PROSPECTIVE CONTROL AND OBJECT REPRESENTATION IN YOUNG INFANTS:
An action-based account

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ABSTRACT


The aim of the present thesis was to study the age-related differences of prospective control and object representation in young infants. The overall set of theoretical and empirical issues addressed in this thesis consists of how infants represent and react to visible and non-visible moving objects. This involves understanding the interrelationship between different actions, such as head and trunk movements, and reaching. Questions about infants’ ability to negotiate different kinds of motions and the notion that infant representation of an occluded object can be graded in strength are also addressed in the present thesis. The hypothesis of graded representation proposed that a concept of object representation is not a clear-cut distinction between whether one has a representation or not. It is rather a graded process, evolving with experience and becoming embedded in processes underlying overt behaviour. Study I showed that perturbing an object affected the quality of grasp, which seems to indicate that the approach and grasp components are, at least partially, integrated by nine months of age. The analysis of the relationship between head and hand movements showed tightness in the coupling between these movements, as indicated by a small correction time difference between them. Study III showed that 6-month-old infants, under certain conditions, can form a dynamical representation of a moving and temporarily occluded object, taking into account the velocity and the direction of the object’s motion. It also revealed three other interesting findings: firstly, that an occluder could provide landmark information about object reappearance; secondly, that reaching was dramatically disrupted when the object was temporarily non-visible either due to occlusion or blackout of the room lights and thirdly, that reaching recovered markedly after a few trials, but only when subject to blackout. Overall, the results supported the hypothesis of graded representations. In Study IV, when infants observed a circular object motion, it was shown that while head tracking is functional in 6-month-old infants, it continues to develop and become more refined up to, and beyond, the age of 12 months. The structural organization of head tracking in both 6 and 12-month-old infants complied with an organizational pattern of accelerations and decelerations, or so-called movement units, which is in line with earlier studies of both goal-directed and spontaneous arm movements. The intersegmental coupling between the head and the trunk showed that the infants tried to stabilise head movements by adjustments of the trunk. In addition, study II presents a method for coding prehensile movements by means of a touch screen system, which is used in study III.
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SETTING THE SCENE

The present thesis: background and specifying the questions

As with all animals, our movements take place in specific contexts, contexts that change over time and require responses to be accurate in timing and scaling. Walking, cycling, and downhill skiing are but a few examples of motor activities that are based on our ability to foresee upcoming events and to learn from experience. According to Bernstein (1967), movement can be seen as the result of the interaction between internal forces that are under neural control and the (often) unpredictable external forces such as gravity and inertia. However, is it really necessary to employ prospective control in order to control our movements? According to von Hofsten (1994), who argues for what he calls “…the necessity of knowing what is going to happen next”(p.64), the answer is yes, for several reasons.

First, there is a time lag between information entering the system and when the action is executed. Waiting for a feedback loop would be disruptive and not facilitate smooth and continuous movement.

The second reason is that the movements themselves generate a momentum that will disturb the equilibrium of the system if not counterbalanced. To maintain posture and balance, it is therefore crucial to perceive moving segments in advance instead of waiting for feedback.

The third reason involves coordinating movement with the external world. For instance, catching a ball requires an immediate adjustment towards a place where the paths of the object and the hand intersect.

To perceive and to act upon external moving objects involve the estimation of velocity and trajectory and an understanding of the rules by which objects move. If an object disappears behind another one, the prediction of its location and its reappearance requires a representation that must span the time and place of non-visibility. This includes representing the visually absent object, predicting where and when it will reappear and anticipating its velocity and direction of motion at that time. In other words, developing an ability to handle moving objects over periods of non-visibility reflects significant achievements in both object representation and prospective control. Finally, the act of prehension allows us to experience
whole entities although the system is known to detect both the intrinsic and extrinsic properties of objects. Prehension is characterized by a tight coupling between the components of reaching and grasping; thus the transport component takes the hand to the vicinity of a target whilst the grasping component picks up the object for further manipulation.

Prospective control ranges from perceiving and analysing both simple and more complex motions to the prehension of moving and perturbed objects. Object representation also incorporates perception, analysed by looking time methods during partial and complete occlusion as well as prehension involving retrieval of temporarily occluded and moving objects.

The act of reaching for a suddenly displaced object was used in Study I in order to address questions regarding how head, reach and grasp movements are coupled in nine-month-old infants. Study II developed a computer system for coding video recorded movements. The system included MicroTouch technology, which made it possible to register movements by contacting a monitor on which the recordings appeared with a finger of light pen. The system was later used in Study III.

Can infants predict the reappearance of temporarily hidden objects? Is the representation of the hidden object dependent on how it was hidden and, thus, how does this affect predictive action such as head tracking and reaching? How significant is the duration of non-visibility? All of these questions were addressed in Study III and are related to the notion of object representation. Another set of questions is related to how 6 and 12-month-old infants organise their head movements in order to predictively track a revolving object presented in a vertical plane. These questions are addressed in Study IV. In addition, a fifth and ongoing study, presented in the general conclusion section, concerns an investigation into how an infant’s representation of a hidden object is preserved during different conditions of non-visibility. The conclusions from that Study are based on the analysis of 39 infants.

Before reviewing the studies included in this thesis, an introduction to the underlying processes involved in prospective control, prehension and object representation will be given.
PROSPECTIVE CONTROL AND THE PERCEPTION OF MOVING OBJECTS

Prospective control can include goal formation, motivation, planning and expectation. In these respects, it encompasses an analysis of the present situation, how that present situation has unfolded in the past, and an integration of those two analyses in order to provide information about the future (Haith, 1993). In script and schema theories, expectation is commonly used as a higher level construct of prospective control, containing the sequence of actions one goes through when taking part in a well-known event (Eysenck & Keane, 1990). However, the development of prospective control can already be seen in sensorimotor actions of infants, ranging from perceiving motion to prehension.

Motion sensitivity

Motion is an effective stimulus for drawing attention and eliciting responses in infants. A motion is perhaps best described as a time derivative of spatial position, i.e., velocity. This in turn can be divided into direction and magnitude (Kellman, 1995). Observing motion leads to responses such as smooth pursuit, (e.g. von Hofsten & Rosander, 1996, 1997) predictive reaching (e.g., von Hofsten & Lindhagen, 1979; von Hofsten, Vishton, Spelke, Feng & Rosander, 1998; Wentworth, Benson, & Haith, 2000) and, thus, observing an optical flow leads to postural adjustments (Berthental & Bai (1989). Kellman (1993) argues that motion-carried information has, in principle, a greater power for identifying the properties of objects, space and events, compared to purely static information (see also Spelke & Newport, 1998).

Lee (1976) has shown that the relative expansion of elements in the optic array supplies information about an object’s future position and time-to-contact. Avoiding collision is one of the earliest signs that young infants can use such information. Infants as young as eight days old show defensive distress reactions (e.g., head retraction) towards approaching objects, both for real ones (Bower, Broughton & Moore, 1970) and those presented in an optical display (Bower et al., 1970a; Ball & Tronick, 1971). The optical display design excluded changes in binocular motion parallax. Later work has questioned this interpretation and argues that undifferentiated movements in relation to tracking behaviour could account for the findings (Yonas, Bechthold, Frankel, Gordon, McRoberts, Norcia & Sternfels, 1977). However,
further studies showed that infants blink more to displays specifying an approaching object than to a single contour from about 1 month of age (Yonas et al., 1977; Yonas, 1981; Yonas & Granrud 1985). According to Carroll and Gibson (1981; see von Hofsten, 1994), infants display differential responses towards approaching objects versus an approaching aperture. In the former case, infants retracted their head, and in the latter they leaned forwards towards the approaching aperture.

Eye tracking

Eye tracking is another early sign of actions involving prospective control. If an infant’s strategy were to fixate on an ad hoc basis without any prospective control, tracking would be jerky. The eye tracking of a smoothly moving object by infants is indeed initially jerky, but over time, shifts to become smooth (Aslin, 1987). Shea and Aslin’s (1990) experiment with squares moving at a range of fixed velocities shows that the pursuit system is functional at the age of 7 weeks. Aslin (1981) observed that smooth pursuit in 3-month-old infants was characterized by them staying on, or being slightly ahead of target. In line with this, von Hofsten and Rosander (1996) recorded infants of 1, 2, and 3 months of age when viewing sinusoidal motions presented in front of a patterned background. The moving object was viewed at either 0.2 or 0.4 Hz with corresponding visual angles of 12.5 and 25 degrees. The object moved in front of the infants across a large vertically striped background. Smooth eye movements were found in the 2- and 3-month-old infants, although the amount varied. The gain of smooth pursuit was found to be task dependent, in that the slowest motion observed had the highest gain (close to the ceiling value), but the gain also increased substantially between the age of 2 and 3 months.

In a longitudinal study, von Hofsten and Rosander (1997) investigated one group of infants (from 2 to 5 months of age) using a sinusoidal and triangular motion with an unpatterned background. For a sinusoidal motion, it is possible to determine when the object is going to turn ahead of time, but to foresee the triangular motion, you need to know the periodicity of the motion. Von Hofsten and Rosander found that prospective smooth pursuit of sinusoidal motion was established at the age of 2 months, but only at 5 months for the triangular motion. The authors argued for a discrepancy between the local and global level. For the sinusoidal motion, prospective tracking could be based on a local level; the next motion could be predicted on the motion just seen. This is
in contrast to the triangular motion for which the periodicity required a global analysis. At the age of 5 months, the infants could master both the global and local characteristics and act prospectively on both sinusoidal and triangular motions.

According to Haith (1993), the shift from jerky to smooth tracking is due to an ability to form visual expectancies. To further investigate this, he developed a visual expectation paradigm in which eye movements were used as an indicator of expectation (Haith, Hazan & Goodman, 1988). The rationale for using saccadic eye movements as indicators of expectation is that these are under control from birth and are very fast. In addition, eye movements place minimal demands on memory and are relatively easy to register (Haith, 1994). The visual expectation paradigm is designed to create a flow of events that in themselves are predictable and unfold independent of the observer's own behaviour. The infants were lying down and they watched attractive pictures appear in sequences from the left and right (displayed on a TV monitor) separated by an inter-stimulus interval. The idea was to measure whether, after some experience, the infants formed expectations as indicated by their visual activity. Evidence for expectation consisted of anticipatory fixations towards the next picture to be presented. The dependent measurements were for all studies the proportions of fixation and reaction times.

A number of studies have investigated the impact of time, spatial location and content issues in the visual expectation paradigm. By using different interstimulus intervals in an alternating series of pictures, Haith et al. (1988) showed that infants were able to form expectations when the timing series were asymmetrical. They argued that the infants' expectations involved a time element, and that they were able to maintain control for at least two time values.

To pursue the issue of spatial location, Canfield and Haith (1991) investigated whether 2- and 3- month-old infants could form expectations when the complexity of the spatial sequence was increased. Instead of a 1/1 series (one picture presented to the left followed by one picture presented to the right and vice versa) the complexity increased to a 3/1 sequence (three pictures presented to left followed by one picture presented to the right and vice versa). The 3-month-old infants exhibited an expectation pattern for the 3/1 sequence, but the ability of the 2-month-old infants was limited to the 1/1
expectation pattern. In a similar vein, Wentworth and Haith (1992) pursued the issue of content by investigating whether 2 and 3 month-old-infants can form an expectation for picture content as opposed to forming an expectation that something will happen at a particular time and place. Wentworth and Haith argue for three possible outcomes. The first outcome suggests that content plays a minor role, thus whether the content in the presentations is constant or changes does not matter. The second possibility, derived by means of habituation, suggests that infants will be tired of a constant presentation and display more anticipatory behaviour towards the side in which the changes occur. The third possibility, which turned out to be most plausible, suggests that infants do form an expectation based on the content, and that they exhibit a superior expectation pattern towards the constant side.

Motion and constraints

Prospective control also implicates the understanding of certain rules by which objects move, i.e., physical constraints. Objects move on connected and unobstructed paths and are systematically affected by gravity and collisions with other objects. Objects also move in accordance with the principle of inertia; they continue in a state of rest or uniform motion unless acted upon by other forces (von Hofsten et al., 1998).

Von Hofsten et al. (1998) designed an experiment in which an object moved in four different visible paths. The idea was to investigate whether an infant’s reactions to a moving object were in accordance with the principles of inertia. The object started in either the upper left or right corner on flat and almost vertical surface. The paths were either linear from each corner or non-linear. In the non-linear path the object turned abruptly at the point of intersection. Because the linear and nonlinear paths were equally frequent and randomly ordered, the object motion at the potential turning point was unpredictable, i.e., either the object turned abruptly or continued. In two separate experiments, they investigated how 6-month-old infants tracked and reached for a linear, or an abruptly turning linear motion, i.e., motions either according to the principle of inertia or in violation of that principle. In order to catch the object, the infants were required to initiate their reach before the object attained the centre and thus aim for a position in front of the object. The result showed that both head tracking and reaching are guided by a linear extrapolation in that they aimed for a position in line with the initial trajectory.
regardless of whether the object turned or not. The measurement of head movements in the nonlinear trials indicated that the infants extrapolated the linear path at least 200 msec ahead of the object. In reaching, infants mainly used their contralateral hand, such that if the moving object came in from the left they used their right hand.

In the second experiment, von Hofsten et al. (1998) presented the object in a block of six trials. This was done in order to evaluate whether the behaviour was influenced by learning. The second experiment replicated, to a large extent, the first, suggesting the infants made a linear extrapolation 200 ms/msec (as above) into the future and that reaching converges to the contralateral side. In addition, infants showed no signs of learning to anticipate the abruptly turning motion (in violation of inertia) despite this being presented over a block of trials. However, head tracking seems to be at least somewhat responsive towards the immediately seen position, as a short stop in the intersection point affected the head tracking behaviour although reaching was unaffected.

The findings from von Hofsten et al (1998) indicate that predicting a linearly moving object can, for 6–month-old infants, be influenced by the laws of physics; constraints exist that can be coupled to specific motions. Thus, infants could not learn to act predictively when presented with a non-linear motion despite two blocks of six consecutive trials, indicating a strategy of simple extrapolation with no learning mechanism. Although learning an abrupt turning motion seems to be a fairly simple perceptual/cognitive task, it appeared that the inertial motion presented in the experiments by von Hofsten et al. overpowered the learning mechanism. However, von Hofsten, Feng, & Spelke (2000) showed that infants could learn to predict the reappearance of a non-linear motion if the trajectory is partially occluded by another object. This behaviour seems to involve a “decision-making” process, taking contextual cues into consideration. Thus, the presence of landmarks (the occluding object) provided perceptual support and made it easier to conceptualise the object’s motion, and without this support, head tracking was overpowered by the extrapolation of the seen motion.

These experiments raise questions about how the observed motion, and the context in which it is presented, affects prospective control for moving objects. If observers have a sufficiently long exposure to the previous trajectory, they can compensate for weak and/or unreliable perceptual
information. Thus, a future-oriented behaviour directed towards a moving object must incorporate both stimulus-derived information knowledge of the rules by which objects move. The former is derived from observing the actual trajectory and the latter reflects a prediction of a potential future trajectory (Sekuler & Sekuler, 1993; Sekuler, Sekuler & Sekuler 1990). Additional cues, from the stimulus itself (So & Griffin, 2000) or from landmarks (e.g., Jonsson & von Hofsten, 2001; von Hofsten et al., 2000), can reduce the uncertainty and increase predictability. Although Gibson (1979) reminds us that not all processes require representations, perceiving a motion is knowing about it and this knowing extends beyond the perception of structure of the object to the perception of affordances. However, this point of view leaves us without any explanation as to the necessary psychological structures of the mind that are needed in order to support perception, action and prospective control (Bremner, 1998).

An obvious assumption is that predicting the future position of a moving object is easier if the object’s trajectory is smooth and predictable. If for instance, in viewing a linearly moving object, the immediately previously seen position is enough to completely specify the position in the near future. However, the world is not so simply organised; a more complex object motion requires some kind of internal predictive model (e.g., Bahill & McDonald, 1983). But despite the motion characteristics, the observer has to extract reliable information from the previously seen trajectory to predict the object’s future position and achieve precise action guidance.

Study IV investigated the age differences in the head tracking of a more complex motion (circular object motion) presented in a vertical plane. Two groups of infants (6 and 12 months old) were compared and their results were referenced to a group of adults.
Prehension

The act of prehension can be divided into two components, transport and grasping (Jeannerod, 1984; Savelsbergh, von Hofsten & Jonsson, 1997). The transport component takes the hand to the vicinity of a target and is little affected by conditions of visual feedback, while the grasping component prepares the hand for the encounter with the object and picks up the object for further manipulation (Jeannerod, 1984). Evidence has also been found for a sudden transformation from a state in which reaching without grasping is the most frequent action to a state in which reaching with grasping is the most frequent (Wimmers, Savelsbergh, Beek, & Hopkins, 1998). The perceptual system involved in prehension allows us to experience objects as whole entities although the system is known to detect both intrinsic (size, shape, texture) and extrinsic (orientation, distance from body, location) properties independently. Even if the two components, transport and grasping, appear to be independently organised (Wing, Turton, & Fraser, 1986), they share a common time course (Jeannerod, 1988). Jeannerod (1988) designed an experiment in which an adult’s prehension movements were directed at three-dimensional objects (a sphere, a cube and a vertical rod) located at different positions along the sagittal axis. It was found that grip formations were anticipatory with respect to the object’s size and position, which shows that both the intrinsic and extrinsic properties of objects are essential attributes in guiding prospective behaviour. However, prehension also involves posturally constrained motility that progresses from general postural activity to specific manipulative abilities (Touwen, 1995).

Reaching

According to Rochat and Goubet (1995), the integration between different sensorimotor systems is expressed in reaching from an early age. It combines the discrimination and recognition of an object in three-dimensional space and goal-oriented behaviour towards that object. Reaching can also be functionally described as consisting of a ballistic part that is visually triggered and a visually-guided part using corrective movements. To investigate
corrective movements, von Hofsten (1977) used prisms, which were either decreasing or increasing in convergence, thus making the object appear to be closer or more distant. He found that reaching, in 4 to 10-month-old infants, was aimed at the distorted position specified by the convergence prisms. The trajectory was corrected on the basis of visual information, although not until the hand arrived at the virtual position of the presented target. From the evidence that the ballistic part of the reach was well aimed, von Hofsten concluded that this decreases the attentional load and enables the infant to get close to the object before any corrections are needed.

In another approach, Ashmead, MacCarty, Lucas and Belvedere (1993) presented 5 and 9-month-old infants with illuminated toys in the dark. In half of the trials, a luminescent marker was attached to the hand. The infants could either see the illuminated toy but not the hand (reaching adjustment based on the seen object and the felt position of the hand) or see their hand as well as the object (adding vision). In addition, they collected data from an adult sample under identical conditions. The 9-month-old infant reaches looked similar to those of the adults and were adjusted by using visual cues from both the location of target and position of the hand. However, the 5-month-old infants showed that they were unable to update their reaches from information provided by the luminant spot on the hand. This finding contrasts with that of von Hofsten (1977) who found that infants of about the same age could correct their reaches for an object in the light.

Reaching in the dark experiments show that preparatory reaching is not exclusively controlled by visual input (e.g., Clifton, Rochat, Litovsky & Perris, 1991; Perris & Clifton, 1988; Clifton, Perris & Bullinger, 1991). In these experiments, infants reached quite accurately in the dark, an ability requiring the successful integration of proprioceptive information from the unseen hand with the seen or heard object. This topic is further discussed in the section on object representation.

Although the earliest sign of reaching towards an object is present in newborns (von Hofsten, 1982; Ennouri & Bloch, 1996), reaching cannot be considered to be functional until about 4 months of age (e.g., von Hofsten & Lindhagen, 1979; von Hofsten, 1991). What is striking about this achievement is that reaching becomes functional not only with regard to stationary objects, but also towards moving objects under certain conditions (von Hofsten, 1991). When infants do attempt to reach earlier than four months of age, they often
fail to contact the target (Mathew & Cook, 1990). These reaching movements are done without any adjustment of the hand to the object’s size, and grip formation is only established after the object has been touched (von Hofsten & Rönnqvist, 1988). However, Butterworth and Hopkins (1988) reported that even newborn infants show signs of a predictive behaviour in relation to their arm movements. During spontaneous arm movements, the mouth is more likely to remain open if the hand goes directly to the mouth instead of touching other parts of the face. Butterworth and Hopkins (1988) argued, with support from de Vries, Visser and Prechtl (1984), that hand-mouth coordination in the newborn may be a centrally organised movement synergy established before birth. They also argued that prenatal activity, which is controlled proprioceptively, might be responsible for the sophisticated behaviour seen soon after birth. Further studies involving spontaneous hand-mouth coordination investigated whether there is a link between hunger and contact with the mouth. Lew and Butterworth (1995) found that the anticipatory hand-mouth contact only occurred before feeding, thus indicating that such predictive behaviour is somehow related to hunger.

The first successful reaches consist of fragmented and irregular movements. Two months later, they have become smooth, rapid and fluent (e.g., Thelen, Corbetta, Kamm, Spencer, Schneider & Zernicke, 1993; Konczak, Borutta, Topka & Dichgans, 1995). A number of studies have found that the normal development of reaching can be described according to changes in an organizational pattern of accelerations and decelerations (e.g. von Hofsten, 1991). These so-called movement units are found even in spontaneous arm movements of neonates (von Hofsten & Rönnqvist, 1993). Each movement unit is defined as containing both an acceleration and deceleration phase. From the onset of successful reaching at 4 months up to the age of 6 months, they decrease in number while the reaches themselves become straighter (von Hofsten, 1991). From 6 months onwards, reaching is structured and ordered in an adult-like pattern of 1 to 2 movement units (Jeannerod, 1984). The evidence that, from its onset, reaching in infants is comprised of movement units raises questions as to whether other actions are organised in a similar way. Thus, Study IV investigated whether head tracking of circular object motion is segmented into movement units and whether there are fewer units having straighter trajectories in 12—month-old infants compared to 6-month-olds.
If the object is moving, a prediction of its future location, as well as prospective control of head, eye and arm movements, is needed in order to achieve a successful reach (van der Meer & van der Weel, 1994). The remarkable thing about this is that when infants try to catch a moving object, under certain conditions, they implement a prospective behaviour by intercepting the object at a convenient and economical position. Von Hofsten & Lindhagen (1979) found that the basic strategy in infants of 12-24 weeks reaching for a semicircular moving object was to use the contralateral hand, thereby giving increased time for catching the object. In line with this, Robin, Berthier and Clifton (1996) presented 5 and 7-month-old infants with an object moving horizontally; an identical strategy was found in which infants in both age groups changed hand so that the contralateral hand was used, also with an increased time available for catching it. This is in contrast to reaching towards stationary objects when the ipsilateral hand is usually preferred (Perris & Clifton, 1988).

Recent research, (Munakata, Jonsson, Spelke, von Hofsten, 1996; Spelke and von Hofsten, 2000; Jonsson and von Hofsten; 2001), has revealed that whilst 6-month-old infants performed reaches well when the object was continuously visible, they hardly reached at all when it was temporarily occluded just before entering the reaching space. In Van der Meer et al. (1994), infants below 6 months of age only reached for the object when they had time to launch the reach after it had become visible again. These outcomes contrast with the results from the reaching in the dark experiments (e.g., Hood & Willats, 1986; Clifton et al., 1991). In these studies, 6–month-old infants continued to orient towards and reach for the non-visible objects, a topic further discussed in the “reaching in the dark section”.

**Grasping**

The actual finger formation during grasping involves two functional requirements (Jeannerod, 1988). Firstly, in order to perform a successful grasp the infant must adjust the hand aperture in relation to the size, shape and orientation (von Hofsten & Fazel-Zandy, 1984) of the object, but it is not until the age of 36-52 weeks that a precision grip can be formed (von Hofsten & Rönnqvist, 1988). Secondly, the timing of finger movements must be coordinated with the transport component, i.e., the part of reach that transports the hand to the object. Initially, the transport and grasping
movements are more sequentially organized before becoming integrated into one adult-like action at about 13 months. However by the age of six months, reaching becomes differentiated relative to the perceived characteristics of the object (von Hofsten & Rönnqvist, 1988). Although neonates reach for objects, under appropriate conditions, they are unable to grasp them, which according to von Hofsten (1990) results from an extension-flexion synergism that makes the hand open when extending the arm and close during arm flexion. Initially, infants grasp objects using the entire palmar surface, but with increasing age, they adjust their reaching and use the hand and fingers more independently (Touwen, 1976). According to Wing et al. (1986), it is evident that reaching and grasping are not independently controlled actions. To study this issue, Paulignan, MacKenzie, Marteniuk and Jeannerod (1991) introduced a procedure in which objects are suddenly displaced at the onset of reach. Accordingly, they demonstrated that reaching and grasping in adults were temporarily reorganized by means of a quick movement of the hand to the vicinity of the object at the same time as it prepares for manipulating the object. Study I investigated whether 9-month-old infants could adjust their prehensile movements (reaching towards an object and grasping it) in a similar fashion when a visible target was perturbed during a reach.

Posture

Although reaching and postural control are often treated separately, there is substantial evidence that ontogenetic improvements in reaching are inseparable from postural development (Reed, 1990). Descriptively, postnatal development abides by two general principles that reflect growth gradients in the cephalocaudal and proximodistal directions. Cephalic structures such as lips, mouth and eyes are first brought under control. Proceeding in a caudal direction, control is increasingly exerted over the trunk, legs and finally the feet. The proximodistal development is characterized by progress in which control is gained over the proximal joints before the more distal ones (Vasta, Haith & Miller, 1999). In accordance with these principles, infants are first able to stabilize the head upon the trunk at around 3 months of age (e.g., Van Wulfften Palthe & Hopkins, 1984). At the age of 6 months they can sit with support from their arms for a few seconds and achieve independent sitting at the age of 8-9 months (Touwen, 1976). One of the major tasks for postural control is to maintain stability, which in turn prevents us from falling. This
necessitates the maintenance of body posture in a range of nearly vertical positions, in the face of imposed perturbations such as stumbling or tripping. A fundamental requirement for carrying out an action is to maintain a stable and a balanced posture (Bertenthal & von Hofsten, 1998). To maintain balance during limb movements, anticipatory postural adjustments are required (Bertental & von Hofsten, 1998). Such adjustments in the trunk muscles were found by von Hofsten and Wollacott (1990) who argued further that postural control becomes even more important in fine manipulation (cited in Bertenthal & von Hofsten, 1998). Massion (1998) pointed out two important features of anticipatory adjustments. The first is the ability to predict the consequences of a movement, thus predicting the postural disturbance arising from actions such as reaching and arm loading and unloading. The second one deals with the problem of how movement performance and the maintenance of postural stability are coordinated. Thus, the performance of reaching movements changes when infants start to sit without support (Rochat, 1992; Rochat & Goubet, 1995). Van der Fits, Otten, Klip, Van Eykern & Hadders-Algra, (1999) argue that reaching, once established, develops relatively independently from postural control.

Anticipatory postural adjustments are also required in gait initiation and include a shift in the centre of foot pressure both backwards and towards the stepping foot. Ledebt, Bril & Brenière (1998) examined adjustment in children at the ages of 2.5, 4, 6 and 8 years and showed that systematic backward anticipation was present at 4 years. Although an anticipatory adjustment could be seen in the 2.5-year-old children, it was considered to be poorly linked to the ensuing gait. Compensating for a loss of balance, anticipating the size, shape and the orientation of objects and locomoting around an obstacle, can all be interpreted as infants becoming more successful in their ability to represent perceived future events (Bertenthal, 1996). Put another way, each of these achievements signals an improvement and prospective control. One aspect of Study IV was to examine the importance of trunk movements in relation to head movements required for tracking a circularly moving object in infants aged 6 and 12 months.
OBJECT REPRESENTATION AND DISAPPEARING OBJECTS

As adults, we experience objects moving in and out of view behind other objects in our everyday cluttered environment, and yet we have no particular difficulty perceiving and understanding that objects are coherent and continue to exist when hidden. Jean Piaget (1896-1980) was the first to systematically study and attempt to explain the origin of the concept of object representation or object permanence and although his findings from infant studies are robust and have been independently replicated, he tended to underestimate the ability of infants in this respect (Wellman, Cross & Bartsch 1987).

Piaget (1954) concluded that infants do not have object permanence until the age of 8 to 10 months and do not achieve a full object concept until they understand invisible displacement at around the age of 18 to 24 months. According to Piaget (1954), the child has achieved object permanence when she understands that objects have a permanent existence in time and space that is unrelated to herself and that objects maintain their identity through changes in location. Piaget refers to this achievement as the prototype of cognitive development. He even described the attainment of the object concept as a necessary condition of early development that will eventually generate logical thinking and mathematical reasoning (Bower, 1982). Piaget used the successful retrieval of completely or partially hidden static objects as a measure of object permanence and found that infants fail to retrieve objects until the age of 8 to 10 months, and after that they continue to make the A-not-B error (see below). This interpretation has generated a large number of studies, but after almost five decades of research there are several questions still remaining to be answered. For instance, how and when do infants acquire object representation? Does the acquisition of an all-or-nothing phenomenon remain incomplete until the age of 8 to 10 months or is it gradual (Munakata, MaClelland, Johnson & Siegler, 1997; Piaget 1954)? Or do younger infants possess an understanding of object permanence, but only display it in certain tasks (Baillargeon, 1993)? If so, why do they fail to search for an occluded object before the age of 8 to 10 months of age and still continue to make the A-not-B-error?
Looking experiments

Object tracking and object representation

In a tracking task testing object representation, infants are typically presented with a moving object that disappears behind a screen. The assumption is that if an infant sees an object move behind a screen, he should expect the object to reappear on the other side of the screen, providing that he believes that object continues to exist when it is out of sight. Nelson (1971) presented a train that was moving around a rectangular track, with one side of the track covered by a tunnel. Two groups of infants, one with a mean age of 5 months and the other with a mean age of 8 months, tracked the train successfully on its visible journey. When the train disappeared into the tunnel, the infants in both age groups continued to look at the entry point with no sign of anticipating the reappearance at the end of the tunnel. However, over a number of trials, the infants’ anticipatory skills gradually improved. Meichler and Gratch (1980) tested in a similar way, but used stop trials in which the object remained hidden longer than expected and transformation trials in which a different object re-emerged. It was found that anticipatory movements occurred in the 9-month-olds but not in the 5-month-olds. In addition, Nelson (1974) presented two objects travelling laterally that temporarily disappeared behind a screen, with 7 months-old infants displaying an anticipatory behaviour that became increasingly more accurate over trials.

Harris (1983) argued that this behaviour could easily be explained within the framework of Piaget’s theory. According to Piaget (1954), the anticipation of the future position of a moving object in stage III infants is based on local contingencies rather than on any understanding that the object remains in existence when out of sight. However, more recent studies are not in line with this interpretation. For instance, studies have shown that 6-month-old infants anticipated the reappearance of a moving object that was made temporarily invisible during its motion (e.g. Munakata, et al., 1996; Jonsson & von Hofsten, 2001). They turn their head towards the point of reappearance before the object arrives there. Jonsson and von Hofsten (2001) argued that the angular velocity relative to the infant increased considerably during the period of invisibility. In other words, the infant needed to speed up its head
turning velocity during the period of non-visibility in order to be on target at the
re-appearance (see also study III). The conclusion drawn was that this
behaviour could not be just a learned extension of tracking. If infants had
continued with the same velocity of head turning as before the occlusion, the
increase in head lag at re-appearance would be substantial. This shows that
infants have some ability to represent the object and its motion over the
invisible period.

The studies by Munakta et al. (1996), Spelke and von Hofsten (2000) and
Jonsson and von Hofsten (2001) also support the hypothesis that an occluder
provides a landmark of where a disappearing moving object becomes visible
again, and that this information facilitates the predictive tracking task. Without
this contextual support, the predictive behaviour is less clear. Thus, when the
moving object temporarily moved out of sight because of a blackout (room
lights were extinguished), the infants continued to move their heads in the
direction of the previously seen object motion, but at a slower rate. This
resulted in a lag when the lights were turned on again.

Moore, Borton and Darby (1978) argue for a different interpretation, that of
event prediction. Since tracking is embedded in a series of trials it is possible
to learn the predictable sequence of disappearing and reappearing events.
However, in predictive tracking studies it has been shown that infants
anticipate the reappearance of a temporarily occluded object more or less
directly (Jonsson & von Hofsten, 2001), before it becomes embedded in a
series of trials. Perhaps the strongest evidence for object representation is to
be found in experiments requiring infants to reach in the dark for both
stationary and moving objects (further elaborated within the “Graded
representation” and “Reaching in the dark” sub-sections). Although the object
tracking experiments provide us with some answers about infants’
understanding of object representation, we now turn to a novelty preference
approach, which has also provided a substantial degree of knowledge of how
infants ‘reason’ about hidden objects.

Novelty preference and the violation of expectation paradigm

Kellman and Spelke (1983) investigated perceptual completion by
showing approximately 4-month-old infants a stationary occluder behind
which a rod was moving from side to side. During this habituation phase, the
ends of the rod were visible above and below the occluder. As the rod moved
laterally, the two ends could be perceived as moving from one side to the other, but the midsection was hidden behind the occluder. The test displayed one complete rod against two unconnected parts of a rod. When the two tests displayed were presented, the infants showed a novelty preference towards the broken rod, suggesting that they expected the rod to be complete. Additional evidence has been provided by Kellman, Spelke & Short (1986) and Slater, Morison, Somers, Mattock, Brown and Taylor (1990). In addition, Johnson & Aslin (1995) found that 2-month-old infants seem to perceive object coherence in a partial occlusion display. In some sense, these experiments go beyond perception and completion, since they relate to the question of object representation.

To address this question further, Baillargeon, Spelke and Wasserman (1985) designed violation of expectation experiments using impossible and possible events and found that young infants looked longer at the impossible event. In a typical experiment, infants were presented with a possible and an impossible event. The possible event was consistent with natural expectancy. The impossible event, in contrast, violated the expectation. Baillargeon reasoned from a novelty preference perspective, that if the infants were surprised to see an impossible event they would react with longer looking times. These longer looking times were taken as an indicator of the understanding that hidden objects continue to exist when they cannot be perceived.

The infants were first habituated to a screen that rotated back and forth through an arc of 180 degrees; after habituation, a solid box was placed behind the screen. In the possible event, the infants saw the screen rotate and stop when it reached the box. In the impossible event, the infants saw the screen rotate the complete 180 degrees, as if it went through the box. If the infants’ expectations were violated by impossible events, then they looked longer at those events. Two groups of 4.5 and 5.5-month-old infants were found to look significantly longer at the impossible compared to the possible event. In another example of Baillargeon’s work, infants were seated in front of a track with a screen positioned in front of the track (Baillargeon, 1986). The screen was raised showing that there was nothing behind it besides the track, and then lowered. A truck was then rolled down a track behind the screen to reappear on the other side; this was done repeatedly until habituation occurred. In the possible event, the screen was raised, showing a
box placed just behind the track, then the screen was lowered and the truck rolled down the track. In the impossible event, the screen was lifted and a box resting on the track was revealed and the truck then rolled down the track. Under these conditions it was found that four-month-old infants looked longer at the seemingly impossible event, indicating that they envisage not only the permanent existence but also the location of the box behind the screen. These experiments and a series of others suggest that some infants as young as 3.5 months of age often have a representation of non-visible objects location, height and whether the object is compressible or not in conditions of complete occlusion (Baillargeon, 1986, 1987a, 1987b, 1991, 1993; Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987; Baillargeon et al., 1985).

However, in a recent study it was argued that the conclusions derived from the possible or impossible events, as claimed by Baillargeon and her colleagues, should not be interpreted as definitive evidence of object representation in very young infants. Cashon and Cohen (2000) investigated 8-month-old infants' perception of object representation in an extension of the rotating screen studies by Baillargeon (1987) and Baillargeon et al. (1985). They found that, in contrast to Baillargeon’s experiments, with a prolonged habituation phase infants showed a novelty preference towards the incomplete arc. Thus, infants did not use the impossibility–possibility of events, but instead displayed longer looking time towards the novel event, i.e., the screen rotated and stopped when it reached the box. In addition, Bogart, Shinskey and Schilling (2000) showed that, dependent on whether the infant was presented fewer or more trials in the habituation phase, the longer looking times were related to familiarity or novelty. Thus, those infants that processed the event more had a preference for novelty while those that processed the event less preferred familiar events.

Under certain conditions, infants also perceive distinctive objects as separated entities, despite the fact that these objects are viewed at different times; i.e., young infants have some capability of simple arithmetical “operations” (Wynn, 1992, 1995, 2000). In these experiments, Wynn used a standard locking-time procedure, involving showing 5-month-old infants a small number of objects that were then covered by a screen. A hand either removed or added an object. The main result was that infants were surprised if the number of objects mismatched the expected number of objects.
Additional studies showed that the infants not only understood that adding an item to another item resulted in a number other than 1, they also expected the item to be 2 in number instead of 3, showing surprise when 1 + 1 added up to be 3.

The violation-of-expectation paradigm has also been applied to the A-not-B task. The A-not-B-error, a hide and seek game, originated from Piaget's *The Construction of Reality in the Child* (1954), and has been continuously studied and found to be both a universal and robust phenomenon in infancy. In the classical A-not-B-error, the infant sits in front of two similar hiding places, which are a relatively short distance (approximately 20 cm) apart. The object is first hidden in location A and the infant, after a predetermined delay, is allowed to search repeatedly a predetermined number of times (the delay and number of searches in A can, of course, be manipulated). Then while the infant is looking, the experimenter moves the object from location A to location B, and after a delay the infant is allowed to search again. This time the 8 to 10-month-old infants reliably looked back and searched at A, i.e. the A-not-B-error (Smith, Thelen, Tizer & Mclin, 1999). Piaget’s (1954) explanation for the A-not-B error was that infants lack the concept of object permanence. From Piaget’s perspective, the object that was out of sight had ceased to exist and the infants therefore associated their search at A with bringing the object back into existence.

However, studies using the looking time paradigm indicate that infants possess a greater sensitivity for change in location than indicated by manual retrieval tasks (Hofstadter & Reznick, 1996). In a study by Ahmed and Ruffman (2000) infants were not allowed to search in the classic sense, they merely observed the experimenter carry out the task. After having been hidden in A, the toy was retrieved and moved to B. After delays up to 15 sec., the infants were shown either a possible event (toy retrieved from B) or an impossible event (toy retrieved from A). A series of experiments showed that infants of 8 to 12 months looked significantly longer at the impossible events (retrieved from the incorrect location). Ahmed and Ruffman (2000) argued that infants do in fact know where the toy is in a manual search task, but that they fail to search correctly for it due to an inability to inhibit the reaching response (Diamond, 1988). Thus, the requirements in reaching, in contrast to looking, may prevent infants demonstrating the knowledge that they do possess. Another possible explanation, according to Ahmed and Ruffman (2000), is
that the representation of the hidden object is graded in strength and that a reaching response requires a stronger representation to be executed (Jonsson & von Hofsten, 2001; Munakata et al., 1997). The concepts of response inhibition and graded representations will be further discussed below. Additional studies that also used looking time tasks as analogues to the A-not-B error retrieval task have shown that infants are sensitive to impossible events after a delay in which a manual retrieval would fail (Baillargeon, & Graber, 1988; Baillargeon, DeVos & Graber, 1989).

The predictive tracking and novelty preference tasks have supplied us with a picture of infant competence far beyond what Piaget claimed, i.e., “out of sight out of mind”. However, it does not solve the apparent dissociation between what infants know and how they act in a manual retrieval task. In the following sections, the means-end approach, reaching in the dark, graded representations and response inhibitions will be discussed as all are related to the attempts to solve the dissociation between manual retrieval and looking tasks.

The use of reaching to identify cognitive abilities in infants

Means-end explanation

An approach that has tried to resolve the discrepancy between an infant’s failure in reaching tasks and success in time looking tasks, is the means-end explanation. The means-end behaviour is defined as an intentional action that goes through a sequence of steps involving, for instance, the removal of a cover to retrieve an object (Piaget, 1952). Piaget argued that the onset of adequate means-end behaviour is dependent on two important achievements. The first achievement is the development of cognitive structures allowing them to set up goals and produce goal-directed behaviour. The second achievement concerns the knowledge of means-end relations, thus specifying the intermediate steps, which define the procedure of removing a cover to retrieve an object hidden underneath it (Willatts, 1999). Piaget also identified a transitional behaviour, replicated by Willatts (1984a). However, Baillargeon (1993) argues that infants have a subgoal ability, which allows them to chain the appropriate operators, but that they have difficulties with situations in
which the means puts them in conflict with the end. She presents the problem as follows:

“….if infants want to grasp a toy placed under a cover, or at the far end of a cover, then grasping the cover puts them in apparent conflict with their goal of grasping the toy. Similarly, reaching around a screen to retrieve an object placed behind the screen may be difficult for infants because it puts them in the position of having to reach away from where they know the object to be” (Baillargeon, 1993, pp. 300-301).

Willatts (1999) designed a longitudinal study that tested the goal-subgoal conflict and judged whether the behaviour was intentional or transitional. The task for the 6 to 8-month-old infants was to retrieve an object resting on the far end of a cloth. Willatts also manipulated object versus no object on the cloth, attaching the object to the cloth (reduces goal–subgoal conflict) and distance to the toy. The main findings go against Baillargeon’s suggestion of a goal-subgoal conflict. The result instead suggests that the youngest infants (6-months) use a transitional approach and that 7-month-olds produce intentional means-end behaviour to a higher degree. In addition, it was shown that the length of the cloth matters, in that when extending the cloth only the 8-month-old infants engaged in intentional behaviour and at 7 months reverted to transitional behaviour. Willatts concluded that his findings are in line with Piaget’s (1952) claim that inappropriate means-end behaviour is due to a conceptual deficit rather than any other factors interfering with performance.

Reaching in the dark

The reaching-in-the-dark studies rely on a manual search as an indicator of object representation (as in the studies of Piaget), but it is assumed not to involve the means-end problems. In general, the studies are designed to present an object that is suddenly made invisible by switching off the lights. Infants cannot see the objects in the dark and a representation of the objects’ existence is presumed to be required; but they can reach straight for the object, so a means-end behaviour is not essential. Bower and Wishart (1972) found that infants search and make contact in the dark with objects that are suddenly made invisible. However, a problem could be that the infants were just flailing randomly in the dark (Harris, 1983; Hood & Willatts, 1986). Following up the idea, Perris and Clifton (1988) designed an experiment in
which infants reached in the dark towards a sounding object. Although this action did not require means-end behaviour, it did not resolve the question of what was guiding the reaching behaviour.

Clifton et al. (1991) pursued this question further by investigating whether 6.5-month-old infants adjust the opening of their hand to the size of the object being grasped. If infants reach towards objects of different sizes with the same hand aperture, it would indicate that they reach towards the sound itself or some non-specific object making the sound. However, the result showed differential reaching behaviour towards the differently sounding objects of different sizes, thus inferring that 6-month-old infants do form representations of the unseen object. Although the criticism has been raised that previous motor routines contaminate memory (Mandler, 1988), neither visual nor auditory experience or the experience of reaching and manipulating in the light before testing seems to be necessary for accurate reaching in the dark (Clifton, Perris, & McCall, 1999).

The reaching-in-the-dark studies seem to support the means-end explanation for the failure of reaching towards an occluded object. Infants cannot see the object when the light is extinguished and therefore a representation of the unseen object is necessary. The crucial point is that they can reach for the object directly without detouring or removing an obstacle, suggesting that the failures with occluded objects are based on a means-end deficit.

*Graded representation*

A somewhat different interpretation is that infants do have sufficient means-end abilities to retrieve an occluded object, but that the problem is related to the very nature of the infant’s representation of the occluded object, (Munakata, et al., 1997). Munakata et al., (1977) proposed that a concept of object representation is not a clear-cut one between having, or not having, a representation. Instead, they argued for a graded representation that strengthens over time. Munakata et al. started by exploring how the means-end deficit can account for an infant’s failure to retrieve occluded objects. Two experiments contrasting two types of conditions for which the means-end ability is required for success were considered to be identically demanding (means-end demand equated). First, Munakata et al. trained infants to retrieve toys by means of pulling a blanket or pressing a button (which caused
a platform on which an object was placed to collapse and the object to slide
down a ramp to the infant). Directly after the training session, infants received
a succession of trials in which either the object or the empty stage was
covered by an opaque or transparent occluder. Infants exhibited more toy-
retrieval in the transparent conditions when the toy was present compared to
trials when it was located behind the opaque occluder. This result shows that
infants can perform different search patterns depending on the conditions.

Munakata et al. held that an infant’s behaviour is not based on a means-
end deficit. The infants failed to retrieve the object although it was evident that
the behaviour was not the problem. They proposed that the failure in the
opaque screen conditions could be explained by a weak representation, i.e.,
lacking the strength to drive and direct appropriate actions. This would in turn
explain why infants understand the existence of a hidden object when only
required to observe an event. Thus, when the representation becomes
stronger, they will be capable of driving the appropriate behaviour.

This approach considers the infants’ object representation as being
graded, evolving with experience and becoming embedded in processes
underlying overt behaviour. Munakata et al. suggested that the ability to form
representations of occluded objects depends on a process of strengthening
neuronal connections. The strengthening process leads, through experience,
so a stronger representation of the occluded object. In particular, a weak
representation cannot drive a manual retrieval action, but might be a sufficient
to guide behaviour during novelty preference tasks. Other studies in which
means-end demands are equated in both the transparent and opaque
conditions also challenge the means-end deficit explanation by showing that
retrieval is more frequent in the transparent condition (e.g., Bower & Wishart,
1972; Gratch, 1972). According to Munakata et al., their theoretical framework
is similar to the hierarchical model (Fisher & Bidell, 1991) and the dynamical
systems approach (Smith & Thelen, 1993; Thelen & Smith, 1994; Smith et al.,
1999). Smith et al. (1999) do not argue for a unitary or localized inhibitory
process but rather for a blend of parameters, which is crucially dependent on
the specific task input. They write:

”... the direction of reach is the blend of multiple directional input, the infant’s
current posture, direction of gaze, immediately preceding activity and longer
term experience in similar tasks” (Smith et al., 1999, p. 257).
Smith et al. (1999) explain infant performance in object retrieval (and A-not-B-error tasks) by a process of self-organization depending on the specific task and the individual’s history of perceiving and acting. In support of this idea, Tizer, Thelen, and Smith (1998, cited in Smith et al., 1999) gave 8-month-old infants transparent containers of various shapes to play with. Subsequent testing provided support for the idea that familiar perceptual cues pull the infant in the right direction, i.e., the infants who had played with the containers rapidly retrieved the objects from the transparent boxes. The similarity between the perspective of graded representation and the dynamical systems approach is that both emphasise the development of experience in a specific context, although Munakata et al. emphasise that representations develop through experience.

In Study III, the duration of occlusion and blackout was manipulated in order to investigate if infants are able to utilize the occluder edges in an optimal way, when the duration of non-visibility is increased. In the occlusion condition, participants were expected to simply move to the reappearance point as soon as the object disappeared. With blackout, there are no landmarks and it is only the reduced representation of the moving object that can guide the infant’s tracking behaviour. Thus, head tracking is expected to reduce with the duration of non-visibility and therefore a repeated experience with the same temporary visual absence of the object should strengthen the representation and improve the tracking. If the representation of the occluder interferes with the representation of the object, less reaching is expected when the visibility of the object is interrupted by an occluder compared to a period of blackout.

METHODS AND MATERIALS

This section summarizes the materials and methods used in the studies reported in this thesis. More detailed information is given within each individual study. Study II focused entirely on the development of software supporting a MicroTouch technology used in Study III, and is therefore excluded from this section, except for summarizing the participants.
**Participants**

The table below summarizes the participants in all studies. The parent(s) present during the experiment were all informed about the purpose of the experiment, before deciding whether or not to participate. The adults in Studies II and IV were informed in the same way. None of the participants declined to participate. All infants and adults were considered healthy and all infants were born full-term.

<table>
<thead>
<tr>
<th>Study</th>
<th>Ages</th>
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<td>8/8</td>
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<tr>
<td>III</td>
<td>6 months (24-26 weeks)</td>
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**Apparatus used in producing moving objects**

**Study I**

In Study I, a table was mounted onto a self-standing infant chair. A black and white coloured ball was initially positioned at the midline, 18 cm in front of the infant. The infants were placed in a specially designed chair equipped with a table on which a 50 mm diameter black and white (painted) soccer ball was positioned at the midline 18 cm in front of the infant. By means of two thin nylon strings (attached to each side of the ball and hanging over the side of the table), two 200 gr. weights were used to quickly move the ball in either the left or right direction. This was accomplished by simply lifting one weight, the weight on the opposite side pulling the ball 15 cm in the opposite direction.

**Study III**

In Study III, we used a computer-controlled plane plotter (Roland DPX-4600) in which the pen was replaced by a small magnet (von Hofsten et al., 1998). The plotting area was topped with a sheet of aluminium that was painted white, coated with a silicone lubricant, and placed in a supporting structure such that it tilted 15° forward from the vertical position. The
aluminium sheet served as the background for an object, which was supported by a 10-cm wooden dowel rod firmly attached to a second magnet. When the magnet on the object's supporting rod was placed on the aluminium sheet directly over the plotter magnet, the combined attraction held the object in place and caused it to undergo whatever motion was produced by the plotter. To achieve total darkness, two-photocell switches were used which could be activated and deactivated by the object’s movement.

**Study IV**

In Study IV, we constructed a vertically positioned board producing circular motions. Directly behind the board, an electrically powered engine with a mechanical arm was mounted and used to produce the circular motion. The mechanical arm had an adjustable magnet (sliding on the arm) allowing a change in the diameter of the object’s motion. A laminated square shaped, wooden board (72 x 72 cm), surrounded by an wooden frame served as a background for the objects and was held vertically by a supporting structure in front of the mechanical arm. In turn, a magnet was placed directly over the adjustable magnet with the combined attraction holding the two magnets together. Replaceable painted table tennis balls, 3.74 cm in diameter, served as the objects in this Study. The balls had a small bell attached that sounded when taken down and became silent when they were put back on the magnet.

**Apparatus and methods for analysing motor performance**

**Study I**

Study I used the SELSPOT II system (Selspot AB, Möndal, Sweden) as the means for analysing reaching towards an object that suddenly changes position. The SELSPOT II system is an optoelectronic device that is used for measuring three-dimensional movement parameters in space, including duration, latency, velocity and acceleration. The SELSPOT system has been used in a wide range of areas e.g., an examination of the Moro response in newborn infants (Rönnqvist, 1995); reaching to targets at different locations (Alstermark, Isa, Lundberg, Pettersson & Tantisira, 1993); quantification of
hind limb lameness in the horse, (Buchner, Kastner, Girtler & Knezevic, 1993); coupling of arm and finger movements during prehension (Paulignan et al., 1991).

The system we used in Study I included two cameras (up to 16 are possible), and gives two-dimensional information, later converted to three-dimension positional data. Five light emitting diodes (LEDs), 4 mm in diameter and two cameras equipped with optoelectronic plates were used to record the infants’ movements. The two LEDs were used to monitor head movements, one was placed on the forehead and the other 4 cm further back in the sagittal direction. Two LEDs monitored the reaching movements and were placed on the back of each hand. Finally one LED was placed on the ball. A video camera recorded the whole experiment and was also used in the analysis of grasping the target.

The SELSPOT system uses markers with an active infrared light identified by their firing sequence. It provides a high-resolution measurement combined with high accuracy. It can sample up to 10,000 frames per second (depending on the number of markers) with a resolution of 1:4000 (see Samuelson, Wangenheim and Wos, 1987, for review). The advantages of SELSPOT II are its high resolution and accuracy that generates a precise data pattern of the measured movement. The main problems with the SELSPOT system are the risks of reflection from light sources other than the markers, maintaining visibility for the cameras, cable attachments that can become unattached and which might interfere and restrict movement (Sandström, Bäckström and Olsson, 1995). In addition, the timing of the data collection and the participant’s movements are crucial, especially as infants can behave somewhat unpredictably. All trials during Study I were recorded on video, which made it easier to interpret the SELSPOT data. For instance, the video recording could provide information about data that seemed unusual and whether the movements were spontaneous or related to the experimental task.

Study III

Study III used two infrared cameras for recording of the infants' movements. One camera provided an overhead view and the other a side view. The two images were mixed onto a single video record, which was later used for the coding of head movements and reaching. Reaching was
analysed by defining an area around the object during a specific time-interval, during which time the hand had to be within the defined area. For analysing the head movements, we used a MicroTouch monitor equipped with a special light pointer. By simply pointing on the monitor, we were able to extract the X and Y coordinates that were later used to compute the changes in head angle (see also Study III).

Study IV

Study IV used the ProReflex system (mcu 1000, Qualisys AB, Sweden) in order to analyse the head and trunk movements. ProReflex is a digital motion system and utilizes digital image processing technology. An infrared light is emitted in short pulses with a frequency of up to 1000 Hz with a resolution of 1:60000. The light is produced by one or several Motion Capture Units (camera of the size of a camcorder) and the light is then reflected back from passive markers that have been attached to the participants. This enables the marker’s position and size to be analysed in every camera with a high resolution and accuracy. ProRelex and its precursor (MacReflex) have been used in several studies of both humans and animals e.g., chewing movements in TMD patients and a control group before and after use of stabilisation splints (Soboleva, Jokstad, Eckersberg & Dahl, 1998); the influence of the force applied and its period of application on the outcome of the flexion test of the distal forelimb of the horse (Keg, van Weeren, Back & Barneveld, 1997). In study IV, the movements of passive markers affixed to the head of the participant were recorded by a six-camera ProReflex (Qualisys Inc., Sweden) at 240 Hz. In addition, a video camera with two monitors recorded all experimental sessions. One monitor enabled the experimenter to observe the infant, but also to have the possibility of checking back if and when questions arose during the analysis of the Pro-Reflex data. The video recordings could, for instance, tell us if the infants were looking away from the object during some of the recording intervals. The second monitor was placed outside the area surrounding the participant so that the parents and the person who was following the ProReflex recordings on a computer screen were able to observe the infant or adult participants.

The advantages of the ProReflex system are its high resolution and accuracy. In addition, the cameras, in comparison to its predecessors MacReflex and SELSPOT, are relatively easy to calibrate. The disadvantage
is essentially the same as in the SELSPOT system, except that that passive markers are used and thus no cables are attached to the markers. All trials during Study IV were recorded on video for the same reasons as in Study I

SUMMARIES OF THE STUDIES

This section presents a summary for each study in the present thesis. Study I investigated the coordination between head turning, reaching and grasping in 9-month-old infants. The questions as to how this coupling was affected when objects moving on a predictable trajectory were made temporarily non-visible were addressed in Study III, as was the question of the nature of the infants’ representation of non-visible objects. Study II described and evaluated a system for coding and measuring movements based on video recordings, a system explicitly developed for study III. In Study III, only a simple linear motion was used. However, as yet there are few studies relating to an infant’s ability to comprehend and negotiate different kinds of object motion. Study IV therefore aimed to identify age differences (6 and 12-month-old infants) in the head tracking of a circular object motion presented in a vertical plane.

Study I (Savelsbergh, von Hofsten & Jonsson, 1997)

Study I investigated the coordination between head turning, reaching and grasping in 9-month-old infants. The main purpose of the study was to examine how the behaviour of nine-month-old infants was affected by the perturbation of target location during a reaching task. The methodology of reaching for a suddenly displaced object in order to perturb the transport component was proposed by Paulignan et al. (1991). We asked whether an infant at this age is able to plan a second approach to the perturbed target whilst the first is underway or whether they have to finish the first approach before starting the second one. The second question asked was whether the transport and grasp component is sequentially organised. The underlying assumption was that a perturbation of the target location would not affect the quality of grasp towards the relocated target. In other words, the second approach would be a new reach to the relocated target and subsequently would not affect the quality of the grasp. The third question was related to the coordination of head and arm movements: how well are head and reaching
movements coordinated at this age during a task of reaching towards a suddenly relocated target? A high correlation of the latency between the head and arm movements would, according to Jeannerod (1988), correspond to more experience, whilst a low correlation would reflect the opposite. The final aim of this study was to examine the coupling between head and arm movements by comparing the corrective features of onset time and peak velocity time after perturbation. Sixteen 9-month-old infants, 8 girls and 8 boys participated in the experiment. The analysis of the correction time between head and hand movements revealed a tight coupling between them as indicated by how tight these movements were.

It can be concluded from Study I that prehensile movements towards a suddenly relocated target in 9-month-old infants are at least partly integrated. The analyses of the transport component indicated that infants at this age do not control the reach visually on line, as shown by the similar temporal organisation of reach between the two movements and the doubled movement time. The way in which the perturbation affected the quality of grasp suggests that the approach and grasp components are at least partly integrated. Finally, the coupling between head and reaching movements seems to be organised as components of a unified system.

Study II (Jonsson & Noushandeh, 2000)

Study II developed a system for coding and measuring movements based on video recordings. The unit consisted of two computers, one with a MicroTouch screen equipped with TouchPen, and another to which the COM port for the MicroTouch was connected in order to receive information from each touch generated. The screens, being touch sensitive, allow the user to point using either a finger or a special light pen (Dix, Finlay, Abowd, & Beale, 1998). The MicroTouch monitor, together with the specifically developed software, made it possible to extract coordinates by simply pointing on the monitor using a light pen-pointer. For the video coding (see Study III) the system also included a video recorder connected to a TV-board mounted in a computer, which made it possible to display the recorded video sequences on the MicroTouch monitor. The coordinates from each touch were transferred to a computer and specially written software automatically saved them in a text-file format. The system provided a reasonably high level of reliability of approximately 0.5 millimetres validated against a SELSPOT system.
Correlations of 0.89 and 0.90 between the MicroTouch and the SELSPOT systems were obtained for the y and x coordinates, respectively. The main disadvantage is that the resolution is limited to 50 or 60 hz, depending on the video system used. Other disadvantages are the relatively low spatial resolution and the time-consuming nature of the coding procedure.

Study II also tested an alternative use for the system. Müller-Lyer illusions (Hochberg, 1971) of differing lengths were randomly presented on the MicroTouch screen in a horizontal position with either inward or outward arrowheads at each endpoint. After each presentation, four right-handed participants were asked to estimate the length of the horizontal line by pointing out (using the pen) the positions on the screen of the previously shown endpoints. Every touch generated coordinates as to where they actually touched and could be compared to the correct coordinates. The results showed that on average subjects estimated the horizontal line in a Müller-Lyer illusion with inward lines as being 10 millimetres shorter compared to one with outward lines. It was subsequently concluded that the illusion was sustained during a manual pointing task.

Study III (Jonsson & von Hofsten, 2001).

The aim of Study III was to examine the ability of 6-month-old infants to predict the reappearance of an object that temporarily moved out of view. This was investigated by studying two actions, head tracking and reaching. The underlying assumption was that infants have to form a dynamical representation of the moving object, and take into account the velocity and the direction of its motion. This ability includes maintaining a representation of the non-visible object and anticipating when and where it will reappear. In Study III, we proposed that young infants can form representations of both visible and hidden objects, and that their object representations are similar to those of adults in five respects. Firstly, representations of an object are more precise, at all ages, when the object is visible than when it is hidden. Secondly, representations of different objects compete with one another, the more one attends to one object in a scene, the less precise will be one’s representation of other objects. Thirdly, more precise representations are required for reaching than for head tracking: to reach for an object, one must know where it is, how big it is, what shape it is, and how it is moving. In contrast, less precise representations suffice to determine that a hidden object
exists behind a screen in a scene that one observes but does not manipulate. Fourthly, the representation of an object will degrade with time when it is in visually absent. Fifthly, the representation of a hidden object involved in a specific event is strengthened with experience with that event.

The study was run according to an ABBA design in which the first and last block consisted of 6 trials each with 12 trials in between during which the object was not visible. Sixty infants were randomly assigned to one of six conditions derived from the durations of non-visibility (400, 800 or 1200 ms) during occlusion (in which an occluder was interposed in between the object and the infant), or blackout (room lights were extinguished). The main focus of the study concerned the effects of differences in duration of non-visibility on reaching and head tracking. It was expected that both head tracking and reaching would deteriorate with decreases in the duration of non-visibility. With repeated trials, however, object representation should become stronger with reaching and head tracking showing signs of recovery. In contrast, there would be less recovery of reaching when the object was hidden by the occlusion of another object. Head tracking was precise in all the visible conditions and over time it became more predictive in all occlusion conditions. When the occlusion time was short, the infants anticipated object reappearance almost immediately. During prolonged occlusions, they anticipated the reappearance only after experiencing the event a few times. It was also shown that an occluder served to guide head tracking by providing information about an object’s reappearance.

Compared to tracking, reaching for moving objects requires more vivid dynamical representations because of the planning involved. To get to the vicinity of a moving object, the observer must time his reaching in a precise way. The infants did not do that to begin with, an outcome in accordance with the ‘graded representation’ hypothesis. However, there was a substantial recovery of reaching over trials for the two shorter durations in blackout conditions. Further support for this hypothesis was provided by the fact that the recovery was greater for the 400 ms than for the 800 ms blackout. At 1200 ms in this condition, reaching never recovered. In summary, these results confirm at least four of five predictions made by the ‘hypothesis of graded representations’.
Study IV (Jonsson, Rönnqvist & Domellöf, 2001).

Most studies of infant tracking have concentrated on simple horizontal or vertical linear motions. A prediction of linear motion only requires information from the immediately viewed position. The world, however, is not that simply organised and thus this study incorporated a circular object motion presented in a vertical plane. The key features of such a motion are that it is both simple and complex. The simplicity is characterized by its repetitive displacement (the object always returns to its original position), a predictability that facilitates tracking and makes it easier for the observer to anticipate the object's future position. The complexity involves two time scales: the motion of a revolving object can, locally, be considered as uniform without rotation, and globally, as being essentially rotational (Price & Gilden, 2000). This is in contrast to tracking a simple linear motion in which the previously adjacent position relative to the present position (the motion's local characteristics) is enough to completely specify the object's future position. However, the information extracted for both types of motion needs to be precise in order to specify the object's future position and the subsequent guidance of action.

In Study IV, we explored how head movements are organized in order to track an object moving on a circular trajectory. Earlier studies have found evidence that the development of successful reaching (von Hofsten & Lindhagen, 1979; von Hofsten, 1991) and the spontaneous arm movement (von Hofsten & Rönnqvist, 1993) of newborns can be described according to an organizational pattern of accelerations and decelerations, or so-called movement units. These findings led us to raise the question as to whether other behaviours in young infants are organized in a similar way. Also included were, for example, the cumulative distance covered by the head, a segmental analysis of both the head and trunk movements and measures of the relationship between trunk and head control. Finally, we also included an adult group in order to establish the developmental criteria for normal tracking behaviour and its organizational characteristics.

What are the differences between 6- and 12-month-old infants regarding the organization of head movements and how are head and trunk movements organized and related to each other during tracking of a circularly moving object. These questions were asked in relation to two groups of infants and one group of adults.
Eleven infants and six adults participated in this study. The infants were divided into two age groups, one consisting of six 6-month-old infants and the other of five 12–month-olds. The participants were presented with a circular moving object on a vertical flat surface. The objects (painted table tennis balls) always started their motion at the circles' highest position and were randomly presented in either a clock-wise or counter clock-wise order across two blocks of six trials. Head tracking was functional even in 6-month-old infants, but it continued to change further up to and beyond the age of 12 months. The differential effects were especially pronounced during head tracking in the vertical direction.

Another interesting finding was that older infants moved their trunks more smoothly than their younger counterparts as indicated by fewer trunk movements and a smaller number of movements units. The segmentation into movement units seems to be a fundamental function across ages and not affected by the level of skill, a finding in line with earlier studies of both goal-directed (von Hofsten 1991) and spontaneous arm movements (von Hofsten & Rönnqvist, 1993). In addition, it was found that the trajectory within such units shows a sharp increase in straightness between 6 and 12 month-olds, indicating that mature tracking of circular object motion not only consists of relatively small phases of acceleration and deceleration, but also of trajectories within these units that are rather straight. The straightening within movement units will enable head tracking to become energetically less demanding. Apart from improvements in postural control, another possible explanation is that prospective head tracking is acquired with age, and thus, take into account the global characteristics of the moving object. This in turn enables straighter trajectories within movements units as the infant now can take “shorthcuts” and, thus, are probably less stimulus driven.

Further discussions were related to the coordination of muscles responsible for head turning. Thus, the question of how the trapezius and sternocleidomastoid muscles are coordinated to achieve successful head tracking of a circular object motion was raised.

GENERAL CONCLUSIONS AND FUTURE DIRECTIONS

Prospective control was viewed as being involved in a range of abilities, varying from perceiving and analysing both simple and more complex motions
to the prehension of moving and perturbed objects. Similarly, the involvement of object representation ranged from perception as revealed by looking time methods during partial and complete occlusion, to the level of prehensile abilities required for the retrieval of temporarily occluded and moving objects. In this section, I will try to pinpoint how prospective control and object representation relate to the empirical studies in the thesis. Subsequently, I will present an ongoing study by Munakata, Spelke, Jonsson, von Hofsten and O’Reilley (2001), which provides further evidence for the hypothesis of graded representations. Finally, I will briefly discuss what the present studies suggest about future directions of research concerning the development of predictive actions.

**Prospective control**

Study I addressed the issue of how prehension was affected when a visible target was perturbed during reaches made by 9-month-old infants. With regard to prehension, the grasp component was initiated during the reach when the object was suddenly perturbed. As for the relationship between head and hand movements, the main finding was that while correction times for both head and hand were mainly between 300 to 1000 ms., most of the differences between them only varied from 100 to 200 ms. This tightness of coupling between head and hand movements shows that they function as part of a unified system which does not operate on an ad hoc basis as reaching would then be more discontinuous and jerky (von Hofsten, 1994). On the contrary, in order to adjust for the mechanical lag, the maintenance of a continuous coupling between head and hand depends on the infant being able to control actions in a prospective manner.

The question as to how prospective control is affected when an object moving on a predictable trajectory is made temporarily non-visible was addressed in Study III. The prospective ability to foresee an upcoming event, the reappearance of an object that had temporarily moved out of view, was used as the indicator of whether or not there was a representation of the non-visible object. Evidence for this ability was sought in two different actions, namely, head tracking and reaching. It was shown that, over time, head tracking was performed in a predictive manner in all occlusion conditions and
the occluder provided perceptual support for head tracking and made it easier to conceptualise the object and its motion.

Having demonstrated in Study III that head tracking and reaching for moving objects in 6-month-old infants is guided by a linear extrapolation, the question of how infants dealt with other kinds of motions was considered. In Study IV, infants of 6 and 12 months of age were confronted with the task of head tracking a circular object motion presented in a vertical plane. Such a motion is both simple and complex in that it contains both global and local features. The results from Study IV showed that the prospective control required in order to specify the object’s future position and to achieve the requisite degree of tracking was less precise for the infants and in particular for the 6-month-olds. It was also shown that smoother and more controllable head movements are accompanied by increasingly straighter trajectories and shorter distances within each movement unit. The straightness within movement units for 12-month-old infant head tracking was similar to adults in this regard.

Object representation

Study III confirmed all four out of five predictions made by the ‘graded representation’ hypothesis. It was shown that 6-month-old infants have an ability to maintain a representation in that they were able to adjust their head tracking to increased angular velocity during the period of non-visibility. A less vivid representation of the object motion might make the tracking velocity converge on a value similar to the angular velocity at disappearance and consequently lag behind the reappearing object. There was a marked decline in predictive reaching for the early trials involving non-visibility, both in the occlusion and the blackout conditions. However, predictive reaching had a tendency to recover at the later non-visible trials, with the most pronounced recovery observed for the 400 ms and 800 ms blackout conditions. The notable decrease in reaching indicates that this action requires a more salient representation compared to head tracking. In support of the hypothesis of “graded representation”, it was shown that recovery was greater for the 400 ms than for the 800 ms durations of non-visibility during the blackout conditions.
The ability to understand how moving objects will behave in the near future is an ability that emerges early in infancy (von Hofsten & Rosander, 1977). When an object disappears, the prediction must be made across time and space and not only requires a maintained representation of the object’s existence, but also a representation of its future position. The ability to perceive the motion of the future position is dependent on an understanding of certain rules by which objects move. In Study III, only a simple linear motion was used following the rule of inertia, which holds that in the absence of forces acting upon the object, it will maintain its speed and direction of motion. In Study IV, the increased complexity of the presented motion, characterized by the global-local distinction and a minimal expansion pattern, suggested that the representation of the object’s motion was not as precise in the 6-month-old infants compared with the 12 month-olds. Although Study IV does not inform us how the representation would be maintained during occlusion, it does indicate that a representation can depend not only on the type of non-visibility (Study III) but also on the sort of motion that is presented.

Recent studies by Cashon and Cohen, (2000) and Bogart et al. (2000) suggest that the responses infants have displayed in what are termed ‘violation of expectation’ experiments (e.g. Baillargeon, et al., 1985) may depend on declining perceptual information such as familiarity and response to novelty. However, there is still a substantial amount of evidence that some kind of object representation is developed already in young infants (e.g. Baillargeon, 1993; Kellman & Spelke, 1983; Slater, et al., 1990; Clifton et al., 1991).

Why then is it that infants fail to reach and retrieve hidden objects? This lag in time between the acquisition of object representation and the resolution of the A-not-B error does not seem to depend on a motor problem, as by 6 months of age, infants have sufficient manual dexterity to remove an occluder or reach around it (von Hofsten, 1989). The hypothesis of graded representations is a plausible explanation in that the interference from the visible occluder makes the representation more fragile compared to the condition of darkness in which no such interference is present. Another possible explanation offered by Spelke, Vishton and von Hofsten (1995) is that the representational system, which guides infant actions on objects, is distinct from the representational system underlying object recognition, which is different again from adults for whom the systems may work together.
The empiricist-nativist debate about if, how early and how much 'core knowledge' (Spelke, 1994, 1998) is necessary in order to make a system work properly will certainly continue. It seems possible, however, that there are at least some abilities that are already present at birth. One piece of evidence comes surprisingly not from infant studies, but from comparative studies of vertebrates, or to be more specific, newborn chicks. Regolin and Vallortigara (1995) used an imprinting method in which triangles were presented as being visible from a central position and never occluded by another object. After two days, the chicks had developed imprinting towards the fully visible triangle, controlled by a proximity measurement in a novel environment together with a novel object. When presented with a centrally occluded and coherent triangle together with a fully visible but non-coherent triangle, the chicks showed imprinting towards the occluded triangle. Spelke (1998) argues that this provides evidence that chicks perceive the occluded triangle as connected and therefore that some mechanisms for representing partly occluded objects are ‘innate’ in chicks. If there is an ‘innate’ mechanism with some sort of representation in vertebrates, then it is more than likely that human newborns are equipped with some sort of initial ‘understanding’ of non-visible objects as being more plausible.

**Future directions**

*Combining occlusion and blackout (ongoing study)*

An ongoing study by Munakata, Spelke, Jonsson, von Hofsten and O’Reilley (2001) is investigating how infants’ (39 so far) representation of a hidden object is preserved during different conditions of non-visibility. Six-month-old infants are presented with a moving object at a visible position far beyond reach. The object then moves on a horizontal trajectory and passes the infant at the height of the nose. During its motion the object becomes temporarily non-visible either by occlusion (in which an occluder is interposed in between the object and the infant), blackout (lights were extinguished), or a combination of blackout and occlusion. According to the thesis of graded representations (see also study III), the infant’s action is guided by object representation in both the looking and reaching contexts, which vary in strength depending on the environmental context. In addition, external objects
can interfere with one another, resulting in a weakened representation. The prediction from the graded representation thesis is that turning off the room light when the object becomes occluded would result in a decreasing interference from the occluder. This prediction is currently being tested in 6-month-old infants.

The experiment is being run according to an ABBA design in which the first and last block consists of six visible trials (as in study III). In between the trials, a period of non-visibility is introduced, always 0.5 sec in duration, ending just before the object moves within reaching distance. The non-visible trials are presented in two blocks of six. In each type of trial, the object is hidden for approximately for 0.5 sec. The objects are hidden either by an occluder, by the blackout of the room lights or by a combined occluder/blackout condition in which the occlusion is accompanied by a blackout of room lights.

The equipment for stimulus presentation was identical to the one described in study III. Coding was achieved by placing the cursor on the appropriate position (i.e., infant’s index finger or markers on the infant’s head), pressing return caused the program to store the X and Y coordinates. The position of each hand in three-dimensional space was reconstructed for the analysis of reaching. Head tracking was analysed by computing the changes in head angle.

The experimental findings from the first 39 infants support the prediction from the graded representations thesis. In the case of head tracking during occluder and occluder/blackout conditions, the smooth tracking is replaced by a behaviour that can be characterised by ‘jumping’ ahead of the toy, suggesting (as in study III) that the infants used the occluder boundaries as landmarks to anticipate where the object should reappear. In the blackout condition the behaviour is somewhat different. The infants continue to move the head in the direction of the moving object, but at a slower rate, resulting in a lag when the object reappears. In other words, blackout and occlusion/blackout conditions have the opposite effect on the timing of head tracking. However, the strongest evidence comes from the finding that reaching improves in frequency in the occlusion/blackout condition, compared to the occluder condition, suggesting that the induced blackout removes the visual conflict between the object and occluder and consequently strengthens the representation.
Why is it then that reaching for a temporarily invisible object is disrupted in the occlusion condition whilst head tracking is enhanced in the same condition as well as in the occlusion/blackout condition? According to the hypothesis of graded representation (Munakata et al., 1997) this dissociation is explained in terms of a more salient representation being required for reaching than for head tracking. A more salient representation is required to drive reaching than to drive visual tracking. The recovery of a reach in the occlusion/blackout condition supports the hypothesis that the representation of the seen occluder interferes with the representation of the unseen object behind it. Another possible explanation is that the infants simply forget the object. However, the head tracking behaviour found does not support this possibility.

Questions about predictive reaching and tracking that involve circular object motion and both occlusion and blackout also warrant further investigation. For instance, how is reaching affected when presented with a circular object motion? In some reaching studies, infants were confronted with a semi-circular moving object in the horizontal plane and they conducted the reach prospectively so that they were able to prehend it successfully (von Hofsten & Lindhagen, 1979; von Hofsten, 1983. Prehending a moving object with a hand requires a greater degree of prospective control than just looking at it. Circular object motion presented as either moving in a horizontal or vertical plane appears to have the same objective displacement. However, the proximal information originating from the movement of an object in the horizontal plane and viewed at about the line of sight contains both a revolution and an expansion pattern.

The pattern of expansion conveys time-to-contact information at least up to the point after the rate of dilation begins to decrease. In contrast, the proximal information available from a vertically presented, circular motion of the object is viewed more or less orthogonal to the line of sight. In this condition, the object projects a revolutionary motion on the retina with minimal optical expansion. It should also be borne in mind that the object as presented in study IV had no internal frame of reference, while in the study of von Hofsten & Lindhagen (1979), for example, such a feature was present. This was the case as the object was mounted on the end of a rod, which was attached to the shaft of an electrical motor that rotated the object around its axis. On the basis of these contrasts concerning object motion, the fact of whether or not there
was a distinct local environment through the object moved pinpointed a rationale for future research. For example, are there age differences in how infants organize their prehensile movements when faced with an object displacement along a circular trajectory? And what happens to their reaching and grasping when a circular object motion is combined with a temporary occlusion at a different point on the trajectory? Does providing patterned or textured information on the background over which an object is moving enhance reaching or grasping for both for younger as well as other infants? Other questions to address are how the integration between tracking and reaching is affected and how infants act if the circularly moving object is subject to occlusion or blackout conditions. Derived from the hypothesis of graded representations, reaching should be much more depressed in an occluder rather than a blackout condition. Thus, if the representation of the seen occluder interferes with and dominates that of the unseen circular moving object, the representation of the occluded object will be less precise. This outcome would not pertain in a blackout condition for which no visual conflict is present when the object is hidden in the dark. However, the critical question is whether the features of circular object motion will affect the behaviour in a unique way.

Another question to pursue is how eye movements (both saccades and smooth tracking) in relation to head movements are organised when tracking a circular object motion presented in a vertical plane. The different sets of extraocular muscles responsible for horizontal and vertical eye movements and the different underlying neural circuits controlling these eye movements need to adjust to the reciprocal coordination between head and eyes.


