A cognitive road map

for developmental robotics

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Cognitive development of an embodied system is about actions. Cognition is expressed in the actions of the child and is to begin with the only way cognition can be expressed.

- ***Actions are organized around tasks and defined by goals.*** It is the goal that is important not the means by which it is achieved.
- ***Perception and action are mutually dependent.*** Together they form adaptive systems.
- ***Actions are initiated and maintained by a motivated subject.***
- ***Actions are guided by prospective information.***

(Proactive, feed-forward, predictive)

The necessity of predictive control

Adaptive behavior has to deal with the fact that events precede the feedback signals about them. In biological systems, the delays in the control pathways may be substantial. The total delays for visuo-motor control, for instance, are at least 200-250 ms. Relying on feedback is therefore non-adaptive. The only way to overcome this problem is to anticipate what is going to happen next and use that information to control ones behavior.

Most events in the outside world do not wait for us to act. Interacting with them require 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 world as well as the unfolding of our own actions.

Modes of predictive control

Predictive control is possible because events in the world are governed by rules and regularities (e.g. natural laws, task specific rules, biologically and socially determined rules).

- Perception provides us with direct information about what is going to happen next.
- Our knowledge of the rules and regularities of events enable us to go beyond perception and predict what is going to happen over longer periods of time.

Together the sensory based and the knowledge based modes of prospective control supplement each other in making smooth and skillful actions possible.

Infants mastering of new actions entails prediction of what is going to happen next. When infants start to reach for objects, they prepare the grasp by aligning the hand with the target, close the hand around the object before it is encountered, and aim their reaching for moving objects at a future position.

The predictive nature of infants catching can be tested by abrupt perturbing the motion of the object they are going to catch.

Development

In order to understand development we need to consider 3 different factors.

1. What is innate.
2. What drives development.
3. How is new knowledge acquired.

Core abilities and core knowledge

An organism cannot develop without some built-in ability. If all abilities are built in, then the organism does not develop either. There is an optimal level for how much phylogeny should provide and how much should be acquired during the life time.

Core abilities should facilitate and not hinder flexible adaptation to many different environments. Thus, knowledge of inertia and gravity is good but not, for instance, the vocabulary of a particular language.

Most of our early abilities have some kind of built-in base. One of the greatest challenges of development is to find out what those core abilities are. It is important to note however that core abilities rarely appear as ready made skills but rather as **something that facilitates the development of skills.**

What is the starting point?

There is evidence that the fetus can act on the surrounding world as soon as it can move, that is around 10 weeks after conception. Then it moves the hands and legs to touch the walls of the amniotic sack, grasp the umbilical cord, and put the thumb in the mouth. The only mode of perceiving that it does not have available is vision.

Movements are always actions even in the newborn. The actions of neonates are special in the sense that all aspects of them are innate, including the motives that drive them, the sensorimotor system that supports them, and the ability to extract the information that guides them. In this sense they may be regarded as **instincts** but not as reflexes. Newborn infants have reflexes just as adults, but the notion of neonatal reflexes is a myth.

Newborn reaching

One example of newborn actions that we have studied is reaching. Newborn infants directs arm movements towards attractive objects in front of them.

The movements are:
Organized
Goal-directed
Prospective

The importance of motivation

The two most important motives that drive development are **social** and **explorative**.

1. **The social motive** is crucial for development. It puts the subject in a broader context of other humans that provide comfort, security, and satisfaction. From these others, the subject can learn new skills, find out new things about the world, and exchange information through communication. The social motive is so important that it has even been suggested that without it a person will stop develop in all respects.

There are at least 2 explorative motives.

a) **Finding out about the surrounding world**. New and interesting objects (regularities) and events attract infants' attention.

b) **Finding out about ones own action capabilities**. It is not the success that motivates them but the possibilities the new modes of action creates. When it is known, action problems can be solved in efficient ways independently of whether the subject has encountered the specific situation before or not. **Only by moving can the child discover the limits and possibilities of their action systems.**

I will exemplify these principles with the following basic skills

- Developing posture and locomotion.
- Developing looking and and other modes of exploration.
- Developing reaching and manipulation.
- Developing of social skills.

Development of posture and locomotion

Basic steps: Control of head posture. (turning head to look), Control of trunk (turning over), sitting, crawling, standing alone, and walking.

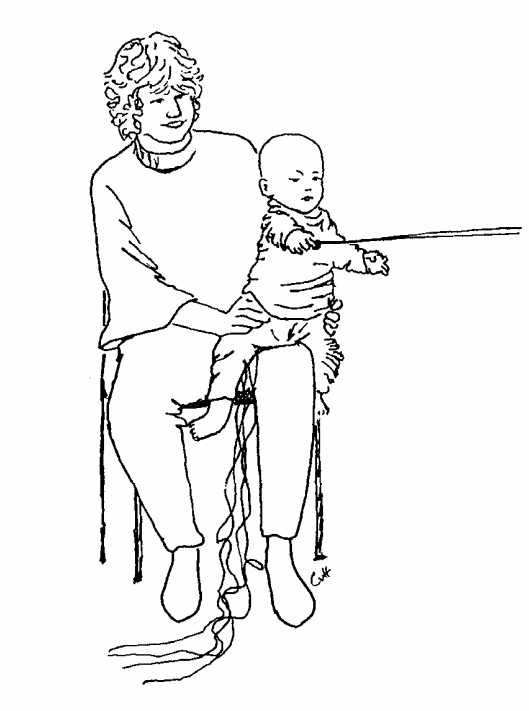
Posture is controlled by vision, proprioception and the equilibrium sense. The contribution of vision is crucial for supporting balance prospectively.

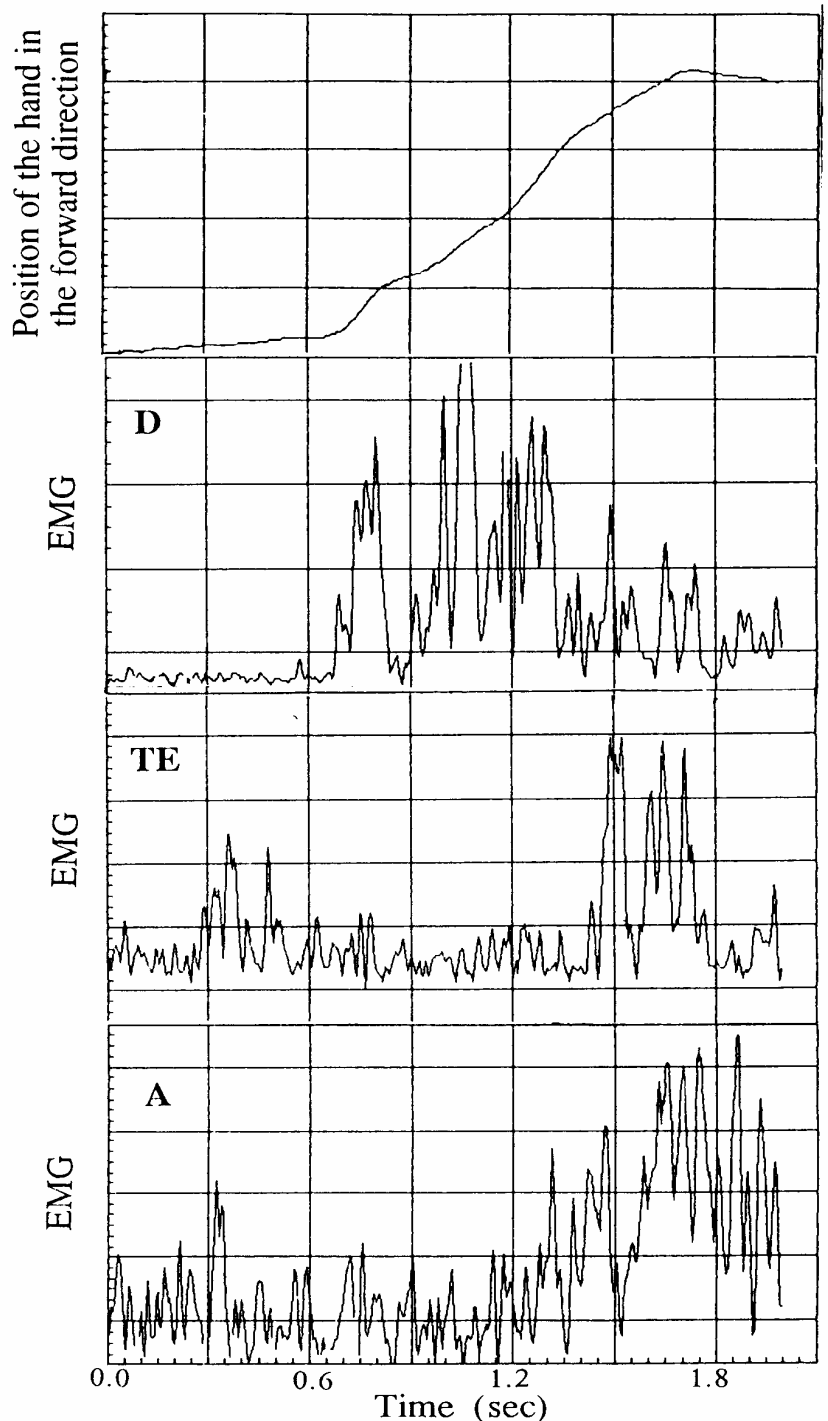
The development of posture and locomotion is associated with improved spatial orientation. As the platform for action expands, the infant needs to be able to construct mental maps of the area within which it moves.

The control of posture has to be prospective. It is crucially dependent on predicting the effects of changes in the equilibrium of the body and the inertia that results from movements. Postural reflexes are insufficient to maintain continuous control of balance during action. They typically interrupt action.

Reaching for an object, for instance, upsets balance and has to be dealt with before the reaching starts.

Woollacott and I found that when 9-month-old infants sit astride on the mothers knee, they prepare reaching for an object in front of them with appropriate trunk activations.





Development of looking

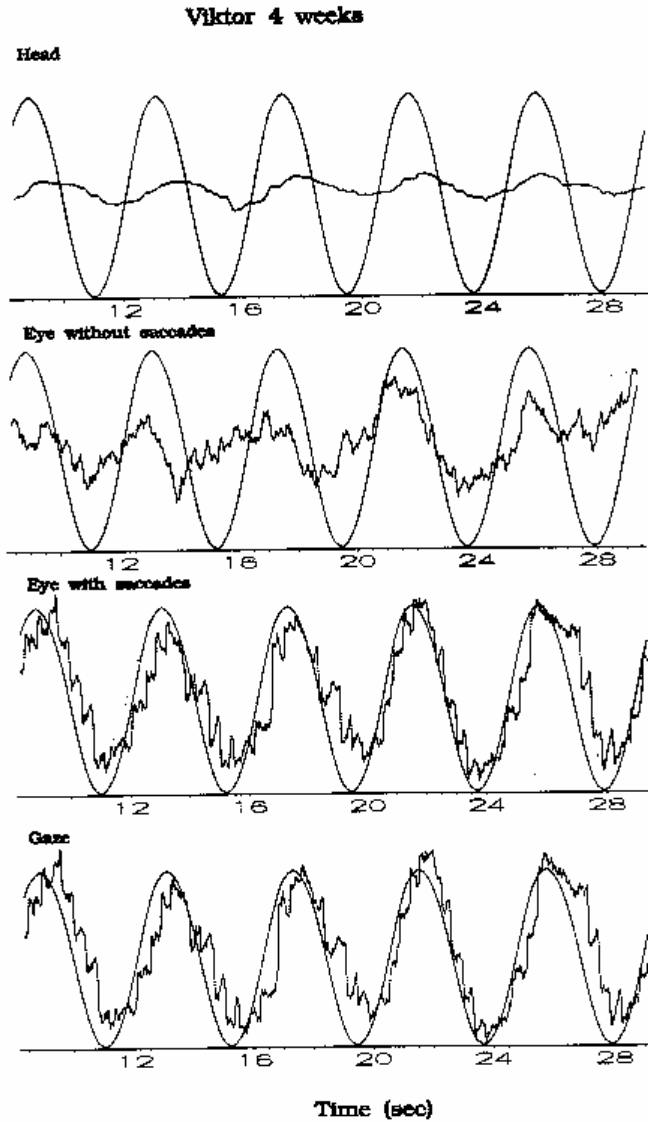
Looking relies on eye, head, and body movements that all have to be coordinated to form a single system. It is guided by visual as well as vestibular and proprioceptive information.

Basic steps: Looking is one of the first actions to be mastered. Neonates manage saccadic refocusing, smooth pursuit of moving objects appears from 2 months, coordination of eye-head-body movements during the first year, and development of efficient scanning patterns throughout childhood.

The development of looking requires ability to shift and maintain attention on specific objects and events. The ability to control these actions is a basic aspect of cognitive development. What infants look at reflect their cognitive development and their interests in what is happening around them.

Vision is able to maintain contact over distance. It therefore becomes extremely important in establishing and maintaining social interaction and in learning by observation (for instance, imitation).

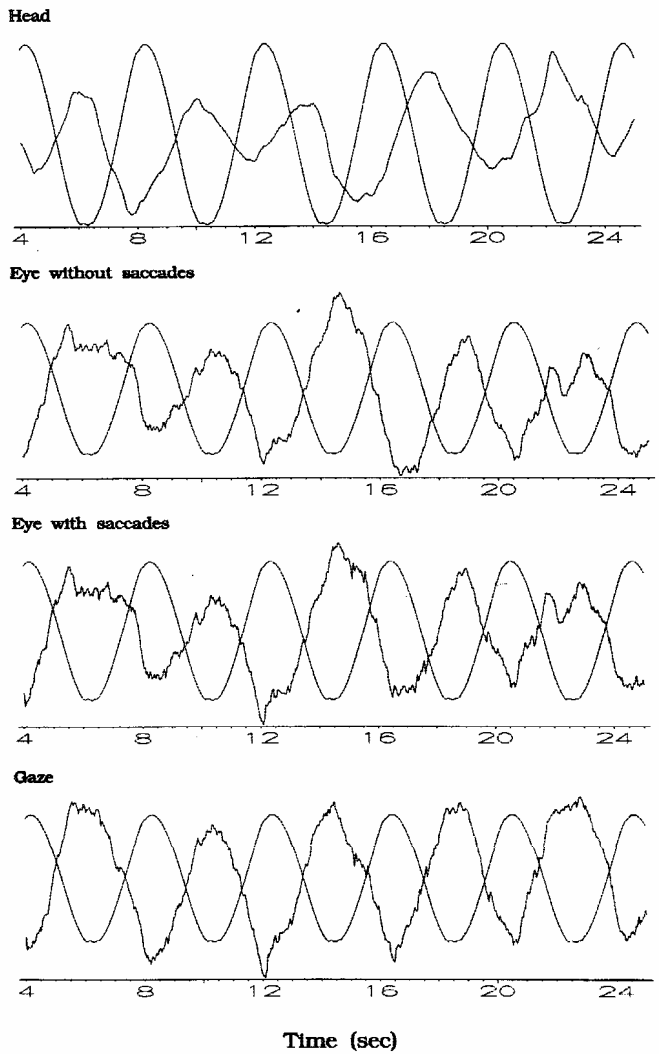
To be able to use vision efficiently, infants must be able to stabilize gaze on the objects of interest. Tracking a moving object with smooth eye movements functions very poorly in infants 4 weeks and younger. In this example, the head lags 600 ms and the eyes 300 ms. There are almost no smooth eye movements.



Observe that the object moves and the infant is stationary

The poor performace is not because the child cannot make smooth adjustments. It is a control problem.

When they move themselves, the eyes must counter-rotate to remain on the object. This mode of control functions very well in this 4-week-old infant. There is no lag! The compensations are primarily guided by vestibular information.

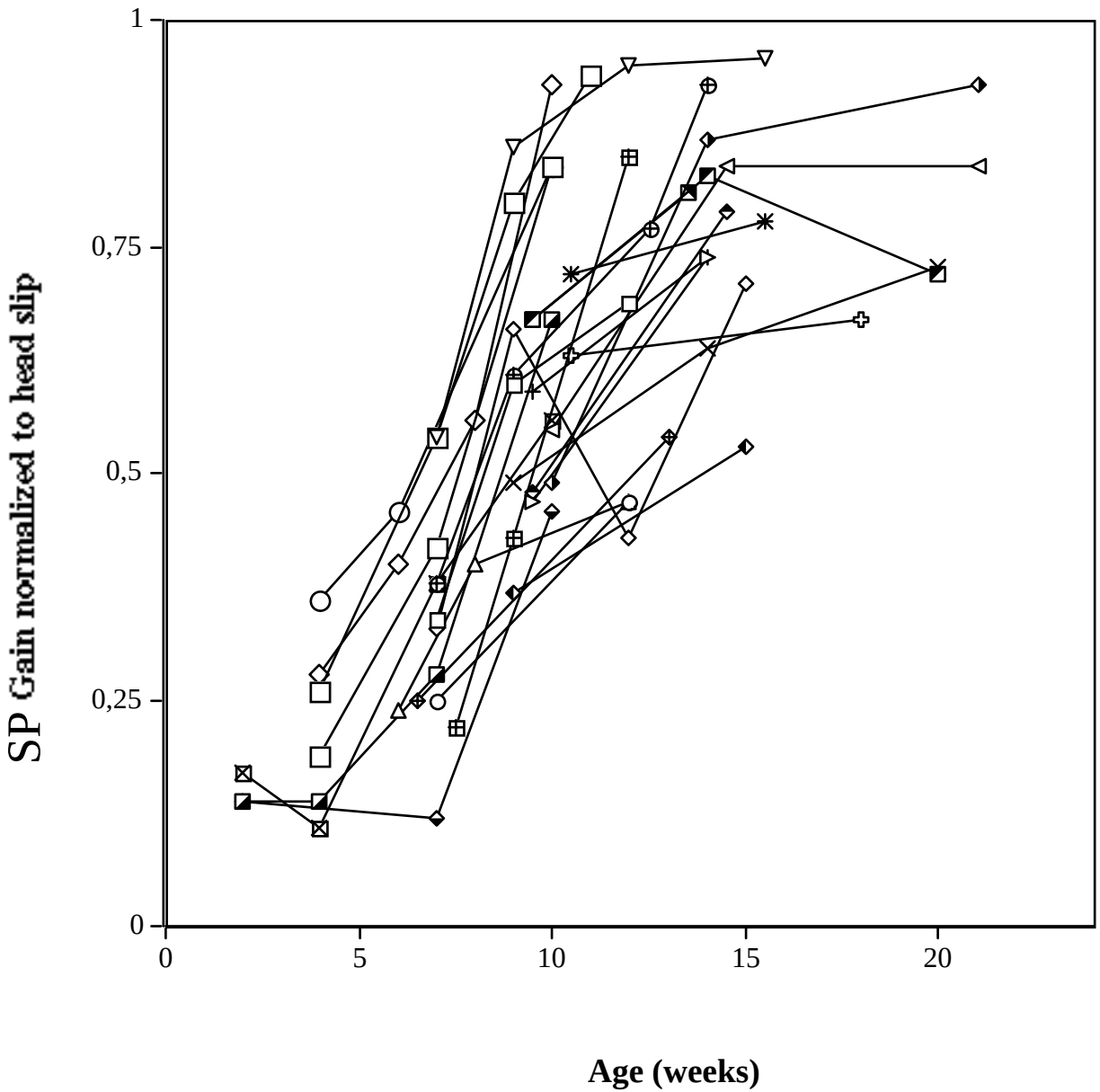


The camera is in the stationary object

At 2 months, infants begin to master smooth pursuit

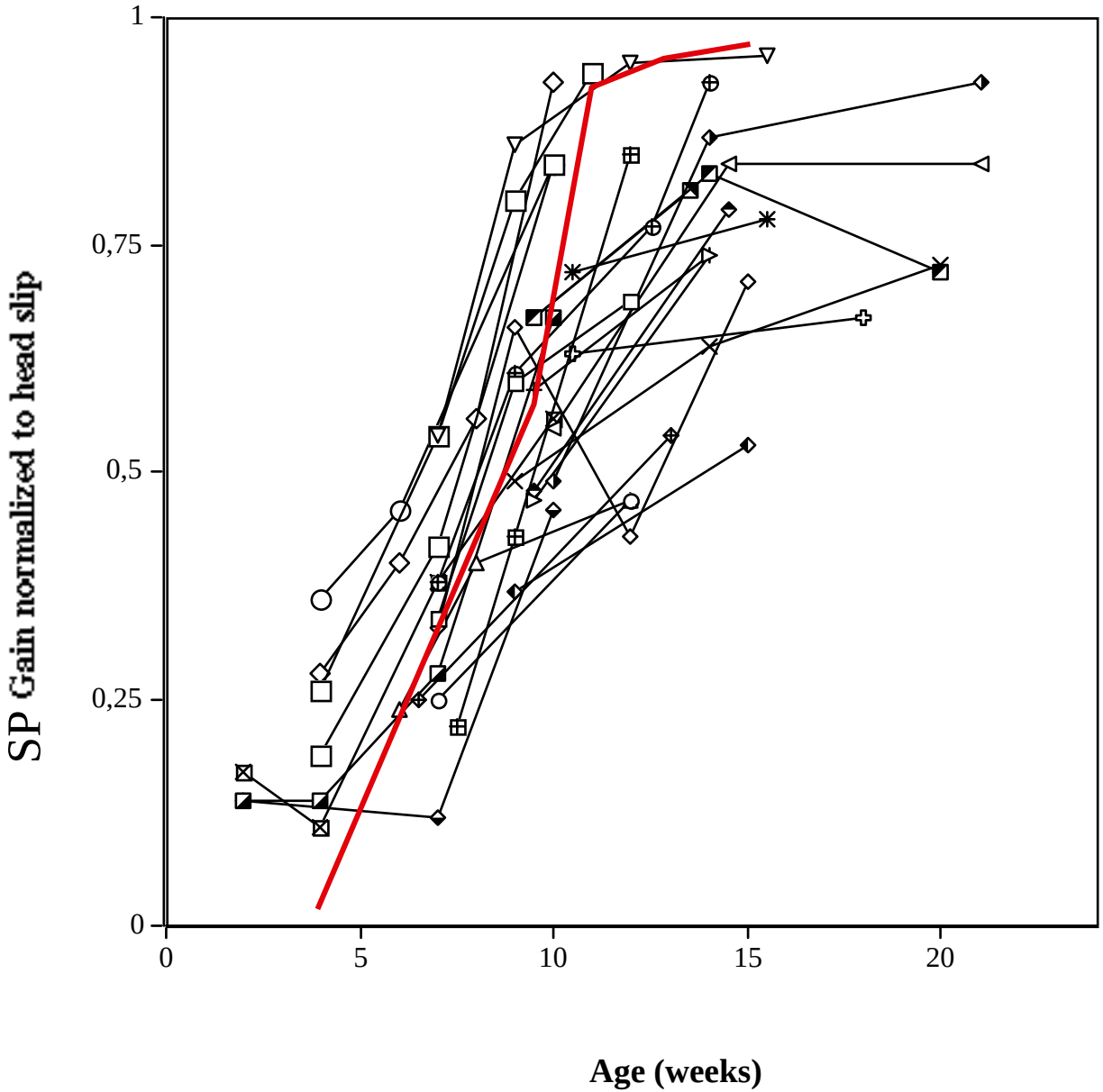
The object moves. The infant is stationary

The gain of smooth pursuit reflects its maturity



26 subjects from 3 different studies followed longitudinally over parts of the first 5 months of life. (von Hofsten & Rosander, 1997; Rosander & von Hofsten, 2000,2002)

The gain of smooth pursuit reflects the maturity of the motion processing area of the cerebral cortex.

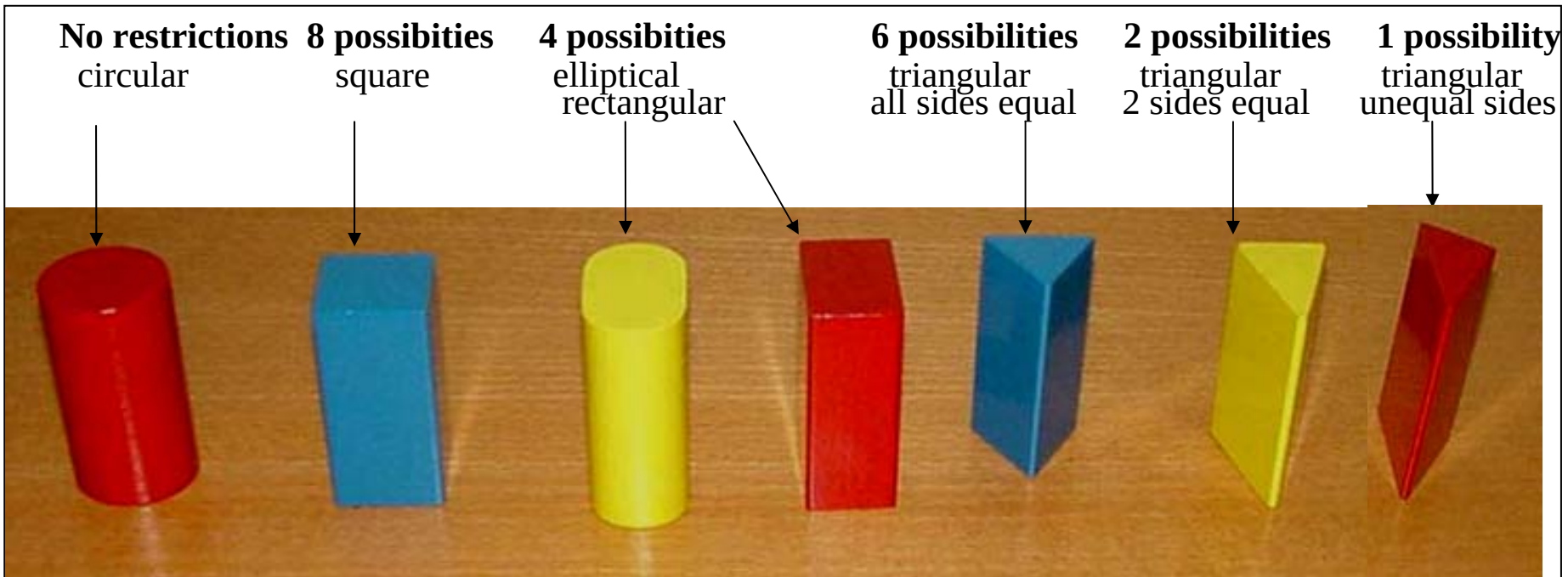


One important indication that this development reflect the maturation of the MT-MST areas is the finding that sensitivity to motion direction in attention getting tasks emerges at the same age (Atkinson, 2000). Red curve.

Development of reaching and manipulation

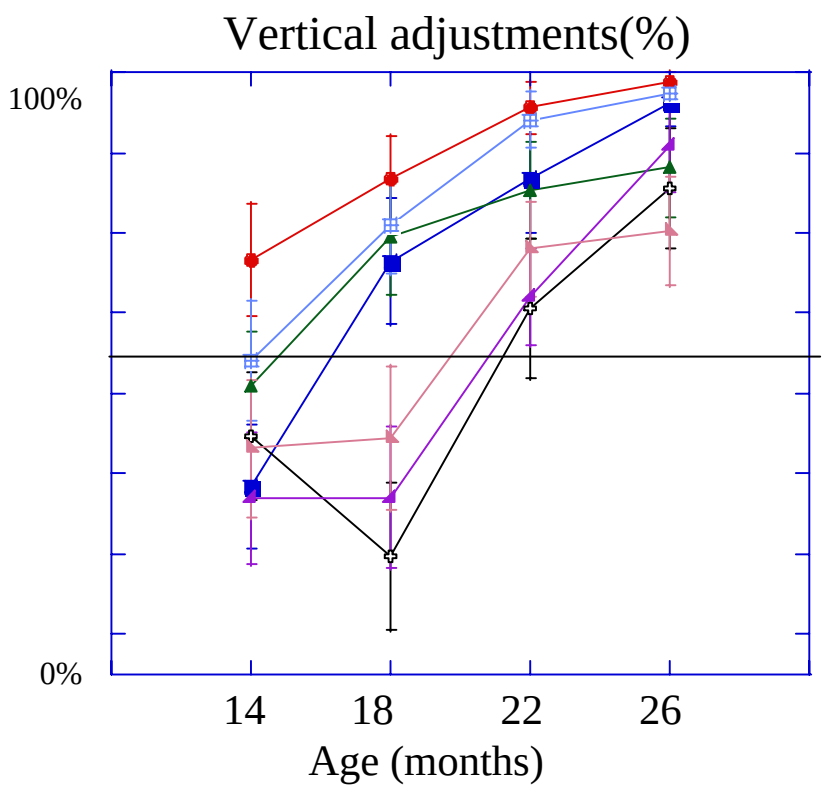
- Visual control of the arm is present at birth. Infants can also move the fingers in a differentiated way, but they cannot control them in grasping or manipulating objects. Both arm movements and finger movements are governed by global extension and flexion synergies.
- Reaching and grasping emerge by 4-5 months of age. The first grasps are palmar and engage the whole hand. Grasping that engage differentiated finger movements emerge around 9-10 months of age (e.g. pincer grasp).When reaching first emerges, both stationary and moving objects can be negociated, and infants can use both one and two hands. Laterality develops gradually over the first year of life. It is most apparent in demanding tasks. Laterality also includes what each hand will do in bimanual tasks.
- Handling objects reveal their different affordances and knowledge about affordances improves the handling of them. The close connection between vision and manipulation, makes it also possible to learn about object affordances by viewing events that engage them and other people manipulating them. This is especially relevant when learning about the functions of tools.
- The development of skills in reaching and manipulation are closely related to the development of such cognitive skills as mental rotation and means-end relationsships.

When manipulating objects, the subject need to imagine the goal state of the manipulation and the procedures how to get there. We have studied how infants develop their ability to insert blocks into apertures. All objects had the same length and the difficulty was manipulated by using different cross sections. The objects were both presented standing up and lying down. (von Hofsten & Ornkloo, 2005)

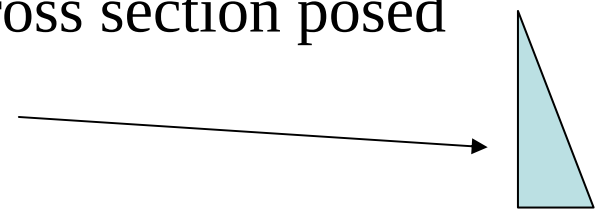


The youngest infants were quite unsuccessful in inserting the objects in spite of the fact that they tried very hard. The 14-month-olds were only able to insert the blocks in 20% of the trials and then mostly thye cylinder. 14- and 18-month-olds failed in raising up objects that were presented lying down. When failing they often tried brute force.

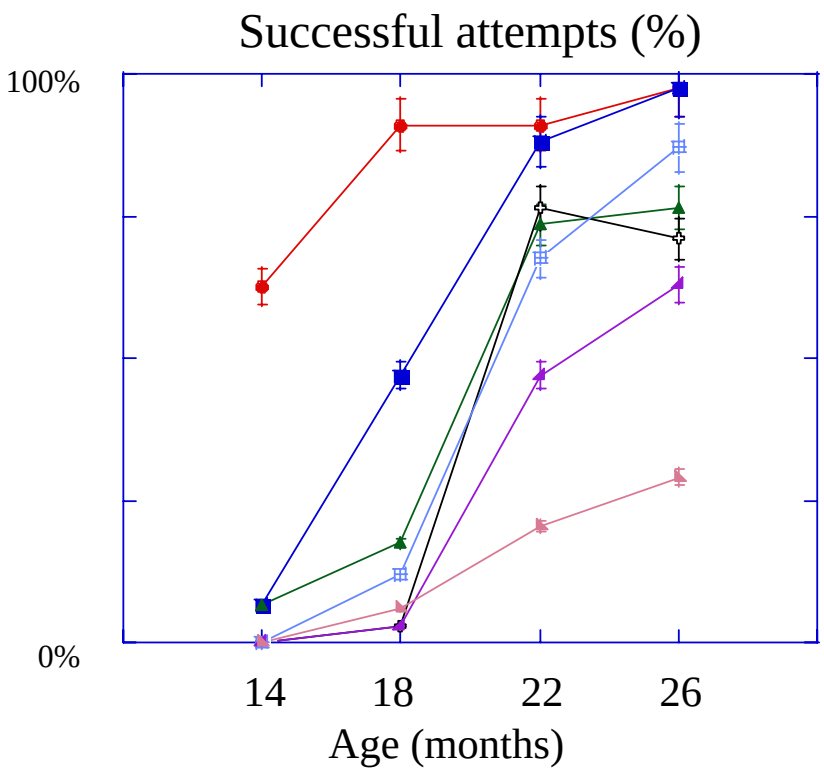
Infant 14 months triangular object



From 22 months of age infants made great progress. This is the age when they also systematically preadjusted object orientation both vertically and horizontally before they arrived with it to the aperture. Even for the 26-month-olds, one of cross section posed real problems – the triangle with unequal sides.



3-year-old child, unequal side triangle



Development of social abilities

Social interaction is primarily based on vision, touch, and proprioception. The mouth, face, eyes, and hands are the primary instruments for such actions.

The infant is a social being from birth. Newborns imitate gestures and engage in face-to-face interactions. Such primary intersubjectivity serves to establish strong bonds with caregivers at an age when infants crucially depend on them. From the first months of life, infants understand basic emotions communicated by facial gestures and use such gestures themselves.

During the first year of life, infants become increasingly skilled at understanding the emotions and intentions of other people, and engage in referential communications. Among other things this requires infants to perceive the direction of attention of others. Perceiving what another person is looking at is an important social skill. One can comment on objects and immediately be understood by other people, convey information about them, and communicate emotional attitudes towards them.

Perception of gaze direction in static images

We asked whether 1-year old infants perceive where a person is looking. We used still images not to confound the posture information with dynamic information about attention direction. The subjects saw the model **look and point**, **look**, or just **point** at each of four object positions while gaze was measured. A control condition was also included where the model just looked straight ahead.

In the real experiment there was a pause between each image.

Goals and motives, and predictive control are essential components of all behavior at all ages. The difference between the actions of young infants and those of adults has to do with the means available for carrying out the actions, the information available for guiding them, and the knowledge acquired for predicting what is going to happen next.