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# 1 General Introduction

Human infants are distinguished by a number of unique properties. This holds true, for example, for their motor development. Compared to other primates, it covers a relatively prolonged period of immaturity. While monkey and ape infants are already mobile and agile at early ages [Gould 1977, Thelen 1983, 1984], human infants start their lives with limited body control. The long period of time between birth and the emergence of voluntary and skilled actions in humans offers an unparalleled insight into the construction of movement [Thelen, 1984].

Spontaneous movements of newborn babies have long been dismissed as purposeless, unintentional or reflexive [Gesell & Amatruda 1947, Piaget 1952, White et al. 1964]. However, there was a renewed interest in motor development in the last decades, looking not only at how babies come to control their bodies but also at motor development as an entry for understanding human cognitive development in general [Thelen 1995, 2000]. This revitalized interest was, amongst others, inspired by Nicolai Bernstein [1967]: He suggested that movements require acting in conjunction with external gravitational and internal biomechanical forces and that they cannot be planned in any pre-programmed way, insensitive of these contextual forces. Actions must be represented at an abstract level to allow for on-line perceptuo-motor control in a continually changing force field [Thelen 1995]. This view led to the idea that movements are function-specific in contrast to muscle-specific. Movements are organized in synergies - a functional linking together of muscles into assemblies that work together – in order to solve the so called ‘degrees of freedom problem’ [Bernstein 1967]. Bernstein’s perspective on motor organization put forward the dynamic systems approach and the action- perception approach to motor development. Together they prioritize the theoretical framework for investigating and discussing a wide range of different aspects of the motor behavior of neonates and adults. These two approaches form the framework for the present study of principles of coordination in spontaneous newborn movements.

In the following, first, an overview of previous relevant studies on movement coordination in neonates is presented. Second, the concept of dynamic systems and the action- perception approach to motor development are introduced. Third, concepts derived from animal exploratory behavior and hierarchical organization in behavior are presented. The

latter are applied in chapter 2 and 3 to discuss the results of the present study of newborn motor behavior.

### **Movement coordination in neonates**

In the postnatal period, there are already examples of simple but coordinated actions, some of which have functional significance: The neonatal reflexes, such as the Moro, grasp, palmar, plantar and asymmetric tonic neck reflexes, are probably the most well-known [e.g. Barnes et al. 1978, Capute et al. 1978, Meer et al. 1995, Bartlett 1997] along with ingestion movements, such as rooting, sucking, and swallowing [e.g. Crook 1979, Rochat & Hespos 1997, Craig & Lee 1999]. Spontaneous hand-mouth contact and a positive relationship between grasping and sucking reflects a kind of synergistic hand-mouth organization [e.g. Korner & Beason 1972, Takaya et al. 2003]. Eye-hand coordination is apparent in visual control of arm movements [Hofsten 1982, Meer 1997].

Limb movements, including kicking and waving, have been described by Thelen (1981) and interpreted as “fundamental structures underlying the construction of voluntary movement” [Thelen & Fisher 1983, p. 130]. The authors depicted these fundamental structures as “intrinsic oscillations of functionally related muscle groups” (p. 130). Patterns of interlimb coordination have been studied in spontaneous arm waving and reaching [e.g. Hofsten 1982, Corbetta & Thelen 1996, Thelen & Spencer 1998, Zaal et al. 1999] as well as in the coordination of leg movements in spontaneous kicking and adaptive dynamics of movement patterns [e.g. Thelen & Fisher 1983, Thelen et al. 1987a, Jensen et al. 1994, Angulo-Kinzler et al. 2002]. These separate accomplishments on the investigation of coordinative features in arm *or* leg movements of newborn infants inspired the analysis of the coordinative dynamics of the entire 4 limb system of neonates in the present study.

### ***Coordination of leg movement patterns***

Lower limb movements have been studied mainly in the context of dynamic systems theory. Intralimb coordination is expressed in spatial and temporal organization: Flexion and extension of hip, knee and ankle joints show spatial and temporal synchrony. Constrained movement durations and paths result in rhythmical or periodic organization over time [Thelen et al. 1981, Thelen & Fisher 1983]. Temporal stability was demonstrated by these authors for flexor and extensor phases as well as the kick cycle, which is considered as a fundamental unit of movement. Variations in kick frequencies resulted from variable time periods between kicks or kick phases, but not as a function of variation of flexion or extension durations.

Investigation of infant bilateral coordination of leg movements showed distinct modes of interlimb coordination. One leg is usually coupled with the contralateral leg: Most of the time in an alternating fashion with one leg flexing during the extension of the other leg. Alternatively, but more seldom, the coupling is in phase [Thelen & Fisher 1982, 1983, Thelen et al. 1983].

Interestingly, it was shown that the patterns of muscle activation that reflect the neural control of the motor behavior were less patterned than the movements themselves: Electromyographic (EMG) recordings detected phasic antagonist coactivation at the initiation of the flexor phase, but little or no activity in either muscle group in the extensor phase. During coactivation, there was less activity in the dorsal muscles, the gastrocnemius and hamstrings than in the ventral pair, tibialis anterior and quadriceps femoris [Thelen & Fisher 1982, 1983]. Extensive antagonist coactivation is considered to be characteristic of immature and unskilled movements [Mortier & Prechtel 1971, Schloon et al. 1976]. Kicking movements seemed to rely strongly on passive forces since the braking of the flexor movement and the initiation of the extension appeared both not to be controlled by active muscle intervention.

Thelen & Fisher [1983] concluded from these findings that the patterning of space and time, observed in supine limb movements, reflect the interplay of actively supplied *and* reactive forces. Already in the postnatal period, the limbs as a whole rather than individual muscles or joints are elementary units of control, as seen in studies of locomotion in various vertebrates [Shik & Orlovsky 1976] and skilled human bimanual tasks [Kelso et al. 1979, 1981].

From a dynamic view, Thelen et al. [1987b] proposed to consider single kicking movements as spring-like oscillatory movements: Energy pulses from co-active muscle bursts provide a forcing function for the whole leg so that the space time trajectory results naturally from the biodynamic properties - without a one-to-one correspondence between the neural impulses and the limb trajectory. In dynamic terms, spring-like oscillatory limbs exhibit limit-cycle behavior [Thelen et al. 1987b]. From this perspective, interlimb coordination is explained by coupled single-leg oscillators that can produce various modes of interlimb coordination.

Thelen et al. [1981] had suggested a resemblance between newborn lower limb movements and stepping in mature locomotion. This idea is in accordance with locomotor-like interlimb coordination that developed significantly ahead of function in the cat and rat fetus [Brown 1915, Narayanan et al. 1971, Bekoff & Lau 1980], newborn rat [Bekoff & Trainer 1979], mouse [Fentress 1978] and chick [Provine 1980, Bekoff 1981]. Human pre-

and postnatal kicking is also thought to provide perceptuo-motor loops for the developing neuromuscular system. Stability in the patterning of intra- and interlimb synchrony of newborn leg movements reflects some type of constraint in motor organization and demonstrates a reduction of the degrees of freedom of the system already in the neonatal period [Thelen 1984].

Furthermore, a great body of longitudinal studies on adaptive dynamics of leg movements have shown mechanisms of transitions to new forms of behavior within the first year [e.g. Thelen & Ulrich 1991, Goldfield et al. 1993, Thelen et al. 1993, Corbetta & Thelen 1996, Spencer & Thelen 1996, 2000, Angulo-Kinzler et al. 2002].

### ***Spontaneous arm movements***

Arm movements of neonates have also been studied from the perspective of nonlinear dynamics. However, particularly reaching has also received attention in the context of the perception-action approach. These researches showed that newborn arm movements are subject to several sets of organizing constraints. The pattern of neonatal arm movements is similarly synergistic as the organization of leg movements: Spontaneous movements of the hand are coupled to the movements of the arm in a synergistic way. Forward extensions of the arms are accompanied by opening (extensions) of the hand [Trevarthen 1974, Hofsten 1982] and when the arm flexes, the digits of the hand have a tendency to flex, too [Hofsten 1989].

Several studies documented a naturally occurring division of arm movements into distinct phases of acceleration and deceleration, termed movement units [Hofsten 1979, 1991, Fetters & Todd 1987, Mathew & Cook 1990]. The analysis of the curvature showed that speed valleys coincided with turning points in movement direction. This means that changes in movement direction occurred between these units [Hofsten 1991]. Therefore, temporal and spatial aspects are involved in the structuring of spontaneous arm movements into units [Fetters & Todd 1987, Hofsten & Rönnquist 1993]. This is consistent with kinematic patterns reported for adult single-limb reaching movement trajectories, in which accelerations are also associated with redirecting the movement [Abend et al. 1982, Hollerbach & Flash 1982, Morasso 1981]. Units of action that are demarcated by the relationship of inflection points in the speed-curvature profiles are considered as fundamental building blocks of adult reaching movements and handwriting [Viviani & Terzuola 1980, Abend et al. 1982]. Similar movement structures have also been found in primate kinematic studies [Christel et al. 1998] and in extreme flexible extremities - both completely without and with multiple joints [Martin & Niemitz 2002, 2004].

Analysis of interlimb coordination in neonates showed that the movements of the two arms were distinctly coupled in all three dimensions of space. They moved vertically together, abducted and adducted together and extended together in the forward direction [Hofsten & Rönnquist 1993]. Corbetta & Thelen [1996] found that spontaneous coordination tendencies of the arms are reflected in patterns of interlimb coordination in reaching: When nonreaching interlimb activity showed a tendency to be synchronized, reaching interlimb activity also tended to synchronization and infants reached primarily with two arms. When there were no coordination tendencies in nonreaching interlimb activity, reaching activity also was inclined not to be coordinated and reaching movements were predominantly unimanual.

Thus, definite preferences of interlimb coordination are apparent in both arms and legs, whereby these preferences are limb specific: legs tend to coordinate in alternation, and arms are predominantly coordinated in phase [Corbetta & Thelen 1996].

Meer et al. [1995] investigated spontaneous arm-waving movements and demonstrated that neonates are able to intentionally control their arm movements in the context of external forces. This indicates that development of visual control of upper limb movements is underway soon after birth [Meer et al. 1995]. The assumption that neonates are capable to control their arms is supported by studies of arm movements in the presence of a visual target [Trevarthen 1974, Hofsten 1982, 1984]. These authors suggested that upper limb movements may occasionally come under the control of vision and that neonates may direct their arm movements toward a visually presented target.

Meer et al. [1995] argued that watching their moving arms helps neonates to acquire information about bodily dimensions and movement limitations and to construct a bodily frame of reference that is essential for actions. The establishment of a bodily reference frame on the basis of a flow of information between perceptual input and motor output is required for a later successful control of motor behavior [Meer et al. 1995].

### **Dynamic systems approach**

Motor development has long been considered as a set of motor milestones that yields insight into the maturational process of the neuromuscular system – largely autonomous changes in infant's brains, muscles and growing bodies with little significance for the psychology of the child [Gesell 1954, McGraw 1945]. Prominent impact on the contemporary perspective of motor development involves the dynamic systems theory that originates in the study of physical dissipative systems. The view from dynamic systems on motor development was first inspired by the Russian physiologist Nicholai Bernstein [1967] and further expanded

by developmental psychologist Esther Thelen. From the dynamic perspective, motor behavior is both part and expression of the cognitive system and emerges from the confluence of many interacting factors - each with its own developmental trajectory.

The dynamic systems approach to cognition applies the mathematics of dynamical systems to the understanding of cognitive function. Cognition is conceived as an emergent phenomenon evolving continuously and simultaneously with a steadily changing nervous system, body (active and passive biomechanical apparatus) and environment. Mature cognitive systems are the outcome of a long-lasting, permanently ongoing process of self-organization of brain and behavior. The dynamical approach was inspired already more than fifty years ago by research in neuroscience [Hodgkins & Huxley 1952] and work on motor activity of the limbs [Feldmann 1966, Bernstein 1967]. More recently, it is related, amongst others, to the idea of embodiment of the mind [Port & Gelder 1995, Hendriks-Jansen 1996, Clark 1997, Thelen 2000].

Generally speaking, a dynamical system is a set of quantitative variables (e.g. distance, velocity, rates of change, etc.) that are changing simultaneously in real time as a result of their mutual interferences with each other. These interactions can be described by differential or difference equations [Gelder & Port, 1995]. For example, Newton's equations of motion for physical bodies were the first dynamical models. Strengths of the dynamical approach are first the ability to describe the emergence of complex structures and processes in real time and second the recognition of the importance and detection of qualitative transitions that are essential for the understanding of the system's dynamics. A prominent example from motor control is the Haken-Kelso-Bunz model [Haken et al. 1985].

Traditionally, motor development was seen from the perspective of maturational and hierarchical neural models, in which lower centers of the nervous system - like primitive reflex pathways and spinal pattern generators - controlled newborn movements [e.g. Forssberg 1985]. However, nonlinear dynamics of the neuro-musculo-skeletal system play a crucial role in motor development. The theory of nonlinear dynamics, according to which spatio-temporal patterns arise spontaneously from the system's dynamically interacting components with many degrees of freedom [Haken 1977, Nicolis & Prigogine 1977], has revolutionized the conceptualization of human movement [Kelso et al. 1980, Kugler et al. 1980, Turvey et al. 1978]. The idea of self-organization of the individual parts of a system conceptualized the assembly of movement coordinative structures as a nonlinear, dissipative system to produce a more complex organization as a result of their interrelations. Therefore, self-organization is a brilliant solution to the question of how to regulate the enormous

amount of degrees of freedom of the motor system, asked by Bernstein [1967]. Self-organization is the emergence of patterns from the complexity of the system and its energetic status into preferred states or attractors. For example oscillations or cyclicity are common attractors of motor systems [Kugler et al. 1980].

Using the methods of nonlinear prediction and surrogate data processing, Taga et al. [1999] found evidence that newborn infants' general movements [Precht & Hopkins 1986] were generated by nonlinear dynamics, which can be distinguished from linear processes and correlated noise.

The rapid development of computer resources and the growing body of theoretical knowledge about complex dynamics allowed researchers in natural sciences to look for nonlinear dynamics in data, whose evolution could not be explained by linear (Auto-Regressive-Moving Average, ARMA) models. Systematising of the disperse set of methods have led to the Nonlinear Time Series Analysis (NLTSA) [Kantz & Schreiber, 1997]. From these techniques we used the methods of recurrence plots and symbolic dynamics to analyze the kinematic time series obtained from video recordings of the movement behavior of neonates.

### ***Recurrence Plot Analyses***

Recurrence plots (RP) are a tool to visualize the time dependent behavior of dynamical systems [Eckman et al. 1987]. This method reveals the dynamic nature of a system e.g. random or structured, stationary or non-stationary, periodic or aperiodic etc..

Whether a time series is periodic or not is not necessarily a yes-or-no question. In the presence of measurement noise, a data set from an originally periodic system can appear aperiodic. Since dynamic systems can vary in the degree of aperiodicity, it can be of value to quantify 'how aperiodic' a time series is. Aperiodicity means, that the state variables never return exactly to former values. However, in aperiodic systems, state variables may reoccur in the vicinity of former values.

Recurrence is a basic property of dissipative systems. Even though small perturbations of such a dynamical system create exponential divergence of its state, the system will come to a state that is arbitrary close to a previous state and pass through an analogue evolution. Recurrence plots reveal such recurrent behavior of dynamical systems. They represent a graphical method to detect hidden patterns and structural changes in time series and visualize pattern similarities over different time scales. The basic assumption underlying the concept of recurrence plots is that the observable data set is the realization of

the dynamical process of interaction of the relevant variables over time. Since the influence of all potential variables is incorporated into the time series of the regarded variable, a topologically equivalent image of the underlying multidimensional system behavior can be recreated by the usage of a single measurable input.

The method of recurrence plots [Eckmann et al. 1987] is utilized for finding hidden correlations in complex data. Particularly in the analysis of systems whose dynamics may be changing, RPs are a suitable tool, because they make no demands on the stationarity of a time series. The main advantage of recurrence analysis over other widely used methods - like for instance Fourier analysis - is the preservation of temporal and spatial dependencies within the time series. RPs have been successfully applied in the field of physiology, for example to heart-rate-variability data [Marwan et al. 2002], breathing patterns in rats [Webber & Zbilut 1994] and neuronal spike trains in cats [Kaluzny & Tarnecki 1993]. But also mathematical problems have been addressed by RPs, predominantly for the identification of transition points in non-stationary data sets [e.g. Trulla et al. 1996].

The RP is a method for visualizing the dynamical behavior of high dimensional phase space trajectories. Typically, the dimension of a phase space is higher than two or three that can be illustrated. Phase spaces of higher dimensions can only be pictured by projection into the two or three dimensional sub-spaces. The RP is a technique that allows the visualization of the n-dimensional phase space trajectory through a two-dimensional representation of its recurrences.

Illustrations of recurrence plots from a periodic system, a chaotic system and white noise are presented in chapter 2. In chapter 2 and 3 recurrence plots are applied to data from spontaneous movements of neonates revealing organizational features of the underlying dynamics of this behavior. Statistical evaluation of recurrence plots, with the use of recurrence quantification analysis, is introduced in chapter 3 and is used to quantify visually detected results from recurrence plots statistically.

### ***Symbolic dynamics***

Symbolic dynamics is a mathematical tool belonging to the theory of dynamical systems for describing data that appear as sequences of discrete states. Basically, states and trajectories of discrete-time dynamical systems with continuous state space are transformed into symbolic sequences by partitioning the system's state space into a finite number of regions, each of which is labelled with a symbol [Hao 1989, 1991, Engbert et al. 1997a,b, Graben & Kurths 2003]. It has been successfully applied to physiological data including time

series from neuronal spike trains [Rapp et al. 1994] movement control [Tass et al. 1996, Engbert et al. 1997a,b, Scheffczyk et al. 1997], bone structure [Saparin et al. 1998] and cardiorespiratory time series [Kurths et al. 1995, Engbert et al. 1997a, Schiek et al. 1998]. The approach of symbolic dynamics is based on a coarse-graining of the dynamics. This way some amount of detailed information is lost, whereas some of the invariant, robust properties of the dynamics are kept.

In order to construct symbolic dynamics of an ensemble of real valued time series  $x_i(t)$  obtained by a measurement of some natural system, the state space of the underlying dynamical system has to be partitioned into a finite number of pair wise disjunctive subsets. The subsets are defined by letters of a finite set or alphabet. It has been shown that every segmentation of the data set yields a segmentation of the state space automatically, even if the state space is unknown and has to be reconstructed from the experimental time series by delay embedding methods [Takens, 1981]. The easiest way of gaining a symbolic dynamics is the procedure of static encoding [Wackerbauer et al. 1994]: a classification of the time series  $x_i(t)$  into two or more nonoverlapping intervals. A binary static encoding segments the time series into two subsets according to a threshold  $\theta$ . The encoding rule  $s_n = \{ 0: x_i(t) < \theta ; 1: x_i(t) \geq \theta \}$  maps each value  $x_i(t)$  to the  $i$ th time series at time  $t$  to “0” if  $x_i(t)$  is below the threshold  $\theta$  and to “1” if otherwise.

The construction of symbolic dynamics from the data sets of spontaneous movements and resultant outcomes are demonstrated in chapter 2 for joint angle displacement trajectories of the limbs and in chapter 4 for distance trajectories of distal effectors. In both cases a binary static encoding of single limb trajectories and the composition of the obtained symbolic strings into 4 dimensional symbolic time series was used.

### **Perception-Action Approach**

A second impact on the research of motor development is the perception-action approach inspired by James and Eleanor Gibson. According to this concept, perception and action are linked together: Actions need perceptual information to be planned and adaptively executed. Perceptual information needs movement to create the relevant patterns in perceptual systems.

Inspired by the work of these researchers contemporary research on motor development focuses on perception-action coupling. Movement is regarded to be embedded in a continuous perception-action chain, in which perceptual information provides the basis for adaptive and prospective motor control [Gibson & Pick 2000, Hofsten 1993, Lee 1993]. In

turn, the key to prospective control are exploratory movements. Active exploration is accounted as the link in the perception-action loop, which generates or allows for gathering information for deciding what to do next.

Self-exploration through spontaneous motor activity serves the investigation of the various musculo-skeletal organizations in the context of bodily and environmental constraints. It is assumed to be a mechanism that underlies the changes in early development and to be a precursor of later motor control [Thelen & Fischer 1983, Forssberg 1999, Piek 2001]. The meaning of active exploration of objects and events has long been recognized in developmental psychology [e.g. Gibson 1988, Bushnell & Boudreau 1993]. From the dynamic approach to motor development, attention has been paid to the information gained by self-exploration through spontaneous movements for the process of bootstrapping new and emergent forms of motor activity: It can help the infant to find out how to use the dynamics of their on-going bodily activities more effectively [Schneider et al. 1990, Schneider & Zernicke 1992]. Goldfield [1993] suggested that the process of self-exploration serves “to ascertain a state of awareness about the self and its environment by means of activities, which involve the gathering of information specific to stable regions in the high-dimensional space of possible actions” (p.167). According to Piaget [1953], infants are exploring their own action system by performing certain movements over and over again and evaluating the continuous multimodal flow of sensory information. Likewise, Hofsten [1991] proposed that exploratory movements are directed towards the infant’s own action system instead on the external environment, which is traditionally expected. In a nutshell, one of the predominant driving forces of changes in behavior and development is proposed to be the exploration of the capacities of the individual.

Traditionally, neonatal motor behavior has been dismissed as reflexive, namely as a set of stereotyped, elicited and automatic reflexes that reflect a hardwired sensor motor loop organization at a spinal or para-spinal level [Sherrington 1932]. Although they serve fundamental functions for the subject, they are not considered as goal-directed or volitional. However, converging evidence suggests that neonatal behaviors are prospective and flexible goal-directed actions: For example for neonatal sucking [Caspar & Fifer 1980, Craig & Lee 1999] and rooting [Rochat & Hespos 1997], re-examination of these so called reflexes indicated that they are goal-directed and by no means automatic. Meer et al. [1995] demonstrated that infants are in control of their arms in the Asymmetric Tonic Neck Reflex (ATNR) and in the face of visual stimuli [Meer et al. 1997]. Furthermore, newborn infants are able to imitate facial gestures [Meltzoff & Decety 2003] and to control their gaze [Haith

1980, Farroni et al. 2002]. These kinds of basic skills are suggested to provide activity-dependent input to specific sensor-motor systems.

Chapter 4 addresses the questions of how biomechanical qualities of spontaneous motor activity in neonates make a contribution to sensor motor patterning and to what extent it can be related to the notions of perception/action coupling and goal-directedness.

### **Exploratory behavior**

As outlined above, spontaneous motor activity of neonates is considered as exploratory behavior of the bodily action system. Organizational features found in the kinematic data of newborn spontaneous movements showed parallels to concepts derived from studies of exploratory behavior of animals, which are discussed in chapter 2 and 3. In account of this, principles of the ideas of exploratory behavior of rats in a novel environment and searching behavior of ants are presented in the following.

Exploratory behavior is considered as a natural manifestation of spatial learning [e.g. Biegler & Morris 1996, Etienne et al. 1996, Gallistel & Cramer 1996]. Information on processes of spatial memory has been obtained from the study of kinematics of exploratory behavior of rats [e.g. Tchernichovsky et al. 1998, Tchernichovsky & Benjamini 1998] and of searching behavior of ants [e.g. Wehner et al., 2006]. On the first glimpse, spontaneous spatial behavior appears to be stochastic. However, it has been shown that apparently unstructured paths reveal some rules, when measured towards a reference point in studies of exploratory behavior of rats [e.g. Eilam & Golani 1988, Golani et al. 1992, Tchernichovsky & Golani 1995] and of searching behavior of ants [e.g. Wehner & Srinivasan 1981, Müller & Wehner 1994].

Reduced to a point moving in local space, rat's exploratory behavior displays an alternating pattern between progression and stopping [Golani et al. 1993]. Spatial analysis reveals a pattern of regular excursions into the environment from a preferred place. In this location, the number of visits and the cumulative time of staying are of a higher order of magnitude in comparison to the values estimated in all other places. This place, termed home base, is assigned by high and often the highest incidences of typical behaviors [Eilam & Golani 1989].

Home base location varies individually in the same testing environment, indicating that the extended preference for a certain location must be based on memory [Eilam & Golani 1989]. The location of the home base is considered as a reference place, which patterns the exploratory behavior into natural units of regular excursions between two successive visits.

These excursions are shaped by home base attraction in several ways: First, phase plane analysis of the relationship between location and velocity revealed a geometrical pattern: Rats show low velocity and intermittent progression on outward journeys and high velocity while moving back to the home base [Tchernichovsky & Golani 1995, Tchernikowsky et al. 1998]. Second, the probability of terminating the excursion by performing the next stop at the home base increases with every additional stop - first slowly and then quickly. Third, the cumulative process of home base attraction is constrained by an intrinsic upper bound of stops that mark the return to base. The upper bound varies from session to session but is not increasable by increasing the size of the testing environment. Home base attraction is reset once the rat visits the home base [Golani et al. 1993].

In the course of the exploratory process over repeated exposures to the same environment, the home base lost its unique status and several transient bases were established. This reflects a transition from constrained movement patterns referred to one home base to a more diverse and free activity. Moreover, it suggests the involvement of both one *and* several reference places in the process of spatial learning [Tchernikowsky et al. 1996].

Home base behavior of rats shows striking similarities to the searching behavior of desert ants: Getting lost, a homing ant does not perform a random walk but pursues a stereotyped search strategy. The search pattern consists of loops of ever increasing size and different azimuthal directions centred about the origin [Wehner & Srinivasan 1981, Wehner & Wehner 1986]. Müller & Wehner [1994] suggested an underlying spiral search program that is transformed into the visible system of loops by the ant's path-integration system. Path-integration is the dominant system of long-distance navigation in insects and mammals. It has been extensively modelled and investigated in rats, ants and honeybees [e.g. Gallistel 1990, Biegler 2000, Wehner and Srinivasan 2003, Etienne & Jeffrey 2004] and is referred to in chapter 2 and 3.

### **Hierarchical organization of behavior**

Another concept that is used in chapter 3 to discuss results obtained from recurrence plot analyses of kinematic data from the motor behavior of neonates is the scheme of a structural hierarchy. This conception represents the approach from behavioral sciences. It has been successfully used for research on various kinds of behaviors including human speech. Spoken language can be described as a stream of behavior, where acoustically filled segments alternate with silent segments [Todt 2004]. Segmentation is a basic step in the investigation of behavior. In human speech, the most conspicuous segment is the sentence or phrase, which

exhibits a typical duration [Pöppel 1978, Vollrath et al. 1992]. From the perspective of information processing, phrase duration appears to provide optimal units of information. Sentences form an intermediate level of a structural hierarchy, in which the highest level is given by an episode of speaking. On hierarchically lower levels, several structural compounds can be distinguished: In a top-down order, the constituents of sentences are single phrases, words, syllables and morphemes or phonemes [Bierwisch, 2000]. Usually the basic level of elements serves as a basis for analysis, in which basic units are compared and classified according to parametric features such as measures of frequency, amplitude and duration. The pool of classified elements is then used to categorize units of the next higher level and determine the respective repertoire of unit- types.

Segmentation of serial information into smaller subsets is a process well known from the chunking of information as a coding mechanism in short term memory. Chunking has been extensively studied in human list learning and has also been observed as an organizing principle in the serial behavior of rats [e.g. Fountain 1990, Macuda & Roberts 1995] and birds [review: Terrace 1991, Hultsch et al. 1999]. A chunk representation is considered to overcome the limitation of working memory capacity - with chunks working as functional units that altogether comprise a higher-order sequence - by forming a hierarchical structure. Therefore chunking appears to be a fundamental strategy involved in processes of memory formation and in the acquisition of complex sequences of actions.

The concept of a structural hierarchy implies two kinds of separation: a vertical separation that distinguishes levels from above and below, and a horizontal separation that segregates the elements of each level into groups that define the next higher level. Each of these levels is distinguished by specific rules of unit combination [Hultsch et al. 1999]. Vertical separation is based on behavioral frequencies: Focussing on a single level, higher level behavior appears so slowly that it is perceived as constant, while lower level behavior occurs so rapidly that all that is observed is a sampled statistical behavior [Webster 1979].

From a dynamic perspective, in which the idea of levels and time scales plays an important role, higher level behavior results from a synergism, which is something more than the sum of the lower level components. The concept of a structural hierarchy from behavioral biology is used in chapter 3 to interpret the structures found in recurrence plots on different time scales in the movement behavior of neonates.

**Aims of the study**

The motor behavior of neonates is generally accepted as an extremely important topic of infant research and - as elaborated above - has been studied already in terms of different aspects [see e.g. Thelen & Smith 1994]. Nevertheless, the current knowledge is still limited. The aim of my own investigation was to supplement such knowledge and to thereby improve our understanding of neonate motor behaviour in reference to higher cognitive accomplishments.

Core questions for this purpose were “if the intrinsic dynamics of the movement behavior give rise to higher level organization” and second, “if this organization facilitates the development of abstract representations” that are considered as the precondition for cognitive processes. With this in mind, emphasis was set on (i) the movement behavior of the entire 4 effector system (ii) the observation over time spans of several minutes and (iii) the interaction of principles of coordination and mechanisms of variation within a dynamic framework. Thus, my approach was new, as compared to other studies of motor development concerning intralimb coordination on a time scale of seconds [Thelen & Fisher 1982,1983] and separate investigations of interlimb coordination within lateral-symmetrical extremities on a time scale of several month [Thelen et al. 1983, Corbetta & Thelen 1996]. Furthermore, my conception was designed to bridge a gap between research on the development of human limb movement coordination and studies on spontaneous neural network activity of embryonic and neonatal vertebrates attributed to spontaneous movement behavior of the limbs. There is a growing body of evidence for such activity playing an essential role in the development of the spinal neural network-, the musculo-skeletal system and higher representations of the latter [Thelen 2000]. On account of this, my own study combined concepts of nonlinear dynamics and action/perception coupling, which both seemed expedient to finally elucidate these matters.