsma, van Dijk, Steenbeek & van Geert, 2014; Schwartz, & Fischer, 2003, 2005; van der Steen, Steenbeek & van Geert, 2013). The characteristics of these studies lies in the conceptual articulation of complex systems mechanisms studying these psychological phenomena, but also the implementation of analytical procedures that are used to study developmental processes over time. One of the main implications of the complex systems approach is the collection of repeated measures in order to capture the intra-individual variability as a main source to describe how changes occurs at different time-scales of development (Nesselroade & Ram, 2004; Nesselroade & Molenaar, 2010).

Traditional studies in psychology often examine big samples, for instance by inferring relations from the comparison of aggregated data of individuals. From this view, a normal distribution of the observed phenomenon is often assumed. As a consequence, it needs to be distinguished from the measured phenomenon (van Geert & van Dijk, 2015). This is a nomothetic procedure that consists of examining the average of the variable of interest of large groups and comparing conditions (Barlow
& Nock, 2009). In contrast, a dynamic approach contemplates the variables of interest as complex systems that are constantly changing from moment to moment. Variability in performance is conceived not as the result of a measurement error, but as the nature of developing human behavior (van Geert & van Dijk, 2002). As a result, many complex dynamic systems studies are based on multiple measures (i.e. time series) in order to establish relationships between the variables observed across the sequence of measurements of the same individual and studying the variability, rather than general statements about a population (Nesselroade & Ram, 2004).

By acknowledging that psychological processes are not homogeneous, neither static, it is necessary to also recognize that they are non-ergodic. Ergodicity is defined by the Oxford dictionary as “denoting systems or processes with the property that, given sufficient time, they include or impinge on all points in a given space and can be represented statistically by a reasonably large selection of points”. In other words, ergodicity indicates that the system's components are equally representative of the whole system. It has been argued that this assumption does not hold true for most psychological phenomena (Molenaar, 2004; Molenaar & Valsiner, 2005). For this reason, nomothetic procedures cannot be used to understand psychological processes. As an alternative, an idiographic method is considered to offer a detailed focus on individual development across time (Molenaar & Campbell, 2009). The aim of this method is to provide insights into the dynamics of psychological processes evolving in real time.

The studies in this dissertation are motivated by the application of the complex dynamic systems approach and the idiographic method as a source to understand the real-time performances. The goals of this dissertation is to understand the development of scientific reasoning and dyadic interaction of 5 year-olds, in a setting were children are repeatedly confronted with a sequence of tasks/on hands. We worked with dyads of 5-year-olds, because according to Fischer and others (e.g. 1980; Fischer & Bidell, 2008) around this age, children are expected to show a transition in their cognitive level. Their initial performance, characterized by a sensorimotor level (single representations) where the focus is on the attributes of the materials, change to a representational system (representational mapping) in which the focus is on causal relations. In addition, we framed our studies in a context of spontaneous reasoning during problem-solving. This refers to the examination of the natural comprehension that children display in a task without a previous instruction about the solution or the formal concepts involved in it. Viewed in the educational context, the ecological validity of our setups is relevant because it reveals the children's initial knowledge that teachers will scaffold towards a formal knowledge. Furthermore, we
gain information about how the learning process emerges in a spontaneous way, as occurs in most activities of daily life.

In order to address the goals of this dissertation, various techniques are used to zoom in at the variability of the children’s performance at different time scales (micro and macro level).

![Figure 1. Relationship between the components of the different studies of this dissertation.](image)

The most important elements of the studies are depicted in Figure 1. These are the children –as a dyad– relating to each other in the context of problem solving tasks. Each task presents its own demands of content (air pressure / inclined plane), and the children during their attempts to solve the task influence each other. As a result, the moment-to-moment relation between the children and the task generates two trajectories of dyadic behaviors: one about interaction and another about scientific reasoning. Our interest is centered in the patterns of variability of these trajectories because they constitute the main source of information about the dynamics of the dyad. The upper part of Figure 1 represents the emphasis on the structure of variability of children’s trajectories of reasoning and interaction that characterized the research questions and methods of the different studies rather than the specific content of the children’s performances, which are represented in the bottom part of the figure.
2. Overview of the Dissertation

This dissertation presents four independent studies (chapters 2 to 5) that together provide understanding of how scientific reasoning and dyadic interaction emerge in the short term (within a single session) and the long-term (along six waves of data collection, lasting one year of observation). Chapter 2 presents a methodological study that demonstrates the use of a fine-grained analysis of the within-session changes of scientific reasoning skills and children’s interactions. This chapter also establishes the basis for the categories of interaction that will be used in subsequent studies. The studies presented in Chapters 3 to 5 are based on the longitudinal design (see Appendices A and B) in which two sets of problem-solving task were presented to two groups of dyads along six waves of data collection (4 dyads in the air pressure task set and 3 dyads in the inclined plane task set).

Each task set consists of one familiarization task and six experimental tasks, increasing in difficulty (see Figure 2) which has been used in previous studies (Meindertsma, Verbrugge, van Dijk, Steenbeek & van Geert, 2015; van der Steen, Steenbeek and van Geert, 2012). The protocols of both task sets (air pressure and inclined plane) were suggested as open problem-solving situations to elicit the spontaneous experimentation of the dyads and to provide verbalizations based on the use of three scientific reasoning skills (i.e. descriptions, predictions and explanations). In a previous study by van der Steen, Steenbeek and van Geert (2012), the air pressure set was presented in an adult-child assessment to examine children’s comprehension through the use of structured protocols based on their verbalizations. Similarly, for the inclined plane tasks, an adult-child assessment was used in the study of Meindertsma, Verbrugge, van Dijk, Steenbeek and van Geert (2015). We use the tasks from these previous studies, and an adjusted version of the coding schemes of verbalizations in order to address new research questions. In this case, the target is the examination of dyads of preschoolers in the context of problem solving.

An ‘overlapping’ design was used to track the variability within a session and between sessions. This means that in each session two tasks were presented to the children. In each of the following sessions, the last task was presented again and a new task was introduced (Figure 3).
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The following paragraphs introduce the contents of the chapters of this dissertation.

*Chapter 2* presents a methodological study that illustrates the microgenetic analysis of the intra-individual variability of children's behaviors in a single session. Two case studies are used to explore the spontaneous types of interactions emerging in a single problem-solving session (a balance-scale task). The observed types of interaction are presented with the use of three types of scientific reasoning skills (descriptions, predictions and explanations). Several descriptive techniques (time series analysis, transition matrices and hierarchical agglomerative clustering (HAC) are implemented to capture the changes in a sequence of data (time-series).

*Chapter 3* elaborates on the types of interactions described in chapter 2, suggesting a dyadic model that examines the children’s interactions as a dyadic system with two main states: distributed and unequal interactions. Using a multiple-case study, this chapter analyzes the verbal interaction between the children and links it with the use of scientific reasoning skills. By using a state space grid technique (SSG, Hollenstein, 2013), recurrent states (attractors) of dyadic interaction will be identified within and between sessions. In addition, the co-occurrence of the interaction states and types reasoning is investigated.

*Chapter 4* introduces a more detailed analysis of the development of the structure of real-time dyadic interactions in the two states of dyadic interaction.
(distributed and unequal) proposed in chapter 3. A cross-recurrence quantification analysis (CRQA) is used to identify the short-term interpersonal coordination. Based on the categorical data of children's interaction (time series), the CRQA technique quantifies the coupling behaviors of the dyads in the two states of interaction and its recurrence over time. This analysis provides information about the patterns (attractor states) of the coupling behaviors, revealing the self-organization of the dyad as a system that changes over time.

Chapter 5 focuses on the spontaneous experimentation elicited by a sequence of problem-solving tasks. This study in particular, describes the complexity of children's reasoning in actions (to solve the tasks) and verbalizations (explanations) and its change over the six sessions. The analysis is based on two main aspects of reasoning: the most complex actions (nonverbal reasoning/implicit knowledge) and the most complex verbalizations presented by the children (explanations/explicit knowledge) in each session. The complexity of these two types of reasoning is quantified by the application of Skill Theory (1980) and was compared between sessions and over time. The study thus aims to describe the more global development of the performance of the children. In addition, children's transfer of scientific reasoning (in actions) is analyzed by comparing the key elements they used to solve a sequence of tasks.

Chapter 6 consists of a summary and discussion of the main conclusions and implications of the four empirical studies and its relation to the complex dynamic systems. Additionally, based on the limitations and insights identified across the studies, we provide suggestions for future research.