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Abstract:
Motor development may seem to be the simplest aspect of development but it is also the most complex one. To perform motor movements, children do not only need to acquire control over muscles; they also need to develop their perception, cognition, and motivation. Motor movements have to deal with the fact that events precede the feedback signals about them. The only way to overcome this problem is to anticipate what is going to happen next. Therefore, motor development should more appropriately be called action development.

Keywords: Action; Head movements; Individual differences; Looking; Manipulation; Mirror neurons; Neonatal behavior; Postural control; Prospective control; Reaching grasping; Smooth pursuit; Walking

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Biographical Sketch for Online Version

Claes von Hofsten received his PhD in 1973 with Gunnar johansson as superviser. He was lecturer at Uppsala University, then professor at Umeå University until 1997, and finally professor in psychology, especially perception, at Uppsala University. In 1982–84 he was visiting professor at University of Minnesota, and fellow at the Center for Cognitive Studies at MIT. In 1988–89 he was a fellow at the Center for Advanced Studies in the Behavioral Sciences at Stanford and in 1997–99 he was visiting professor at University of Virginia. In 1996 he became Honoris Causa at the University of Normandie. Claes von Hofsten is one of the Action editors of developmental psychology. For 30 years the research has been devoted to the development of perception, cognition, and action in infants and young children. Both normal and abnormal development is considered. The central idea is that, from birth onwards, children are agents who act on the world. Actions are at the heart of development and reflect all its different aspects, including perception, cognition, planning, motivation, and emotional expressions. For instance, all communications are action based. Before language is developed, actions are in fact the only way through which we can learn about the child's mind.

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a0005 # Motor Development from an Action Perspective

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Glossary

g0005 **Oculomotor** The motor system or nerves and musculature of the eyes.

g0010 **Ontogeny** The development of an individual organism.

g0015 **Otoliths** An organ in the inner ear (a part of the vestibular system) for the sensing of linear acceleration.

g0020 **Proprioception** Sensing the positions and orientations, and movements of the different bodyparts in relation to each other.

g0025 **Prospective** Future directed.

g0030 **Shuffling** Propelling forward by sliding on the bottom.

g0035 **Synergy** The combined action of several muscles.

g0040 **Vertebrates** Animals with a spine.

s0005 ## Introduction

p0005 The motor performance of the child gives the clearest evidence of how children develop. Parents notice with joy the first time their children for instance roll over, when they succeed in reaching for and grasping an object, or when they take their first step. These changes are so predictable that motor development has often been described in terms of milestones. A child is expected to grasp objects at a certain age, and walk at another. This simplified description makes motor development appear to be rather uneventful and mostly the result of maturation. The true story is much more fascinating. At all stages of life, children are agents who act on the world. Actions reflect all the different aspects of development, including perception, cognition, and motivation. Even in the newborn child, the movements are never just reflexes, but purposeful goal-directed actions. Furthermore, motor development is not just a question of gaining control over muscles; equally important are questions such as why particular movements are made, how the movements are planned, and how they anticipate what is going to happen next.

p0010 Actions have to deal with the fact that events precede the feedback signals about them. Relying on feedback is therefore nonadaptive. The only way to overcome this problem is to anticipate what is going to happen next and use that information to control ones behavior. Furthermore, most events in the outside world do not wait for us to act. Interacting with them requires us to move to specific places at specific times while being prepared to do specific things. This entails foreseeing the ongoing stream of events in the surrounding world as well as the unfolding of our own actions. Such prospective control is possible because events are governed by rules and regularities. The most general ones are the laws of nature. Inertia and gravity for instance apply to all mechanical motions and determine how they evolve. Other rules are more task specific, like those that enable a child to grasp an object or use a spoon. Finally, there are rules that facilitate social interaction and enable us to communicate and exchange information with each other. Some of those rules like the facial expressions of emotion have deep biological roots, while other rules have been agreed upon for practical reasons. Knowledge of these different rules makes smooth and skilful actions possible. It is accessible to us through our sensory and cognitive systems.

Infants begin to move much before they are born as every mother is aware. These movements are not just startles or twitches of muscles. They are organized movements requiring the coordination of several groups of muscles. Already in the third month of pregnancy, the first movements are produced. Some of them are rather complex, like swallowing, yawning, sucking, and the movements that are later used for breathing. In the fourth month, the child moves around in the womb, touches the walls of the amniotic sack, grasps the umbilical cord, and puts the thumb in his or her mouth. All these movements require some kind of sensory guidance. In fact, the sensory system and the motor system develop together. The activities of the child in the womb are most probably of crucial importance for preparing the child for a life outside the womb. At birth, infants are ready to act on the world, although their movement repertoire is still quite limited. p0015

Preparations for Action s0010

The most obvious way in which the child has been prepared for action is the design of its body. It is obvious that hands are made for grasping and manipulating objects, feet are made for walking, and eyes are made for looking. However, there is no grand plan for evolution. It just optimizes what is at hand. Therefore the same body-part may look rather different in different species depending on its function. For instance, the limbs of horses, lions, and humans differ for obvious functional reasons. It is also true that different body parts may have p0020 evolved to serve the same function. The trunk of elephants and hands of humans are both examples of how the morphology of the body has been altered in special ways in order to facilitate object manipulation.

p0025 What is less obvious but equally valid is that each of these body parts contributes to a perception-action system that also includes specially designed perceptual and neural mechanisms. The design of the body of any animal, its sensory and perceptual system, its motor system, and indeed its neural system have been tailored to each other for solving specific action problems. The changes in the morphology through evolution of the body also include adjustments of the perceptual system to improve extraction of information for controlling specific actions. For instance, the frontal positions of the eyes in primates give access to better information for controlling manual movements. In lower vertebrates, it often appears as if action systems have evolved independent of each other. Thus the frog seems to possess independent perceptual mechanisms for extracting spatial information needed for catching flies and for negotiating barriers. In higher vertebrates, movement patterns are more flexible and the perceptual skills more versatile. When new skills evolve, the animal may re-use some of the mechanisms already evolved for other tasks instead of developing completely new ones. This leads to more general mechanisms and more generalized skills. A similar trend seems to be going on in ontogeny. The earliest appearing skills seem more task specific than those appearing later.

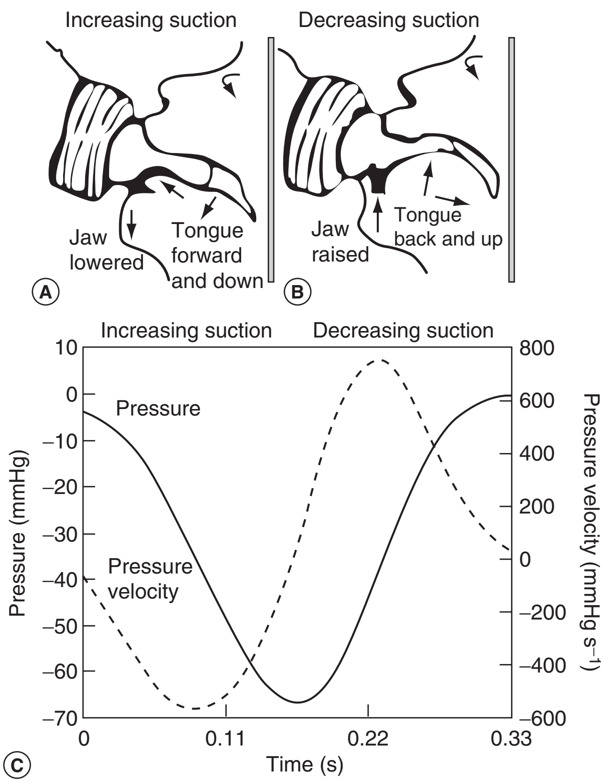
p0030 Although perception and action are mutually dependent, there is an asymmetry between them. Perception is necessary for controlling actions and every action requires specific information for its control. Without perception there will be no action. Action is a necessary part of perceiving but only in a general sense. Specific actions are not required for producing specific percepts and actions do not tell perception what to perceive. It only provides opportunities for perceiving and guides the perceptual system to where the information is. This has clear consequences for development. The ability to extract the necessary information must be in place before actions can be organized. Before vision can guide looking, there must be a correspondence between the position in the visual field where a stimulus appears and the kind of eye movements evoked to refocus gaze on that stimulus. Such correspondences are present in the newborn child. In order to localize significant objects to look at, the visual system must divide up the visual field into object defining entities. Although little is known about when these processes of perceptual structuring start to emerge in development, the object-directed actions performed by newborn infants indicate that neonates can visually segregate objects from their background.

p0035 All sensory systems are available from birth and can be used to guide basic forms of actions. Most of them have been available in the womb where the child has had opportunities to use them. Tactile and proprioceptive information become available when the child moves and sounds penetrate the womb. The sensory system that has been least exercised is the visual system because the light that reaches the eyes in the womb is only minimally structured. At birth the visual acuity is only 3-5% of the adult one. However, this enables the children to see their hands and the gross features of another person's face. The newborn child can also crudely guide his or her arm movements by vision. Such visual-motor maps could be innate but it is also possible that the unborn child detects the luminance changes when they move an arm in front of the eyes and in this way begin to develop a visual-motor map.

Neonatal Behavior s0015

The movements of newborn infants have traditionally p0040
been described in terms of reflexes. The reflex concept was defined over 100 years ago by the British physiologist Charles Sherrington. It refers to a sensory-motor arc organized at a spinal level such that when the sensory part is activated by a stimulus, a simple and stereotyped motor response is elicited. A typical example is the stretch reflex. When the position of a limb is perturbed and certain muscles are stretched, a reflex is activated that regains the original position of the limb. Thus, a reflex is not spontaneously activated by a motivated subject but automatically elicited by a stimulus. An increasing number of studies of the movements performed by newborn infants show that their behavior cannot appropriately be described as reflexes. This is not to deny that neonates have reflexes. They have them just like adults. However, to describe normal neonatal behavior as expressions of reflexes is wrong. Most movements of newborn infants are driven by motives, their structures are flexible, and they anticipate future goal states.

Take, for instance, sucking. It is traditionally described as p0045
a reflex but is in fact a very complex behavior with very little in common with reflexes. Controlled measurements of sucking in newborn infants show that they anticipate the upcoming flow of milk and adjust their sucking ahead of time to produce the most efficient behavior. In a typical sucking cycle, the vacuum in the mouth increases up to a point where the milk is released. If the child is not ready for this influx of milk, the vacuum will drastically decrease and the flow of milk will stop. This does not happen because the child changes its sucking action ahead of time and maintains the pressure as the milk is released. See **Figure 1**. Newborn infants will also alter their sucking rate to achieve advantages. If one arranges the situation such that they will hear their mother's voice when they suck with a slower or faster pace, they will discover this contingency and change the sucking rate to produce the voice more often.



Au3 f0005 **Figure 1** The different movement processes that take place within a newborn infant's mouth to bring about smooth changes in the intraoral pressure. (a) The increasing suction period, where the tongue moves forward and down as the jaw is lowered. The culmination of these processes brings about an increase in suction, which facilitates the flow of milk from the bottle into the mouth. (b) The decreasing suction period, where the tongue moves upwards and backwards as the jaw is raised. These movements help to propel the milk expressed during the increasing suction period to the back of the mouth, where it waits to be swallowed. (c) Actual recorded sucking pressures from inside the mouth of a feeding infant. The first part corresponds to the increasing suction period and the second part to the decreasing suction. Source: Craig CM and Lee DN (1999) Neonatal control of nutritive sucking pressure: Evidence for an intrinsic t-guide. *Experimental Brain Research* 124: 371–382.

p0050 Another example of neonatal behavior traditionally considered as a reflex is 'rooting'. When the cheek or chin of the newborn infant is touched, the child tends to turn the head as to center the touching object on his or her mouth. This behavior is, however, by no means automatic or stereotyped. When the child is hungry the response is elicited more reliably and when the child happens to touch him or herself on the chin or side of the mouth, no rooting response is produced. A more functional description of this behavior is thus that the children turn toward things that touch face and that they obviously cannot see, in order to explore them with their mouth. During, at least, the first 1/2-year of life, infants have a great tendency to explore objects in this way.

p0055 A third example of functional neonatal behavior is imitation. Newborns tend to imitate facial gestures. The most reliable observations have been obtained from mouth opening and protrusion of the tongue. Although contingent on the model's behavior, this is not a reflex. The tongue protrusion of the model does not just elicit the tongue protrusion of the child. It changes the frequency and the appearance of spontaneously performed tongue protrusions. The movements are by no means just elicited or stereotyped. The infant might wait for a while before repeating them and the repeated movements are different every time they are performed. If the adult model opens the mouth instead of sticking the tongue out, the child will increase the frequency of mouth openings but not the frequency of tongue protrusions. Neonatal imitation provides important information about newborn capabilities. It shows that neonates have a visual acuity good enough to identify the mouth among other facial features and that they can discriminate different mouth movements. It also shows that neonates apply differentiated and appropriate behaviors to the seen facial patterns. It makes sense for nature to invest in such innate abilities. Neonatal imitation has great social significance. It provides a means for social contact between the mother and her newborn child. However, it is also the embryo of a social communication system based on gestures.

A fourth example is visually guided arm movements. p0060
When an attractive object is moved slowly and irregularly in front of a newborn infant, he or she will extend the arms toward it. It is not a very precise movement, but I have shown that if several such movements are considered, the mean direction is toward the object in front of them. The immediate function of this reaching behavior cannot be to grasp and manipulate objects, because the infants do not yet control their hands independently of their arms. On the contrary, the arm and the hand movements are coupled in such a way that when the arm extends the hand opens up and vice versa. The successful grasping of an object necessitates flexion of the hand while the arm is extended. However, newborn reaching has another very important function. When the hand moves toward the object of interest it enters into the visual field and its movements may then become controlled by visual information. Closing the visual-manual loop in this way is of crucial importance for the development of manual control. This is precisely what is needed for the system to develop. It makes it possible for the infant to explore the relationship between commands and movements, between vision and proprioception, and discover the possibilities and constraints of manual movements.

Newborn infants also find it attractive to view their p0065
own hands and they are able to move them into the visual field. Audrey van der Meer at Trondheim University performed the following interesting experiment. She placed newborn infants in a semi-dark room and had a beam of light shine across their visual field. When the infants happened to put their hand into the beam of

light, it was seen brightly against the dark background. The subjects quickly learnt to move their hands to where the beam of light was and when the spotlight itself was moved the infants adjusted their arm position to the new location.

p0070 The question whether to regard the movements of newborn infants as reflexes or actions has important implications. If they are seen as reflexes, then the child is no more than a complex mechanical device. If the movements are seen as purposeful, however, the child becomes an agent that acts and explores. Grasping is a good illustration of this point. If you place an unseen object in the hand of a newborn child, he or she will probably close the hand around it. Is this a reflex or a voluntary action? The traditional account says that it is a reflex. If you instead place an unseen object in the hand of an adult, he or she will also most probably close the hand around it. In this case, however, the traditional account says that it is a voluntary action. What the accumulating evidence of today tells us is that both the adult's and the newborn infant's closing of the hand should be regarded as voluntary actions.

p0075 What makes the movements of newborns special is the fact that the nervous system is still quite undeveloped and many of the mechanisms necessary for controlling movements are not yet established. Although newborn infants scan their surrounding, fixate attractive objects including other people, and follow moving objects with their eyes, they do not track moving objects with smooth eye movements because the neural structures necessary for doing that are not yet established. Newborn infants do not stand alone or walk because the necessary neural mechanisms for maintaining balance are not yet developed. However, when newborn infants are held in an upright position and lowered toward a surface they move their legs in walking movements. This behavior is also traditionally regarded as a reflex although it is never stereotypical or just automatically elicited. An interesting observation is that the walking movements of neonates are organized in the same way as those of 1.5-year-old infants who walk successfully. At both ages, infants, step with the toes first just like other mammals. Striking with the heel first only develops gradually over childhood.

p0080 Finally, the attention of newborns is unstable and the children seem to wander off into own world every now and then. However, this does not change their basic way of functioning. Like any other biological organism, they are agents that spontaneously act and their movements are planned and goal directed. The function of neonatal actions is primarily explorative. By moving, children can begin to find out about the relationship between the different senses, between commands and movements, and discover the possibilities and constraints of their actions.

The Developmental Process s0020

Infant development is most clearly reflected in motor behavior. These developmental changes can indeed be dramatic. Sometimes, they almost occur from one day to the next. Suddenly, the parents observe that the child stands up without holding onto something. The processes that lead up to these changes may be more continuous but they are not necessarily less dramatic. They are a function of both the developing nervous system and the activities of the child. Together they constitute a self-organizing dynamical system. When certain thresholds are attained, this can lead to radically new modes of functioning. p0085

The brain, undoubtedly, has its own dynamics that makes neurons proliferate in certain ways and at certain times. Once a critical mass of connections is established, a self-organizing process begins that results in new forms of perception, action and cognition. As new pathways open up in the central nervous system and new connectivity emerges, new modes of control become possible. There are a number of such programmed changes in the CNS that have great impact on the organization of actions. p0090

The emerging capabilities, however, are also crucially shaped by the subject's interactions with the environment. Without such interaction there would be no functional brain. Perception, cognition, and motivation develop at the interface between neural processes and actions. They are a function of both and arise from the dynamic interaction between the brain, the body and the outside world. A further important developmental factor is the biomechanics of the body: perception, cognition, and motivation are all embodied and subject to biomechanical constraints. Those constraints change dramatically with age, and both affect and are affected by the developing brain and by the way actions are performed. Therefore, there is not an exact sequence or schedule for motor development that is set in advance. What is optimal for one child raised in one environment may not be optimal for another child raised in a different environment. Every child does not need to crawl. Sliding on one's bottom, for example, is an excellent mode of locomotion in an apartment with polished floors but rather inefficient in a house with wall-to-wall carpets. p0095

Two kinds of developmental processes are distinguishable. The first has to do with coordinating muscle activations to make efficient movements and assembling those movements into functional synergies. When infants begin to extend the arms toward objects in front of them early in life, the movements consists of several small submovements with little overall organization. At around 4 months of age, the hands consistently get to the object but the grasping is still not an integrated part of the reach. Reaching and grasping will only be integrated into a fluent integrated whole toward the end of the first year p0100 of life. Building functional synergies is also about coordinating perception and action. In the case of reaching it is about integrating the movements of eyes and head with reaching. The second process has to do with acquiring prospective control. Actions are directed into the future and must anticipate what is going to happen next. This is possible because the world is governed by natural laws, rules, and regularities. For instance, if a ball rolls, it will continue to roll in the same way unless something interferes with its motion. This is the law of inertia. When infants reach and grasp objects successfully at 5 months of age, they correctly perceive the upcoming motion of the object. At that age they catch moving objects, and in doing so they aim for a future position of the object. Anticipation of what is going to happen next is also necessary for being able to control ones own movements. Because newborn infants can control some of their movements, a part of this knowledge is obviously innate, but most of it is has to be acquired. The relationship between muscle contractions and movements, however, is too complex to make it possible to completely determine every movement ahead of time. Continuous perception is always needed to guide actions to their goals.

s0025 ## Looking

p0105 Although each perceptual system has its own privileged procedures for exploration, the visual system has the most specialized one. The whole purpose of movable eyes is to enable the visual system to explore the world and to stabilize gaze on objects of interest. The development of oculomotor control is one the earliest appearing skills and marks a profound improvement in the competence of the young infant. It is of crucial importance for the extraction of visual information about the world, for directing attention, and for the establishment of social communication. Controlling gaze may involve both head and eye movements and is guided by at least three types of information: visual, vestibular (the semicircular canals in the ear sensing head rotation), and proprioceptive (receptors in the neck sensing head movements). How do young infants gain access to these different kinds of information, how do they come to use them prospectively to control gaze, and how do they come to coordinate head and eyes to accomplish gaze control? Two kinds of tasks need to be mastered, moving the eyes to significant visual targets and stabilizing gaze on these targets. Each of these tasks is associated with a specific kind of eye movement. Moving the eyes to a new target is done with high speed, saccadic, eye movements and stabilizing them on a moving target is done with smooth pursuit eye movements. The second task is, in fact, the more complicated one. In order to avoid slipping away from the fixated target, anticipations of its forthcoming movements is required. When the subject is moving relative to the target, which is almost always the case, the smooth eye movements need to anticipate those body movements in order to compensate for them correctly.

Shifting gaze s0030

The ability to shift gaze is of crucial importance for the development of visual perception, because it turns the visual sense into an efficient instrument for exploring the world. The saccadic system for shifting gaze develops ahead of the system for smooth tracking. It is functional at birth and newborn infants turn their eyes to fixate significant visual stimuli such as faces and moving objects. Newborns, however, cannot track moving objects smoothly. p0110

Stabilizing gaze on a moving object s0035

From about 6 weeks of age, infants begin to track objects smoothly. Together with Kerstin Rosander, I have studied the development of smooth pursuit eye tracking and found that the improvements in smooth pursuit tracking are very rapid and consistent between individual subjects. Smooth pursuit attains adult-like levels from around 14 weeks as can be seen in **Figure 2**. In normal infants, smooth pursuit is always predictive, that is, it never lags the object it is geared to. p0115

Before 3 months of age, the head is minimally engaged in the tracking of moving objects. However, head tracking p0120

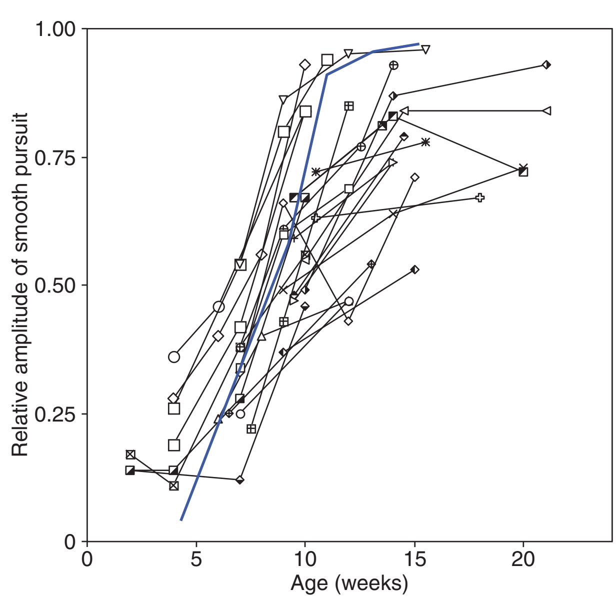
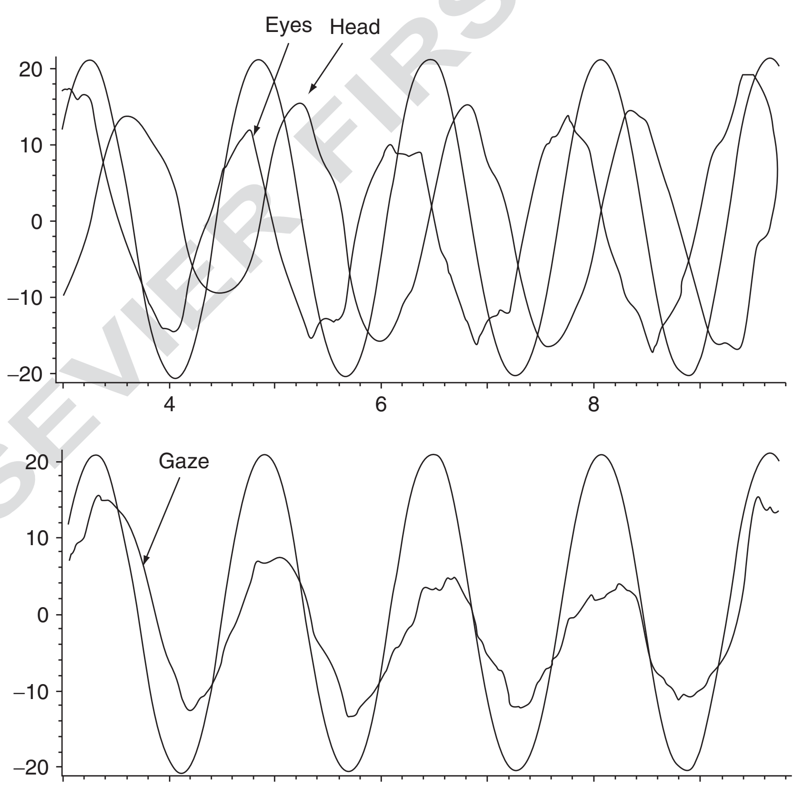


Figure 2 The relative amplitude of smooth-pursuit eye movements in 26 infants followed longitudinally over parts of the first 5 months of life. Zero means that no smooth pursuit is produced and 1.0 that all eye movements are smooth pursuit. As a comparison, the development of sensitivity to direction of motion is indicated by the blue line. f0010

increases very rapidly from then on. At 5 months the amplitude of the head tracking is often as large as the amplitude of the object motion. However, the head lags the target at that age (1/3 s or more). In order to stabilize gaze on the object of interest, the eyes must therefore lead. This creates a phase differences between the eyes and the head that may be so large that the eye tracking and the head tracking counteract each other. Instead of contributing to stabilizing gaze on the fixated moving object, head tracking may then deteriorate gaze stabilization. **Figure 3** shows an example of a 5-month-old infant tracking a fast target with large head movements. It can be seen that the head lags substantially. The eye-tracking record shows that in order to keep the gaze on the target, the eyes must make large and fairly complicated movements to compensate for the head lag. In fact, the task would be much simpler if the head had not moved at all. The reason why infants persisted in engaging the head can only be because infants are internally motivated to do so. Just as in the early development of reaching this is an expression of important developmental foresight because in the end, the ability to engage the head will result in much more flexible tracking skills.

Stabilizing gaze while moving s0040

When infants turn the head or move in other ways, the direction of gaze is perturbed. In order to maintain the original gaze direction, the eyes must move to counteract those body movements. Such compensatory eye movements are primarily controlled by the vestibular system. They are present in newborn infants and attain adult level of performance within a few weeks. When infants begin to track objects with the head a problem arises, because the sensory signals from the vestibular system tell the eyes to compensate those head movements. Thus, while the head moves with the object, the eyes turn in the opposite direction leaving gaze unaffected. This paradoxical effect can sometimes be observed in 2-month-old infants and demonstrates an important problem that the oculomotor system must solve before functioning appropriately. It has to distinguish between head movements that are a part of the tracking effort and head movements unrelated to it. This requires that the head tracking commands are available to the oculomotor system ahead of time, so that the tracking movements can be separated from other head movements. By 4 months of age, they obviously are. p0125



f0015 **Figure 3** An example of a 5-month-old infant tracking a rapidly moving object with large head movements. The vertical axis shows the deviation from straight ahead. The object oscillates on a horizontal path with 0.63 Hz which means that one cycle was completed in 1.6 s. The top diagram shows that the head lags very much and that the eyes lead with about the same magnitude. The time difference is so large that gaze amplitude suffers. Instead of contributing to the tracking, the head movements counteract the smooth pursuit eye movements.

s0045 ## Posture and Locomotion

p0130 Basic orientation is a prerequisite for all functional activities and purposeful movements are not possible without it. This includes balancing the body relative to gravity and maintaining a stable orientation relative to the environment. Gravity gives a basic frame of reference for such postural stability and almost all animals have a specialized mechanism for sensing gravity (in humans it is the otoliths). In addition, vision and proprioception provide excellent orientational information.

p0135 Gravity is also a potent force and when body equilibrium is disturbed, posture becomes quickly uncontrollable. Therefore, any reaction to a balance threat has to be very fast and automatic. Several reflexes have been identified that serve that purpose. For instance, when one slips on a patch of ice, ongoing actions are interrupted, and a series of fast automatic responses are elicited that serve the purpose of regaining balance. However, disturbances to balance are better handled in a prospective way, because if the problem can be foreseen there is no need for an emergency reaction and ongoing actions can continue uninterrupted.

p0140 The newborn child cannot control posture very well. Even lifting the head is a great challenge to the child at this age. Maintaining the head in an erect posture, raising the trunk by stretching the arms, sitting, and crawling are all major steps in the development of postural control, but the greatest challenge of them all is standing and walking. At around 3 months, infants show the first signs of being able to actively control gravity. When in a prone position they will lift their head and look around. To hold the head steadily, its sway must be correctly perceived and used to control head posture. Such control seems to be attained over the first few weeks of head lifting. The next step in mastering postural control is controlling the sitting posture. This is normally accomplished around 6 months of age and requires the child to control the sway of both head and trunk in relation to each other.

p0145 Toward the end of the first year of life, infants begin to control their erect posture. The difficulty of maintaining balance in this position is dependent on the length of the body. Contrary to what is intuitive, it is more difficult to keep a short body in balance than a long one. To convince yourself, try the following experiment. Take a short rod, like a pencil, place it vertically on you index finger tip, and try to balance it. It is almost impossible. Now, try instead to do the same thing with a walking stick. It is rather easy. This is because balancing is a question of controlling sway. The natural sway frequency decreases with the length of the rod. This is also valid for the body. The shorter the body, the faster does it sway and the faster it sways, the quicker does it get out of control. For instance, a child who is only half the size of an adult will sway with a frequency which is 40 percent higher than that of the adult and will consequently have 40% less time in which to react to balance disturbances. Thus, when the child for the first time can stand alone, he or she has mastered a problem that is more difficult than ever after.

Everything that the child does will perturb balance in one way or another. Just reaching out to grasp an object will displace the point of gravity of the body and if the reach is fast the momentum of it will push the body column out of its equilibrium. All these disturbances need to be dealt with ahead of time if ongoing activity is to be maintained. When the child starts to walk, the problem of maintaining balance becomes really difficult, because then the body is systematically pushed out of equilibrium. In fact, walking has been described as controlled falling. A child who has just started to walk looks like he or she is about to fall at every step. p0150

Postural control is crucially dependent on anticipations of what is going to happen next. Balance is maintained through continuous adjustments of body sway. These adjustments must be made ahead of time and before balance is threatened. If they are not, the control of the body is lost and the ongoing activity is interrupted. Recent research has shown that at the same time as children gain control of their erect posture, they begin to compensate disturbances to their balance ahead of time. p0155

A nice example of how this prospective mode of control emerges as the child gets to master upright stance was provided by Barela, Jeka, and Clark. They examined how infants used a supporting contact surface (a handrail) during the acquisition of upright stance. The infants were studied at four developmental epochs: pulling to stand (10 months), standing alone (11 months), walking onset (12 months), and walking mastery (13.5 months). The subject's body sways and the forces applied to the contact surface by the subject were measured. They found that the subjects up to walking onset applied forces to the contact surface as a reaction to or as a physical consequence of their body sway whereas the oldest infants applied forces to the contact surface in anticipation of body sway. p0160

Because of its central role in movement production, postural control becomes a limiting factor in motor development. If the infant is given active postural support, goal directed reaching can be observed at an earlier age than is otherwise possible. For these reasons, development of reaching and other motor skills should be studied in the context of posture. p0165

Reaching and Grasping s0050

Although newborn infants have some ability to visually control their arm movements, they cannot grasp objects successfully. One important reason is that the extension and flexion of the arm is coupled to the extension and p0170 flexion of the fingers, usually referred to as flexion and extension synergies. Thus, when the arm is extended the hand usually opens up and when the arm is flexed the hand closes. This synergistic mode of moving the upper limbs facilitates the overall control of the limb but prevents independent use of the hand. Therefore one of the major challenges that infants face at the transition to functional reaching is to gain separate control of the arm and the hand. It has been found that the extension-flexion synergy is broken up at around 2 months of age and infants then begin to fist the hand when the arm is extended. At the same time the movements also appear more voluntary, as if the child really tries to reach out and get to the object. A month or so later, the forward extended arm movements become more fluent again and the hand opens and closes in the extended state. That hand control is a limiting factor in pre-reaching is supported by the work of Needham and associates. They provided 3-month-old infants with velcro mittens and velcro covered objects. Thus, when the infants reached out, the objects got attached to their hands. The infants became quite excited by this sudden ability to retrieve objects. The experienced infants became focused on objects, and showed more sophisticated object exploration strategies compared to their inexperienced peers.

p0175 In addition to being able to independently control the arm and hand movements, a number of other developments are required for functional reaching to appear. First, infants must be able to control their posture while reaching. Otherwise the forward extension of the arm might upset the balance of the trunk. By 3–4 months of age, infants can sit upright with support. Secondly, the exact position of the object in space relative to the body must be perceived. This prerequisite is fulfilled with the emergence of binocular space perception at around 3–4 months of age. Finally, the child must have a motivation to reach for and grasp objects. Accordingly, at around 4 months of age infants begin to devote much of their waking time to such activity.

p0180 Early reaching is accomplished thorough a series of sub-movements (movement units) that during development merge into a more continuous and fluent sequence. To begin with the average duration of these movement units is about a quarter of a second. They can be thought of as feed-forward packages. A new goal can be defined at the beginning and evaluated at the end of each unit. With age, the number of such units decreases and, one unit comes to dominate the reaching movements (the transport unit), and the units by the end become rather small (grasping units). Toward the end of the first year of life, most reaches consist of one approach unit and one grasp unit.

p0185 When infants first begin to reach for and grasp objects, they cannot independently control the movements of the fingers. On the contrary, objects are grasped with the whole hand in a power grasp. It is only toward the end of the first year of life that infants begin to use the fingers in a differentiated way. At around 9–10 months of age, infants begin to pick up small objects with just their index finger and thumb in a precision grip. This is made possible by the maturation of a direct pathway between the motor cortex and the hand (the cortico-moto-neuronal pathway). Kuypers showed that when he lesioned this pathway in very young monkeys they never developed an ability to control the fingers independently as measured by their ability to pull out a peanut from a depression in a board. The ability to control the fingers in this differentiated way marks the beginning of tool use in infants.

In the act of reaching for an object there are several p0190
problems that need to be dealt with in advance, if the encounter with the object is going to be smooth and efficient. The reaching hand needs to adjust to the orientation, form, and size of the object. The grasp must be timed in such a way that the hand starts to close around the object in anticipation of and not as a reaction to encountering it. Such timing has to be planned and can only occur under visual control. A grasp that is initiated after contact will induce an interruption in the reach-and-grasp act. The reach-grasp action is most efficient if the opening and closing of the hand is an integrated part of the approach. While grasping is almost always controlled visually, it takes until around 1 year of age until infants integrate the approach and the grasping into a fluent single action.

From the age when infants start to reach for objects p0195
they have been found to adjust the orientation of the hand to the orientation of the object reached for. For instance, when reaching for a rod, they grasp it around the longitudinal axis. Adjusting the hand to the size of a target is less crucial. Instead of doing that, it would also be possible to open the hand fully during the approach. This would lessen the spatial end point accuracy needed to grasp the object. Adults use this strategy when reaching for an object under time stress. The disadvantage is the additional time it takes to close a fully opened hand relative to a semi-opened hand.

A remarkable ability of infants to time their manual p0200
actions relative to an external event is demonstrated in early catching behavior. Claes von Hofsten and colleagues found that infants reached successfully for moving objects at the very age they began mastering reaching for stationary ones. Eighteen-week-old infants were found to catch an object moving at 30 cms^{-1}. The reaches were aimed toward the meeting point with the object and not toward the position where the object was seen at the beginning of the reach. Eight-month-old infants successfully caught an object moving at 120 cms^{-1}. **Figure 4** shows an 8-month-old infant who tries to catch an object moving

f0020 **Figure 4** An 8-month-old infant attempting to grasp a fast moving object that abruptly stops. Upper left: The object approaches from the right. The infant prepares to catch the object. Upper right: The object stops.Lower Left: The infants closes the hands around the position where the object should have been if the motion had continued. Lower Right: The infant discovers the true position of the object.

at 60 cms^{-1}. In this trial the object suddenly stops and the infant reaches for a position of the object where is should be if the motion had continued.

p0205 When infants begin to reach, they do not have a clear hand preference. It gradually emerges over the first year of life and is most apparent in demanding tasks. Rather than just providing an absolute preference of hand, laterality determines the role of each hand in bimanual tasks. For instance when trying to get something out of a jar, one hand is used to hold the jar and the other to poke.

s0055 Manipulation

p0210 During the second year of life, infants become fascinated by problems of how to relate objects to each other. For instance, they find it very attractive to pile objects, put lids on pans, and insert objects into holes. The ability to solve such problems reflects infants' developing spatial perception and cognition in addition to their dexterity. To pile blocks on the top of each other in making a tower requires increasingly delicate visual control of the hand as the tower gets taller. To fit an object into an aperture, infants must understand how the 2D aperture is related to the 3D object form. Finding this relationship requires the subject to see or imagine different projections of the objects. Planning the fitting action in a prospective and economical way also requires the subject to imagine how to rotate the object in order to make it fit. These are rather sophisticated expressions of spatial cognition. They include mental rotation, as well as, the ability to imagine goal states and understand means-end relationships. Thus, manipulation tasks provide a window both for learning about the development of these spatial abilities and how children develop their motor skills when solving them.

Örnkloo and von Hofsten studied young children's p0215
ability to fit object of various forms into snugly fitting apertures. They found that infants from around 1 year of age just loved this task although they only solved a minority of the object placements. Fourteen-month-olds understood that the objects should go into the apertures but had little understanding of how to orient the objects in order to make them fit. When they failed, they often used brute force and tried to press the object through the lid. Clearly, they lacked an understanding of the spatial relationship between the object and the aperture. In contrast, the 26-month-old infants moved the objects into the correct position before or during the approach of the aperture and turned the objects appropriately before the hand arrived at the lid. What characterizes the development between these two endpoints? The results showed that the infants could not solve the problem of inserting the object into the aperture by just moving it around. Success was associated with appropriate pre-adjustments before the

hand arrived with the block to the aperture. Such pre-adjustments require the child to somehow imagine the goal state of the action before it is carried out. The results show how these pre-adjustments become more sophisticated with age.

s0060 What Determines Motor Development?

p0220 Although motor development may seem to be the simplest aspect of development, it is also the most complex one. To plan and perform motor movements, children do not only need to acquire control over muscles. They must also learn to perceive and anticipate the sensory consequences of those movements not only for the body part that is moved, but also for the postural stability of the whole body. Motion planning requires the child to be able to perceive the spatial layout of the surrounding and what it offers. In order to manipulate objects, their form and function has to be correctly perceived. To understand and predict the movements of objects in the surrounding, children must distinguish object motion from their own movements, and the movements of other people. Social development is a fundamental aspect of motor development. To be able to communicate with and learn from other people, the child must both be able to understand their gestures and speech and be able to perform those gestures and speech movements. Thus, motor development is not an independent entity. It is, in fact, at the heart of development and reflects all the developmental processes of the child, such as the physical growth of the body, the development of sensory and perceptual processes, the growing ability to reflect on the world and foresee future events, and the changing motives and preferences of the child.

p0225 In order to develop new modes of action, infants must solve the specific problems associated with those modes and this can only be accomplished through their own activity. The persistence and effort invested in developing new modes of actions is one of the greatest enigmas of development. Long before infants master reaching, they may spend hours trying to attain an object in front of them and although they fail most of the time, they persist and seem to enjoy it. Another example is walking. At a certain time in development, infants will try to take their first step. To begin with, they will fail repeatedly. Why bother to try this new mode of locomotion when they most certainly already possess a different and more efficient mode? It cannot be that they realize that walking in the end will be superior to crawling. The motivating force has to come from within. It seems that infants find it very pleasurable to explore their action capabilities and to find out about new ways of moving.

p0230 Apart from learning new action skills from moving around, children also learn them from observing others perform the actions. A special devoted system in the brain, the mirror neuron system, helps us to perceive and understand other people's actions. It is a distributed system with one part situated close to Broca's area, one in the rostral part of the parietal cortex and one part in the temporal cortex (STS). The mirror neuron system enables us to simulate other people's actions in our own motor system through a direct matching process in which observed actions are mapped onto the observer's motor representations of those actions. This enables us to understand the motives and goals of the observed actions and to repeat those actions ourselves. It is important to note that the mirror neuron system does not create new motor competences. An infant does not learn to stand alone or walk simply by observing other people do it. The motor representations of the observed actions correspond to what is spontaneously generated during everyday activities and whose outcome is known to the acting individual. Thus, imitation learning has to do with learning new instances of actions including their purposes and goals. Therefore, infants are not expected to predict others' action goals before they can perform such actions themselves. Infants begin to master important socially based manual competences such as imitation, and communication by means of gesture at around 8–12 months of life. It is, thus, expected that the mirror neuron system begins to function for such actions during this period of life.

When we perform visually guided actions, action plans p0235
encode proactive goal-directed eye movements, which are crucial for planning and control. We also spontaneously look at the goal of an observed action when it is performed by others, indicating that action plans guide the oculomotor system also in action observation. Falck-Ytter, Gredebäck, and von Hofsten studied 6- and 12-month-old infants' tendency to fixate the goal of an observed manual action before the hand arrived there. We found that the 12-month-olds consistently shifted gaze to the goal of the observed action before the hand arrived there, but the 6-month-olds did not, thus supporting the mirror neuron hypothesis.

Individual Differences s0065

Parents often ask what makes one child develop a specific p0240
motor competence early and another late. Because motor competence is the final common path for several different developments, there are also several different reasons for such variability. The body can grow fast or slow and a fat child may develop at a different pace than a thin one. The development of the nervous system may be slower in one respect and faster in another. Infants tend to focus on one aspect of their motor competence at a certain period and on another at a different period and this will also produce variability. Thus, if an infant is very much engaged in object manipulation or speech, he or she may delay the onset of walking or vice versa. An efficient

crawler may delay the onset of walking in comparison to a child who has not found an equally efficient mode of crawling. If motor development is much delayed, however, there is reason to suspect neurodevelopmental disturbances. This does not mean that the problem is easy to identify. Injuries and impairments in the neural structures that control movements usually do not only result in delays but also in abnormal movements. Impairments in the sense organs that supply the motor system with information will also result in developmental delays. Visually impaired children, for instance are usually delayed in their postural development as well as in the development of reaching and manipulation. Finally, delays can be caused by impairments to the motivational system of the child because normal motor development requires the child to actively explore the world and their own action capabilities.

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See also: Breastfeeding (00030); Future Orientation (00068); Imitation and Modeling (00082); Milestones: Physical (00103); Motor/Physical Development: Locomotion (00104); Perception and Action (00119); Reflexes (00133); Sucking (00157).

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