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Infants' Knowledge of Occluded  
Objects:  
Evidence of Early Spatiotemporal  
Representations

BY

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**Abstract**

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This thesis demonstrates that infants represent temporarily non-visible, or occluded, objects. From 4 months of age, infants could accurately predict the reappearance of a moving object after 660 ms of non visibility; indicating accurate spatiotemporal representations. At this age predictions were dominated by associations between specific events and outcomes (associative rules). Between 6 and 8 months of age predictions became dominated by extrapolations (Study III). From 6 months infants could represent occluded objects for up to 4 seconds. The number of successful predictions decreased, however, if the information contained in the occlusion event diminished (time of accretion and deletion). As infants grew older (up to 12 months) they produced more accurate predictions. (Study II). The similarities between adult and infant performances were numerous (Study I). These conclusion are based on one cross sectional (Study I) and two longitudinal studies (Study II & III) in which an object, a 'happy face', moved on circular (Study I, II, & III) and other complex trajectories (Study III). One portion of each trajectory was covered by a screen that blocked the object from sight. In each study participants gaze were recorded with an infrared eye tracking system (ASL 504) and a magnetic head tracker (Flock of Birds). This data was combined with data from the stimulus and stored for of line analysis.

*Keywords:* infants, occlusion, gaze, object representations, temporal, spatial, associative rule, extrapolation

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## List of Papers

This thesis is based on the following papers, which will be referred to in the text by their Roman numerals:

- I Gredebäck, G., von Hofsten, C., & Boudreau, J. P. (2002). Infants' visual tracking of continuous circular motion under conditions of occlusion and non-occlusion. *Infant Behavior and Development*, 25, 161-182.
- II Gredebäck, G., & von Hofsten, C. (in press). Infants' evolving representations of occlusion. A longitudinal study of 6 to 12 month-old infants. *Infancy*.
- III Gredebäck, G., & Kochukhova, O. (2004). Spatial representation during occlusion. Manuscript submitted for publication. Department of Psychology, Uppsala University, Sweden.



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# Introduction

Actions are intentional and oriented into the future. This is true for playing tennis and climbing rocks but also for everyday activities such as reaching for a container of milk or driving a car. In these tasks it is essential to overcome the time lag inherent in all behavior. This includes the time consumed by information processing of the central nervous system and mechanical constraints of muscles and joints. In addition, every movement made has to be counteracted by equal forces in the opposite direction to keep equilibrium and maintain balance. Life without future oriented actions is hard to imagine. Without these abilities we would not only miss every incoming ball during a tennis match but in addition each arm extension would offset our balance and make us fall flat on our face.

Luckily for us, evolution has provided a solution to the problem of prospective control; a tight coupling between action, perception, and cognition. It is our own actions that provide the basis for perception and allow learning to occur. Perception on the other hand provides the only window through which unexpected events, and the outcome of our actions, can be detected and evaluated. This interaction combined with a never quenching desire to explore provides a large portion of the foundation on which development rests.

‘...the perception-action relation is a reciprocal one, a kind of continuous cycle with perception guiding action, and actions furnishing new information for perception – information about the animal itself, its own dimensional and dynamic properties, and about the environmental consequences of its own actions .... actions even in the simplest, is always organized, related to what is going on in the rest of the body, potentially flexible, nearly always intentional, and frequently anticipatory, in the sense of preparing for later action.’ (Gibson & Pick, 2000, p. 22-23).

Cognition works in this context; it is bound and framed by performed actions and perception, by experience and memory. Ecologically relevant cognitive solutions are as such grounded in the soil of real world problems. By these interacting systems we are able to interrelate with the environment, form expectations about upcoming events, and assess earlier experience. Combined, these systems are constructed to deal with goal directed voluntary actions that are intentional, prospectively controlled, and directed towards the environment.

So what are the origins of actions? Are we born with an inherent intentionality and a preference for prospective control? In a series of reaching studies Claes von Hofsten (1982) was able to demonstrate that newborn infants direct their arm movements towards bright moving objects. Even though their reaches were highly inaccurate more extended arm movements were performed when infants attended to the object than when it was absent. It has also been demonstrated that neonates use proprioceptive information to guide the hand towards the mouth. During these arm movements the mouth was far more likely to be open if the hand approached the mouth than if the hand ended up touching another part of the face (Butterworth, 1986). Another example comes from van der Meer, van der Weel, and Lee (1995). In their study infants were either allowed to view their own hand in real life or on a video screen. When a small pressure was applied to the hand (pressing it out of view towards their feet) infants resisted. This tendency was only observed if visibility of the hand was threatened, not during complete darkness.

In these examples actions are goal directed and future oriented from start. If the opposite was true infants would open their mouth as a reaction to the hand touching the mouth not in anticipation of the same event. That successful reaching for stationary objects co-occurs with the onset of successful catching further strengthens this argument. These abilities appear between 4 and 5 months of age. At this time infants reach reliably for stationary and moving objects alike. Reaching for moving objects has been demonstrated with velocities up to 30 degrees/s (von Hofsten & Lindhagen, 1979). In all above mentioned examples prospective control develops ahead of (or simultaneously with) manual skills.

This is not always the case, often motor behaviors can be elicited prior to fully functioning prospective control. These early actions are highly inaccurate and are often followed by a rapid increase in precision, fueled by an emerging prospective ability. One clear example can be found in the development of gaze tracking. At birth gaze tracking is primarily composed of saccades (Aslin, 1986). This means that newborns have the ability to swiftly relocate gaze to new areas of interest. The amplitudes of these saccades are often too small to reach the target (hypometric saccades). To compensate for this multiple saccades have to be initiated to reach a preferred location (Aslin & Salapatek, 1975). With increased age the numbers of saccades decrease at the same time as precision increase (Rosander & von Hofsten, 2002).

During these first few months of life infants experience a rapid development of smooth pursuit (SP); the ability to continuously track small targets (von Hofsten, 2004). Already at 2 to 3 month of age, infants have developed the ability to predictively track a horizontally moving sinusoidal trajectory (the target decelerates before it turns and then accelerates to reach full velocity halfway between the turning points). An

additional two months will be needed before infants predicatively track oscillating constant velocity trajectories (called triangular motions). This difference is presumed to depend on the input needed to form accurate predictions. During sinusoidal tracking only local information is needed to estimate the turning point of the target. If the target, on the other hand, moves at a constant velocity its turning must be predicted with the help of more global experiences; a representation of the entire trajectory. (von Hofsten & Rosander, 1997).

The intention of this thesis is to further explore the development of predictive abilities using a setting that maximizes the mutual dependency of perception, action, and cognition. In every day life perceived objects often become occluded by other parts of the scenery. This might happen while observing a bird that flies behind a tree in the foreground. It might also occur during active goal oriented actions; when visibility of a thrown ball is blocked by the catchers arm. In both of these situations it is important to represent the tracked object independent of temporary interruptions in visibility.

As adults such tasks are seldom problematic. We are able to comprehend the continued existence of the bird and the ball; neither fall out of conscience. In an attempt to experimentally examine adults' perception of occluded objects Burke (1952) asked adults to draw the trajectory of a moving object after having observed it move through a tunnel. He reported that 'practically all the observers trace the path of the movement as if there were no tunnel' (p. 137). Young infants do not find such tasks easy, instead performance is highly variable and task dependent (Beer, 2000).

More specifically, this thesis aims to answer questions related to the development of object representations during occlusion. Special attention is focused on spatial and temporal representations of occluded objects. The various forms of representations investigated are all operationalized through differences in success rate and accuracy of successful predictions during gaze tracking of occluded targets. The question is; to what extent can infants successfully predict when and where moving objects will reappear after an occlusion event?

## Introducing Occlusion

Piaget (1954) was the first to direct attention to infants emerging object representations. According to his observations infants acquire progressively more sophisticated knowledge of the workings of the world through active exploration. This process is restrained by, and dependent on, the sensory-motor development. To investigate how infants enlarge their understanding of hidden objects Piaget played different games

with his children. During their play a toy was covered by a cloth. Below 8 months of age his children made no attempts to remove the cloth and retrieve the toy. Based on this observation Piaget argued that infants are unable to represent non-visible objects as independent units until they reached 8 months of age. However, those infants who did reach (8 months and older) were often unable to redirect their reach if the toy was hidden at a second location; still directing their reach to the first hiding location. Piaget called this the A, not B error (hereafter A, -B) and it has been used in numerous studies since this time (Mareschal, 2000). As infants grow older this error diminishes and disappears, at 12 months infants generally move to the correct location. One illustrative example of this phenomenon was provided by Piaget during an observation of his son Laurent at 9 months and 17 days of age.

‘Laurent is placed on a sofa between a coverlet (*A*) on the right and a wool garment (*B*) on the left. I place my watch under *A*; he gently raises the coverlet, perceiving part of the object, uncovers it, and grasps it. The same thing happens a second and a third time.... I then place the watch under *B*; Laurent watches this maneuver attentively, but at the moment the watch has disappeared under *B*, he turns back toward *A* and searches for the object under that screen. I again place the watch under *B*; he again searches for it under *A*.... ‘ (Phillips, 1969, p. 28).<sup>1</sup>

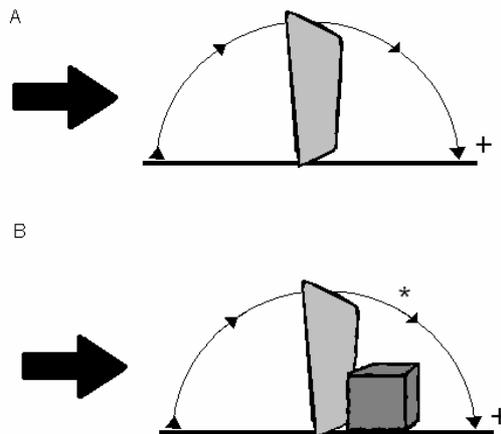
The theories of Piaget reached a wide audience. However, during the last 15 years several studies have questioned whether Piaget’s description of the developmental process is accurate, especially with respect to object representations (Mareschal, 2000). Much of the early critique originates from a preferential looking paradigm. Within this research tradition each experiment starts with a presentation of a normal situation such as an occlusion event. After infants have habituated to this event they are presented with one of two additional situations. One is consistent with the phenomenon being examined (called possible event) and the other involves a violation of this phenomenon (called impossible event). During such violation-of-expectation studies infants looking times to each display is measured. If infants look longer at the unexpected event they are assumed to perceive the violation, and be surprised at this effect.

According to Baillargeon and co-workers this surprise is based on the very same cognitive functions that are used to evaluate and act towards objects and situations external to the test situation (Baillargeon & Wang, 2002). In one such study (Baillargeon, 1987) 3.5 and 4.5 month-old infants were habituated to the rotation of a solid screen that moved back and

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<sup>1</sup> Original quote appeared in *The Construction of Reality in the Child*, translated by Margaret Cook, New York: Basic Books, Inc., 1954, p. 53 (Original French edition, 1937).

forth like a drawbridge (see Figure 1). After habituation infants were presented with a box placed in full view behind the lowered screen. On consecutive trials the drawbridge again started moving back and forth. Either stopping at the box (possible event) or continuing through the place where the box was last seen (impossible event). At both age groups infants looked reliably longer at the impossible event. According to Baillargeon this meant that infants continued to represent the box while the drawbridge hid it from sight and expressed surprise when the drawbridge went straight through its place.



**Figure 1.** During the baseline (A) the infant watches the screen rotate backwards until horizontal (+). On subsequent trials (B) the screen either stops at the box (\*) or rotates through this location to the same location as during baseline (+). The large arrows indicate the direction of infants' gaze.

Using the same methodology Baillargeon and co-workers have mapped out how infants' looking times are influenced by observing violations to numerous occlusion related events. According to Aguiar and Baillargeon (2002) 2.5 month-old infants have a simple comprehension of occlusion contra non-occlusion. This is based on experiments where 2.5 month-old infants increase their looking times when a moving object does not appear in an opening between two separate occluders (Aguilar & Baillargeon, 1999). One half-month later infants' act surprised if the target does not appear within a discontinuity of the lower edge of the occluder. Three and a half month-olds are sensitive to the height of a target relative to an occluder. At all three ages, baselines constitute a moving object that passes behind a single occluder (Baillargeon, 1999).

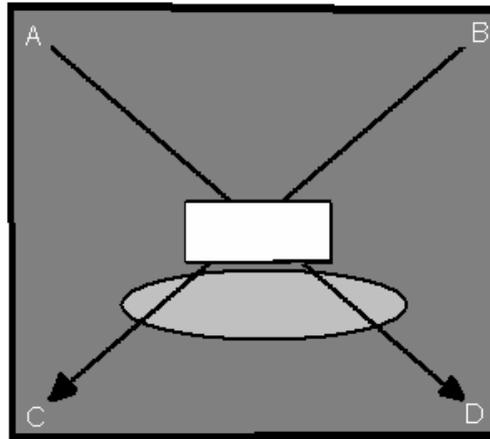
Using a similar design Spelke, Breinlinger, Macomber, and Jacobson (1992) investigated whether 4 month-old infants can comprehend the notion of contiguity, that is, whether infants understand that objects move on connected and unobstructed paths. In this study infants were

presented with a ball that moved downwards behind an occluder. After infants had habituated to this event one of two novel events were presented; both involved a ball being dropped behind an occluder. In one event the ball landed on a shelf (consistent with contiguity), on the other the ball transverse the shelf (inconsistent with contiguity). During consistent trials the ball appeared on the shelf and during inconsistent trials it appeared below the shelf once the occluder was removed. On each of three experiments infants looked reliably longer at the inconsistent event. This was interpreted as evidence of an early existing notion of contiguity. The same paper also looked at infants' abilities to reason according to the notion of gravity and inertia. The later term refers to an understanding that occluded objects continue on the same path as observed prior to occlusion. Neither of these notions appeared to guide infants preferential looking at 4 months of age.

In a study by von Hofsten and Lindhagen (1982) 4.5 month old infants were presented with a short occlusion duration (less than half a second). Either the same stimuli were presented to the infants both before and after occlusion or the identity of the stimuli changed during occlusion. Changes in the identity of the object were followed by a cardiac deceleration, whereas no changes were observed when the object remained unchanged. This was interpreted as an orientation response, and as such a sign of object permanence.

Another way to investigate infants' abilities to deal with occlusion events involve measuring the timing of infants' reaches and head tracking to moving objects. If infants systematically initiate object related reaches while the target is still behind the occluder infant must somehow represented the object and its reappearance.

This logic was adopted by two studies in which 6 month-old infants reached for a moving object (Spelke & von Hofsten, 2001; von Hofsten, Feng, & Spelke, 2000). In both studies infants were seated in front of a vertical sheath on which a toy moved on linear paths. Half of all trials started with the target moving from either of the upper edges of the screen, moving downwards on a diagonal path (linear trials). During others the toy started moving in the same manner but changed direction at the center of the screen; continuing downwards but reversing the horizontal direction (non-linear trials). In the intersection between these trajectories (the center of the screen) the toy became occluded (see Figure 2). This event hindered infants from perceiving whether the toy moved on a straight or turning trajectory. To predict its reappearance infants had to turn their head or reach to either the right or left side of the occluder (occlusion durations were 400 & 900 ms). Spelke and von Hofsten (2001) contrasted these occlusion events with fully visible trials.



**Figure 2.** Arrows and letters indicate the four trajectories used (A→D, B→C, A→C, B→D). The white square indicate the approximate location of the occluder while the light grey ellipse represent the optimal reaching space of infants.

The combined experience from these studies tell us that occlusion drastically decreased the number of performed reaches; from ~35 % reaches on fully visible trials to ~3% on occluded trials. A better estimate of performance was obtained from the head tracking. During the first occlusion event infants did not anticipate the reappearance of the toy. However, with experience infants rapidly predicted the reappearance on linear trials. Even non-linear trials were anticipated, but learning was much slower. This indicates that infants' predictions are originally based on inertia. They expected the toy to reappear along a linear continuum of the pre-occlusion trajectory. With massive experience the reliance on inertia could be inhibited in favor of recent outcomes.

Continuing this investigation Jonsson and von Hofsten (2003) measured infant's head tracking and reaching during occlusion and blackout. During these events a target moved on a straight horizontal path in front of the infants. Either the object was fully visible during the entire trajectory or it became invisible during a period just prior to the optimal reaching space. Three different occlusion durations were used in combination with two modes of non-visibility; either the object moved behind an occluder or the lights were turned off. In either case the object was invisible for 400, 800, or 1200 ms. Generally, infants' head tracking was more inhibited by blackout than by a visible occluder; the opposite effect was observed during reaching. No consistent effects of occlusion duration was observed during blackout, however during occlusions success rate (frequency of leads at first target reappearance) and size of the mean lead both increased with prolonged duration of non visibility. Reaching in the dark experiments have also demonstrated that six and a half month-old infants searched more often for a

toy in the dark compared to when it was visible but covered by a cloth (Shinsky & Munakata, 2003).

To summarize, research on object representations have demonstrated a high degree of context specificity. Dependent on the methodology used, infants appear sensitive to different aspects of the occlusion event. Infants display sensitivity to inertia whilst tracking occluded targets but they do not increase their looking times to inertia related violations. In this later paradigm infants appear more sensitive to violations of contiguity. Performance also depends on an interaction between type of non visibility and the response system chosen for investigation. Head tracking is affected to a lesser degree but an occlusion event, compared to blackout. Reaching displayed the opposite results. Similar discrepancies are found during the original A, -B task. Here the number of performed errors can be decreased by making the hiding locations more distinct. Furthermore, decreasing the delay between hiding and retrieval; motivating the infants by hiding cookies rather than toys; changing infants' posture between trials; or measuring looking rather than reaching are all factors that increase accurate performance and diminish the A, -B error. (Beer, 2000).

## Explaining Performance

With the revitalization of object representation research the number of interpretations and formal models directed at this developmental process have boomed. In the section to follow short summaries of the most influential explanations will be presented. All of these differ with respect to the source of infant knowledge. That is, whether development is founded on some innate knowledge structures (Nativism) or spurred from experience (Empiricism). These descriptions also differ in how development is described; either emphasizing what knowledge infants have acquired at a particular age or focusing on the underlying continuous developmental process. One theorist with strong opinions on both the nature of infants' knowledge and the developmental process was Piaget (1952).

According to him infants are born with a few reflexes and a motivation to learn. Comprehension of the world and prospective control both develop through action. In his view each infant progress through a number of fixed stages. At birth infants are equipped with pre-wired sensory motor mechanisms. Between 1 and 4 months infants are occupied with integrating these processes. Infants learn to combine sound, vision, and touch through experience. This process is labeled primary circular reactions because of the immediate relationship between sensory experience and motor behavior. At this age infants have no object permanence and representations fade once out of sight or touch. Between 4 and 8 months of age infants integrate new experiences with existing schemata (called

secondary circular reactions). It is at this age that the first signs of object permanence are visible. Infants can search for hidden objects for a brief period, the search is however restricted to the activated sensory modality; infants will look after seen objects and reach for touched toys. The reason why these infants are not thought to have object permanence is that they are unable to represent objects in a modality independent format. They are for example unable to reach for an occluded target that they have only seen, but never touched.

Not until after 9 months of age will infants begin separating means from ends and objects can be represented independently of the infants own actions. This stage involves coordination of secondary schemata and range from 8 – 12 months of age. Initially, 8 month-old infants lack the ability to represent objects independently of their own actions. This means that infants will reach for the location where hidden objects were last retrieved; producing the A, -B error. As experience accumulates infants become able to represent the existence of hidden objects independent of their own actions; the A, -B error disappears. The evolution of object representations is illustrated in the rather lengthy quote to follow. It starts when Laurent is 6 months of age;

‘I present Laurent with a match box, extending my other hand laterally to make an obstacle to his prehension. Laurent tries to pass over my hand or to the side, but he does not attempt to displace it.... Same reactions at age six months, eight days; six months, ten days; six months, twenty-one days; ... and seven months, ten days....

Finally, at seven months, thirteen days, Laurent reacts quite differently. I present a box above my obstacle hand, but behind it, so that he cannot reach the matches without setting the obstacle aside. After trying to take no notice of it, Laurent suddenly hits my obstacle hand as though to remove or lower it. I let him, and he grasps the box. I recommence to bar his passage, but I use as a screen a sufficiently supple cushion to keep the impression of the child’s gesture. Laurent tries to reach the box, and, bothered by the obstacle, he at once strikes it, definitely lowering it until the way is clear.

.... With Laurent aged seven months twenty-eight days, instead of simply hitting the things that intercede between his hand and the object, Laurent applies himself to pushing them away or even to displacing them.... I present him with a little bell 5 cm. behind the cushion. Laurent first strikes the cushion, as previously, but then depresses it with one hand while he grasps the object with the other. ... At nine months, fifteen days, he pushes my hand away with his left hand while pulling at the object with his right....’ (Piaget, 1952, p 216-219).

Piaget framed this transition as part of the ‘sensory-motor period which lasts up to 2 years-of-age. Beyond this age infants enter the ‘pre-operational period’ which lasts from 2 to 7 years-of-age, here infants increases their ability to represent symbols and make their first attempts at

logic thought. To summarize, Piaget used a stage theory to describe development, a process stimulated mainly by experience.

Another theoretical standpoint which holds an even stronger Empiricist approach is the dynamic systems theorem. According to this perspective development is seen as a product of many local and decentralized interactions that occur in real time; a non linear dynamic system with transitions and relative equilibriums. That is, observable developmental changes are controlled by numerous variables within a complex dynamic system. This system is self organized and characterized by relative states of stability and variability (Smith & Thelen, 2003). In an attempt to simulate the A, -B error using a dynamic system Thelen, Schöner, Scheier, and Smith (1999) modeled the neural representation of the two hiding locations. In this model the space entered by the arm during a reach will be facilitated while surrounding areas are inhibited. Over numerous trials of hiding the toy at location A strong memories of this location is built up. During initial B trials the representation for location A is still strong enough to elicit a reach to this location. As a true dynamic system the modeled effect is task dependent; it can be made to disappear and reappear using many of the above mentioned variables. The dynamic systems approach has been used to study the A, -B error in older infants (with increased task demands; Spencer, et al. 2001), postural control during reaching (Thelen & Spencer, 1998), and the relationship between physical growth and stepping (Thelen, Fisher, & Ridley-Johnson, 1984/2002).

Quite the opposite assumption is proposed by Spelke (1994). She argues that infants are born with a capacity to reason and represent the world beyond immediate perception (called the active representation hypothesis). By operating on these representations infants come to expand their knowledge of the world. However, this knowledge does not spring out of thin air but is grounded on a few mature, commonsense principles (called core knowledge) (Spelke, 1994; Spelke, Breinlinger, Macomber, & Jacobson, 1992). These core knowledge principles include basic rules about objects; that they move on connected paths (contiguity), that they maintain their boundaries over time (connectedness), and that they influence each other if they touch (contact). Connectedness was investigated by Kellman and Spelke (1983). Four month old infants were presented with a vertical rod that moved back and forth with its central part being occluded by a barrier. After habituation infants were presented with either the common motion of two separate rods or a single rod, in both cases without the presence of the occluder. In response to these presentations infants increased their looking times to the broken but not to the continuous rod, suggesting that infants had represented one continuous rod all along. Experiments demonstrating early sensitivity to contiguity have been addressed above (Spelke, et al., 1992). According to Spelke these innate knowledge structure are needed to reduce

the difficulties of early mental structuring by limiting the possible interpretations of external events.

Baillargeon and Wang (2002) suggest a slightly different approach. They agree with Spelke on the necessity of innate knowledge structures. They do however hold a different interpretation of their content. According to Baillargeon infants first hold all-or-none distinctions of occlusion events such as occluded / not occluded. With increased age infants learn new concepts that complement the initial understanding and produce more and more accurate predictions. The progression of accumulating these concepts has few similarities over abilities tested. As such no event-general progression can be seen; instead each concept evolves according to its own laws. Whilst watching events in the external world infants are here assumed to categorize each event and thereafter select the knowledge concept most applicable to the event observed.

A third alternative is proposed by Melzoff and Moore (1998). According to their view infants pick up regularities in the world based on some initial concepts. These have little in common with adult experience but are crucial to development. One such concept is an early version of object identity that is based on spatio-temporal representations of objects and the pre-occlusion trajectory. With this representation infants are able to predict and identify future contacts with the visible object following reappearance from behind the occluder. This does not mean, however, that infants have the ability to represent the actual object during occlusion. These abilities appear later in development.

The difference between dynamic systems thinking and pure Nativist approaches appear hard to bridge and critique can be directed at both accounts. The Empirist approach, as here represented by the dynamic systems theory, clearly offers an appealing view on development. It focuses on multi-causality and variability as developmental indicators. This perspective is however largely descriptive and does not allow certain variables to have priority over others; all dimensions are equally important whether they account for body weight or development of the prefrontal cortex. In reality, it appears that some variables are more important than others and a distinction between necessary and sufficient parameters are needed.

The Nativist account also has advantages. It is clear that development becomes far easier to comprehend with some innate capabilities. Whether these are sets of explicit knowledge structures or simply a capacity to perceive and represent aspects of the external world is still an empirical question. At the same time most of the Nativist accounts fail to produce clear evidence of innate knowledge, often relying on the performance of 3 to 4 month-old infants. Much learning can and do occur during the first few months of life.

One view of development that does stand somewhere in between the two is the graded representations hypothesis. According to Munakata, McClelland, Johnson, and Siegler (1997) knowledge underlying infants' performance is graded in nature; it evolves with experience, and is embedded in the specific processes that control the behavior at hand. This means that infants' understanding of the world is not dichotomous; it is not simply present or absent. Based on this understanding it becomes apparent that no one method (such as preferential looking) can unveil the full complexity of any ability. Nor is it advisable to generalize method-specific performance to task-independent knowledge. Whether a task is successfully carried out depends on the resources that a specific task requires; some tasks requiring strong and others weak representations. This line of reasoning has been applied to the A, -B task (Munakata, 1998), memory, and executive functioning (Munakata, 2001). The A, -B task is explained as a competition between latent memory traces for location A and active memory traces of location B. Which location infants will prefer depends on the relative representational strengths of the two locations. These are as such graded, their relative strength competing to guide performance (Munakata, 1998).

So what can be learned from the above mentioned theories? Do they have any common ground on which to stand? Two universal aspects are easily detectable. First, all above mentioned theories motivate the usage of longitudinal designs. According to the Empirist account this is essential since the transitions from stable to unstructured states are fast and unsynchronized between subjects. Among the Nativist approaches all theories make strong and contradicting statements about the exact developmental process. It is only through careful continuous observations that these theories can be validated or falsified. The second point is illustrated in the chapter introducing occlusion and discussed with respect to the different developmental theories stated above. Namely that there appears to be a broad consensus that knowledge is task dependent. Given this fact what method should be used to further broaden our understanding of this developmental process?

Preferential looking has been the method of choice for many researchers, partly because of the small technical demand placed on the experimenter. These methods have been criticized for holding a low correspondence between performance and interpretations; between looking times and attributed cognitive functions. According to Meltzoff and Moore (1998) many of the violation-of-expectation results reported by Baillargeon can be explained without object permanence. In a similar tone Haith (1998) and Hood (2001) argue that any discrepancy from baseline can result in increased looking times. Baillargeon (1999) has answered much of the critique directed at her approach by presenting additional experiments using the same methodology. The most essential critique however can not be addressed using this paradigm. According to Bates (1999) the interpretations

made by Baillargeon (1999) are unsupported. This relates especially to Baillargeon's interpretation of her results using words like 'belief', 'realize', 'expect', and 'reason'. Relating these terms to looking times must be done using different empirical tasks.

A more direct approach is perhaps better, varying different parameters of an occlusion event while measuring object related behavior. Reaching is one reliable candidate, it is goal directed, easily observed, and in accordance with the original reports made by Piaget (1954). However, it has a late onset, making it inappropriate to investigate early object permanence (Mareschal, 2000). Furthermore, reaching often demands solving means-end problems as well as representing objects (Diamond, 1991; see also citation of Piaget above). In the classical A, -B task this manifests itself as a difficulty with planning multiple actions; to remove the cloth and retrieve the object. Performance might, as such, be hindered even though infants readily represent the occluded object. Head tracking is neither optimal since gaze can move independent of the head. The solution, as brought forward in this thesis, is to measure gaze and observe how infants' expectations change with each independent variable used.

Measuring gaze during active pursuit of occluded targets hold many advantages. If infants consistently predict when and where an object will reappear it is much easier to discuss this behavior in terms of cognitive processes. Gaze tracking exists from birth (Aslin, 1986); in addition, the eyes do not suffer from the same mechanical constraints that affect reaching. There are no effects of gravity and little disturbance from inertia due to the spherical properties of the eye. The relatively few muscles controlling eye movements also help to reduce the degrees of freedom needed to control gaze (Leigh & Zee, 1999). Because of these properties gaze tracking might be expected to express early object representations better than reaching and more accurately than head tracking. Anticipatory gaze tracking also holds a tighter mapping to cognitive structures than found during preferential looking studies. Gaze tracking performance and their neural correlates will be addressed below.

## A Note on Eye Movements

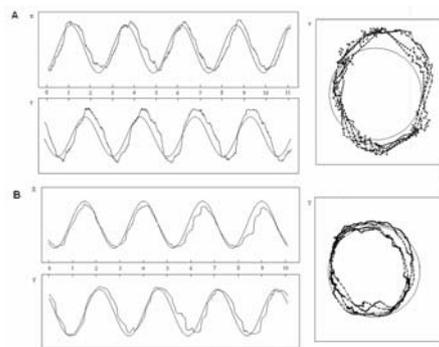
### Performance

In the introduction different onsets of anticipatory tracking was discussed as consequences of the trajectory used (sinusoidal vs triangular). Here follows a general walkthrough of the development of SP and saccades. The studies to be discussed will mostly address sinusoidal trajectories and 2-dimensional tracking. Data from Study I will be addressed

in connection with this discussion. In this study both fully visible and occluded trajectories were presented to 9 month-old infants.

As indicated in the introduction neonates do not generally track objects smoothly. Instead saccades (fast eye movement which centers interesting objects on the fovea; Zeight and Lee, 1999) are used to update looking direction (Aslin, 1986; Bloch & Carchon, 1992; Rosander & von Hofsten, 2000). In the 2<sup>nd</sup> month of life smooth tracking is introduced (Dayton & Jones, 1964). Below 5 to 6 weeks-of-age the gain (see page 28 for definition) of the SP component in horizontal visual tracking is generally below 0.25 and the timing is rather poor. Between 2 and 3 months of age gain improves dramatically with gaze consisting of anywhere from 45 to 80 % SP dependent on the stimuli presented. This transition is accompanied by a rapid improvement in timing. From between 2 and 3 months of age, timing was generally predictive (von Hofsten & Rosander, 1996, 1997; Rosander & von Hofsten, 2000, 2002).

Up to a few years ago no studies had looked at 2-dimensional tracking in infants; most studies were performed using strictly horizontal trajectories. In a series of experiments (Study I; Gredebäck, von Hofsten, Karlsson, & Aus, 2004) we investigated the development of 2-dimensional tracking. In the first part of Study I, 9 month-old infants were presented with a fully visible circular trajectory moving at 0.05, 0.1, 0.2, and 0.4 Hz. The results showed that infants tracked the target; focusing on its inner periphery. Overall, the horizontal component of the circular trajectory had reached adult levels at this age. Gain was adult like and timing included predictive components. Vertical tracking was however immature, with poor calibration of gain and reactive gaze tracking. One example of continuous tracking performance can be found in Figure 3 below.



**Figure 3.** Example includes two 0.4 Hz presentations at 6 (A) and 12 (B) months of age (Gredebäck, von Hofsten, Karlsson, & Aus, 2004).

In a longitudinal extension of Study I (Gredebäck, et al, 2004) the above mentioned results were replicated. During this study 6 to 12 month

old infants were presented with 2-dimensional circular trajectories. The results clearly indicated that horizontal and vertical tracking was mutually dependent. In a previously mentioned study by von Hofsten and Rosander (1997) 1-dimensional horizontal tracking was predictive from between 2 and 3 months of age; the current study did not result in predictive horizontal performance until the infants were 8 months of age. Overall, vertical tracking was even further delayed with highly variant gain, delayed predictive abilities, and longer average distances to the target. Saccades were however predictive from 6 months onwards.

Grönqvist, Gredebäck, and von Hofsten (2003) presented infants with pure horizontal, pure vertical, and 2-dimensional circular trajectories. We were here able to separate out head tracking, SP, and saccades. When presented with a 1-dimensional horizontally moving target gaze and SP were both mature from the earliest age tested (5 months). This level of performance did not generalize to 1-dimensional vertical nor horizontal or vertical components of a circular trajectory. In all these conditions infants did not display accurate tracking until they reached 7 to 9 months of age.

The studies mentioned above all look at the development of anticipatory control. Knowledge of fully visible tracking is a necessity in order to comprehend performance during gaze tracking over occluders. We know, for example, that it is impossible to transverse occluders with SP (Knowler & Steinman, 1979). Instead saccades are used to track temporarily non visible objects. One aspect of saccadic performance that cannot be addressed using predictable sinusoidal trajectories is the establishment of a reliable threshold for distinguishing reactive from predictive saccades. Without such a criterion it becomes difficult to separate these two forms of saccades in order to isolate predictions.

According to Engel, Anderson, and Suechting (1999) adults have a saccadic latency of 197 ms (SD = 28 ms). This was derived from a tracking study in which an object moved with one of two constant velocities on a linear path, changing direction at a random position near the center of the screen to one of 11 different directions. The relationship between the average adult saccadic latency and infants' reactive saccade latencies (the time between a shift in the stimulus array and a saccade in response to this shift) was however unclear. To remedy this situation Gredebäck and Örnkloo (2004) used a similar design as Engel et al. to measure saccadic latencies of 3, 5, and 7 month-old infants. The average latency ranged from ~500 ms at 3 months to ~430 ms at 7 months; variance also decreased. At all ages less than 5 % of all reactive saccades had latencies below 200 ms. This criterion has been used to distinguish reactive from predictive saccades in Studies I, II, and III alike.

In an attempt to replicate and extend these results Gredebäck, Örnkloo and von Hofsten (preliminary data) measured 4, 6, and 8 month old

infants' reactive SP, head tracking, and saccades in response to the sudden shift in trajectory of a real 3-dimensional target. According to this study saccadic latency decreased from ~500 ms at 4 months to ~400 ms at 8 months; at all ages the minimal latency exceeded 200 ms criteria. Corrective SP was generally initiated prior to saccadic corrections; the latency decreased from ~340 ms at 4 months to ~300 ms at 8 months. At all ages the minimum latency of SP was lower than 150 ms. Movements of the head were small and uncorrelated with the motion of the target.

## Neural Correlates

The motion processing streams originate in area V1, here coding is local and simplistic. The next active area integrates individual motion components to code the true direction of perceived objects; this is done in the middle temporal area (MT). Further upwards, the medial superior temporal area (MST) code for expansion, contraction, rotation, and translations. This is done through large receptive fields which also code for direction of self motion in the optic array (Graziano, Andersen, & Snowden, 1994). Finally, perceived motion, independent of actual motion seems to be coded in the lateral intraparietal area (LIP) (Leopold, 2003; Williams, Elfar, Eskandar, Toth, & Assad, 2003).

The structures responsible for saccades and SP are partly common to those responsible for motion perception. The control structures responsible for eye movements do however include both cortical and subcortical paths; all of these originate in the retina and converge on the superior colliculus (SC). This area projects to the brainstem where saccades are generated; the actual motion of the eye is produced by 6 extra-ocular muscles. According to Johnson (1990) three distinct pathways that guide eye movements develop at different rates during the infants' first few months of life. The first pathway is up and running from birth and includes a direct connection from retina to SC. The function of this pathway is to generate saccades to easily detectable targets in the peripheral visual field. During the second month of life primary visual cortex and area MT become involved in controlling the eye movements. It is at this age that SP is first reliably measured (von Hofsten & Rosander, 1997). Not until infants are three months-old do frontal eye fields (FEF) interconnect with MT and SC; at this time anticipatory tracking improves.

According to Tehovnik, Sommer, Chou, Slocum and Schiller (2000) predictive saccades are preceded by activation in both FEF and the supplementary eye fields (SEF). The later structure does not only code for saccades but also for other limb movements such as reaches. Canfield and Kirkham (2001) conclude that these cortical eye fields are active at 3 to 4 months of age. Decisions to make saccadic eye movements are preceded by activation in area LIP (Andersen, 1997). This area has also been reported to

code direction and amplitude of remembered target locations. Cells in this area continued to fire until an eye movement is made, regardless of the visibility of the target and the time lag between target offset and saccade onset. If the eye movement was withheld for a few hundred milliseconds or up to one and a half second did not matter (Gnadt & Andersen, 1988).

On a larger scale Milner and Goodale (1992, 1995) have proposed a division between ventral and dorsal stream processing. The first is assumed to process consciously perceived information (sometimes referred to as the 'what' stream), the second process visual guidance of action outside awareness (called the 'how' stream). Goodale and Humphrey (1998) stated that the ventral stream projects to inferotemporal cortex, which is connected to structures in the medial temporal cortex and prefrontal cortex involved in long-term memory and other cognitive activities. The dorsal stream projects to the posterior parietal cortex; it is assumed to have the ability to store visual information for between 1 and 2 seconds. During continuous tracking of visible targets the processing is likely to be largely dorsal. However as targets become occluded the processing must shift in favor of ventral structures, especially if occlusion durations are long.

There are a few studies that have addressed the age at which these two systems might be integrated. Mareschal and Johnson (2003) presented 4 month-old infants with violations of surface features or locations of targets during an occlusion event. They concluded that infants at this age have difficulty integrating information processed independently in dorsal and ventral streams. There is however indications that dorsal and ventral information might be functionally integrated by 9 months of age (Kálldy & Leslie, 2003).

## Gaze Tracking and Occlusion

The first attempts at measuring gaze tracking during occlusion date back to the early 70's. In one study by Nelson (1971) 5 and 8 month-old infants observed a toy train move around a rectangular track and trough a tunnel (800 ms of non-visibility). Direction of gaze was coded from video recordings of infants' eyes. On initial presentations infants of both age groups followed the train as it moved around the track. When the train became occluded by the tunnel gaze tracking stopped and infants fixated the location where the train disappeared. Infants continued to look at this location until they perceived the reappearing train. After numerous occlusion events infants moved further towards the reappearance side of the tunnel before the train reappeared. In this manner infants increased their anticipatory responses, at the same time infants decreased the reaction time of non-predictive trials. These results were replicated in a second study by

Nelson (1974). In a similar study Mailer and Garth (1980) temporarily halted the train inside the tunnel, making the occlusion event longer than expected. Nine month-old infants readily moved gaze to the reappearance location of the train within the expected time interval (800 ms). However, 5 month-old infants did not anticipate the reappearance of the train.

Van der Meer, van der Weel, and Lee (1994) investigated 4 to 12 month-old infants' abilities to predicatively track and reach for an occluded toy which moved on a horizontal plane. Infants first started to reach for the toy at five months of age. At this time infants reaches were reactive though gaze anticipated the reappearance of the toy. Not until infants were 8 month-old did they plan the reaching for the object while it was still occluded. This indicates that anticipatory tracking emerges prior to anticipatory reaching; the former exists from at least 5 months of age. This general assumption was confirmed and extended in a study by Rosander and von Hofsten (2003). Here 7 to 21 week-old infants were presented with an object that oscillated back and forth on a horizontal trajectory at 0.25 Hz in each of four conditions. Either the target moved with a constant velocity or accelerated and decelerated in a sinusoidal fashion behind a central or peripheral occluder. Over single trials the average latency (gaze lag) at target reappearance decreased at all ages tested. After less than 20 s experience within a trial gaze predicted the reappearance of the target from 17 weeks-of-age during constant velocity motion and from 21 weeks-of-age during sinusoidal motion. There were however no learning effects between trials, possibly due to the random ordering of trials.

These studies are all groundbreaking in their own right. The early studies by Nelson (1971, 1974) were the first to measure gaze tracking during occlusion and to demonstrate the importance of learning in occlusion events. The first study to look at eye-hand interaction during occlusion in infancy was provided by van der Meer et al. (1994). The results of Rosander and von Hofsten (2003) provide a unique illustration that development does not consist of multiple hierarchical knowledge categories. Instead development of object representations is a continuous process which begins as early as 7 weeks-of-age and continues far beyond the 21 weeks-of-age. However, none of these studies provide us with any understanding of what parameters control gaze tracking during occlusion. We do not know how object representations are affected by time of non-visibility (temporal representations) nor do we know how infants represent the location of attended objects (spatial representations) when non-visible. These are the two main questions addressed by this thesis; each will be discussed below.

## Temporal Representations

It is not enough to just know about the existence of an occluded object if you want to track, catch, or otherwise act towards it as it reappears. Crucial to the anticipatory process is the ability to represent the duration of non-visibility. We are here interested in two questions related to this process. Can infants accurately represent the duration of occlusion and if so, how do these representations change over time?

We know that infants and adults both have a decent ability to estimate the duration of occlusion of a moving target. This estimation is at least partly determined by the perception of the pre-occlusion trajectory. Adult observers are more likely to report two separate object motions if the duration of occlusion is too short (if the target reappears directly following its disappearance, without the proper delay). According to Burke (1952) two factors increased the probability of perceiving two objects; slow target speeds and large occluders.

It is known that infants react to violations of the temporal arrow of causation. In one study 4 and 8 month-old infants were presented with everyday activities such as pouring a liquid into a container in normal (forward) and reversed (backwards) temporal order. At both ages infants looked reliably longer at the events played backwards (Friedman, 2002). Infants are also responsive to manipulations of occlusion duration. Wilcox and Schweinle (2003) presented 4.5 month-old infants with an oscillating object that moved in and out of view behind an occluder. After a number of occlusion passages the object being tracked stopped behind the occluder and the screen was removed; either to reveal one or two objects. If the moving object had crossed the occluder faster than expected infants increased their looking times when a single object was revealed behind the occluder. According to the authors these results indicate that contiguity of the speed of motion is fundamental to the perception of object unity.

In addition, Johnson et al. (2003) performed a set of experiments where an object moved behind an occluder followed by one of two additional occlusion events. Either the object moved in the same way as any real object once the occluder was removed; in a continuous fully visible manner. In the other situation the object behaved in the same manner as during occlusion but without a visible occluder. The target disappeared and reappeared successively (accretion/deletion), this way the object motion was the same but no visible occluder could account for its disappearance. Looking times were compared between the baseline occlusion event and the other two events. At 4 months of age infants looked reliably longer at the accretion-deletion event than baseline during a short occlusion event (67 ms). Not until 8 months of age did infants demonstrate this same behavior during longer occlusion intervals (667 ms). The interpretation proposed by Johnson et al. is that infants represent the continuous moving target during

the occlusion event and becomes surprised if the target disappears in the absence of the occluder.

Somewhat different results were obtained by Jonsson and von Hofsten (2002). They investigated the effects of occlusion duration (400, 800, or 1200 ms) on head tracking. This study is described in section Introducing occlusion, above. The authors conclude that the lead of head direction to target location increased at target reappearance with increased occlusion durations. This effect was only consistent during the occlusion event (not during blackout) and only evident as a result of experience.

Johnson, Amso, and Slemmer (2003) claims that 4 month-olds do not have robust object representations. In their study infants increased their anticipatory responses after viewing fully visible trajectories prior to the occlusion events. No such benefit was observed at 6 months of age. According to their interpretation the older infants have acquired stable object representations that are not present at 4 months of age. A number of questions can be raised with respect to this interpretation. It is important to note that an increase in anticipatory responses represent an improvement not the onset of a previously dormant ability. The study does neither address the durability of the effect. In Rosander and von Hofsten (2003) infants decreased the average saccadic latency over successive occlusion events. Indicating in a similar manner that experience can facilitate anticipatory tracking. This effect was however restricted to each trial and no positive effects were found across trials.

Study I and II vary occlusion duration from 250 ms up to 5000 ms to investigate infants' temporal representations. In addition Study III looks at 4 months-olds ability to represent circular trajectories during 660 ms occlusion duration. In this later study participants had no previous experience of similar trajectories and were therefore completely novel to the task. If 4 months olds were able to predict the reappearance of these targets the interpretation of Johnson, Amso, and Slemmer (2003) may need to be revised.

## Spatial Representations

The second important factor for predictive actions is the ability to represent the spatial location of objects that temporarily become non-visible. This ability has been extensively studied using the original A, - B task. In addition to the works of Piaget (1954) others have posed specific questions with respect to spatial representations.

With the help of a preferential looking paradigm Wilcox, Nader, and Rosser (1996) presented infants with an object that was lowered behind one of two occluders. After a delay of between 5 and 30 s the object was recovered from behind the right (possible) or wrong (impossible)

occluder. At 2.5 months of age infants looked longer at the impossible event after a 5 s delay, 4.5 month-old infants showed the same result with delays up to 10 s, while 6.5 month-olds responded in a similar fashion during all delays presented (5, 10, & 30 s). It has also been demonstrated that infants increase their looking times to errors in the final orientation of a rotating object that moves behind an occluder. In this study (Hespos & Rochat, 1997) 4 to 8 month-old infants acted surprised if the final orientation of the object did not equal the extension of the movement seen. This indicates that infants at these ages are sensitive to violations of the extrapolation of seen rotations.

Studies of spatial representations have also been performed during reaching. Von Hofsten, Vishton, Spelke, Feng, and Rosander (1998) nicely demonstrated that infants have a strong preference for reaching along the linear extrapolation of currently perceived trajectories. In this study 6 month-old infants were presented with the same linear and non-linear trajectories as described above (von Hofsten, Feng, & Spelke, 2000; Spelke & von Hofsten, 2001). In their study (von Hofsten et al., 1998) all trajectories were fully visible and no occluder was ever presented. During this fully visible tracking infants directed their reaches to the natural continuation of the current motion regardless of how the object moved (linear or non linear). These results indicate that infants use the notion of inertia to predict the future location of fully visible targets. With the addition of an occluder (von Hofsten, et al., 2000; 2002) infants initial predictions still accord with inertia but given consistent experience with non-linear trajectories infants adjust, and accurately predicted non-linear trajectories.

The result of these studies suggests that infants extrapolate the targets trajectory during occlusion. The processes that govern accurate predictions are still inadequately documented. It is still unclear to what extent infants actually extrapolate the trajectory or whether infants formulate and apply rules based on previous experience to predict the reappearance of the target.

If infants extrapolate the motion of the occluded target it is still uncertain if these are based on the tangent at disappearance (producing strictly linear extrapolations) or if infants have the ability to produce more complex extrapolations; assuming that whatever forces act on an object prior to occlusion continues to guide unseen trajectories. In this later case all sinusoidal 2-dimensional trajectories (for example a circle) will be represented as such, and accurately predicted.

If rules are used to predict the reappearance of the target this can not be done on their first trial; experience is needed to form stable representations. Infants might rely on simple rules of reappearance or form associations between pre- and post-occlusion trajectories. By applying simple rules repeated occlusion events can be accurately predicted. However, if the reappearance location changes constantly the resulting prediction will be inaccurate and based on the average reappearance

location. Associative rules on the other hand will not suffer from such errors since they associate a specific pre-occlusion event with its outcome. With such a complex rule all trajectories can be predicted, not only sinusoidal ones; as is the case during extrapolations.

Study I and II discusses performance as an extrapolation process. It is here investigated whether linear or complex extrapolations are performed whilst tracking circular trajectories. Study III focuses on the mechanisms responsible for accurate predictions. When multiple cues are available will infants extrapolate or use rules to guide predictions?

## General Aims

Four questions are posed and investigated in three studies. The first address infants' *temporal representations*. (1) How are representations of non visible objects affected by duration of occlusion? The second attends to *spatial representations*. (2) At what age can infants predict the reappearance of objects moving on a 2-dimensional trajectory, and what processes are involved? The third question concerns *learning* effects. (3) How does the rate of learning change with age, more specifically, what experience is needed to form stable representations and how durable are these effects? The fourth and final question address *development* at large. (4) Can we make any statement about the development of object representations, for example are the underlying processes continuous or discrete?

Study I poses a number of initial questions about 9 month-old infants' abilities to represent and predictively track occluded targets. In this study infants are presented with fully visible and temporary occluded targets moving on circular trajectories. Study II extends the results obtained in Study I by looking at the development of infants' abilities to predict occluded targets from 6 to 12 months of age. Both of these studies focus on how occlusion duration affects the spatio-temporal representation by measuring the time of the gaze shift over the occluder and the position to where it shifts. Study III focuses more on the spatial representations by manipulating where the target will reappear. In this study 4, 6, and 8 month-olds are presented with a variety of trajectories with different reappearance locations. In this study duration of occlusion remains constant. By integrating the questions raised in each study we are able to extend our understanding of infants' spatiotemporal representations while cross-validating the results between studies.

## Method

### Participants

In preparation for each study we sent an introductory letter to all parents with infants of appropriate age in close vicinity to the university. The addresses of these families were available to us through vital birth

records after being scanned by hospital personal; making sure that only parents of healthy infants were contacted. This letter briefly explained the purpose and procedure of the study at hand and asked interested families to respond. At the beginning of their first visit a more detailed explanation of the procedure was presented and a consent form was signed. All studies were approved by the ethics committee of the Research Council in the Humanities and Social Sciences. All three studies are therefore in agreement with the ethical standards specified in the 1964 Declaration of Helsinki. Respondents were predominantly white middle class families who received either two movie tickets or eight bus tickets for participation at each session (value ~20€).

In Study I both 9 month-old infants ( $n = 16$ ) and adults ( $n = 4$ ) participated. The infants (10 males & 6 females) with an average age of 276 days ( $SD = 11$  days) and were recruited as described above. Participating adults (2 male & 2 female) were naive to eye tracking and the purpose of the study. Study II and III were both longitudinal studies. The first of these (Study II) investigated the development of 10 boys and 10 girls from 6 to 12 months of age (mean age 173, 237, 293, & 354 days;  $SD$  6, 7, 5, & 6 days, respectively). Of the 20 infants participating in Study II 3 boys and 2 girls were excluded from the analysis either because of fussiness or an inability to participate at each follow-up. The later (Study III) focused on the development of slightly younger infants, ranging from 4 to 8 months of age (mean age 123, 181, & 238 days;  $SD$  3, 3, & 6 days). In this study 16 infants participated (10 boys & 6 girls). One boy and one girl were excluded from this study for reasons similar to those stated in relation to Study II.

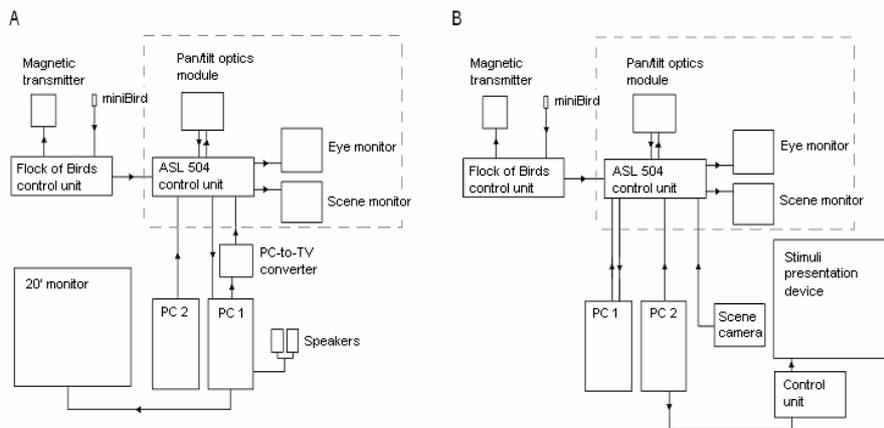
## Procedure and Stimuli Presentation Devices

Both infants and parents were seated inside a small semi-enclosed experimental room (106 cm x 122 cm, 204 cm high) with a light and sound blocking curtain covering one of the long walls. All experiments were performed with infants seated in an infant car seat placed on the lap of participating parents. Within this room infants were presented with different target trajectories and occlusion events presented on a computer screen (Study I & II) or on a custom made stimulus presentation device which produced movements of real 3-dimensional targets on a blank vertical surface (Study III). The ASL 504 infrared camera was placed on a shelf below the opening through which the stimuli was seen. A Flock of Birds transmitter magnet was located on the opposite wall, on the outside of the experimental room, behind the parent and infant. It was held in place by a Plexiglas framing attached to the wall with copper screws. The Mini-Bird was placed above the infants' right eye, using a Velcro strap attached to an infant cap; its cord exiting the room behind the infant close to the location of the transmitter.

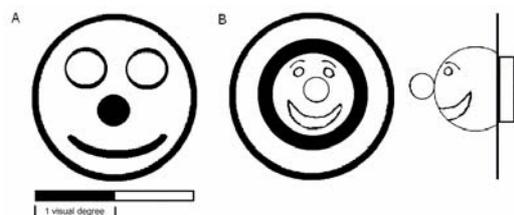
Many parts of the procedure did not change between studies. Infants always wore the infant's cap with the Mini-Bird while being seated on the parent's lap. During this procedure, a distraction task was performed. The purpose of the distraction was to focus the infants' attention forward whilst locating the right eye with the ASL camera and setting threshold values for pupil and cornea reflection. Just prior to stimuli presentations a two point calibration procedure was performed, the accuracy of which was tested immediately following calibration. The accuracy of calibration was considered adequate if gaze centered on the target at each of the four corners of the screen. If the variance was large (gaze appeared outside the calibration target) the calibration procedure was redone until it was satisfactory.

At Study I and II both the stimuli presentations and the initial distraction task were displayed to the infants on a 20 in. computer monitor (for a full schematics of setup see Figure 4A). The distraction task involved a movie of the Muppet Show character Kermit dancing to music. Once thresholds were set Kermit was replaced by a blue and white sphere which expanded and contracted (expanded radius = 1.4 visual degrees) over a black background in synchrony to an attention getting sound (Johnson & Johnson, 2000). This calibration stimulus appeared in succession at the upper left and lower right corners of the screen. After calibration accuracy was tested by presenting this stimulus at each of the four corners of the screen. If gaze appeared stable within the area covered by the target at all four locations calibration was considered successful and the study could commence. During the actual experiment a round yellow 'happy face' (radius = 1 visual degree) moved in a circular trajectory over a grey background (see Figure 5A) and was occluded by a black screen at one of several locations. During these events the target simulated the appearance of real occlusion events; successively disappearing and reappearing (accretion – deletion). At the start of each trial an attention catching sound was presented twice (the Microsoft 'ding.wav').

In Study III a real life occlusion event was presented to the infants complete with a 3-dimensional target and a real occluder. During this setup all distraction tasks were performed as real life puppet shows using squeaky toy animals. As substitute for the calibration stimuli used in Study I and II a dark rod that ended in a homemade toy (composed of a large led, a bell, and a bright face) was presented in a manner similar to that described above. Once an accurate calibration was performed a new real life puppet show was presented to the infants during the time it took to attach the occluder and target to the vertical surface. The stimulus presentation device moved a magnet on one side of a metal sheath using two servo engines on the opposite side. Similar stimulus generation devices have been used before (Hespos, von Hofsten, Spelke, & Gredebäck, 2002; von Hofsten & Spelke, 1985; von Hofsten, et al., 1998) however the previous device was controlled by step engines unable to produce non-linear motion. Visible to the infants



**Figure 4 A & B.** Demonstrate the hardware setup for Study I & II (A) and Study III (B). Both the ASL (within the dotted line) and the Flock of Birds systems are interlinked in the same fashion in all three studies. Control of the system is performed through PC 1, here one can locate the eye (also available via remote control) and set threshold values for cornea and pupil. Visible in the eye monitor is the recorded eye together with information on reflection quality, through the scene monitor experimenters can observe the stimuli presented to participants and the location of gaze within this scene. In setup (A) PC 2 holds a custom made stimuli generation program which displays stimuli on the monitor at the same time as sending information on target location and whether the target is occluded or not to the ASL control unit. Gaze and target related information was sampled at 60 Hz and recorded on PC2 at 85 Hz. In setup (B) PC 2 controls the two servo engines on the back of the stimuli presentation device and sends information on trial initiation to the ASL control unit (50 Hz sample rate). This information was integrated with location of gaze and recorded on PC 1 at 50 Hz. Displayed on the scene monitor are pictures of the stimuli presented; fed from a scene camera placed in front of and below the infant.



**Figure 5 A & B.** Demonstrate the targets used in Study I & II (A) and Study III (B). The first is a computer generated 2-dimensional target whilst the second is a 3-dimensional face constructed from paper and wood. The eyes of target B were red LEDs that glowed during presentations; these were activated by pressing the nose.

was the side of the sheath which held the magnet; on top of which a 3-dimensional 'happy face' was placed. This target had a yellow spherical face, a blue spherical nose, two red glowing eyes (LEDs) and a red mouth

(see Figure 5B). The occluder was black and the background blue-grey. To increase the perception of depth, a light was directed towards the screen from a position in front of and below the participants. A more thorough description can be seen in Figure 4B.

## Data Analysis

For all studies, an emphasis was placed on the occlusion event. Study I and II focused on gaze shifts during occlusion, measuring when (timing) and where (spatial accuracy) gaze reached the reappearance side of the occluder. Study III included only those trials where gaze crossed the occluder with saccades, measuring when saccades were initiated (timing) and where the saccade ended (spatial accuracy). A more rigid inclusion criterion was applied to Study III in an attempt to strengthen the rational of the analysis; making sure that predictions were saccadic and focusing on saccade initiation as apposed to saccade terminations. In reality only five occlusion events in all infants at all ages were excluded because the occluder crossing was not saccadic.

Trials where the infants did not attentively track the target both prior to and following the occlusion event were excluded; inclusion being defined by three criteria. Firstly, target related smooth pursuit had to be visible just prior to occlusion (of > 500 ms duration in Study III). This criterion made sure that participants actively perceived the disappearance of the target. Secondly, participants needed to move gaze (only saccades were included in Study III) over the occluder and end in a fixation of at least 200 ms or target related smooth pursuit (> 500 ms of target related smooth pursuit in Study III). The 200 ms criterion was determined by the saccadic latency described above (Gredebäck & Örnkloo, 2004). Thirdly, smooth tracking of the target after occlusion had to commence whilst the target was still inside the area in front of the reappearance side of the occluder. Gaze was said to have arrived on the reappearance side of the occluder when it had passed a position 2 visual degrees inside reappearance side of the occluder. This cut-off was based on an estimation of the accuracy of infants gaze shifts and the accuracy of calibration.

Included trials were dichotomized as either predictive or reactive. The classification of individual included trials was calculated on the targets time of reappearance (first sight of target) after occlusion minus the time when gaze arrived on the reappearance side of the occluder (saccade initiation in Study III). If the target had been visible for less that 200 ms when gaze crossed the occluder (Study I & II) or saccades were initiated (Study III) the trial was termed predictive; trials with higher latencies were considered reactive. All three studies report on the temporal characteristics of predictive and reactive trials. The second measurement, spatial accuracy,

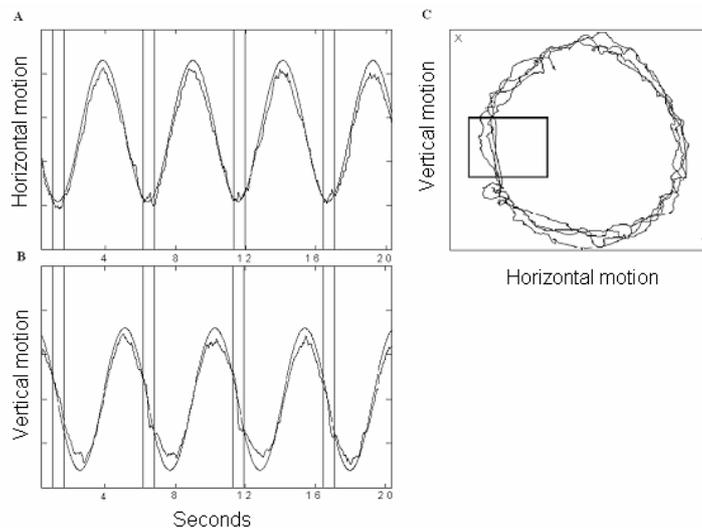
was calculated from the endpoint of gaze shifts and saccades. It investigated where along the occluder participants assumed the target to reappear and compared this to the correct location of target reappearance. Study I also reports on tracking abilities during fully visible trajectories. These trials had to include a minimum of 4 s of target related smooth tracking. On such trials gain, timing, and average distance was calculated<sup>2</sup>. All analyses except the timing of fully visible trajectories were performed using custom made analysis programs (Matlab, Mathworks). During Study I analysis were performed using MANOVAs, Study II used multiple regression analysis with age and occlusion duration as regressors, whereas Study III used a combination of different analysis. A general linear model was applied to aggregated data (success rate); these datasets contained few missing values. Confidence intervals were used to define the spatial accuracy during circular trials. Thereby differentiating the predicted reappearance location from the nearest alternative reappearance location (O1 during C2 trials). Shifts in spatial accuracy from 'O1' to 'O2' were tested with Wilcox Matched pair tests. Performance during the first occlusion passage of complex trials were dichotomized as correct or incorrect dependent on which side of the occluder they predicted the target to reappear and analyzed with  $\chi^2$ , and confidence intervals for each specific condition at each particular age. Measures of temporal accuracy were analyzed using multiple regression with age, presentation order, condition, and experiment order as regressors. When presenting these results, significance for individual components (t-values) are reported in the text. Significance of the analysis as a whole (F-values), beta-values and  $R^2_{adj}$  are reported in footnotes.

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<sup>2</sup> Gain measures the relative amplitude of gaze and target at the targets fundamental frequency using the Fast Fourier transformations. Timing is calculated from the peak correlation of target and gaze position with a cross-correlation function in FYSTAT (Umeå University, Bäckström). Average distance is simply the mean position of gaze - target. All analyses were performed separately for vertical and horizontal components of the circular trajectory.

## Initial Questions (Study I)

In Study I 9-month-old infants and adults tracked a target that moved on a circular trajectory during both fully visible and occluded conditions. The aim of this study was to survey the methodology used as well as produce an initial assessment of infants' abilities to track moving targets during a wide range of conditions. The total stimuli setup included four fully visible trajectories of different velocities and eight occluded trials with occlusion durations from 250 to 5000 ms. Our initial assumption was that performance would deteriorate with increased occlusion durations. Therefore nine month old infants were chosen because we wanted to make sure that the group tested had some object representations (making sure that we avoided floor effects). One example of infant performance can be observed in Figure 6.



**Figure 6.** Example of one infant's gaze tracking during 0.2 Hz, 10 % occlusion, separately for horizontal (A) and vertical components (B) and 2 dimensional tracking (C) over 20 s. Vertical bars in A & B indicate the location at which half the object has become occluded and reappeared from behind the occluder.

## Design

Infants and adults were first presented with 4 fully visible trajectories (see *Table 1*) of different frequencies; appearing in a randomized order. The stimuli always moved counter-clockwise in a circular trajectory with a diameter of 18 visual degrees. On all trials the target appeared and started moving from the vertical midline of the circular trajectory, half to the far right and half to the far left of the horizontal axis. Each trial lasted 20 s independent of the frequency used. As such, the number of laps presented at each frequency differed from 1 to 8. After these fully visible trajectories participants were presented with the same trajectories during two blocks of occluded trials.

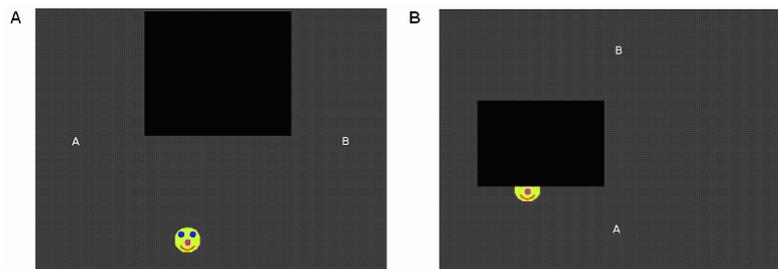
**Table I.** Stimuli definitions organized by occlusion duration, occlusion percentage, frequency, speed in visual degrees/s, no. of laps/presentation, and total presentation time in seconds.

Occlusion duration	Percentage trajectory occluded	Hz	Speed (°/s)	No. of laps	Total presentation time (s)
-	-	0.4	22.6	8	20
-	-	0.2	11.3	4	20
-	-	0.1	5.6	2	20
-	-	0.05	2.8	1	20
250	10	0.4	22.6	8	20
500	10	0.2	11.3	4	20
625	25	0.4	22.6	8	20
1000	10	0.1	5.6	2	20
1250	25	0.2	11.3	4	20
2000	10	0.05	2.8	1	20
2500	25	0.1	5.6	2	20
5000	25	0.05	2.8	1	20

Note: ‘-’ refers to fully visible trials

During one of these blocks the participants were presented with each of the four frequencies and an occluder that covered 10 % (6.8 x 10 degrees) of the trajectory. The other block contained the same four frequencies with an occluder covering 25 % (10 x 11.4 degrees) of the trajectory. The order of the two blocks and presentation order within each block was randomized. For half of participants in each group these occluders were located at the top of the circular trajectory. The others were presented with occluder positions which were shifted 90 degrees counter-clockwise towards the leftmost part

of the circular trajectory. As such, half the occluders covered a large shift in vertical position but no horizontal change from disappearance to reappearance, the other occluder locations inverted the relationship between the axes (two pictures of stimuli presented can be viewed in Figure 7). Combining frequencies with the two occluder sizes resulted in 8 different occlusion durations (5000, 2500, 2000, 1250, 1000, 625, 500, & 250 ms). The entire session rarely took more than 15 minutes to complete.

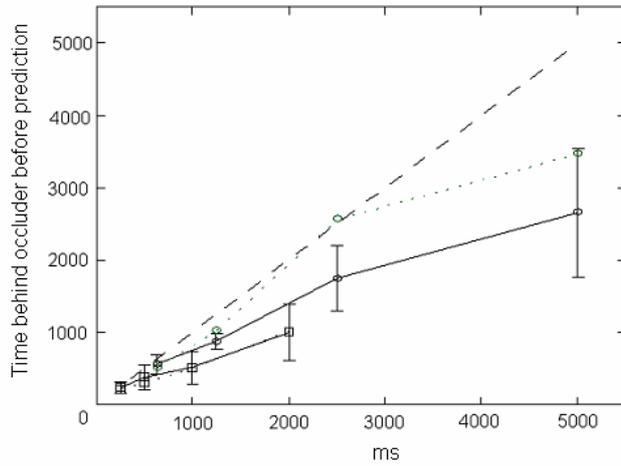


**Figure 7.** Panel A illustrates top 25 % occlusion, and B left 10% occlusion. Letters A and B in each graph represent the different starting positions used with each corresponding occluder position. Letters in Figure 7 also corresponds to the starting point of fully visible trajectories.

## Results

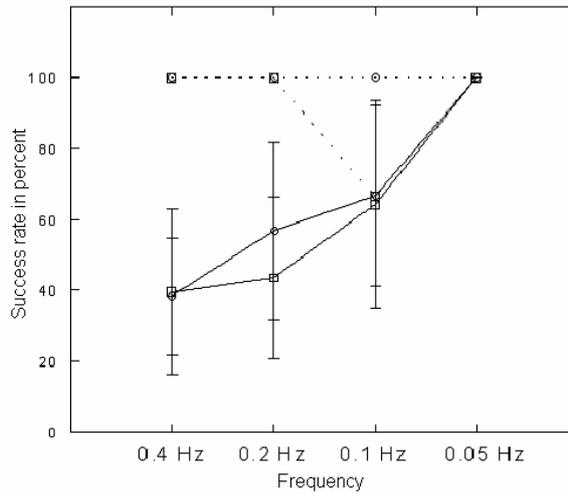
Fully visible targets were tracked in a predictive manner with higher gain for horizontal than vertical components in adults. For the 9-month-olds the horizontal timing was on average predictive at 3 out of 4 frequencies and the gain closely resembled adult performance. Vertical components of tracking appeared less mature than the horizontal components, since gain was far larger than expected from adults; in addition, timing was poor with a large proportion non-predictive trials at 3 out of 4 frequencies.

The occlusion event was, as expected, easily managed by adult perceivers. Nearly all attended trials were predictive (with the exception of two 2500 ms occlusion durations; equal to 0.1 Hz with 25 % occlusion).



**Figure 8.** Time in ms behind occluder before prediction in all predictive trials. The diagonal dotted line indicates total duration of occlusion. Solid lines represent infants and dotted lines adults, circles depict the 25 % occlusion and squares the 10 % occlusion. Error bars indicate 95 % CI.

How is the performance of the 9-month-olds compared to the adults? As can be seen in Figure 9, 9-month-old infants performance was far below the asymptotic adult level in terms of percentage of predictive trials [ $F(1,18) = 13.6, p < .002$ ]. For our infants 52 % of included trials were predictive, their distribution being unsymmetrical over frequencies investigated.



**Figure 9.** Percentage predictive trials for infants (solid lines) and adults (dotted lines), circles 10 % and squares 25 % occlusion. Error bars represent 95 % CI.

Among the predictive trials there were few differences between infants and adults. Both infants and adults displayed sensitivity to occlusion duration [ $F(3,6) = 22.3, p < .002$ ]; waiting at the disappearing edge of the occluder until the target was about to reappear before moving gaze over the occluder (See Figure 8). In terms of spatial accuracy few differences were found between infant and adult performance (see Table 2). Both adults and 9 month-olds predicted the reappearance of the target to be either within the boundaries of the real target location or further towards the center of the circular trajectory. Compared to adults, infants' performance was far more varied, indicating poorer calibration of spatial representations (see Table 2). An effect of occlusion size was also observed; with infants and adults both waiting longer during 25 % occlusion compared to 10 % [ $F(1,2) = 44.4, p < .03$ ].

**Table 2.** Spatial accuracy, as defined by the deviation of gaze from the target center at occluder reappearance (deg. visual angle).

Occlusion duration	Percentage trajectory occluded	Hz	Mean		SD	
			Infant	Adult	Infant	Adult
250	10%	0.4	.400	.966	2.161	.902
500	10%	0.2	1.317	.433	2.311	.568
625	25%	0.4	1.440	.486	2.299	1.174
1000	10%	0.1	1.846	.537	1.646	.841
1250	25%	0.2	.562	.579	2.183	.983
2000	10%	0.05	1.687	.494	3.743	.639
2500	25%	0.1	1.069	-.250	3.779	.565
5000	25%	0.05	.796	.325	1.92	1.758

Note: Positive numbers indicate an underestimation of the motion amplitude.

## Conclusions

These results provide four major contributions to the field of object representations. The first point is methodological, and related to the techniques and analysis used. The second and third points are related to spatial and temporal representations, respectively. The fourth point addresses development at large. Each of these topics will be addressed below.

One of the primary reasons for this study was to test the usability of the cornea-reflection technique during continuous tracking in infancy and adulthood. This has, to my knowledge, not been done before. The ASL 504 was easy to use, while the calibration was swift and accurate.

Both of these contributed to minimizing data loss due to technical difficulties; in the end all 16 tested infants were included in the final analysis. This indicates that the cornea-reflection technique as implemented by the ASL 504 system provides a sound and reliable way to measure infants' goal directed behavior. The second methodological issue deals with the analysis used. Previous studies of occlusion have focused on different global indicators of development such as changes in success rates (von Hofsten, Feng, & Spelke, 2000) or looking times (Wilcox, Nadel, & Rosser, 1996). In addition to reporting success rate we decomposed predictive performance into more basic elements, investigating infants' and adults' abilities to represent the duration of occlusion (timing) and reappearance location (spatial accuracy) separately.

By using a curvilinear trajectory it became possible to focus on spatial accuracy. With such a trajectory perceivers were forced to estimate where along the occluder edge the target would reappear. Where participants predicted the target to reappear was assumed to reflect the properties of the spatial representation, of the circular trajectory, behind the occluder. Adults, indeed, moved gaze to the correct reappearance location of the target. In a similar fashion infants moved gaze either to the correct reappearance location or to a location further towards the center of the circular trajectory. This was interpreted as evidence that participants represented circular motion. These results indicate that both age groups act in a manner consistent with a notion of inertia which states that whatever forces influence an object prior to occlusion will continue to influence the object during occlusion. This was similar regardless of occluder size and location. Together, these results indicate that 9-month-old infants and adults both have the ability to represent targets for rather long periods of non-visibility and produce accurate spatial predictions of the reappearance of circularly moving targets.

Temporal representations, as measured by timing of saccade relative to target reappearance, indicate that both 9 month-olds and adults wait equally long before moving gaze over the occluder. When occlusion duration was short both age groups moved gaze over the occluder just as the target became visible. During longer occlusion intervals the saccadic latency increase. However, with increased occlusion duration there is also a decrease in precision. It is important to note that this is not a developmental issue because it is equally large in adults. Regardless of this fact, 9 month-olds and adults can represent non visible targets for up to 5000 ms of non visibility.

Few differences between adults and infants were observed. To find a variable that describe the transition from infancy to adulthood we must turn back to success rate and occlusion duration. During long occlusion durations both adults and 9 month-olds equally often predicted the reappearance of the object. However as duration of occlusion shortened infants' predictive abilities deteriorated.

One could make the argument that the increase in percentage predictive trials observed during prolonged occlusion durations is an artifact produced by changes in size of the time window investigated. Or stated differently; is it possible that with shorter occlusions fewer infants will spontaneously wander past the occluder edge while the target is still behind the occluder? I will argue that this interpretation is altogether false. First, infants waited at the disappearance edge of the occluder until the target was about to reappear. Secondly, we know that infants cannot smoothly pursue an object that gets occluded (Knowler & Steinman, 1979). As the tracked target disappears smooth tracking will end. To reorient gaze to the reappearance location of the target infants and adults both use saccadic eye movements, these are under voluntary control (Leigh & Zee, 1999).

This means that another explanation must be sought that explains performance during short occlusion durations. One such possibility might be differences in the strength of representations of the trajectories based on duration of visibility prior to occlusion. At the slowest speed and shortest occlusion event the longest time of visibility lasted 14 s prior to occlusion, at the fastest speed and longest occlusion the shortest time of visibility equaled 1.9 s (the rest falling between these values). The question that one has to ask is, for how long do infants need to perceive a trajectory before a stable representation is formed? According to Sekuler, Sekuler, and Sekuler (1990) the adult visual system requires 500 – 700 ms to form a stable enough representation to overcome initial directional uncertainty caused by occlusion (Sekuler & Sekuler, 1993). We know that infants' saccadic latencies often lag adult oculomotor behavior (Gredebäck & Örnkloo, 2004); however, the shortest visibility prior to occlusion was more than 2.5 times the adult value. Thus, it appears unlikely that this effect by itself can account for the results.

An additional possibility involves difficulties with switching modes of tracking. Based on the works of Milner and Goodale (1995) it is possible that the current task involves both dorsal and ventral neural processes. Whilst tracking a fully visible target with smooth pursuit one is engaged in dorsal processes, whereas predicting the reappearance during occlusion is a typical ventral task because visual contact is hindered and saccades are voluntary. So, at the occluder edge perceivers have to switch from dorsal to ventral processing. This is an easy task for a fully integrated adult brain but might cause difficulty during infancy, especially if speed of processing is essential (as is the case during shorter occlusion durations). According to this later notion infants at 9 months of age and adults can represent occluded targets for 5000 ms of occlusion, when predictive both spatial and temporal representations appear adult like. Unlike the adults, infants at this age still have some problems integrating dorsal and ventral information at a sufficient speed. This diminishes performance during short occlusion durations but preserve performance at large occlusion durations.

This study poses numerous additional questions with respect to the development of spatial and temporal representations as well as the development of success rates. In Study II a similar design was used to evaluate spatio-temporal representations during the second half of the first year. Those results indicate that the abilities reported above exist at a much earlier age; in addition a new interpretation of the inferior performance at short occlusion durations is suggested.

## Temporal Representations (Study II)

Study II investigates 6, 8, 10, and 12 month-old infants' abilities to represent the spatial and temporal dynamics of occluded targets. During each visit of this longitudinal study infants were presented with circular trajectories of four different velocities which all were occluded for 500, 1000, 2000, and 4000 ms. The purpose of this study was to replicate and extend the results of Study I. By adding a longitudinal design with ages extending +/-3 months from the 9 month-olds studied in Study I we hoped to gain a better understanding of how these representations change as a function of age.

### Design

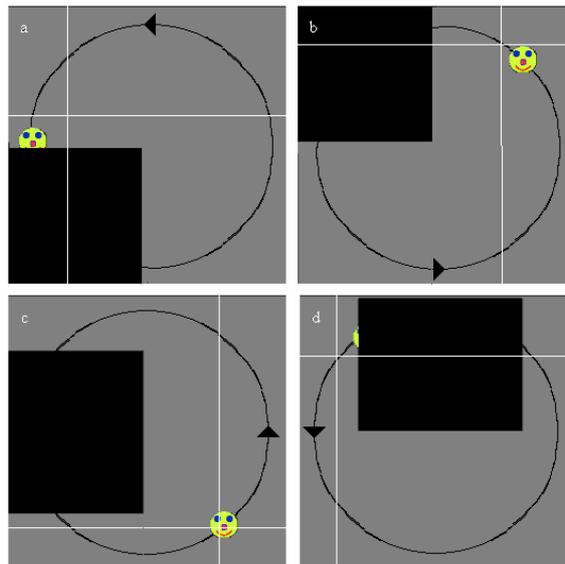
Many aspects of the design are identical to Study I. There are however some critical differences. In this study the same 'happy face' moved in a counter-clockwise, circular trajectory with a diameter of 16 visual degrees. At each visit participating infants were presented with 3 blocks of trials each consisting of four 20 s presentations. During the first block 4 fully visible trials were shown. (see Table 3.) These stimuli are not addressed in Study II, but reported as a separate study. Following these presentations, there were 2 blocks of occluded trials, each containing the same four frequencies. One of these blocks included occluders placed over the top of the vertical trajectory (see Figure 10 D) or occluders placed over the far left of the horizontal trajectory (C), these were termed 'horizontal or vertical occluders' since the location of disappearance and reappearance were similar in one of the two dimensions. The other block contained 'oblique occluders'; these included both a horizontal and vertical change in the direction of the motion behind the occluder. As can be seen in Figure 10 these occluders appeared at the lower- (A) or upper-left (B) section of each trajectory. The order of these blocks and presentation order within blocks was randomized. All in all, infants were presented with four occlusion durations (4000, 2000, 1000, and 500 ms) twice. On all occasions the target moved on a circular trajectory behind the occluder. However the demands on the observer changed. During horizontal or vertical occluders infants simply

had to move gaze over the occluder in a horizontal or vertical direction to reach the reappearance location, during oblique occluders gaze had to shift 90 degrees to reach the reappearance location.

**Table 3.** Stimulus definitions organized by occlusion duration, occlusion percentage, oblique (here 2D) vs. horizontal or vertical (here 1D) occluders, frequency, speed in visual degrees per second, no. of laps/presentation, and total presentation time in seconds.

Occlusion duration	Percentage trajectory occluded	1D/2D	Hz	Speed (°/s)	No. of laps	Total presentation time (s)
-	-	-	0.4	20.0	8	20
-	-	-	0.2	10.0	4	20
-	-	-	0.1	5.0	2	20
-	-	-	0.05	2.5	1	20
500	20	1D	0.4	20.0	8	20
1000	20	1D	0.2	10.0	4	20
2000	20	1D	0.4	5.0	8	20
4000	20	1D	0.1	2.5	2	20
500	20	2D	0.2	20.0	4	20
1000	20	2D	0.05	10.0	1	20
2000	20	2D	0.1	5.0	2	20
4000	20	2D	0.05	2.5	1	20

Note: ‘-’ equals fully visible trials



**Figure 10.** Display the 4 occluders used in Study II together with the target and location of gaze at this particular point in time; the circular arrow represents the trajectory of the target and does not appear in the display. Occluders in (A) and (B) are oblique occluders whereas (C) and (D) are vertical and horizontal occluders, respectively.

## Results

No significant differences were observed between horizontal or vertical and oblique occluders. Because of this data was averaged over the different occlusion locations in the analysis below. The proportion of included trials (see Data analysis) that were predictive changed as a function of age and occlusion durations. As infants grew older their performance improved [ $t(212) = 3.91, p < .0002$ ], infants also succeeded more often with longer occlusion durations [ $t(212) = 5.36, p < .00001$ ]<sup>3</sup>. Both effects are visible in Figure 11.

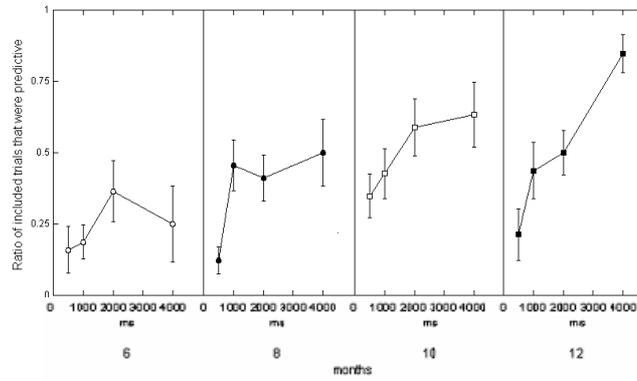
Moving from the global scale to a specific analysis of predictive trials indicated that occlusion duration significantly contributed to infants' performance. As is indicated in Figure 12 infants of all ages adjusted the timing of their predictive saccade to the time of target reappearance [ $t(143) = 7.25, p < .00001$ ]<sup>4</sup>. During short occlusion durations (500 ms) infants' timed their saccades extremely well to target reappearance. At 6 months of age infants waited 530 ms before moving to the reappearance side of the occluder, at this time the target had been visible for 30 ms. At 8 months of age the infants shifted gaze to the reappearance side, on average, 90 ms prior to visibility; infants at 10 and 12 months displayed intermediate results. At the longest occlusion duration (4000 ms) infants were less precise, averaging 1190 ms prior to visibility at 10 months and 1840 ms at 6 months. The timing of infants' successful predictions at 8 and 12 months fell in between these values.

The other measure of infants' predictive performance, spatial accuracy, reported where along the occluder edge infants predicted the target to reappear. With increased age infants moved gaze further towards the inner edge of the occluder [ $t(142) = 3.6, p < .0005$ ]<sup>5</sup> (see Figure 13).

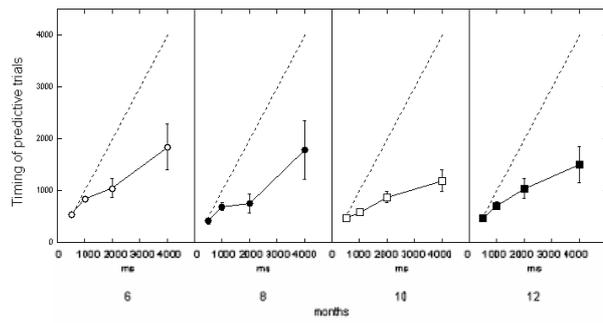
<sup>3</sup>  $F(2,213) = 23.8, p < .00001; R^2_{\text{adj}} = .175; \text{beta}_{\text{age}} = .243, \text{beta}_{\text{duration}} = .334.$

<sup>4</sup>  $F(2,143) = 26.3, p < .00001; R^2_{\text{adj}} = .259; \text{beta}_{\text{duration}} = .523.$

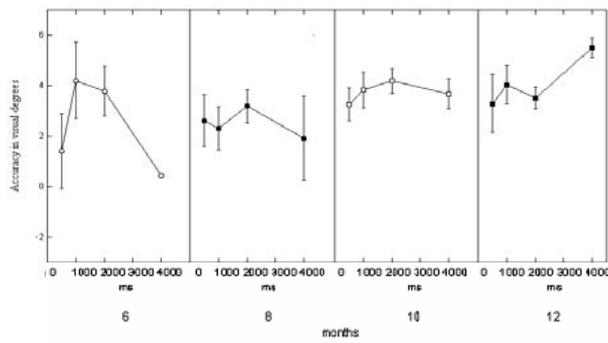
<sup>5</sup>  $F(2,142) = 6.7, p < .002; R^2_{\text{adj}} = .073; \text{beta}_{\text{age}} = .291.$



**Figure 11.** Proportion predictive trials plotted against occlusion duration and age. Error bars represent standard error.



**Figure 12.** Timing of predictive attempts plotted against occlusion duration and age. Error bars represent standard error.



**Figure 13.** Spatial accuracy in predictive attempts plotted against occlusion duration and age. Error bars represent standard error.

The average latency of non-predictive gaze shifts was 470 ms. The latency of reactive responses were dependent on age and occlusion duration. With age reaction time decreased from 600 to 410 ms over the age range investigated [ $t(212) = 4.72, p < .00001$ ] at the same time as the average reactive latencies decreased with diminished occlusion durations [ $t(212) = 5.01, p < .00001$ ]<sup>6</sup>.

## Conclusions

Study II replicates the findings of Study I whilst extending the results to incorporate the second half of the first year. At each age success rate changed as a function of occlusion duration, with a higher rate of reactive responses during short occlusion durations. At the same time predictions were geared to target reappearance and spatial predictions were accurate. Each of these aspects will be addresses below.

The result most difficult to interpret from Study I was the surprising decrease in success rate with short occlusion durations. In that study this was discussed as an effect of time of visibility or a difficulty with shifting from dorsal to ventral processing. Of these two the second appeared most promising; however it does not deliver a fully satisfactory explanation. This is because it attempts to explain a gradual change by relating to specific processes of fixed durations. If this explanation was valid the time needed to switch from dorsal to ventral processing would be exceeded at some point. Beyond this time nothing would hinder performance and an asymptote be reached. This is not the case; instead the diminishing effect of fast targets gradually weakens as the target slows down. It is likely that a number of factors contribute to regulating performance. However, a full explanation must account for the gradual change in performance.

Perceptual information about an occlusion event is contained in the successive deletion of the target by the occluder (Gibson, Kaplan, Reynolds, & Wheeler, 1982). With a slow deletion the representational strength of the target might increase because of that. At the highest target velocity (20 visual degrees / s) the target was occluded for 500 ms and the deletion event lasted only 100 ms. At the slowest velocity (2.5 visual degrees / s) the target was occluded for 4000 ms and deletion time equaled 800 ms. It is thus possible that an explanation for the diminished performance during short occlusion durations can be found in the very short duration of accretion and deletion in these conditions. According to this explanation performance is limited by the amount of information that can be derived from the scene. From 6 to 12 months of age this variable does not change.

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<sup>6</sup>  $F(2,212) = 23.7, p < .00001; R^2_{adj} = .256; \beta_{age} = -.49, \beta_{duration} = .54.$

What does change is the strength of formed representations. With increased age these representations become less vulnerable to duration of non visibility and more able to withstand competition from co-occurring objects. This is in accordance with the suggestion that representations evolve in a graded manner (Munakata, McClelland, Johnson, & Seiger, 1997). The ability to represent targets during occlusion strengthens with age and at 6 months representations during long occlusion events (4000 ms) are subject to some deterioration. This effect is less evident when the child is two months older. It is here necessary to note that weaker representations may fail to guide gaze but that it does not systematically distort the representation.

In Study II a two-factor process is presented which attempts to describe the factors that limit performance on this and similar tasks. In order for a successful prediction to occur, rich information is needed during encoding together with an ability to represent the events seen. Together these two factors explain the gradual improvement in performance with age and occlusion duration.

In the same way as demonstrated in Study I predictive performance changed little with age. At all ages, infants scaled their successful predictions to time of reappearance. At the same time spatial accuracy was good. Infants at all ages demonstrated no signs of linear extrapolations, moving gaze to the correct reappearance location or a location further towards the center of the circular trajectory. It is also worth mentioning that there were no measurable differences between horizontal or vertical and oblique occluders. In this sense infants did not simply move gaze over the occluder in a straight line ignoring the circular trajectory. Instead gaze changed direction during successful predictions by as much as 90 degrees, fixating the correct reappearance location.

The combined results of Study I and II indicate that infants from 6 months during optimal circumstances can represent the motion of the occluded object for up to 4000 ms and that 9 month-olds can do the same with up to 5000 ms of occlusion, in all instances producing accurate spatial predictions independent of disappearance and reappearance locations. The actual performance is dependent on the information available during accretion-deletion together with an increasing ability to represent non visible objects and their spatio-temporal characteristics.

## Spatial Representations (Study III)

The purpose of the 3<sup>rd</sup> and final study was to further examine the development of spatial representations of occluded objects. A longitudinal design was used with a group of infants studied at 4, 6, and 8 months of age. The object was a real 3 dimensional object moving on curvilinear paths. At each age the experiment started and ended with 4 trials where the object moved on a circular trajectory. In between these baseline trials infants were presented with one of two more complex trajectories with occlusions. These differed with respect to the information available to guide accurate spatial predictions. Either infants' were forced to rely on memories of previous occlusion events to estimate the current reappearance location (rules) or additional information about the occluded path was available from the pre-occlusion trajectory (extrapolations). Study III was designed to critically evaluate the assumption that predictions are largely based on extrapolations. The large number of occlusion events with constant occlusion durations also made it possible to evaluate the effect of experience on temporal representations, independent of the trajectories spatial properties.

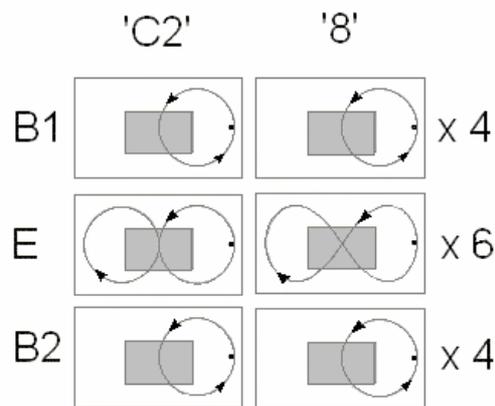
### Design

Two groups of infants were followed in this longitudinal study. Each was presented with different occlusion events, from circles (baseline) to complex trajectories (experimental condition). Presented stimuli are depicted in Figure 14 below. Both groups were first confronted with an identical baseline in which an object moved on a circular trajectory that temporarily became occluded for 660 ms. The trajectory had a diameter of 9 visual degrees, lasted 6.1 s, and moved with a velocity of 4.5 degrees/s.

After these trials participants were presented with novel stimuli that had similar or identical pre-occlusion trajectories but reappeared at a different location. Instead of continuing on a circular trajectory the motion continued along its diagonal extension; reappearing on the other end of the occluders lower edge (this first occlusion event is referred to as O1). After the initial occlusion event the target moved around the occluder and

again descended on a diagonal path (O2). Each trial was completed after the second occlusion event, when the target reached its starting position.

Despite these similarities differences did exist between the complex trajectories viewed by the two groups. One group was presented with a combination of two circles, here referred to as 'C2'. The other group was presented with a novel stimulus constructed from natural sinusoidal components (a special case of 'cassini's oval'). It will be referred to as '8' because it resembles a horizontally oriented 8. Both complex trajectories were occluded for 660 ms and extended  $9^\circ$  in vertical and  $18^\circ$  in horizontal dimensions. To maintain occlusion duration across trajectories the velocity differed slightly between baseline and 'C2' (4.5 degrees/s) vs. '8' (5.5 degrees/s) trials. Because of this difference 'C2' trials completed its path in 12.2 s whereas '8' trials lasted 10 s.



**Figure 14.** Stimulus presented to the two groups of infants in Study III. 'C2' trials include a double circle stimuli whereas '8' trials include a natural sinusoidal trajectory. The first pre- and post-occlusion trajectory (during O1) is indicated by the two arrows. Both groups include two blocks of circular trajectories (B1 and B2) with only one occlusion event per trial. The black dot at the far right of each trajectory represents the starting and finishing point of each trial.

All stimuli started moving from the right most corner of the screen. In the text to follow locations that are situated on the right side of the occluder will be represented by positive numbers whereas locations on the left side of the occluder will be represented by negative numbers. During baseline (circular trajectories) the target reappeared  $0.42$  visual degrees to the right of the central location of the occluder. On the first occlusion event of the complex trajectories the target reappeared on the left side of the occluder ( $-0.42$  degrees off center during 'C2' trials and  $-1.42$  degrees during '8' trajectories). After the second occlusion event the target again reappeared

to the left (0.42 degrees for 'C2' and 1.42 degrees for '8'). Each session ended with four additional baseline trials.

The difference between 'C2' and '8' trials relate to their degree of spatial predictability. 'C2' trajectories and circles have identical pre-occlusion trajectories; this makes it impossible to predict the reappearance location of 'C2' trials on the basis of its pre-occluded trajectory. However, '8' trajectories can be accurately predicted on the first trial if infants extrapolate the occluded trajectory.

In Study I and II it was assumed that infants extrapolate the trajectory of the target. Study III was designed to evaluate the extent to which infants use simple rules, associative rules, or extrapolations to predict the reappearance of the target. If simple rules are applied infants are assumed to base their predictions on the accumulated average of previous experience. Associative rules are more complex, infants are here assumed to formulate rules based on the specific relationship between pre- and post-occlusion trajectories. Extrapolations on the other hand are based solely on a continuation of the pre-occlusion trajectory.

Because baseline circles (a natural sinusoidal trajectory) occurs multiple times in a row both types of rules and extrapolations will result in accurate predictions, given sufficient experience. The relevant test for distinguishing these three alternatives is performance on the complex trajectories. If infants consistently guide their predictions to the center of the occluder without distinguishing between the alternating reappearance locations (O1 & O2) and produce equal performance on both '8' and 'C2' trials this will support simple rule use. The assumption that infants use extrapolations will be supported if higher or more accurate performance is achieved during '8' trials; especially if this can be demonstrated on the first trial, independent of experience. If infants are accurate and produce a high success rate on 'C2' trials this favors associative rule use. It is here worth noting that associative rules can be applied to both 'C2' and '8' trajectories. One can however assume that such associations between pre- and post-occlusion trajectories will particularly favor performance on 'C2' trials. Since the pre-occlusion trajectory is identical to baseline trials infants only need to update the expected outcome. This is assumed to be much easier than formulating entirely new rules to the novel '8' trajectory.

## Results

The rate of predictive occluder passages increased from ~28 % at 4 months to ~66 % at 8 months [ $F(2,12) = 7.65, p < .01$ ]. These predictions were not evenly distributed across conditions, instead a higher rate of predictive performance was obtained during complex trajectories than

during baseline circles [ $F(1,6) = 11.67, p < .02$ ]. No other significant difference was found between the two groups.

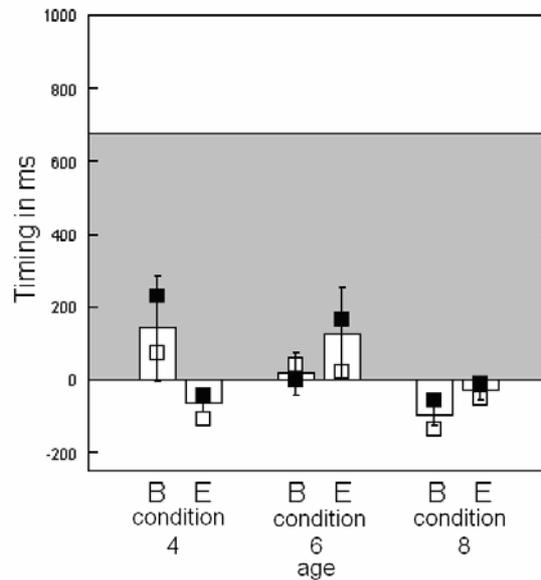
Overall, the latency of saccades decreased with age [ $t(126) = 2.54, p < .02$ ] and as a consequence of experience within session [ $t(126) = 23.34, p < .002$ ]<sup>7</sup>. At 4 and 6 months of age the median saccade was reactive (315 & 234 ms, respectively). At 8 months of age, however, more than half of all saccades were predictive; in this case the median latency was 129 ms. As can be seen in Table 4 baseline performance generally coincide over groups during baseline. At 4 months of age early occlusion events were tracked with reactive saccades whereas performance was predictive on the later trials. This general trend did not change until infants reached 8 months of age; at this age the median latency was predictive in all conditions. Differences did occur between the two different complex trajectories [ $t(61) = 2.21, p < .02$ ]<sup>8</sup>. During ‘C2’ trials the median occlusion event was tracked with predictive saccades at 4, 6, and 8 months of age whereas ‘8’ trials were not tracked with predictive saccades until their 8<sup>th</sup> month of life.

**Table 4.** The median saccadic latency at each age and segment, separately for the two groups. Dark grey areas signify predictive performance.

Age	Segment	Median	
		C2	8
4	B1	-280	-324
4	E	-129	-363
4	B2	+25	+41
6	B1	-230	-301
6	E2	-198	-313
6	B2	-211	-167
8	B1	-125	-167
8	E2	-101	-136
8	B2	-149	-196

<sup>7</sup>  $F(4,126) = 5.22, p < .001; R^2_{adj} = .115; \beta_{age} = .213, \beta_{experience} = .276.$

<sup>8</sup>  $F(4,61) = 3.24, p < .02; R^2_{adj} = .122; \beta_{‘C2’ vs ‘8’} = .264.$



**Figure 15.** Timing of predictive saccades separately for baseline (B) and experimental condition (E) at each age. Bars indicate overall performance whereas filled squares represents the ‘C2’ group and open squares the ‘8’ group. Error bars are standard error of both groups combined and the grey area indicate duration of occlusion.

The timing of the predictive occlusion events can be observed in Figure 15. At all ages timing was geared to the reappearance of the target and no differences were observed over age or condition. Reactive saccades did however decrease their latency with age from 447 ms at 4 months to 293 ms at 8 months [ $t(83) = 2.03, p < .05$ ]<sup>9</sup>.

During baseline trials infants restricted their prediction of object reappearance to an area surrounding the reappearance location of the target. At all three ages the spatial accuracy at baseline significantly deviated from the nearest alternative reappearance location (the reappearance location during the first occluder crossing (O1) during each ‘C2’ trial; see Figure 14). On average predictive saccades terminated 0.7 degrees to the right of the midline at 4 months of age; the confidence interval ranged from 0.14 to 1.26 degrees (closest reappearance location at O1 = -0.42 degrees to the left of the midline). The same averages for 6 and 8 months of age are 0.22 and 0.93 degrees with confidence intervals ranging from -0.4 to 0.8 degrees and 0.4 to 1.46 degrees, respectively.

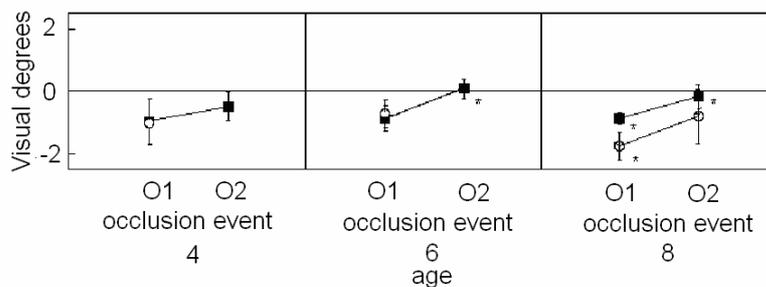
Figure 16 depicts the relative shift in the location where infants predicted the target to reappear. In this figure, data from the experimental conditions ‘O1’ and ‘O2’ were normalized with respect to

<sup>9</sup>  $F(4,83) = 2.19, p < .05; R^2_{adj} = .061; \beta_{age} = .212.$

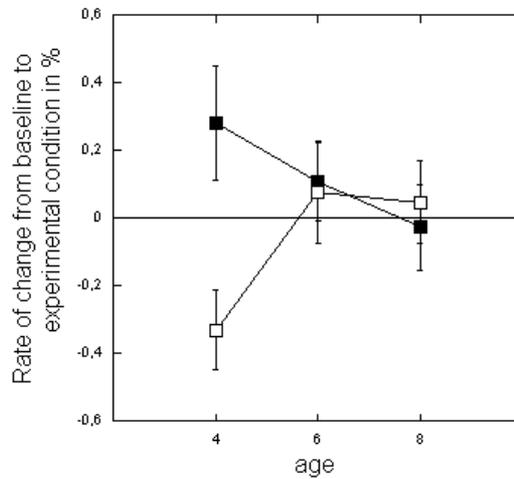
overall baseline performance, separately for each condition and age. This means that zero is equal to the average spatial accuracy on circular trials. On ‘O1’ trials the target appear 0.84 visual degrees to the left of the reappearance location at baseline during ‘C2’ trials and 1.84 degrees to left during ‘8’ trials (-0.84 & -1.84 in Figure 16). At ‘O2’ trials the reappearance location of the target is equal to baseline for ‘C2’ trajectories and appear 1 degree further towards the right during ‘8’ trajectories.

Infants of all ages correctly predicted the reappearance location of the target. This tendency was however not significant at 4 months of age. The first significant shift towards the new reappearance location occurred between ‘O1’ and ‘O2’ at 6 months of age in the ‘C2’ condition [ $p < .03$ ]. At 8 months of age infants displayed sensitivity to shifts in the reappearance location of all conditions; between baseline and ‘O1’ [ $p < .005$ ] and between ‘O1’ and ‘O2’ [ $p < .03$ ]. The only difference obtained in the group presented with ‘8’ trials occurred between ‘O1’ and ‘O2’ at 8 months of age [ $p < .005$ ].

The data presented above does not provide a direct comparison of the two groups performances. The difficulty of the two complex trajectories can be assessed by looking at the relative change in success rate from baseline to each complex trajectory. As can be seen in Figure 17 it is only at 4 months that infants presented with the ‘8’ trajectory deteriorated in performance, compared to baseline. This is expressed as a main effect of condition, with higher overall relative performance during ‘C2’ than ‘8’ [ $F(1,6) = 13.52, p < .01$ ], and as an interaction between age and condition [ $F(2,212) = 4.57, p < .03$ ].



**Figure 16.** Shift in spatial accuracy normalized with respect to predictions at baseline. Filled squares equals the ‘C2’ group whereas open circles equals the ‘8’ group. The midline of the occluder represents zero on the vertical axis with positive numbers indicating a position further to the right along the occluder. ‘\*’ represents a significant change from previous predicted reappearance location (from ‘B’ to ‘O1’ and from ‘O1’ to ‘O2’), error bars depict standard error.



**Figure 17.** Change in percentage successful predictions from circular to ‘C2’ (filled squares) and ‘8’ trials (open squares) at each age. Error bars represents standard error.

Predictions at the first trial of baseline and experimental conditions can be observed in Table 5. Here data has been dichotomized as correct or incorrect dependent on which side of the occluder participants expected the target to reappear. Overall (independent of age) more accurate spatial predictions were performed during the first presentation of ‘8’ trials then during ‘C2’ trials [ $\chi^2(1) < .03$ ]. Only two conditions displayed a substantially large number of correct predictions to significantly distinguish itself from chance (0.5). Both groups belong to the 8 month-olds and include baseline [CI =  $.875 \pm .229$ ] and ‘C2’ trials [CI =  $.9 \pm .186$ ]<sup>10</sup>.

<sup>10</sup> A test of spatial accuracy on the first trial during ‘C2’ and ‘8’ groups, separately for the 8 month group using  $\chi^2$  depict a trend in favor of ‘8’ presentations [ $\chi^2(1) < .06$ ].

**Table 5.** Infants' response to the first presentation of complex trajectories. Grey area highlights 8 month-olds performance. \* = significantly different from chance (0.5).

Age	Condition	Predictive	Correct placement
4	B1	1	1
4	C2	3	2
4	8	1	1
4	B2	4	2
6	B1	4	2
6	C2	3	2
6	8	3	3
6	B2	4	1
8	B1	8	7*
8	C2	8	4
8	8	10	9*
8	B2	7	3

## Conclusions

Both Study I and II focused on temporal representations. In both of these studies the results were interpreted as products of an extrapolation process. Study III was designed to emphasize spatial representations and critically evaluate what process guides performance. This was done by varying the trajectory and reappearance location of the target at the same time as duration of occlusion was held constant at 660 ms. In the following three major points will be addressed, they relate to temporal representations with an emphasis on learning, spatial representations, and a discussion on which mechanisms control accurate predictions.

Regardless of age, when infants made predictive gaze shifts over an occluder they waited at the disappearance edge until the target is just about to reappear. This effect has been demonstrated for 9-month-old infants and adults in Study I, for 6- to 12-month-olds in Study II, and now for 4- to 8-month-olds in Study III. At the same time, the overall timing (combined over reactive and predictive trials) decreased with age and within sessions. At 4 and 6 months of age infants needed to view at least 16 occlusion events to form stable representations of occlusion duration. The rate of learning could be enhanced if the pre-occlusion trajectory was similar during all 20 occlusion events. This was the case in the 'C2' condition; here infants produced stable predictions of occlusion duration already during complex trajectories; after 4 baseline events. All differences (with respect to timing) between the two groups disappeared at 8 months of age. At this age infants produced more than 50 % predictions in all conditions of both groups.

Much can be said with respect to spatial representations, starting with baseline performance. In Study I 9 month old infants and adults both predicted the reappearance location of occluded objects moving on circular trajectories following occlusion. The same precision was found in Study II from 6 to 12 months of age. In Study III infants were able to accurately predict the reappearance location of circular trajectories at 4, 6, and 8 months of age. The current study replicated the previously observed spatial accuracies and adjusted the lower age limit at which this ability is observed to include 4 month-olds.

The complex trajectories were designed to give an indication of how the process guiding spatial accuracy is constructed. One possibility is that infants simply remember the reappearance location of previous trials, regardless of the targets trajectory; here referred to as *simple rules*. An alternative and more complex form of rule use is based on an association between pre- and post- occlusion trajectory; called *associative rules*. The third alternative is obviously that infants base their prediction on an *extrapolation* of the trajectory, as originally assumed in Study I and II.

All three alternative hypotheses predict accurate performance on baseline trials. These circular trajectories have a constant reappearance location (in accordance with simple rule use) and a constant relation between pre- and post- occlusion trajectories (in accordance with associative rules). The trajectory is furthermore consistent of two natural sinusoidal trajectories (making extrapolations possible).

During complex trajectories the predictions do however differ. In a situation with constantly changing reappearance locations (as is the case during ‘C2’ and ‘8’ trials) the results do not support an overall reliance on simple rules. If infants consistently used this strategy their predictions would average at the center of the occluder, halfway between the reappearance locations at both ‘O1’ and ‘O2’. At all ages the average performance shifted to the left during ‘O1’ and back to the right during ‘O2’ trials. The fact that no significant shift from ‘O1’ to ‘O2’ were found at 4 months of age might result from partial simple rule usage; which cause an increase in variability but only marginally affects the average performance. It is clear that infants at this age decrease their success rate in response to ‘8’ trajectories, compared to baseline performance. During ‘C2’ trials infants even increase their performance.

Together the results at 4 months indicate that infants use associative rules to predict the reappearance of the target. This ability is accentuated if the pre-occlusion trajectory is identical throughout the entire experiment. In the transition from baseline to ‘O1’ infants did not need to formulate new rules from scratch, only update the expected outcome and act accordingly. The same information is not utilized during ‘8’ trials because of the trajectories novelty. In this situation infants do not have enough time to produce a new rule based on the novel pre-occlusion trajectory.

At six months performance is more equal in the two groups with similar rates of success during circular and complex trajectories. However, there is still a large portion of reactive occluder crossings in the '8' group, and only significant differentiations between 'O1' and 'O2' predictions during 'C2' presentations. Previous studies (von Hofsten, Feng, & Spelke, 2000) have demonstrated that 6 month-olds have a tendency to base their predictions on an extrapolation of the trajectory. It is likely that the current results are caused by an emerging ability to extrapolate the trajectory, in combination with a sustained ability to form associative rules.

At 8 months of age infants have the ability to form associative rules and extrapolate the trajectory at both baseline and experimental conditions. The former is learnt rapidly whereas the later is present from the first trial.

## General Discussion

In Study I our goal was to investigate how object representations deteriorated with increased occlusion durations. Study III was thought of as an opportunity to validate the claims made in Study I and II that successful predictions were caused by an extrapolation process. The results reported above were surprising, to say the least. We did not expect to find an improvement in performance with prolonged occlusion durations. Nor did we expect infants to use associative rules prior to extrapolations. One should however not be discouraged by unexpected results. As it appears infants have a much more robust sense of object representations than originally assumed. In the following each of the four questions asked in the general aims section above will be addressed separately.

### Temporal Representations

In Study I both infants and adults demonstrated similar response patterns to different occlusion durations; adjusting their predictions of object reappearance to the reappearance of the target. On average 9 month-olds waited ~2300 ms and adults ~3500 ms before moving to the reappearance side of the occluder during a 5000 ms occlusion event. The latency during a 2500 ms occlusion event equaled ~1700 ms for 9 month-olds and ~2500 ms for adults; the same latencies for a 1250 ms occlusion event were ~900 and ~1000 for infants and adults, respectively.

In Study II this general trend was replicated. During a 4000 ms occlusion event the average latency of predictive saccades ranged from ~1800 ms at 6 months to ~1200 at 10 months of age. At a 500 ms occlusion duration infants waited ~530 ms at 6 months and ~400 ms at 8 months of age. Performance at the other ages averaged within a range restricted by the above mentioned values. In Study III occlusion duration was constant at 660 ms throughout the entire session. From 4 months of age infants were able to predict the reappearance location of the target after massive experience. This learning effect will be addressed separately below. For now it will suffice to note that the average prediction of object reappearance was geared to

occlusion duration. At four months of age saccades over the occluder were initiated ~150 ms prior to the targets reappearance during circular trajectories (baseline). During complex trials the latency averaged ~50 ms following reappearance.

From the data presented above it appears as if infants and adults have a similar notion of occlusion duration. The exact latencies obviously fluctuate to some degree but average near 2/3 of the actual occlusion duration (see Figure 8 & 12). What is the significance of this finding? Does this represent an optimal strategy based on a time/accuracy tradeoff or does this reflect a ratio of perceived to real time?

If infants have the ability to represent time of occlusion it does seem reasonable that perceivers wait until the target is just about to reappear before gaze moved across the occluder. This increase the time available to calculate where and when the target will reappear. In the same line of reasoning it also makes sense to move gaze across the occluder ahead of the target. This way gaze is close to the target as it emerges and possible errors can be corrected swiftly.

There is, however, indications that adults underestimate time of occlusion in other situations that can not be attributed to a time/accuracy tradeoff. Luca Bonatti (personal communication) has run experiments where adults estimate the time of occlusion. At most velocities presented, the time of occlusion was underestimated. In their study the target had to move at a sufficiently low speed (2 to 4 degrees/s) for occlusion durations to be accurately estimated. In our study these velocities still resulted in underestimations and it is unclear to what extent the two situations are parallel. It is unlikely that the two studies use the same relationship between occlusion duration and velocity. Furthermore, in Bonatti's study adults simply indicated when they thought the target was about to reappear whereas Study I measured gaze shifts without prior instructions to match timing with occlusion duration. Whether these results are the first indications of a perceived to real time ratio or not is obviously (as everything else) an empirical question, best resolved outside this thesis.

Regardless of which alternative interpretation one prefers it is obvious that infants have the ability to form stable representations of occlusion duration from 4 months of age. There are no indications that performance deteriorate with increased occlusion duration. Instead, the rate of successful predictions was guided by the amount of information available during encoding. If the actual accretion-deletion event (the time for the target to disappear and reappear) was long stable representations were formed, however, if this event occurred quickly the rate of successful predictions decreased.

## Spatial Representations

In Study I and II, infants were presented with two blocks of occlusion events, each containing four trials. In both studies infants predictions centered on (or near) the actual reappearance location of the target. No differences were found with respect to the position of the occluder or whether the change from pre- to post-occlusion locations involved horizontal, vertical, or oblique translations. Because the expressed spatial accuracy had a tendency to underestimate the amplitude of the circular trajectory it was assumed that infants (and adults) held a complex understanding of inertia. This means that their predictions were guided by the assumption that whatever forces acted on the target prior to occlusion would remain constant during occlusion. This interpretation was contrasted with the possibility that subjects made a linear extrapolation based on the tangent of motion just prior to occlusion. If infants were guided by the later assumption, predictions would end at the opposite end of the occluder. No such tendencies were observed.

Study III replicated these results. Here infants moved to the correct side of the occluder at 4, 6, and 8 months of age. It thus appears that infants have the ability to accurately predict the reappearance of circular trajectories at all ages tested. However, if infants actually extrapolate the trajectory or not is difficult to assess based on these results. It is possible that infants associate the pre- and post-occlusion trajectories and thereby learn where the target will reappear. Study III was designed to evaluate these alternatives. Based on the results from this study it is obvious that infants have the ability to change their expectations based on experience. We also found indications that the ability to create rules emerges at an earlier age than the ability to make predictions based solely on the current pre-occlusion trajectory. According to this study 4 month-olds base their predictions on associative rules, guided by experience. The results at 6 months demonstrate an intermediate result, with large similarities between the two groups. It is not until infants reach 8 months that clear evidence of extrapolations are observed, with accurate predictions on the first complex occlusion event.

The results at 6 months can be interpreted in two ways, either as more efficient rule use or an emerging extrapolation process. Previous studies (von Hofsten & Spelke, 2001; von Hofsten, Feng, & Spelke, 2000) have describes an initial tendency to extrapolate the trajectory at this age. The same studies have also demonstrated that this initial tendency can be overcome, in favor of non linear predictions given experience. It is therefore likely that predictions can be guided by both associative rules and extrapolations from 6 months of age. Obviously more experimental evidence is needed before one can make any global statement about the relative contributions of associative rule use and extrapolations.

## Learning

We know that learning can occur quickly and without explicit rewards. This was demonstrated by Saffran, Aslin, and Newport (1996). In their study 8 month-old infants were able to segment units of syllables based on the statistical properties of a two minute exposure to nonsense syllables. We also know that learning occurs during presentations of occlusion events. Nelson (1971; 1974) demonstrated that both 5 and 8 month-olds moved gaze further towards the reappearance location of an occluded train with experience. Rosander and von Hofsten (2003) demonstrated that young infants decreased the latency of saccades during an occlusion event from 7 weeks onwards. In addition von Hofsten, Feng, and Spelke (2000) and von Hofsten and Spelke (2001) demonstrated that infants can learn to expect a linearly moving target to change direction behind an occluder from 6 months of age.

Johnson, Amso, and Slemmer (2003) brought forth the argument that experience is needed for 4 month-olds to hold stable object representations. In their study 4 and 6 month old infants were presented with non-occluded trajectories prior to occlusion events. The younger infants were found to benefit from this treatment and increased their predictions in the occlusion events to follow. No such benefits were found at 6 months of age. The notion that 4 month-olds need training with fully visible trajectories received little support in Study III. Half of these infants were presented with linear non occluded trials with little resemblance to the occluded trajectories. This had no effects of performance. Instead we have demonstrated that all infants increase the strength of their representation with experience. Over occlusion events presented the latency of saccades decreased. Given a sufficient number of similar presentations (16 at 4 months-of-age) the median occluder crossing was predictive. From Study III one can conclude that learning is a crucial element at both 4 and 6 months of age. It appears that infants can rely solely on experience independent extrapolations from 8 months of age.

Based on the above mentioned results it becomes rather evident that infants can learn from experience, a fact that will come as no surprise to most of us. But what do we know about the endurance of the acquired information. Rosander and von Hofsten (2003) claimed that learning was rapid but also that infants forgot at an equally rapid rate. In their study saccadic latency decreased within each trial but at the beginning of the next trial the latency was once again back to original levels. Study I and II did not find any evidence of learning. What all these studies have in common are randomised block designs in which different parameter of the occlusion event change within each session. In Study I and II both occluder locations and target velocities varied within the session. In Rosander and von Hofsten both occluder location and the targets trajectory varied between

trials. Perhaps the absence of continuous experience limits the ability to learn in these studies. In Study III infants benefited from experiences across trial boundaries. For such long term learning to occur there had to be a high correspondence between trajectories presented at the same time as occlusion duration was held constant and the occluder remained at the same location over trials. This is why saccadic latency rapidly decreased during ‘C2’ presentations but not during presentations of ‘8’. If events are repetitive and clear learning will be both rapid and long lasting.

## A Final Note on Development

The ability to predict the reappearance of temporarily occluded objects as described in this thesis represents a good example of prospective control. At each age infants matched the spatiotemporal dynamics of their predictions to the target. Given this consistency across age, is there any evidence of actual development?

All in all, three major developmental trends can be found, each of which can be represented by one of the three components of prospective control (action, perception, and cognition). Of course neither is isolated and the discussion of each will incorporate all.

The *action* component is manifested as an increase in the percentage of predictive responses with age. There are no indications that development of success rate (at least using a tracking paradigm) can be separated into discrete steps. This means that the ability to represent and predicatively track occluded objects is not guided by a sudden understanding of the workings of the world. Instead infants have the ability to accurately represent the spatio-temporal dynamics of occluded events from 4 months of age. Whether the target will be tracked with predictive or reactive saccades depends on the strength of underlying representations; if these are strong actions will be prospectively guided. What differs with age is the amount of information needed to form stable representations. This continuous development is best represented by the graded representations hypothesis (Munakata, 1998).

In Study II it was concluded that success rate was determined by a two component process. The first involve the strengthening of representations with age. The second relate to the amount of information available in the scene. If the time of accretion/deletion is lengthy the resulting representation will be strong, if the same event occurs quickly representations will be weak. Additional factors might include the richness of the scene. For example a 2-dimensional simulation of an occlusion event (Study I & II) is assumed to result in more impoverished representations

than a real 3-dimensional occlusion event complete with shadows and depth (Study III).

The *perception* component involves perceiving regularities and structures in one's surroundings and applying this information to the current context. Developmental differences are here measured as differences in rate of learning with age. At 4 and 6 months of age a relatively large amount of experience with close to identical trajectories are needed before infants have an accumulated representation that is strong enough to guide behavior in a consistent manner. However as infants reach 8 months of age they rapidly update the expected outcome. At this age infants have the ability to act on information provided in the previous trial but also to disregard this information if the current context points in a novel direction.

The *cognitive* component deals with which process actually guides predictive performance. In Study I a possible interpretation of data included an increased ability to integrate dorsal and ventral processes. We concluded that this effect could not alone account for the complexity of data but such system integrations likely holds some influence on the results. Instead we must conclude that numerous different processes can result in similar accurate performance. Development is here classified as a transition towards parallel processing of differentiated systems, each with a slightly individualized job description. Much is still unknown about the actual processes involved in processing temporarily non-visible objects. This transition is partly illustrated in Study III where predictions are first based on long experience and associative rules. With increased age additional abilities appear; such as the ability to extrapolate the trajectory without previous experience.

## Future Directions

The three studies included in this thesis have, hopefully, increased our understanding of the development of object representations during infancy. Much of this thesis has discussed what factors limit performance. It is my understanding that the main limiting factor during an occlusion event is the strength of object representations available to guide actions. Our understanding of how different stimulus properties influence these representations is still limited. Future studies need to focus attention on mapping the stimulus array and compute the relative contribution of duration of accretion/deletion, velocity of target, size of the occluder, and of course duration of occlusion.

A second important future direction involves a more systematic untangling of the processes guiding accurate predictions. This

work was started in Study III but is far from complete. Two kinds of studies are highly needed at this time.

1) There is a need to map out the relative contribution of extrapolations and associative rules. The stimuli presented in Study III found clear evidence of early associative rule use. It is still uncertain whether other situations will favor extrapolations at an earlier age or if associative rules is the only tool available at 4 months of age? For now little can be said with certainty on this matter but it is my firm belief that these processes are *not* dichotomous but graded (as most other cognitive capabilities). If this is the case we have a second landscape to explore; what stimulus parameters enhance rule use and what parameters enhance extrapolations?

2) The name associative rule was chosen to describe an unknown process that guides predictions based on previous experience. We do not know whether these predictions are organized through associative learning as described by the Rescorla-Wagner theory (Rescorla & Wagner, 1972) or through rules created on the rational assessment of contingencies (Waldmann & Holyoak, 1992; Cheng, 1997). There are strong claims made in both camps but it is unclear what mechanisms guide early actions. My own contribution to this discussion did not favor the associative framework. As parts of my undergraduate work myself, Anders Winman, and Peter Juslin was able to demonstrate that adults can represent and report perceived events in a far more accurate manner than predicted by associative theories; in support of more rational theories of human cognition (Gredebäck, Winman, & Juslin, 2000). Which mechanisms actually guide early object representations is a critical but also difficult question to ask. Perhaps the answer must be sought on a broader level beyond object representations. As always these are empirical questions hopefully addressed in the near future.

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Uppsala, February, 2004.  
Gustaf Gredebäck



# Acta Universitatis Upsaliensis

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