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Chapter 1

Normal psychomotor development

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INTRODUCTION

The brain is the most complex organ of the body and undergoes developmental changes throughout the fetal period, infancy, childhood, and adolescence. The dynamic course of this maturation is one of the most fascinating aspects of the human condition. Although brain change and adaptation is part of a complex and long-lasting process, the earliest phases of maturation, i.e., during fetal development and childhood, are the most dramatic and important. A description of the embryogenesis and maturation of neural structures is beyond the scope of this chapter, and some aspects of it will be covered by further parts of this book. Even if neurons do not continue to proliferate after fetal life, it is now clear that maturational processes extend well into postnatal life, eventually reaching adulthood. Brain plasticity and reorganization after insults are surely the most desirable consequences of such a prolonged maturation: the immature brain is capable of impressive rearrangements of pathways and of regional specialization. For example, language areas may shift from the dominant to the contralateral hemisphere, while the damaged primary motor area may reorganize either around the lesion or contralaterally, depending on lesion timing and extension.

Many concepts around the clinical assessment of neurological functions in children, as well as the understanding of their disorders and the ways in which they can be approached and treated, have changed in the last decades, according to more updated models of normal or better typical development. Therefore, we will devote this introductory chapter to the review of traditional and modern concepts around functional development.

HEREDITARY AND ENVIRONMENTAL FOUNDATIONS OF DEVELOPMENT: THE NATURE–NURTURE DEBATE

In the past, many scientists took up opposing positions on what was familiarly referred to as the nature–nurture issue that involves the debate about whether development is primarily influenced by nature or by nurture. Nature refers to an organism's biological inheritance, nurture to its environmental experiences. Researchers who were more biologically oriented emphasized the role of heredity and maturational factors in human development, whereas those who were more environmentally oriented emphasized the role of learning and experience. Almost no one today argues that development can be explained by nature alone or by nurture alone. In fact, the old debate on the relative contribution of nature versus nurture to the construction and maintenance of brain architecture has led to the widely accepted consensus that genes and environment work in concert in shaping neural circuits and behavior. Gene–environment interactions are highly complex; not only do environments influence how genes are expressed, but genes can also help shape the environments to which people are exposed. Although the contribution of genetic programing to development has been characterized and accepted early on in the debate, the role of the environment has remained vague for a long time, mostly because of the difficulties in quantifying environment-induced changes in the brain. It was not until the early 1960s that brain development ceased to be considered as an entirely experience-independent process. Some authors developed the concept of range of reaction, which shows the notion that a human being's genetic make-up establishes a range of possible developmental

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outcomes, within which environmental forces largely determine how the person actually develops. According to this concept, heredity does not rigidly fix behavior, but instead establishes a range of possible developmental outcomes that may occur in response to different environments. Gilbert Gottlieb (2007) has offered a view of gene–environment interaction in which individual development is organized into multiple levels – genetic activity, neural activity, behavior, and environment – all of which influence each other bidirectionally. The most important aspect of this view is the recognition that genes are part of an overall system and that their activity is affected by events at other levels of this system. Both genes and environment are inextricably linked and always operate in a mutually dependent fashion in shaping development (Parke and Gauvain, 2009).

Another factor in gene–environment interaction is the stage of the child's development and the importance of critical periods (see later). The evidence showing the interdependence of genetic and environmental influences as they affect behavior has changed the ways in which nature and nurture are viewed with respect to their operation over the course of the lifespan. Four main types of gene–environment interplay occur: epigenetic effects of environments on genes; variations in heritability according to environmental circumstances; gene–environment correlations; and gene–environment interactions. The effects of genes are most appropriately viewed as involving a dynamic process in which the effects of a single gene are influenced by multiple-inherited DNA elements and by the actions of environments and of a random stochastic variation. The gene–environment correlations concern genetic influences on individual variations in people's exposure to particular sorts of environments. This comes about as a result of passive, active, and evocative gene–environment correlations. Passive refers to the effects of parental genes on parental behaviors that help shape the rearing environments that they provide for their children. Active and evocative differ in that they refer to the effects of the child's genes on those child behaviors that help the child's selection of environments (active) or that serve to influence interpersonal interactions and, hence, influence other people's reactions to the child (evocative). For the genetic–environment interactions there are four key reasons for expecting them to be influential. First, evolutionary considerations argue that genetic variation in response to the environment provides the raw material for natural selection. Second, developmental considerations indicate that biological development at the individual level involves adaptations to the environmental conditions that prevail during the formative period of development. Third, environmental evidence indicates that there is great variability in responses to environmental hazards. Fourth, there is the biological evidence showing numerous examples of their interaction in biology and increasingly in medicine, i.e., this interaction often plays some role in multifactorial traits and disorders (Rutter, 2007).

CRITICAL PERIODS OF DEVELOPMENT

A critical period is a time during early postnatal life when the development and maturation of functional properties of the brain, its "plasticity," is strongly dependent on experience or environmental influences. This concept plays an important role in the nature versus nurture debate (Sengpiel, 2007). However, not all neuroscientists agree on what defines a critical period for neural circuit development. One strict interpretation defines the critical period as a subset of sensitive periods. Sensitive periods are special time-windows in early development where experience has a profound effect on the brain, while critical periods are a special case wherein experience is absolutely required at fixed developmental periods for subsequent normal function. The critical period should include the onset of robust plasticity response to sensory experience, a defined period of time when induction of plasticity is possible. One of the major concepts currently being investigated in neuroscience is that such critical periods represent heightened epochs of brain plasticity, and that sensory experience during these periods produces permanent, large-scale changes in neuronal circuits. The various critical periods start very shortly after the relevant sensory information first becomes available and a certain level of intracortical inhibition marks the onset of the critical period. The development of cortical inhibitory circuitry initially lags behind that of the excitatory circuitry. The critical period is characterized by changes not only at the level of synaptic transmission, but increasingly by structural changes, which result in closure of the critical period. The most significant changes in the cortex towards the end of the critical period are those seen in the extracellular matrix, a network of macromolecules, which becomes more and more rigid during postnatal development. Thus, three phases of plasticity define the critical period: (1) pre-critical period: the initial formation of neuronal circuits that is not dependent on experience; (2) critical period: a distinct onset of robust plasticity in response to experience when the initially formed circuit can be modified by experience; and (3) closure of the critical period: after the end of the critical period, the same experience no longer elicits the same degree of plasticity (Hooks and Chen, 2007).

In humans, critical periods are extended over years and there are different critical periods for different brain functions (for example binocular vision or language acquisition) and unless a certain function is learned during this period, the function will remain poor. The well-known classic experiments by Hubel and Wiesel showed how early sensory deprivation dramatically affects anatomy and functional organization of the visual cortex. These authors reported that occluding one eye (monocular deprivation) early in development led to a severe reduction in the number of visual cortical cells responding to that eye, with a very strong increment in the number of neurons activated by the open eye. They termed this the critical period during which synaptic connections in the primary visual cortex are modified by visual experience. The critical period shown by Wiesel and Hubel (1963) has remarkably influenced not only biologists but also psychologists, philosophers, physicians, politicy makers, parents, and educators. In fact, this sensitive period is also considered present in humans, involving language, music, sport, and even sociability. The brain continues to develop throughout infancy, childhood, and adolescence and psychologists assert that, through the same periods, one acquires increasingly higher mental functions. During growth, the brain accumulates information about the external world in order to build an internal world in the temporo-parietal association cortex. In thinking, the frontal association cortex exerts its executive function on the internal world to manipulate thought models such as images, ideas, and concepts to simulate what could happen in the external world. In fact we acquire knowledge and new skills over our entire lives; it is likely that there are differently timed sensitive periods for acquiring different types of knowledge and skills such as literacy, numeracy, music, art, and physical education. A new field of research, called “nurturing the brain,” is expected to provide accurate knowledge about sensitive periods, which will help formulate an efficient learning timetable for curricula in nurseries and schools (Hensch, 2004; Ito, 2004; Konishi, 2004).

CRITICAL PERIODS AND THE EFFECTS OF ENVIRONMENTAL ENRICHMENT

The regulation of critical period onset and duration is not simply by age, but rather by experience and enriched environments may prolong plasticity. In fact, fundamental contributions to the development of the nature–nurture debate came from the experiments by Rosenzweig and Bennett (1996) in which environmental enrichment (EE) was introduced as an experimental protocol specifically devoted to investigate the influence of environment on brain and behavior, showing that the morphology, chemistry and physiology of the brain can be remarkably altered by modifying the quality and intensity of environmental stimulation. Enriched animals are reared in large groups and maintained in widely stimulating environments where a variety of objects (e.g., toys, tunnels, nesting material, and stairs) are present and change frequently. An essential component of a typical environmental enrichment setting is the opportunity to attain high levels of voluntary physical activity on running wheels. Therefore, living in environmental enrichment provides the animals with optimal conditions for enhanced exploration, cognitive activity, social interaction, and physical exercise. Environmental enrichment has remarkable effects on adult brain function in several species. Recently, it has been shown that environmental enrichment from birth leads to a conspicuous acceleration of visual system development in rodents, appreciable at the behavioral, electrophysiological, and molecular levels. The first environmental enrichment effects have been shown at the anatomical level, with environmental enrichment determining robust increases in cortical thickness and weight, size of cell soma and nucleus, dendritic arborization, length of dendritic spines, and synaptic size and number. One of the most amazing properties of environmental enrichment is the capacity to modify behavior, especially in tasks involving complex cognitive functions. Environmental enrichment enhances learning and memory and reduces the cognitive decline typically associated with aging. A large number of genes change their expression levels in response to environmental enrichment, most of them in functional classes linked to neuronal structure, synaptic transmission and plasticity, neuronal excitability, and neuroprotection. The most striking effect on visual system development elicited by an environmental enrichment paradigm starting at birth is a marked acceleration in the maturation of visual acuity, a sensitive and predictive index of visual system maturation. The acceleration effect is strong: in the timescale of human visual development, it is as if a child will reach his or her final visual acuity around 3 years of age (i.e., approximately 2 years before the age at which children’s acuity development normally ends).

It has been suggested that, in the earliest phases of exposure to environmental enrichment, the effects of environmental enrichment do not stem from a direct action on the developing pups but rather from a variation in maternal behavior in enriched conditions. Indeed, it has been shown that pups in environmental enrichment receive a higher level of tactile stimulation through licking, grooming, and physical contact. The level of licking and grooming provided by the mother has been shown to influence hippocampal structure and function, to affect molecules crucial for plasticity such as Brain-derived neurotrophic factor (BDNF) and N-Methyl-D-aspartate (NMDA) receptors, and to leave long-lasting traces in the offsprings’ behavior. The offspring of mother rats with high or low licking and grooming behavior show once they become adults differences in novelty reaction, in exploratory behavior, in spatial learning and memory, in the level of glucocorticoid receptors in the hippocampus, leading to a difference in the feedback control on hypothalamus–pituitary–adrenal axis, and in spine density and synaptic plasticity in the hippocampus (Sale et al., 2009). Recently body massage and multisensory stimulation are increasingly included in neonatal care in human newborns, with some evidence for a significant effect on the rate of weight gain. Our group (Guzzetta et al., 2009) has hypothesized that enriching the environment in terms of body massage may thus accelerate brain development in infants. The effects of body massage were explored in preterm infants and it was found that massage accelerates the maturation of electroencephalographic activity and of visual function, in particular visual acuity. In massaged infants, higher levels of blood Insulin-like growth factor-1 (IGF-1) were found. Massage accelerated the maturation of visual function also in rat pups and increased the level of IGF-1 in the cortex. Antagonizing IGF-1 action by means of systemic injections of the IGF-1 antagonist JB1 blocked the effects of massage in rat pups. These results demonstrate that massage has an influence on brain development and in particular on visual development and suggest that its effects are mediated by specific endogenous factors such as IGF-1. Further evidence of the effects of environmental enrichment in critical or sensitive periods of development may have important consequences on timing and modalities of early intervention.

THEORETICAL PERSPECTIVES ON CHILD DEVELOPMENT

A wide range of theories makes understanding children's development a challenging undertaking. No single theory has been able to account for all aspects of child development. Each theory contributes an important piece to the child development puzzle. Although the theories sometimes disagree, much of their information is complementary rather than contradictory (Santrock, 2009).

Structural–organismic perspectives

Freud and Piaget, who were interested in psychological development, adopted an approach called "structuralism." The theories they introduced focused on different aspects of development: Freud (1938) was interested in emotions and personality, whereas Piaget (1951) was interested in thinking. Yet both devised theories that incorporated their mutual interest in biology, especially evolutionary theory, which was prominent at the time. Both Freud and Piaget used what has come to be known as the structural–organismic perspective in their theories. They shared the view that the organism goes through an organized or structured series of stages, or discontinuous changes, over the course of development. Both also saw the stages they proposed as universal; that is, all members of the human species were thought to experience these stages regardless of when and where a child develops. Despite these common features, Freud's and Piaget's theories are markedly different from each other. In the early 1900s, Freud introduced psychodynamic theory, which emphasizes how the experiences of early childhood shape the development of adult personality. This theory is complex and covers many aspects of psychological functioning. As is well known, for Freud the developing personality consists of three interrelated parts, the id, the ego, and the superego. The roles of these three components of personality change across development as the infant, who is largely under the control of the id, or instinctual drives, gradually becomes more controlled by the ego. The ego is the rational and reality-bound aspect and attempts to gratify needs through socially appropriate behavior. With further development, the third component of personality, the superego emerges when the child internalizes parental or societal morals, values and roles, and develops a conscience or the ability to apply moral values to his or her own acts. One of Freud's primary contributions to developmental psychology is his emphasis on how early experiences, especially in the first 6 years of life, influence later development. On the other hand, Piaget introduced a structural–organismic theory to describe intellectual development. Piaget's theory states that children actively construct their understanding of the world and go through four stages of cognitive development that are underlied by two processes: organization and adaptation. The principle of organization reflects the view that human intellectual development is a biologically organized process, thus, the child's understanding of the world changes in an organized way over the course of development. Piaget used the principle of adaptation to describe the process by which intellectual change occurs as the human mind becomes increasingly adapted to the world. According to Piaget, cognitive development is a process in which the child shifts from a focus on the self, immediate sensory experiences, and simple problems to a more complex, multifaceted, and abstract understanding of the world. Many studies have expressed doubt about Piaget's theory of development, but this theory has had a marked influence to date. He speculated that neonates develop by repeated interaction with the environment using basic schemas such as innate primitive reflexes, assimilating the environment, extending their own borders as an adaptive system, simultaneously complicating their internal structure, and repeating some further quantitative steps. The theories introduced by Freud and Piaget offer descriptions of development that focus on the structure of the developing system (Parke and Gauvain, 2009).

Learning perspectives (behaviorism, cognitive social learning theory, information-processing approaches)

The behaviorist approach to development is exemplified in the work of J.B. Watson (1913), Pavlov (1927), and Skinner (1935). The foundations of behaviorism essentially hold that we can study scientifically only what can be directly observed and measured; the development is observable behavior that can be learned through experience with the environment. Pavlov (1927) discovered the principle of classical conditioning, in which a neutral stimulus acquires the ability to produce a response originally produced by another stimulus. In the early twentieth century, Watson (1913) demonstrated that classical conditioning occurs also in human beings; in fact he demonstrated that there is in humans a type of learning in which two stimuli are repeatedly presented together until individuals learn to respond to the unfamiliar stimulus in the same way in which they respond to the familiar stimulus. Skinner's notion (1935) of operant conditioning, a type of learning in which learning depends on the consequences of behavior, was also applied to children's behavior. Positive reinforcement of a particular behavior in the form of praise or a special trait was shown to increase the likelihood that a child would exhibit that behavior again. Some psychologists agree with the behaviorists' notion that development is learned and is influenced strongly by environmental interactions. However, they argue that cognition is also important in understanding development. Social-cognitive theory holds that behavior, environment, and cognition are the key factors in development. Bandura (1962) is the leading architect of the social-cognitive theory. He emphasizes that cognitive processes have important links with environment and behavior. His early research program focused heavily on observational learning (also called imitation or modeling), which is learning that occurs through observing what others do. Bandura's most recent model of learning and development includes three elements: behavior, the person/cognition, and the environment operating interactively. Information-processing approaches to development focus on the flow of information through the cognitive system, beginning with an in–out or stimulus and ending with an output or response, much like the way computers process information. Early computers may be the best candidates for the title of "founding fathers" of information-processing theory. Although many factors stimulated the growth of this theory, none was more important than the computer. In human information-processing, output may be in the form of an action, a decision, or simply a memory that is stored for later use. Information-processing theorists are especially interested in the cognitive processes that a child uses to operate on knowledge and the gradual changes over the course of development in children's ability to use these processes. The information-processing theory emphasized that children manipulate information, monitor it, and strategies about it. Individuals develop a gradually increasing capacity for processing information, which allows them to acquire increasingly complex knowledge and skills. This approach has been applied to a wide range of topics of cognitive development, including attention, memory, problem solving, and planning. Information-processing theory is also proving valuable in studying how children develop an understanding of reading, mathematics, and science, as well as in social behaviors, such as social problem solving and aggression (Parke and Gauvain, 2009; Santrock, 2009).

Dynamic systems perspectives

Another approach to child development concentrates on changes over time and considers these changes the result of the coordination of elements of a complex, integrated system. System theory has been applied to a variety of developmental issues, including motor development (see below), perception, language, cognition, and social behavior. In dynamic system theory individuals and their achievements can be understood and interpreted within the framework of the interacting components of the system. For example, in learning to walk infants must coordinate many physical abilities, including muscle strength, balance, and momentum, with the features of the physical word such as gravity and the properties of the walking surface. Only when the entire system of forces is coordinated and mastered does the child succeed at walking (Parke and Gauvain, 2009).

Contextual perspectives (sociocultural theory)

Some theorists have concentrated on the role of contextual factors in human development. For example the sociocultural theory that places particular emphasis on the impact of social and cultural experience on child development. Vygotsky's theory (1962) proposes that the child's development is best understood in relation to social and cultural experience. Social interaction, in particular, is seen as a critical force in development. Through the assistance provided by more experienced people in the social environment, the child gradually learns to function intellectually on her own. Thus, the social world mediates individual cognitive development.

By emphasizing the socially mediated nature of cognitive processes, this approach offers new ways of assessing children's cognitive potential and of teaching reading, mathematics, and writing. Sociocultural theory has also increased our appreciation of the profound importance of cultural variation in development. The ways in which adults support and direct child development are influenced by culture, especially the values and practices and organize what and how adults and children think and work together and use cultural tools to understand the world and solve cognitive problems. These tools are devised by cultures and take a variety of forms, including language, mathematical symbols, literacy, and technology. As children develop, different tools help them function more effectively in solving problems and understanding the world. Thus, tools of thinking, which are products of culture, become incorporated into the ways individuals think about and act in the world (Parke and Gauvain, 2009).

New perspectives: imitation and model of the mirror neurons (Hebbian learning theory)

Imitation provides a foundation for language acquisition, skill learning, socialization, and enculturation. The discovery of mirror neurons (MNs) by G. Rizzolatti and his group (1996) has stimulated considerable interest in action observation and imitation among cognitive neuroscientists, because human development would be unthinkable without the capacity to learn by observing others' behavior. MNs, first described in the premotor cortex of macaque monkeys, have the property of responding both while the individual executes an action and while he/she sees or hears another individual performing a similar action. This suggests that these neurons are part of a circuit that translates the actions of other individuals into the language of the observer's own actions, enabling the observer empathically to understand the actions of others while at the same time learning to perform a similar action. If MNs are important for the social development of children, understanding how MNs themselves develop is an important question for developmental psychology and neuroscience; but the function of these intriguing cells is itself a focus of controversy. Imitation can be understood whether it depends on a special purpose mechanism (specialist theories) or within a general learning and motor control framework (generalist theories). The specialist theories suggest that imitation is mediated by a special purpose mechanism. The most important specialist theory is the active intermodal matching (AIM) model. AIM proposes that, when a body movement is observed with the intention to imitate, the initial, visual representation of the movement is converted into a supramodal representation which contains information about organ relations. Supramodal coding allows a visual representation of an observed action to be matched up with a pattern of motor activation that produces the same action. Generalist theories of imitation imply that MNs – and other neural systems that are active during both action observation and action execution – can do imitation but are not dedicated to imitation. They suggest that MNs acquire their properties in the course of ontogeny as a side-effect of the operation of general associative learning and action-control processes. Once established, MNs might be involved in the generation of imitative behavior (and in several other functions), but, according to generalist theories, the properties of MNs are not innate, and the learning and action-control processes that lead to their formation evolved in response to much more general adaptive problems. Empirically, the question of whether there are neurons with mirror properties present at birth remains unresolved. However, the finding that MNs for tool use can develop during ontogeny suggests that learning plays a crucial role. The environments in which humans develop might be such that they yield MNs with greater imitation-relevant specificity, and/or human imitation might represent the interplay between MNs and more complex cognitive abilities (Brass and Heyes, 2005).

Hebbian synaptic potentiation, sometimes paraphrased as "what fires together wires together," can link motor neurons involved in producing an action with visual/auditory neurons responding to the sight/sound of the action itself. Hebbian learning and genetic preprogramming can be integrated in a broader perspective, by suggesting that the MNs might initially develop through experiential canalization of Hebbian learning. Canalization is the result of predictable interactions between genetic mechanism and reliable features of the environment. The organism's sensory experience plays an essential role in directing ontogeny, leading to experimental canalization. In a recent paper, the authors argue that this hypothesis has three distinct advantages: first, it goes beyond simple nature–nurture dichotomies and is consistent with current evolutionary biology; second, it helps to make sense of some otherwise puzzling developmental phenomena; and lastly it suggests interesting new questions for empirical research. The idea of Hebbian learning in the mirror system has been proposed to show that the MNs could develop without the need for genetic pre-wiring, without necessarily denying the possibility of genetic predetermination. Activity in a certain population of premotor neurons causes the infant to perform a particular action. The infant views and hears him- or herself perform this action, and activates populations of neurons in the temporal cortex that respond preferentially to this action.

This sensory signal reaches the original premotor population of neurons that caused the action and other neurons responsible for different actions. In the case of premotor neurons responsible for the action execution, the synaptic input reaches neurons that are active, and this synchrony leads to Hebbian potentiation. In the case of the neurons responsible for different actions, the synaptic input will reach inactive neurons, leading to Hebbian depression of the synapses. The hypothesis that Hebbian learning is involved in the ontogeny of MNs is also part of the Associative Sequence learning theory of imitation (Heyes, 2001; Brass and Heyes, 2005). This theory, which links explicitly imitative behaviors to the activity of the MNs, assumes that imitation is experience-dependent and that repeated observation of self-produced movements is necessary to link visual and sensory-motor representations of actions. So, these authors proposed an ontogenetic model for the development of MNs for grasping. Spontaneous motor activity in fetuses and infants is indeed cyclic, characterized by nonrandom chaotic dynamics. It involves the entire body, including arms and hands, which are often moved repeatedly in short bouts of activity. So, a key function of cyclic movement (and especially of their persistence in the first 4–5 months of human life) may be the optimization of Hebbian learning in the brain via enhancement of long-term potentiation (LTP) consolidation. Moreover, EEG activation during infants' spontaneous activity is poorly investigated, but infants aged 2–11 months, when reaching and handling objects, show increased theta synchronization in the parietal and frontal lobes, which are critical for the mirror system. Infants pay remarkable attention to their own actions, with a strong preference for moving hands; generate spontaneous motor activity with cyclic parameters that might be in the optimal range for Hebbian learning; and the synaptic activity in their parietal and frontal lobes synchronizes in the theta-band during grasping. The hypothesis is that evolution optimized infant behavioral patterns to produce canalized, reliable Hebbian learning in the parietal-temporal-frontal system (Del Giudice et al., 2009).

MODELS OF MOTOR DEVELOPMENT

Following the debate on nature versus nurture, and the models of interpretation of child development, the way in which human motor development has been perceived has changed over time (Table 1.1).

Neural-maturationist approach

In the first half of the twentieth century, normal and abnormal motor developments have been interpreted within the framework of the Neural-Maturationist Theories. These theories described the relatively uniform development of motor milestones in children and suggested that motor development is based on a gradual unfolding of predetermined patterns in the central nervous system and an increasing cortical control over lower reflexes. The idea that behavioral patterns emerge in an orderly genetic sequence resulted in the distinctions of general development rules, such as the cephalo-caudal and central-to-distal sequences of development. These Neural-Maturationist ideas left little place for developmental modification by environmental stimulation and experience on motor development. Among the Neural-Maturationists, McGraw (1943) has an atypical position. Even though she considered endogenous maturational processes the main driving forces of development, she acknowledged that experience during particular time-windows could modify motor development. In the middle of the century, the concept of "epigenetic systems" appeared, suggesting that the characteristics of the phenotype develop through a complex series of interactions between genetic programs and environmental signals. Some aspects of these programs were presumed to be tightly constrained, species-specific that resulted in important aspects of the phenotype, even in abnormal environments, whereas others were less constrained and provided the basis for phenotypic variation. In 1967, Bernstein introduced a system approach to the study of motor control (Bernstein, 1967). He argued that motor acts cannot be controlled by the explicit mapping of neural commands and movement trajectories, but that additional factors contribute to the performance, including inertia and reactive forces. He also formulated "the degrees of freedom problem," referring to the infinite number of movement patterns through which a movement can be performed. He suggested that the CNS develops a limited repertoire of "muscle synergies" that produce the muscle activation pattern (Forssberg, 1999; Hadders-Algra, 2002).

Dynamic system approach

It has become increasingly clear in the domain of normal motor development that development is not merely a matter of an unfolding of innate programs. Thelen (1985) was among the first to recognize the significant influence of environmental conditions on motor programs. To explain the role of ambient conditions on motor development, she recognized that human motor behavior exhibits basic properties that are common to dynamic systems. According to this theory, motor development is regarded as a dynamic system, i.e., a complex system which changes over time due to the interaction of multiple components. Perhaps the most fundamental principle of dynamic systems theory is that patterns of

Table 1.1

Overview of the main characteristics of theoretical perspectives on child development (for references see text)

		Continuity-discontinuity issue		Nature-nurture issue	
Theories	Domains mainly studied	Continuity	Discontinuity	Nature	Nurture
Structural-organismic perspectives					
Freudian theory	Emotions/personality		+	+	+
Piagetian theory	Cognition		+	+	+
Learning perspectives					
Behaviorism	Social/cognition	+			+
Social cognitive learning theory	Social/cognition	+			+
Information-processing approaches	Cognition	+		±	+
Neuro-maturationist approach	Several (movement, perception, language, cognition, social)		+	+	−
Dynamic system perspectives					
	Several (movement, perception, language, cognition, social)	+		±	+
Contextual perspectives					
	Social	+		+	+
Vygotsky's theory	Social and influence of cognition	+		+	+
Hebbian learning theory					
	Motor (grasping)	+		+	+
Neuronal group selection theory	Motor	+		±	+

behavior can emerge spontaneously from the cooperation of intrinsic factors (such as muscle strength, body weight, postural support, the infant's mood, and brain development) and extrinsic factors (such as the environmental condition and specific task requirements). Thus, according to this theory, detailed plans for modes of behavior are not represented a priori in the brain, and movement patterns do not arise from the maturation of neural centers or central pattern generators; instead, the patterns arise through self-organization. In fact, The Dynamic Systems Theory postulates that motor behavior spontaneously, as a process of self-organization, adopts specific, temporarily attractive states of organization. Behavior changes and develops in a non-linear way, i.e., by means of transitions, due to changes of the characteristics of the intrinsic or extrinsic component parts. In other words, the Dynamic Systems Theory and the Neural-Maturationist Theories differ, especially in their view on the role of the nervous system in motor development. The Neural-Maturationist Theories consider the endogenously driven maturational state of the nervous system the main constraint for developmental progress, whereas in the Dynamic Systems Theory, the make-up of the neural substrate plays a subordinate role only (Hadders-Algra, 2001, 2002).

Neuronal group selection theory

In the 1990s, the neuroscientist Gerald M. Edelman developed a new theoretical concept on the basis of his work with various types of neuronal networks: the Neuronal Group Selection Theory (NSGT; Edelman, 1989, 1993). This theory which may end the old "nature–nurture" debate might offer a bridge and a perfect balance between the Neural-Maturationist and Dynamic Systems Theories and might facilitate the understanding of the effects of brain damage at early age. According to NGST, the brain, or more specifically, the cortical and subcortical gray and white matters are dynamically organized into variable networks, the structure and function of which are selected by development and behavior. The units of selection are collections of hundreds to thousands of strongly interconnected neurons, called neuronal groups. These groups act as functional units dealing for instance with a specific sensory modality. NGST states that development starts with primary neuronal repertoires, with each repertoire consisting of multiple neuronal groups. The basic structure of the cells and the gross connectivity of the primary repertoires are determined to a large extent by genetic information, which, in turn, can be considered as the net result of ages of evolution. Therefore, genetic information plays a substantial role in the primary determination of brain development and it is thought that the area-specific characteristics of the neocortex are partially based on properties laid down at the time of neurogenesis. According to this theory, the genetic base of the primary repertoires does not preclude variation. On the contrary, the repertoires are variable because of the dynamic epigenetic – and thus variable – regulation of cell division, adhesion, migration, death, and neurite extension and retraction. When most of the anatomical connections of the primary repertoires have been established, development proceeds with selection on the basis of afferent information produced by behavior and experience. The experiential afferent information induces modifications in the strength of the synaptic connections within and between the neuronal groups, resulting in the variable secondary repertoire. The changes and changing connectivity within the secondary repertoire allows for a situation-specific selection of neuronal groups. Thus, the secondary neuronal repertoires and their associated selection mechanism form the basis of mature variable behavior, which can be adapted to environmental constraints. According to the concept of NGST, motor development is characterized by two phases of variation: the phases of primary and secondary variability. These two phases can be regarded as the motor counterpart of NGST's primary and secondary neuronal repertoires. During the phase of primary variability, motor activity is characterized by abundant variation as the nervous system self-produced afferent information and is not strictly tuned to environmental conditions. The motor variations themselves constitute a fundamental developmental phenomenon. In addition, the variable motor behavior gives rise to self-generated, variable afferent information. The afferent information, in turn, is used to select a pragmatic neuronal group, i.e., a neuronal group giving rise to motor behavior which is functional in a diversity of situations, but not neatly adapted to the details of each situation.

The time of occurrence of the phase of selection and the duration of the transition from the phase of primary to secondary variability is function-specific. According to this theory, the rich variation in motor behavior has been documented for the first phases of the majority of motor functions: reaching and grasping, crawling, locomotor motility, and postural control. The neural system dedicated to a specific function explores during the phase of primary variability all motor possibilities available for that information and results in so-called "experience expectant" information storage. The trial and error exploration is associated with a continuous processing of self-generated afferent information, on the basis of which motor behavior which fits the situation best is selected; this is the start of the phase of secondary or adaptive variability. When the secondary variability is formed, the brain is characterized by extensive synapse rearrangement, the net result of synapse formation and synapse elimination. The development of situation-specific motor strategies is guided by active trial and error learning, based on experiences which are unique to the individual (experience dependent information storage).

The properties of primary variability of NSGT can also be illustrated by examining the general movements (GMs) that are the most frequently used movement pattern of the human fetus and newborn infant, described by Prechtl and his group (Prechtl, 1990; Einspieler et al., 1997; Einspieler and Prechtl, 2005). In fact, a remarkable repertoire of fetal movements is revealed by ultrasound from as early as 7½ weeks postmenstrual age. The first movement is lateral bending of the head and slow extensions of the neck followed at 9 to 10 weeks by complex, coordinated, generalized movements of the head, trunk, and limbs, named GMs. GMs show movement variation and complexity with the emergence of synaptic activity in the embryonic cortex. This finding induced the idea that the basic movement form of GMs, i.e., motility of all parts of the body, is brought about by the central pattern generating (CPG) network in the spinal cord and brainstem, and that variable GM activity is the result of modulation of the CPG-networks by activity of the cortical subplate. Many fetal patterns continue virtually unchanged in form and shape after birth. During development, GMs display age-specific characteristics, including so-called "preterm", "writhing," and "fidgety" movements. Around 36 to 38 weeks postmenstrual age (PMA) writhing GMs emerge which are slower, smaller in amplitude, and more powerful than preterm GMs, and show less involvement of the trunk. Typically they are ellipsoid in form, which creates the impression of a writhing quality. These continue until the end of the second month postterm when another transition takes place. The movements become fidgety; a continuous stream of tiny, elegant movements occurring irregularly all over the body. Fidgety movements normally continue until the age of 4 to 5 months when they are replaced by purposeful movements. The first goal-directed movements of the arms occur in the form of mutual manipulation of the hands, manipulation of the clothes, and reaching movements which do not result in successful grasping. Observation of primary variability and namely of GMs has a great value to detect neurologica abnormalities in fetuses, newborns, and young infants (Hadders-Algra, 2000, 2001, 2002, 2008; Einspieler and Prechtl, 2005).

Action perspectives

According to the discovery of MNs (see above) Claes von Hofsten (2004) has proposed an action perspective on motor development. In fact, this new neuroscience evidence shows that the brain represents movements in terms of actions even at the level of neural processes. The movements of newborn infants, traditionally described as reflexes, are instead prospective and flexible goal-directed actions. Action systems do not appear ready-made but they are the result of a process with two foci, one in the central nervous system and one in the subject's dynamic interactions with the environment. Perceptual development is determined by the action capabilities of the child and what objects and events afford in the context of those actions. Humans need to relate their own actions to the actions of other people for learning new actions. So, perception, cognition, and motivation develop at the interface between neural processes and actions. They are a function of both these things and arise from the dynamic interaction between the brain, the body, and the outside world. In summary, the development of action and perception, and the development of the nervous system and growth of the body mutually influence each other in the process of forming increasingly sophisticated means of solving action problems. With the development, the different action systems also become increasingly future-oriented and integrated to each other.

A MODEL OF PSYCHOMOTOR DEVELOPMENT: HAND FUNCTION

The hand is an effective tool that is used in many different tasks of daily life. The usefulness of the hand is highly dependent on cognition because one has to understand the value of using one's hands for a meaningful purpose. Use of the hand for object manipulation involves grasp, release, and the ability to transfer an object from one hand to the other. Stereotyped reflex patterns are often described in newborn infants. However, as mentioned previously, studies have indicated that these early movements can be considered less reflexive and more voluntary. Reaching consists of two distinct and coordinated movement components. The first component is a transportation phase, which brings the hand to the target; in this part of the movement mainly the proximal joints and muscle are involved. The second component is a grasp phase in which the hand is shaped in anticipation of contact with the object; this phase involves mainly the distal joints and muscles. Although these two phases of the reach are separately controlled they are coordinated so that the grasp phase starts during the transportation phase. Children only a few days old already have a rudimentary visual control of arm movement and when initiating an aimed movement toward a visually fixated target, the starting position of the hand must be defined proprioceptively. However, reaching movements, associated or not with touching an object, are not followed by grasping phase. This behavior has been termed prereaching or prefunctional; it is voluntary and has purposefulness not seen in more reflexive behaviors. Before the infant can reach successfully he or she must learn to coordinate the movements of the shoulder, arm, and hand. Several studies demonstrated that the integration between posture and voluntary control is an important prerequisite for coordinated arm and hand movements in reaching. Successful reaching and grasping objects is consistently demonstrated by infants by 4 months of age; however, at this early state the ability to plan the movement ahead of time is still poor. So, the movement path is awkward and the trajectory consists of many movement units. This changes after the infant has practiced reaching for some time, and at around 1 year of age the number of movement units has decreased and while the path of an infant's reaching is curvilinear initially, it becomes smoother and straighter within the first 3 years of life. Lhuisset and Proteau (2004), who studied reaching movements in children 6, 8 and 10 years old, found that although the children clearly planned the movement ahead of time, the planning processes were still more variable than for adults. The ability for anticipatory control and shaping of the hand develops substantially during the first year of life. The 5 to 6 month-old child starts to close the hand before making contact with the object, but he does not adjust his grip aperture in relation to object size. Infants 10 months of age shape their hand to fit different shapes of objects before contact.

The prehension skills that infants develop in their first year of life serve their play goals and enable them to explore and learn about the environment. The development of purposeful grasp occurs later and is usually seen in rudimentary form by 4–5 months of age. However, a recent study suggests that finger and hand movements without object grasp contribute to the development of grasp and that isolated forefinger movement may be used earlier in grasp development as a means to contact and explore objects. By 4–5 months of age, using both tactile and visual information, infants begin to use visual input to prepare the hand for the grasp by opening and shaping the hand before grasp according to the object's size and shape, orienting and adjusting the grip based on visual and tactile clues. The infant becomes capable of using a variety of grasping patterns that are selected based on the affordances of the objects and his or her playful intentions. Initially the infant uses only a few grasping patterns and uses them indiscriminately.

As the infant gains experience and matures, a variety of patterns can be observed. A palmar grasp, characterized by a pronated hand and flexion of all fingers around the object, is most frequently used by 24-week-old infants. By 28 weeks the infant holds the object in a radial palmar grasp or superior palmar grasp when the radial fingers and thumb press a cube against the palm. The radial palmar grasp is a hallmark in grasp maturation because the infant now differentiates the sides of the hand, using the ulnar side to provide stability for the grasping movement and the radial side to grasp and hold the object. Between 32 and 36 weeks the infant demonstrates grasp of the object in the fingers rather than the palm, and by 36 weeks he or she exhibits a radial digital grasp or inferior forefinger grasp, e.g., the infant can grasp a small object between the radial fingers and thumb. A 36-week-old infant can grasp a very small object by a scissors grasp, e.g., prehension between the thumb and lateral border of the index finger. During this type of grasp the hand is stabilized on a surface, and the ulnar fingers are flexed to provide stability of the thumb and radial finger movement. Forefinger grasp or inferior pincer grasp, in which the infant stabilizes the forearm on the table as a base while grasping the cube, is observed at 40 weeks. By 52 to 56 weeks infants can grasp without the forearm stabilizing on the surface, this form of grasp is named superior pincer grasp. As both upper extremities are brought together consistently, bimanual manipulation of objects is observed (about 8 months). At 12 months the infant demonstrates significant increases in both dexterity with one hand and cooperative use of two hands together. Between 12 months and 2 years of age infants develop complementary two-hand use that is a very important step to expand the exploratory options of the objects. There are less studies regarding development of object release; however, controlled release generally develops after grasp. At around 5–6 months, infants start the release of an object in a more purposeful way. Between 40 and 44 weeks the infant demonstrates purposeful release in the context of play. This release is often accomplished by flinging items in a ballistic extension synergistic movement pattern (elbow, wrist, and finger extension). By 52 weeks the infant demonstrates greater proficiency and has acquired graded object release. Development of functional hand skills continues to be refined over a long course of time with complex object manipulation skills not mastered until 7 years of age.

Efficient object manipulation depends on several factors: differentiation of individual fingers' movement, grading of grip force, control over the release, bimanual action, and in-hand manipulation. Maturation in each of these abilities assists the child's mastery over objects and struggle toward competence. These skills are necessary for functional skills such as handwriting and self-care activities because they enable an object to be more efficiently positioned in the hand. The basic categories of self-care are eating, dressing, bathing, and toileting. The acquisition of these skills in childhood is intricately involved with the development of motor skills and is influenced by chronological age, mental age, the child's interest, and social and cultural factors. The integration of these factors influences the ages at which a child develops specific self-care skills resulting in individual differences and high variability (Henderson and Pehoski, 2006; Eliasson and Burtner, 2008).

CONCLUSIONS: FROM THEORIES TO CLINICAL IMPLICATIONS

In recent years clinicians interested in the neurological assessment of newborns and young infants have paid increasing attention to newer approaches to the assessment of the nervous system according to the theories of motor development. These approaches are mainly based on the knowledge that from the first weeks of gestation the human nervous system is capable of many complex and rapidly changing functions (dynamic system and neuronal group system theory). Convergent findings of different disciplines (psychology, neuroscience, pediatrics) have contributed to overcome the traditional image of the "incompetent" and immature newborn and young infant. It is now accepted that the young nervous system (of a fetus, a newborn, or a young infant) is not a simple collection of reflexes (neural-maturationist theories), but a complex organism producing a great deal of endogenously generated behaviors, able to use them for his or her adaptive needs, in interaction with his or her environment. Many attempts have been made to integrate these findings and to introduce new items, exploring more complex motor, perceptual, cognitive, and communicative functions, into the neurological assessment of newborns and young infants. However, the practical contribution of these attempts, in relation to clinical practice, is in many cases still not fully established. To be really useful, new methods of neurological assessment have to fulfil a series of basic requirements; they have to include items strictly related to the age-specific repertoire of the CNS, which changes very rapidly during the pre- and early postnatal periods. New functions emerge, others undergo regression, and there are critical periods when the maturation of functional properties of the brain is strongly dependent on experience or environmental influences. There is a rich variation in infant's and children's development and it is impossible to perform a strict timetable of their progresses. Moreover, there are periods during which time the emergence of typical features of development (e.g., fidgety movements at 3 months) is the target to judge a normal development. There is also a wide biological variation in attaining developmental milestones, e.g., walking independently in neurologically normal infants may happen at any given time between 8 and 18 months of age. Child development comprises of gross motor, fine motor, language, cognitive, and social–behavioral development. Taking into consideration the wide normal variation in attaining any developmental milestone it has to be underlined that the available different norms for developmental screening are more referential by nature than strict standards making a clear-cut difference between normal and abnormal (Cioni and Mercuri, 2007). The WHO Multicentre Growth Reference Study (2006) has collected longitudinal data on the attainment of gross and fine motor milestones in hundreds of children aged 4 to 24 months in different countries. The age reference for upper age limit of attaining fine motor milestones has been reported.

Another characteristic feature of normal development, in addition to a wide variation, is the general forward direction of development, but there are typically more intensive periods of attaining a new skill alternating with developmentally stable periods. Even though normal development allows discontinuity, the typically developing infant does not lose learned skills. Normal development is a dynamic and multifaceted process which sets great demands for any attempt to measure it accurately. For all these reasons, the assessment of psychomotor development is often considered as a difficult and old-fashioned task, and more interest is devoted to modern techniques of exploration of the nervous system, such as genetic tests, electrophysiological measures (EEG, evoked potentials), and neuroimaging. However, these important approaches can by no means replace the essential contribution of neurological clinical examination to diagnosis and prognosis of neurodevelopmental disorders in the young infant.

The examiner should be competent on "normal", or better "typical," development to be able to distinguish, by means of comprehensive and standardized protocols for neurological development, developmental scales and tests (see next chapter) between the normal biological variation and the deviant development. The clinical approach has the great advantage of: being easily repeated; obtaining developmental trajectories that can lead to neurological disorders being suspected; furthering etiological investigations; and treatment in case of no changes, slow development, or regressions or, conversely, can reassure parents by detection of positive changes in development.

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