Rhythmic coordination dynamics in children with and without a developmental coordination disorder
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Chapter 2

Rhythmic Coordinated Movements: 
A Dynamic Pattern Approach

Abstract
In this chapter the dynamic pattern approach to movement coordination and control is described. According to such an approach stable coordination patterns emerge in a self-organized fashion from the cooperative coupling between components of a system. Such coordination patterns are described by a relevant collective variable (e.g., the relative phase between two rhythmic units) and their dynamics (i.e., its evolution in time). Relative phase dynamics are dependent on the lower-level dynamics of the components and their coupling, and by higher-level boundary constraints (e.g., initial conditions, intention, learning history). Relative phase dynamics can be applied to both rhythmic interlimb coordination and rhythmic perception-action coupling, and seem very useful to describe developmental changes in coordination and individual differences in coordination due to movement disorders.

2.1 Self-organization of coordinative movement patterns

The human movement system is composed of a large number of components (e.g., neurons, muscles, joints). How do humans control these multiple degrees of freedom in order to produce skilled, coordinated actions? The Russian physiologist Bernstein recognized that it is unlikely that the central nervous system controls each degree of freedom separately, and therefore defined coordination as “the process of mastering redundant degrees of freedom of the moving organ, in other words its conversion to a controllable system” (Bernstein, 1967, p.127). Bernstein proposed that the motor system functionally organizes itself into synergies, i.e., classes of movement patterns involving collections of muscle or joint variables that act as basic units in the control of movement. Drawing on this concept of synergy, Kugler, Kelso and Turvey (1980) introduced the concept of coordinative structures, which they defined as “a group of muscles often spanning a number of joints that is constrained to act as a single
functional unit” (Kugler et al., 1980, p.17). Coordination, in this context, can be defined as the formation of coordinative structures, control refers to the regulation (i.e., parametrization), and skill corresponds to the optimal parametrization of coordinative structures. It has been suggested that self-organization is the mechanism or principle underlying the formation of coordinative structures (Kugler et al., 1980; Kelso & Schöner, 1988). Self-organization has been particularly studied in the field of synergetics, a theory about spontaneous pattern formation in open, non-equilibrium physical systems (Haken, 1978), and refers to the principle that intrinsic order emerges at a certain level of observation (the macroscopic level) through cooperative coupling among the microscopic components of the system. These levels comprise a circular causal relation: the cooperativity of the microscopic components result in ordered behavior at the next higher level of observation, and, in turn, the collective behavior at the macroscopic level imposes its order on the microscopic components, a phenomenon called ‘enslaving’ (Haken, 1978). This circular causality between microscopic and macroscopic levels results in stable behavior. Enslaving provides a parsimonious solution to the degrees of freedom problem: only one or a few variables have to be controlled by the central nervous system. Two variables play an essential role: the order parameter or collective variable, and the control parameter. The collective variable captures the intrinsic order of the system. The control parameter is the parameter that induces a phase transition from one stable state of the system to another.

The best example of self-organization in the field of movement coordination was given in studies of bimanual rhythmic movement patterns (Kelso, 1981; 1984). Subjects performed oscillatory motions with their index fingers. The main findings were:

1. the presence of two stable coordination modes (bistability), i.e., inphase coordination (simultaneous activation of homologous muscles) and antiphase coordination (simultaneous activation of flexor and extensor muscles);
2. increasing the cycling frequency in the antiphase mode resulted in loss of stability and a spontaneous phase transition to inphase coordination at a critical frequency, whereas a subsequent decrease of frequency did not lead to a transition from inphase to antiphase coordination;
3. the presence of only one stable coordination mode beyond the critical frequency.
### Phenomena

<table>
<thead>
<tr>
<th>Boundary constraints</th>
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**Initial conditions**

\[ f = 0 \text{ or } f = \pm p \]

*E.g., oscillate fingers in a given fashion*

**Non-specific parameters**

\[ b / a \]

*E.g., increase frequency*

**Collective variable**

*Characterizes coordinated states*

\[ V(f) = -a \cos(f) - b \cos(2f) \]

*E.g., relative phase (f)*

**Components**

**Nonlinearly coupled oscillators**

\[ \dot{\varphi}_1 + f(\varphi_1, \varphi_2) = I_{12} + F_1(t) \]

\[ \dot{\varphi}_2 + f(\varphi_2, \varphi_1) = I_{21} + F_2(t) \]

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**Figure 1.** A three-layered scheme to understand coordination between two rhythmic units. The collective variable dynamics (here, relative phase dynamics) are represented by the potential function \( V(f) = -a \cos(f) - b \cos(2f) \) (see for further details chapter 3). The relative phase dynamics are influenced both by higher level boundary constraints (the ratio \( b/a \) is a function of frequency), and by the lower-level dynamics of the component oscillators. In the component oscillator dynamics, the function \( f \) represents the dissipative terms that capture nonlinear characteristics of limb oscillations, the function \( I \) represents the coupling between the oscillators, and \( F_1(t) \) and \( F_2(t) \) represent small stochastic forces (adapted from Kelso, 1995).

Multistability and phase transitions are considered essential features of self-organization. Other features of self-organization, such as critical fluctuations (i.e., increase relative phase fluctuations nearby the critical frequency), and critical slowing down (i.e., an increase of relaxation time after a perturbation of the coordination pattern nearby the critical frequency) have also been found (Scholz, Kelso, & Schöner, 1987; Kelso & Schöner, 1988). From these experiments it was concluded that the relative phase (f) between the fingers is a relevant collective variable, and frequency is a relevant control parameter. It has to be noted that the
control parameter is nonspecific in the sense that it does not specify in any way the phase relation of the pattern that emerges after the transition. More generally, relative phase seems to be an important collective variable, because it reflects the cooperativity among components of a system.

2.2 Elementary coordination dynamics.

Once a relevant collective variable has been identified, its dynamics (i.e., its evolution in time) can be examined. Using the tools of nonlinear dynamics, observed spatiotemporal patterns can be mapped onto attractor states of the collective variable dynamics. For example, stable inphase coordination corresponds to a dynamical system with a point attractor in \( f = 0 \) (i.e., the relative phase converges to the point \( f = 0 \)). The collective variable dynamics can be represented by mathematical equations of motion or so called potential functions (i.e., a graphical representation of the ‘attractor landscape’ of the collective variable). The potential function and attractor landscape for bimanual rhythmic coordination be presented more in detail in chapter 3. Elementary coordination dynamics (Kelso, 1994a) have been introduced to model the coordination between two rhythmically moving components or units. Coordination dynamics apply not only to coordination between components within an organism (e.g., interlimb coordination), but also to coordination between an organism and the environment (e.g., synchronization a moving limb to a metronome; unimanual rhythmic tracking of a visual signal), or between organisms (e.g., visual coupling of limb movements between people). Figure 1 presents a three-layered scheme to describe coordination dynamics using bimanual coordination as an example (Kelso, 1995). It represents the linkages between phenomena and dynamic pattern theory (horizontal) and between levels of description (vertical). The components represent the rhythmically moving limbs, which are modeled as nonlinear coupled oscillators. It should be noted that the collective variable and their dynamics are always functionally defined. The patterns at all levels are governed by the collective variable dynamics. Further, mutability exists among levels. For instance, the component level defined here may be viewed as a collective variable to describe the emergence of kinematic patterns from interactions between agonist and antagonist muscles (i.e., the next lower level of observation). The boundary constraints indicate that the coordination dynamics are task or context dependent. Boundary constraints include behavioral information that is specific (e.g., an intended, instructed, or environmentally specified relative phase pattern) or non-specific to the collective variable dynamics (e.g., movement frequency).

Coordination dynamics have been applied to development (e.g., Whitall & Clark, 1994; Thelen, 1991; Corbetta & Thelen, 1996), and learning (Zanone & Kelso, 1993). Zanone and Kelso (1993) have shown that intrinsic patterns, such as the 180° out-of-phase pattern, can be
modified in the direction of a to-be-learned pattern (i.e., a $90^\circ$ out-of-phase pattern) by behavioral information that is specific to the coordination dynamics. Thelen and colleagues have shown that preferred coordination tendencies exist in young infants for bimanual coordination, and coordination of the lower limbs that emerge from the autonomous dynamics of the body, and that new patterns may arise from the effect of task demands on such existing coordination tendencies. Whitall and Clark (1994) have shown that children’s intralimb and interlimb coordination stability in walking and galloping increase gradually with age. Similarly, the developmental studies in the present thesis will investigate whether the stability of bimanual rhythmic coordination and rhythmic perception-action patterns in school age children increases with age.

Coordination dynamics have also been applied to movement disorders to gain more insight in the spatio-temporal organization of the observed coordination patterns in Parkinsonian patients (Swinnen et al., 1995; Van Emmerik & Wagenaar, 1996), hemiplegic patients (e.g., Wagenaar & Beek, 1992; Balderissa et al., 1994), adult tardive dyskinesia (Newell & Sprague, 1996) children with cerebral palsy (e.g., Holt et al., 1996). These studies investigated, for example, the (in)stability or (in)flexibility of coordination patterns in response to manipulation of a control parameter (e.g., movement frequency), or to applied perturbations (different load conditions), or they investigated the constraints of certain characteristics of the disease (e.g., tremor, spasticity) on the coordination dynamics. In this thesis the coordination dynamics of rhythmic movements of children with DCD will be investigated. A characteristic of children with DCD is that they have problems in movement coordination that is not due to a known neurological disorder (DSM-IV). This implies that the influence of ‘neurologic’ constraints on the coordination dynamics of DCD children is not straightforward. This issue will be discussed further in chapter 5. Nevertheless, to gain more insight in the mechanisms underlying motor difficulties in DCD children, the present thesis will investigate the stability of rhythmic coordination patterns and the loss thereof by applying frequency manipulations and perturbations.