Rhythmic coordination dynamics in children with and without a developmental coordination disorder
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Summary and conclusion

In this thesis, the development of rhythmic coordinated movements in school age children and disorders thereof are examined from a dynamic pattern perspective. Chapter 1 introduces the problem definition and the aim of this thesis. Children with a Developmental Coordination Disorder (DCD) are characterized by a poor performance of daily activities that require movement coordination that is not due to the child’s age or intellect, or caused by a known neurological disorder. The movement behavior of children with a DCD can be characterized as clumsy or poorly coordinated. The mechanism underlying the coordination problems in DCD is largely unknown. Studies from an information processing perspective have suggested that these problems are due to a deficit in motor programming processes. Research from a dynamic pattern perspective focuses on dynamic self-organized processes in coordinated movement behavior. This thesis investigates the role of such dynamic processes in DCD. It focuses on the (relative) timing in bimanual rhythmic coordinated movements and in unimanual rhythmic movements that are synchronized to regularly occurring auditory or visual events (i.e., rhythmic perception-action coupling). A dynamic model is applied in which two rhythmic units are modeled as nonlinearly coupled oscillators, and the relative phase between the units captures the stable behavioral states of the coordination system.

The aim of the thesis is to investigate (1) age related changes in the stability of bimanual rhythmic coordination patterns and unimanual rhythmic perception-action patterns in children of different age, and (2) differences in the stability of such coordination patterns between children with a DCD and age-matched controls. The experiments presented in this thesis have in common that they test the stability of two basic coordination patterns (i.e., inphase and antiphase coordination) in a ‘steady state frequency’ condition, and loss of stability in a condition in which frequency is increased.

Chapter 2 describes how, following dynamic pattern theory, stable coordination patterns may arise in a self-organized fashion from the cooperative coupling between components of a system. Self-organization implies that a high-dimensional complex system can be controlled by only one or a few low-dimensional variables. Two essential variables are the collective variable (i.e., relative phase), which captures the stable states of the system, and the control parameter (i.e., frequency), which is a nonspecific parameter that induces loss
of stability and phase transitions from one stable coordination pattern to another. A three-layered model is described in which the relative phase dynamics are dependent on the lower-level dynamics of the component oscillators and their coupling, and on higher-level boundary constraints (e.g., initial conditions, intention, learning history). Relative phase dynamics apply to both rhythmic interlimb coordination and rhythmic perception-action coupling, and seem a very useful way to describe developmental changes in rhythmic coordination and individual differences in rhythmic coordination due to movement disorders.

Developmental changes

Chapter 3 and 4 investigate developmental changes in the coordination stability of bimanual rhythmic tapping and unimanual rhythmic tapping on an audiometronome using a cross-sectional research design.

Chapter 3 examines age related and practise induced changes in the stability of bimanual rhythmic coordination (i.e., inphase and antiphase tapping) of children aged 6, 8, and 10 years. A decrease in relative phase variability, and an increase in critical frequency (i.e., the frequency where loss of stability occurs) was found, indicating that the coordination stability gradually increased with age. In terms of the coupled oscillator model, this increase is mainly due to an increase in coupling strength between the oscillators. Training of the antiphase coordination pattern (8 trainingssessions in one week) at a frequency just below the critical frequency resulted in an asymptotic increase of critical frequency. The interpretation of this finding is that the training resulted in an increase in stability (increase of coupling strength) towards an age related maximum, which is related to a physical constraint (e.g., synaptic coupling within the nervous system).

Age related differences in unimanual rhythmic perception-action coupling were examined in chapter 4. Children aged 7, 9, and 11 years attempted to synchronize rhythmic finger tappings to the beats of an auditory metronome, either ‘on the beat’ (i.e., inphase coordination), or ‘off the beat’ (i.e., antiphase coordination). A decrease in relative phase variability, and an increase in critical frequency indicated that the stability of the perception-action patterns increased with age. This increase is -in terms of the dynamic model- due to an increase in the unidirectional coupling strength of the limb oscillator to the metronome. Since the coupling is informational in nature, the critical frequency may be related to an informational resolution limitation in the sense that the phase coupling breaks down when the limit for resolving the information that specifies the pattern is reached. This informational limitation apparently changes with age. Some findings were inconsistent with the dynamic model. Firstly, a negative phase shift was found in inphase coordination
(indicating that subjects tap in advance of the auditory stimulus), and, secondly, the relative phase variability did not differ for inphase and antiphase coordination.

**Individual differences: children with and without a Developmental Coordination Disorder**

Chapters 4 and 5 investigate rhythmic coordinated movements in 24 children with a Developmental Coordination Disorder and 24 age-matched control children. DCD children were selected on the Movement Assessment Battery for Children (M-ABC), using the 15th per centile as the selection criterion.

Chapter 5 focuses on the stability of single and bimanual (i.e., inphase and antiphase) rhythmic flexion-extension finger movements of DCD children and controls. Mechanical perturbations were applied to measure the relaxation time, i.e., the time the system takes to return to its initial stability. The stability of single (i.e., limit cycle stability) and bimanual (i.e., relative phase stability) rhythmic movements was determined. In addition, the variability of individual limb oscillations, the relative phase variability, and critical frequency were measured. Children with DCD displayed less stable single and bimanual rhythmic movement patterns than control children. Further, within the DCD group, a subgroup of nine children was identified with a particularly poor bimanual coordination stability. The less stable bimanual coordination is—in terms of the dynamic model—due to a weaker coupling between the limb oscillators. However, our findings also indicate that the variability of individual limb oscillations might have contributed to the reduced relative phase stability. Findings in this chapter are contrasted with those of a study which suggested that timing problems in DCD are due to a deficit in motor programming (Williams, Woollacott, & Ivry, 1992). Further, it discusses the postulation that problems in the timing of rhythmic movements of children with DCD are related to cerebellar dysfunction.

Chapter 6 focuses on the stability of rhythmic perception-action coupling (i.e., visuomanual coordination), and compares results on visuomanual stability with results on bimanual stability (chapter 5). The visuomanual task required the coordination of rhythmic flexion-extension movements of the index finger with a discrete visually specified oscillatory signal, either in an inphase or antiphase mode. Instead of mechanical perturbations we applied ‘visual’ perturbations (i.e., introducing a phase advance in the visual signal). Relaxation time, relative phase stability and critical frequency were used as measures of stability. Children with DCD had longer relaxation times, larger relative phase variability, and a lower critical frequency than matched controls, indicating that their visuomanual patterns were less stable. In terms of the dynamic model, this is due to a reduced coupling strength. Findings that were inconsistent with the model (no difference in relative phase variability between inphase and antiphase coordination) are probably due to
the way visual information was presented (discrete instead of continuous). Within the DCD group, a subgroup of 11 children was identified with particularly poor visuomanual coordination stability.

Comparison of bimanual and visuomanual coordination tasks revealed that 7 DCD children had particularly poor stability in both tasks, 3 DCD children only in bimanual, and 4 DCD children only in visuomanual coordination. Identification of such subtypes in DCD based on movement coordination dysfunction might have important implications for further research and for intervention. Comparison of bimanual and visuomanual tasks also shows that bimanual coordination is more stable than visuomanual coordination. It was suggested that this difference is caused by differences in the nature of the coupling between the rhythmic units involved (e.g., bimanual coupling is predominantly based on kinesthetic whereas visuomanual coupling is predominantly based on visual information), and by the fact that the symmetry-breaking forces were probably larger in the visuomanual than in the bimanual coordination task.

**Conclusion**

The four studies reported in this thesis lead to the following conclusions. First of all these studies show that development and disorders of bimanual rhythmic coordination and unimanual rhythmic perception-action coupling in children can be adequately described by a dynamic model in which the rhythmic units are modeled as nonlinear coupled oscillators, and the relative phase between the units captures the stable behavioral modes of the system. Results from the three measures of stability (relative phase variability, relaxation time, and critical frequency) were largely in line with the model. Secondly, the studies show that coordination stability increased as a function of age, and stability increased as a function of training towards an age related ceiling. Thirdly, our findings in the DCD studies show that children with DCD had less stable coordination patterns than age matched controls. Furthermore, subgroups of children with DCD were identified with particularly poor bimanual and/or visuomanual coordination stability. These findings have both theoretical and clinical implications. Theoretically, they suggest that problems in the (relative) timing of rhythmic movements in children with DCD are not (only) due to a deficit in central timekeeping or programming processes (Williams, Woollacott, & Ivry, 1992) because timekeeper models do not account for inherent stability properties, such as the resistance against perturbations, and loss of stability and phase transitions when frequency is increased. The less stable coordination patterns in children with DCD rather point to a deficit in dynamic control processes. No clear relation was found between DCD children’s
coordination stability and their neurodevelopmental status. Although it has been suggested that timing problems in DCD are related to a dysfunction of the lateral cerebellar (Williams, Woollacott, & Ivry., 1992), our findings point more to a dysfunction of the intermediate cerebellum. Our findings also have clinical implications in the sense that subtypes of DCD could be identified based on the relative phase dynamics (coordination stability) in functionally different coordination systems. Such an identification of subtypes might be relevant for intervention. Further, the control parameter frequency can be used to find optimal and critical values in the stability range of coordination patterns.

Finally, the following proposal for further research on rhythmic coordination in children with DCD is made. The results presented in chapter 5 indicate that the level of fluctuations of the individual limb oscillations may have contributed to the poor bimanual coordination stability observed in DCD children. It was therefore suggested that the limit cycle dynamics of limb oscillations of DCD children both with regard to the functional form of the oscillator (i.e., the dissipative forces) and fluctuations in the limit cycle trajectories (i.e., the stochastic forces) should be examined more in detail, and that the association with the relative phase stability in bimanual coordination should be examined further.