A new perspective on the development of motor variability during middle childhood

Golenia, Laura

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2018

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 29-01-2020
CHAPTER 1

GENERAL INTRODUCTION
VARIABILITY IS INHERENT IN MOTOR DEVELOPMENT

Many researchers have argued in recent decades that describing and examining variability in motor behavior is essential in understanding motor development [1–8]. It has even been proposed that variability is a fundamental measure of change in human behavior [9,10]. In general terms, variability refers to a series of observations that are non-constant [11]. This variability is an inherent characteristic of motor development. In early childhood development (0–5 years of age), several studies have shown how the focus on variability resulted in a more comprehensive understanding about the occurring developmental processes [e.g., 12–17]. For example, the description of variability in infants’ natural walking revealed that omnidirectional steps and curved walking paths generate rich combinations of movements that allow infants to explore the environment [12]. In another study it was discovered that infants’ first goal-directed reaches emerge from variable non-reaching arm movements [14]. Unfortunately, motor variability has been a core theme only in the field of early childhood development. The exciting findings on variability did not yet spark similar enthusiasm in middle childhood (5–10 years of age) research. Middle childhood signifies the developmental phase between early childhood and adolescence. The years of middle childhood are sometimes even labeled as the ‘forgotten years’ of development [18], as this developmental period has often been overshadowed by the focus on the first years of life. Only few studies have described and characterized variations in movements of children aged 5–10 years in detail [19–23], which means that the role of variability in mid-childhood development has received only marginal attention compared to early childhood development.

Describing and understanding variability in movements does not only increase our understanding about typically developmental processes, but also that of atypical processes. Indeed, atypical motor development is often linked with extreme values of variability (either low or high) [e.g., 24–27]. One such disorder is Developmental Coordination Disorder (DCD) [28], a coordination disorder that emerges during middle childhood, which is characterized by high levels of motor variability [e.g., 27,29]. The cause of this disorder is as of yet still unknown. Recently, discussions have been launched in the DCD literature about how the variable motor behavior of children with DCD relates to possible underlying mechanisms of DCD [5,30–33]. It is, therefore, crucial to know more about developmental changes in motor variability during middle childhood in typical as well as atypical developing children.

In this thesis, a novel perspective on motor variability in middle childhood is presented to increase the understanding about age-related changes in motor variability occurring in this developmental period. Doing so, this thesis focuses on the variability that is inherent in reaching movements across repetitions of trials. Studying goal-directed reaching movements is important as they are involved in many everyday life activities. Also, a few studies have shown that reaching skills refine during middle childhood [e.g., 34–38], indicating the importance of understanding the develop-
mental changes taking place in reaching movements during middle childhood. Ideas of the Dynamic Systems (DS) theory guided this novel perspective on motor variability in middle childhood, which is introduced in the study of typical developing (TD) children, but also in children with DCD.

THE DEVELOPMENT OF REACHING DURING MIDDLE CHILDHOOD

The few studies that focused on the development of reaching in middle childhood have given important insight in the developmental changes occurring in reaching in general and in terms of variability [34,35,38–41]. The task of goal-directed manual reaching comprises movements of the joints of the arm (shoulder, elbow, wrist and finger) with the goal of bringing the endpoint (i.e., the index finger) to a desired location in the workspace, considering task and environmental constraints (e.g., gravity, speed and accuracy instructions, or the availability of visual feedback about the moving arm or target) [42].

Short synopsis of the results of the existing studies

Previous studies that examined goal-directed reaching in TD children focused on the performance level of the reach [34,35,39,43–45]. Performance is quantified by the characteristics of endpoint movements. This means that these studies analyzed spatio-temporal measures of movements of the index finger, such as movement time or accuracy at the target. In general, studies showed that reaching performance improves during middle childhood, indicated, for example, by a decrease of movement time from 5- to 10-year-old children [35,38,39,46]. Regarding variability in reaching movements, variability has mostly been quantified by means of the amount of performance variability about a mean or average value, such as the amount of the dispersion of errors around a target across repetitions of the same task [39,46–49]. It has been shown that performance variability decreases between 5 and 10-year-old children, revealed, for instance, by a decrease of errors at the target [35,39,46,47,49]. Variability measured in this particular way reflects inconsistency. The general view on variability in middle childhood until now has therefore been somewhat negative in connotation, taken to mean “less consistent” or error ridden.

Theoretical approaches used in previous studies

Most previous studies examining middle childhood reaching were conducted in the light of the computational neuroscience approach [34,35,39,40,44,45]. Early studies were published at a time in which the information processing approach was popular [35,38,41], whereas more recent studies followed internal model approaches [36,40] and representational explanations [34,37]. Following these approaches, researchers tacitly assumed that there is a single process or component in the system (probably in the brain) that controls motor behavior. It was proposed that developmental changes in motor behavior are caused by developmental changes in this single process or component. For instance, it was suggested that the ability to generate an internal model (i.e., predicting
the outcome of movement commands) and to integrate online sensory feedback within this model is reflected in the performance improvements of reaching errors in middle childhood [36,40]. In sum, over the last decades, useful and interesting explanations of developmental changes in reaching during mid-childhood have been put forward by focusing on the development of specific components or processes, fitting within the theoretical framework underlying these studies.

Regarding variability in behavior, computational neuroscience approaches assume that performance variability originates from intrinsic neuromotor noise arising from all levels of the sensorimotor system, which corrupts information transmission in the neuromotor system, resulting in random fluctuations, i.e., variability [5,11,47,49,50]. Noise is defined as unstructured variability, both in the temporal and spatial domain [11,50]. The internal model approach proposes, for example, that neuromotor noise produces deviations from the single optimal solution generated by the model, causing variability in the system. Changes in the magnitude of movement variability with age have been interpreted as evidence that the level of noise in the sensorimotor system decreases through middle childhood [40,47–49].

**THE VIEW ON MOTOR VARIABILITY IN EARLY CHILDHOOD DEVELOPMENT**

In early childhood developmental literature, it has been shown that the role of variability in development is not so simple [e.g., 1–3,8]. By studying variability in different situations and with different analysis techniques, the conception of variability has changed from its negative conception, to a more positive conception. Thus, a shift has taken place in thinking about variability in early childhood motor development in recent decades [1,3,8]. From its original conception of being noise in computational neuroscience theories, recent approaches, such as the DS theory [7,51–54], have highlighted the adaptive value of motor variability for flexibility and the possibility to explore new solutions. As a result, there has been a renewed interest in the function of motor variability during early childhood development.

**WHAT THE DYNAMIC SYSTEMS THEORY HAS TO OFFER**

The theoretical approach that has engendered the shift in thinking about variability in early childhood development is the DS approach. This theory emphasizes that developmental changes emerge within a complex system involving many components acting on different levels that interact over multiple time scales [7,51–59]. Importantly, the system is not confined to the body, but includes the task and the environment. Automatically, this means that the environment and the task are equally important parts of the system [54]. The starting point of the DS approach is that over development each component is equally important and could potentially contribute to the emerging
behavior. Hence, if one or multiple components change, the behavior might change. In contrast with, for example, the internal model approach, the DS perspective states that there is not one single optimal solution for a task but that there are multiple equivalent solutions [4,7].

Motor variability is elevated in a DS approach as it views variability as signature component of development and motor behavior in general [4,7,51,52,54]. Variability is seen as a ubiquitous and informative biological feature that has inherent structure and meaning in itself [7]. That is, variability can provide information about the state of the system. It can, for example, provide understanding about exploratory processes. Special emphasis is put on the structure of variability. Deutsch & Newell [22,60,61] showed, for example, how decomposing the time and frequency structure of variability in a force task revealed that reductions in the amount of performance variability from middle childhood to adulthood are not reflections of different levels of noise in the sensorimotor system, but are primarily due to a more appropriate mapping of the sensorimotor system to task constraints (more effective use of visual information). The DS theory has increased in popularity in early childhood development in recent decades, but it has not been used a lot in middle childhood development.

**A NOVEL WAY TO APPROACH VARIABILITY IN REACHING MOVEMENTS DURING MIDDLE CHILDHOOD**

Research on variability in goal-directed reaching during middle childhood has mainly focused on performance variability, quantified in terms of the amount of variability about a mean [34,39]. Variability measured in this particular way reflects inconsistency, which resulted in a negative connotation on variability in middle childhood. Considering that in early childhood development variability has been shown to reflect more than inconsistency [12,21,23,60], it is time to approach variability in reaching movements in middle childhood in a novel way. This thesis follows the DS theory’s assumption that variability can also be useful for development and therefore something positive. This creates opportunities for novel ways of characterizing and describing variability in reaching movements during middle childhood, which might reveal a richer, more complex developmental story. This thesis follows the DS perspective by examining variability at other levels of the system and by characterizing structure in variability.

**Variability at the joint angle level**

One aspect that is emphasized by the DS perspective is to focus on all levels of the system and not only on the performance level. As already described in the definition of reaching, endpoint movements emerge from joint rotations of the arm. Thus, an important level in reaching is the joint angle level [20,42]. Joint angles are defined as the relative orientations of the different segments of the arm and hand. The importance of this level is even more underlined when considering that
the joint angles (i.e., degrees of freedom, DoF) are abundant, meaning that the number of available joint angles exceeds the number of joint angles that are minimally necessary to accomplish a task [62–64]. For example, when reaching to a target in the three-dimensional space, the number of joint angles in the arm is larger than three, indicating that multiple joint angle combinations can achieve the same performance. Thus, the abundant DoF of the human body naturally afford variability and lead to variability in joint angles evident in repetitive movements [11].

Ubiquitous variability in joint angles was clearly described in Nicolai Bernstein’s famous experiment of blacksmiths repeatedly hitting a chisel with a hammer [63,65]. He demonstrated that the variability of the hammer trajectory was smaller than the variability in the joint angle trajectories of the arm across repetitive trials. This shows that there is variability in joint angles that does not affect task performance. In reaching movements, the position of the index finger tip reflects task performance. Variability in joint angles not affecting task performance is according to the principle of motor abundance useful and even vital for many aspects of motor behavior [64,66,67]. It allows movements to be both flexible and stable, because the motor system in its interaction with task constraints can create multiple equivalent solutions [68]. In literature on adults, it has been observed in a wide range of tasks that variability in joint angles not affecting performance is not eliminated but used [67,69–74]. Nevertheless, there are also joint angle configurations that do affect performance, which means that also at the joint angle level there is variability that might result in inconsistent motor behavior [62]. Consequently, motor variability at the joint angle level should not all be treated the same, but rather be separated on the basis of its effect on task performance [62,75,76].

**Structure in joint angle variability**

The DS theory emphasizes the importance of structure within variability as it presents a window into the underlying processes of motor development [1,2,8,23]. Structuring joint angle variability based on its effect on task performance is especially informative when the task is redundant and affords a manifold of solutions, like it is the case for goal-directed reaching [68]. In the present thesis, the Uncontrolled Manifold (UCM) method was applied to distinguish variability in joint angles that does not affect the position of the index finger from variability that does affect the position of the index finger [62,76–78].

The UCM analysis is a quantitative approach that was developed to examine the structure of variability in joint angle variability [62,67,76,77]. The uncontrolled manifold represents a mathematical subspace that corresponds to all combinations of motor elements that preserve the value of a task-specific variable. In reaching, the motor elements are the joint angles, and the mean position of the tip of the index finger is the task-specific variable that is preserved [77,79–81]. Thus, in reaching, the UCM is a manifold in the joint space representing the set of joint angle configurations in the arm with the tip of the index finger in one position. Variance in joint angles over repeated trials projected onto the UCM corresponds to the joint angle configurations that do not
affect the mean position of the index finger in space ($V_{\text{um}}$, Figure 1, left panel). Variance orthogonal to the UCM subspace, the ORT subspace, corresponds to the joint angle configurations that lead to a deviation from the mean position of the index finger ($V_{\text{ort}}$, Figure 1, right panel). The UCM method has been applied a lot in adult studies [72,77,79,81–83], but only in two developmental studies in the field of quiet stance [19] and walking [24]. In summary, the UCM method structures variability in joint angles and using it in studying development of upper extremity tasks may give novel insight in the processes underlying motor variability.

**Figure 1.** Variability in joint angles separated based on its effects on task performance in a reaching task. The Uncontrolled Manifold (UCM) method partitions variability in joint angles in variability that does not affect the position of the index finger ($V_{\text{um}}$, left panel) and in variability that does affect the position of the index finger ($V_{\text{ort}}$, right panel).

**DEVELOPMENTAL COORDINATION DISORDER: CHARACTERISTIC FEATURES AND THE ROLE OF VARIABILITY**

How to view and measure motor variability is also a hot topic in research on DCD [5,30,31,33]. But first, what is DCD exactly? DCD is an idiopathic condition that is characterized by impaired fine and gross motor coordination [28]. Of all school-aged children, 6% are thought to be affected by DCD. Children with DCD have difficulties performing everyday fine and gross motor tasks at home and in school [84,85]. For example, children with DCD have problems balancing on one leg, directing their arms to the right location to catch a ball or grasping a glass of water without spilling. These coordination problems might have psycho-social consequences such as low self-esteem and social exclusion [86,87]. The broad bandwidth of problems related to DCD underlines the need of a thorough understanding of the coordination processes in this disorder. Since DCD was first listed in the Diagnostic and Statistical Manual of Mental Disorders, it has received much attention and motor journals have dedicated complete issues to the disorder. Yet, despite this surge of interest, the exact coordination processes that are deviant in this disorder remain unclear.
The majority of investigations into the, still unknown, cause of DCD over the past 25 years adhere to the view that describes DCD as a brain-based deficit in internal model processing [30,88,89]. As a natural outgrowth of this approach it has been suggested that high system’s noise in children with DCD [31,32,90] impacts sensorimotor control, motor output and predictive control, resulting in high performance variability [26,29,90–93] and in the motor problems seen in children with DCD. In reaching it has, for example, been shown that errors are larger and movements are performed slower in children with DCD compared to TD children [94–96]. High performance variability in children with DCD is therefore considered to hinder performance [32,89,90]. That is why also in DCD variability is in general construed in negative terms. However, recent literature reviews have pointed out that not all variability might be hindering and that variability should be approached in alternative ways to get more details about what the underlying source of high variability in this disorder might be [5,30,33,97]. There has been a special plea for focus on variability in coordination, which is not surprising considering that DCD is a coordination impairment [98]. This thesis subscribes to this newly stated opinion in the literature and starts with examining the structure of variability in joint angles in children with DCD.

**AIM AND OUTLINE OF THIS THESIS**

This thesis aims to increase the understanding about developmental changes in motor variability during middle childhood by examining the structure of variability in joint angle configurations over repetitions of trials in goal-directed reaching movements. Chapter two of this thesis examines developmental changes in the structure of joint angle variability in TD children aged between 5 and 10-years of age. It focuses on the joint angle level and the performance level, and therewith aims to give a level-overarching explanation of occurring developmental changes. Chapter 2 also examines how the availability of visual information about the arm influences the developmental trends, which is an important environmental component involved in reaching. Chapter three examines the influence of task constraints on the development of the structure of joint angle variability in 5-to 10-year-old TD children. Adults have been shown to exploit the abundance in their motor system when task demands increase [69,70,74,99]. To assess how children in middle childhood utilize the abundance of their motor system when necessary, a challenging reaching condition is introduced to increase task demands. In chapter four, the structure of variability in joint angle configurations in children with DCD is assessed by comparing children with DCD with age-matched controls. Special emphasis is laid on the role of variability in DCD. Chapter five elaborates on how ideas of the Dynamic Systems approach can positively contribute to the understanding of developmental changes in reaching during mid-childhood. Ideas on how to continue studying mid-childhood reaching based on the DS theory are presented. Chapter six provides a general discussion of the findings reported in this thesis, including clinical implications and directions for future research.
REFERENCES

59. Hollenstein T. Twenty years of dynamic systems approaches to development: Significant
Introduction


78. Tuinert I, Valk TA, Otten E, Golenia L, Bongers RM. Comparing different methods to create a linear model for the uncontrolled manifold method analysis. Motor Control. 2018;


