Predictive action in infancy: Evidence of early prospective behavior

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Abstract

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How do young infants understand and act on their constantly changing environment? An action perspective on motor development was taken into account. The present thesis investigated perception guided predictive action in 6-month-old infants, namely, head tracking and reaching for an object moving on a pre-defined trajectory, linear or nonlinear, fully visible or partially occluded. The motion trials were presented in a randomized order or in a way by using an ABBA block design.

Study I of this thesis began with the exploration of the principles underlying infant predictive action. Infants were presented a fully visible moving object on four trajectories: two linear trajectories that intersected at the center of a display and two non-linear trajectories that contained a sudden turn at the point of intersection. The results supplied evidence that both infants' head tracking and reaching showed an extrapolation of the object's motion on linear paths, which was described by the principle of inertia. No learning effect was found in spite of repeated fully visible trials.

Previous experiments reported that infants of similar age showed a reduction in reaching when object motion was occluded briefly. Thus Study II was undertaken, in part, to evaluate whether differences in the tasks presented to infants or differences in the visibility of the objects account for these findings. This was done by investigating infants' predictive head tracking of an object following the procedure presented in Study I with only one exception: object motion was partially occluded by a small occluder positioned on the motion trajectory. Study II also raised a second question concerning infants' ability to learn to anticipate upcoming object motions. It was found that infants were able to quickly learn to anticipate either linear or nonlinear motion but with a superior learning effect from linear motion. This pattern suggested a tendency to anticipate the upcoming motion in accord with inertia. Although a capacity to anticipate occluded object motion in accord with inertia was present, it was weak, as infants' initial reaction to the occluded object motion revealed no such tendency. Learning in all cases was associated with the trajectory of the object, not the specific locations at which the object appeared. It was suggested that infants might form object representations that are influenced by learning and that are just weakly biased toward inertia extrapolation. This finding supported the claims that occlusion reduces the presentation of object representation, as suggested by single system of object representation theory.

When hand preference was considered as the consistent use of one hand in a given task, findings in infant reaching seem controversial. For studies in infants, most investigations were conducted on stationary tasks, very few, if any, on moving objects. Furthermore, timing and temporal coupling are important to motor control and coordination of many levels. Yet, many characteristics embedded in the temporal coupling of young infants' movement associated with reaching, particularly, for moving objects, remains to be elucidated. Study III made an attempt to do that. Infant's reaching movement was investigated in the same setting as in Study II but without an occluder. It was found that the infant used more unimanual than bimanual reaches during this moving object tasks, and that the rate of hand-object touch was more evident for the right hand than for the left hand. However, no significant hand preference was found. Nevertheless, Study III revealed evidence of an asymmetry pattern in temporal coupling by means of a significant shorter latency and longer duration of left hand movements. Furthermore, a relationship between latency and duration was also evident in a pattern that the longer the latency, the shorter the duration in infant unimanual reaching movements, which was in partial agreement with the previous report.

This thesis for the Licentiate Degree is based on the following studies, which will be referred to in the text by the Roman numerals:

I. von Hofsten, C., Vishton, P., Spelke, E. S. Feng, Q., & Rosander, K. (1998). Predictive action in infancy: Tracking and reaching for moving objects. *Cognition, 67*, 255-285.

II. von Hofsten, C., Feng, Q., & Spelke, E. S. (2000). Object representation and predictive action in infancy. *Developmental Science, 3*, 193 - 205.

III. Feng, Q., & Rönnqvist, L. (2006). Characteristics in reaching for moving object in 6-month-old infants: The effect of predictivity and laterality (manuscript).

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Qi Feng, M.D., M.Sc.
Canada, Winter 2009

The examined life is not a series of jobs. It is beliefs, interests, trials, and dreams to carry through everything we do.
-Adrienne Clarkson, Governor General, Canada

Science without conscience is but the ruin of the soul.
-François Rabelais, French writer and physician

Contents

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INTRODUCTION

Human infants are provided by evolution an urge to use their perceptual systems to explore and act on the external world. During the first year of life, infants develop their knowledge of the permanent features of the world, the predictable relations between events /objects and their knowledge of their own capabilities for acting on them (Gibson, 1979, 1988). However, despite the undoubted attraction of this special period to human science, it remained enigmatic for a long time in history. The reason that hindered the progress in understanding ourselves can be reflected from the Latin root of the word infant-infans, which means "one unable to speak". Without language, the most effective channel of interpersonal communication, the access to the infant's view of the world was effectively barred. Over the last few decades this obstacle was finally surmounted when researchers discovered a variety of ingenious and often powerful tools that turn into account on abilities that the infant does possess from birth and which can be pressed into service as communication media. From then on the study of the infant's perception and action systems turned out to be possible and began to bear fruit when researchers adopted the natural exploratory activity to infer questions: How are perception and action integrated in infants? What kind of information do infants extract from the object presented to them? How do infants apply the information and act upon the object and event? Is their action constraint guided? If it is, what kind of constraint is involved? (e.g., Gibson, 1979, 1988; von Hofsten, Feng, Vishton, & Spelke, 1994; Spelke, Vishton, & von Hofsten, 1995; Spelke & Newport, 1998; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998; von Hofsten, Feng, Spelke, 2000; Spelke & von Hofsten, 2001). Because motor development is at the heart of development and reflects all its various aspects such as perception, planning and motivation (Piaget, 1953, 1954; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; von Hofsten, 1983, 2004), these questions are getting the worldwide attention of developmental science. Two foremost behavior examples of predictive actions: head tracking and hand reaching an object, have been adapted for investigating the cognitive development in pre-verbal infants (e.g., von Hofsten, 1980; Yonas & Granrud, 1985; von Hofsten & Spelke, 1988; van der Meer, van der Weel & Lee, 1994; von Hofsten, et al. 1998; von Hofsten, et al. 2000; Claxton, Keen & McCary, 2003; Summervill & Woodward, 2005).

Perception and Action

Perception is the process by which we gain knowledge about our environment and about ourselves in relation to the environment (Gibson, 1979). More of the human brain is devoted to perceptual information processing than to any other function (Kellman & Arterberry, 1998). Evolution must have a meaningful reason for that.

Perception - the ecological perspective

The ecological approach to perception was developed over a three-decade period by J. J. Gibson and E. J. Gibson and associates (see Gibson, 1950, 1966, 1979; Gibson, 1979, 1988; Gibson and Pick, 2000, for a review). According to Gibson, every species has evolved in a habitat, and in the long course of evolution, its niche and its biological structures have developed in reciprocity with one another. The perceptual systems developed in the context of this mutual relationship as well. Human perceptual systems have adapted to enable the perceiver to actively pick up the meaningful information - the affordances, a term introduced by J. J. Gibson, from things in the environment and this information in turn guides ongoing behaviors (Gibson, 1966). The affordances imply the complementarity of the animal and the environment (Gibson, 1979). Although the ecological views do assert perceptual change (more mature with development and more skilful with practice) through a lifespan, it does stress its essence in that perceptual development begins with meaningful contact with the world; and meaningful contact with the environment is possible without the necessity of enrichment of perceptual experience. Perception is pivotal in human development because understanding and interaction with the physical and social world are both enabled and constrained by what can be perceived. Infants, as now we know, have some remarkable capabilities to perceive important properties of the external world and have considerable capacity to make sense of the world. For very young and relatively immobile infants, visual exploration is the major means to acquire information and knowledge about the physical environment (Bjgelow, 1986, 1992; van der Meer, van der Weel & Lee, 1994; also see Kellman & Arterberry, 1998 for a review). The knowledge of and assumptions about the early perceptual development of the infant have great consequences for our conceptions of perceptual development as a whole (von Hofsten, 1983, Gredebäck & von Hofsten, 2004).

The role of visual perception and self-sitting ability in infant reaching

The study of early visual perception has a long and contentious history. It has been assumed by many theorists (e.g., Piaget, 1953, 1954) that infants have to learn to see by correlating touch with vision - the assumption of "touch tutors vision". If we just consider the poor motor control in the early life, we would be facing the great mismatching due to the errors in the motor system, not to mention other factors (Rochat, 1999). The Gibsonian perspective did therefore not share this "touch tutors vision" ideal. Instead, the ecological view claimed a close coupling of perception and action, reversing the traditional formula that perceptual knowledge originated from sensorimotor activity (Gibson, 1966, 1979; Turvey & Fitzpatrick, 1993, for a review). In fact, initial perceptual competence appears well before the beginning of coordinated crawling, walking, reaching or grasping (von Hofsten & Rosander, 1996, 1997). It is argued that perceptual competence guides the emerging action systems (von Hofsten, 1980, 1983). Observations in blind children also confirmed that perceptual development guides motor development. The lack of visual input would be expected to affect action on almost any account of development. For instance, it was found that onset of reaching happens about 1.5 to 8 months later in blind than in sighted infants. It is suggested then, that the emergence of certain actions such as reaching, crawling, and walking in sighted children depends upon information about the environment and the self (Bjgelow, 1986, 1992). With a firm foundation in perception and perceptual guided action, development could then precede.

Though human infants are born with an immature visual system, their visual abilities emerge and develop dramatically fast during the first few months of life (Banks & Shannon, 1993; Aslin, 1986, Aslin & Salapatek, 1975). When measured by the reduction on the lag of the smooth pursuit, it was found that from one to five months, infant's eye and head tracking to moving objects was rapidly improving (von Hofsten & Rosander, 1996, 1997). At five months infants showed some anticipation in their tracking (Haith, Hazan, & Goodman, 1988; Canfield & Haith, 1991). Saccades were predictive from 6 months onward when measured by average lag (Gredebäck, von Hofsten, Karlsson, & Aus, 2005). Head tracking is also improving between three to five months. Daniel and Lee (1990) studied infants 11 to 28 weeks of age and found that some of the oldest infants used head movements almost exclusively to track the moving objects. It suggested that the co-ordination between eye movement and head tracking improved with age (von Hofsten & Rosander, 1996). In summary, visual perception becomes much more mature and approaches adult-like performance at around the age of six months, that is also at the time when infants' self-locomotion begins (von Hofsten & Rosander, 1996, Rosander & von Hofsten, 2004, Gredebäck & von Hofsten, 2004; Gredebäck et al, 2005).

The emergence of self-sitting ability by 5-6 months of age is a major milestone of early motor development (Gesell, 1946). Recent study suggested that a significant reaching frequency increased in the seated position can be observed as early as 4-month-old (Carvalho, Tudella & Savelsbergh, 2007). It was suggested that the development of self-sitting posture, which occurs within a relatively predictable timeframe, is not only a potential control variable of early action development. In fact, the infant reaching and the infant's whole body engagement in reaching is posture dependent (Rochat, 1992, 1995). Therefore infants who had reached this milestone age were chosen to be the subjects in the studies included by this thesis. However, the interaction between posture and action in infancy and its potential impact on early perception, action and cognitive development is not the main focus of this thesis but can be found in other studies (e.g., Gesell, 1946; Rochat, 1992, 1995; Rochat & Goubet, 1995).

The importance of motion perception

Gibson (1966, 1979) has argued strongly that too much emphasis in psychology has been placed on the perception of static and very simple displays by static observers in a highly uniform when in fact the human perceptual system has actually evolved to cope with a visually extremely rich world in which we are constantly moving and experiencing in the visual array, and the information cues afforded by changes and movement are important in determining the interpretation we place upon a visual scene, in forming our representation of our world and in preparing our action to act upon it.

Detection of movement is essential for survival for animals even at the lower part of the evolutionary scale (Gregory, 1995). In the real world objects and perceivers are often moving rather than stationary. Nothing but change is permanent. The information afforded by movement and change is important in determining our interpretation of a visual scene (Smyth, Collins, Morris, & Levy, 1994). Early sensitivity to motion and change in human infants would be a prerequisite for tapping their reservoirs of dynamic information (Bertenthal & von Hofsten 1997; Canfield & Haith, 1991, Corbetta, 2006). Abilities to perceive motion and moving events serve to support infants' understanding of their environment and their actions upon it. The ability to localize and to follow moving objects by visual fixation and head tracking is part of a pre-adapted system. This system is imperfect but functional at birth (Gibson, 1988). Furthermore, infants preferentially detect and attend to motion, such as an object moving across the field of view (von Hofsten, Kellman, & Putaansuu, 1992). The static object generally arouses little interest to the infant in comparison to the moving object (Robin, Berthier, & Clifton, 1996). Although it is not clear whether infants' attention to motion reflects a response to motion per se or attention to what is most informative, visual motion does supply a powerful stimulus.

"If you want to attract an infant's attention, move something in front of its eyes" (Kellman and Arterberry, 1998, pp. 182).

Characteristics of perception guided action

"…the perception-action relation is a reciprocal one, a kind of continuous cycle with perception guiding action, and actions furnishing new information for perception… 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 for preparing for later action." (Gibson & Pick, 2000, pp.22-23)

As affirmed above, the perception guided action approach has at least three important characteristics: reciprocity, purposefulness and prospectiveness.

First, perception and action systems are reciprocal. Actions are not possible without perception. All spatially and temporally coordinated behaviors require the coupling of perception and action (Bertenthal & von Hofsten, 1997; Bertenthal & Clifton, 1998). If we consider the action system functionally, the perception system is tied-in with the action system (von Hofsten, 1980, 1983; Reed, 1982). For example, reaching for an object in the environment is guided by perceptual (mostly visual) information that changes as the reach progresses. These perceptual changes modulate the effectors to ensure that the reach is successful (Jeannerod, 1997; see also Bertenthal & Clifton, 1998). Perception has evolved to serve action and is a necessary part of any action system (Bernstein, 1967; Gibson, 1979). As J. J. Gibson put it "We must perceive in order to move, but we must also move in order to perceive" (Gibson, 1979, p.223). In the process of development, perceptual control of behavior depends on the detection of the relevant perceptual information as well as the functionality of the actions available to the infant (Bertenthal & Clifton, 1998). All spatially coordinated behaviors, such as visual tracking and reaching require perceptual information and action to be coupled.

Second, purposefulness is a basic irreducible aspect and an important feature of the perception - action system (von Hofsten, 2004, for a review). From a Gibsonian point of view, perception and action have to do with what meaningful information (the affordance) about the world we can obtain by using our perceptual capabilities and what purpose we can apply on it. Although triggered movements have commonly been the subjects of intensive study in attempts to understand motor control, such movements are probably extremely rare in everyday life (Reed, 1982). Even the simplest movements that the nervous system could produce already appeared to be organized purposefully (Jeannerod, 1997).

Third, to adapt quickly and precisely to a varied and often changing environment, our many real-world skills must execute prospectively. Thus, prospectiveness, or future-orientation, as Haith (1993) called it, is then the key component of successive action and is the one to be focused in this thesis. Successful actions must fit many simultaneous constraints defined by the parameters of the world we act in, the physical structures and mechanisms of our bodies, the processing characteristics of our nervous system, and the goals that stimulate our perception and motivate our actions (Bernstein, 1967). Without the feature of prospectiveness, flexibility and precision can be very difficult to achieve jointly, especially under tight time constraints (Roberts & Ordrejko, 1994). Predictive action demands a rather precise temporal and spatial coordination between visual input and motor output (Robin, et al. 1996, Flanagen & Johansson, 2003). For instance, to reach for a moving object the human brain must process incoming information about the object and its motion, it must plan goal-directed actions, send appropriate commands to the efferent system and activate relative muscles that shape the action. Just like any information processing, this process takes time (about tenths of a second) to utilize available perceptual information and to organize any upcoming action (Claxton, Keen & McCary, 2003, von Hofsten & Rosander, 1996). Because of the internal time lag of the perception-action system - a basic problem in sensorimotor systems (von Hofsten & Rosander, 1997), perceptual information must generally be used prospectively, not retroactively (i.e., following feedback from the action) in order to keep the smooth continuity of movement (Bertenthal, 1996; Flanagen & Johansson, 2003). To hit a flying badminton shuttlecock, for instance, I need to make judgment and prediction of where the shuttlecock is heading. I also need to anticipate the racket in my hand to the predicted future position before the shuttlecock arrives there so the racket and the shuttlecock can be met on the right place at the right time, otherwise, I will lose a point in my game.

Predictive Action in Infants

Human adults are readily able to predict, control and anticipate their actions by their prediction about what is going to happen next. As a matter of fact, life without the ability to predict motion and change is hard to imagine, not mention to manage well. What about young infants? Does such ability to predict motion and change already exist when we are as young as a few months of age? In other words, can infants anticipate and act on what's going to happen in the future by perceiving what's happening at present (von Hofsten, Feng, Vishton, Spelke, 1994)?

It is true that as early as life starts, infants act on people, events and objects in their environment. However, as for adults, infants' successive actions require knowledge and prediction of how people or objects behave (von Hofsten et al, 1994; Spelke et al, 1995b). To be successful in their actions, infants must not only perceive what is happening at present (e.g., the current location of the object), but anticipate, as accurately as possible, what will happen in the future (e.g., the future location of the object) (Gredebäck, & von Hofsten, 2004; van der Meer, van der Weel, & Lee; 1994; von Hofsten et al, 1994; Spelke, et al. 1995b). For instance, to successfully catch a moving object, an infant must aim for the future position that the moving object will occupy at the time the reach is completed and where the hand and object meet (Spelke, Kestenbaum, Simons, & Wein, 1995a, von Hofsten et al, 1994; Spelke, et al. 1995b, Gredebäck, & von Hofsten, 2004, Gredebäck et all, 2005). Though the remarkable ability of infants to time their actions relative to an external event, such as a moving object, is demonstrated in early reaching behavior (van der Meer et al. 1994; von Hofsten et al, 1994; von Hofsten, 1980, 1983), in order for movements to be coordinated, activities to be planned, and goals to be attained, infants' predictive abilities need to undergo development. It is reported that under certain conditions infants are able to reach for moving objects as soon as they are able to reach for stationary objects at about 18 weeks of age (von Hofsten & Lindhagen 1979). Nevertheless, the ability to reach predictively for attaining a moving object, does not mature until about the sixth month (von Hofsten, 1980, 1983; von Hofsten & Lindhagen 1979), an age when a more stabilized postural control is established and an anticipatory trunk adjustment is emerging (Rochat & Goubet, 1995, Out, van Soest, Savelsbergh & Hopkins, 1998; Bertental & von Hofsten, 1997; see also Hopkins & Rönnqvist, 2002, for a review).

The tight coordination between perception and action was reported both in adult and infant (e.g. Flanagen & Johansson, 2003, von Hofsten & Fazel-Zandy, 1984). Predictive reaching also requires keeping one's eyes on the target of interest. It is stated that looking is not simply done with the eyes but "with the eyes in the head on the shoulders of a body that gets about" (Gibson, 1979). In general, accurate control of looking with head and eyes is a prerequisite for accurate visual control of movement. In human infants, coordinated movements of the eyes and the head normally accomplish a good visual control of a moving object. The coupling between head and eye movements seems very fundamental. Even infants as young as 2 months of age seem to be able to use head movements as part of the gaze control and predictive tracking of a moving object (von Hofsten & Rosander, 1997). Therefore for the purpose of probing the evidence of early prospective behavior, infants' predictive reaching and head turning for a moving object were studied as the index of their predictive action in this thesis (Study I, II & III).

Task constraints and predictive action

Reaching and head tracking a moving object requires the ability to predict what will happen next, e.g., the future position and motion of the object. To predict what will happen next is possible because of the lawfulness of events (e.g., physical laws) (Spelke, 1991; 1994; Spelke, et al. 1995b). For example, object motion is predictable because it is subject to physical constraints. Objects move only on connected and unobstructed paths over space and time (principle of continuity), objects maintain their connectedness and boundaries as they move (principle of cohesion), and objects act upon each other if and only if they come into contact with each other (principle of contact) (Spelke, Phillips, & Woodward, 1995c). Infants' sensibility to these constraints on object motion has been investigated in studies using the so-called preferential looking method, focusing on if infants tend to look longer, compared to the base line, at novel or unnatural events (Baillargeon, 1986, 1987; Baillargeon & Graber, 1987; also see Baillargeon, 1993, for a review). These studies suggest that infants are sensitive to physical constraints. For instance, when infants are presented a visible or occluded object that moves toward an obstacle or barrier, the infants look longer at an event in which the object appears to interpenetrate the obstacle and reappears on its far side than at an event in which the object comes to a halt into contact with the obstacle (e.g., Baillargeon, 1986).

In addition to the above physical constraints, it was claimed that object motion is in accordance with Newton's law of inertia: objects continue in a states of rest or uniform motion unless acted upon by forces (principle of inertia) (Kim & Spelke, 1992). However, several studies using the preferential looking method supplied no evidence that infants were sensitive to inertia properties of object motion. For instance, when the motion of the presented object is visible and in accordance with the principle of inertia, a number of preferential looking studies reported that infants under 8 months of age do no longer look if the object reappears at a position displaced far from the line of its visible motion, as compared to the reappearance of the object on the original line of motion (e.g., Baillargeon & Graber, 1987; Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994; Spelke et al, 1995a).

While preferential looking studies results suggest that infants fail to extrapolate object motion on a linear trajectory, predictive action study suggested that the capability of prediction might partly be built on pre-wired components in the human infant (von Hofsten, 1980).

Furthermore, predictive action study claims that there was no effect of practice in the experimental situation on success in grasping the object, nevertheless, the target objects in these studies always traveled the same circular path, albeit at different speeds, distances and starting places (von Hofsten and Lindhagen, 1979). By altering the object motion trajectories, studies of this thesis (Study I) investigated these differences by presenting 6-month-old infants an object, which either moved on a linear (in accord with inertia) or a nonlinear (violating inertia rule) motion trajectory (for details see Method). The motion trials were presented in random order (Experiment 1of Study I, Appendix I) or by applying an ABBA block design, using the same type of trials (linear motion trials vs. nonlinear motion trials from the same start place) repeatedly presented (Experiment 2 of Study I, Appendix I).

Occlusion and predictive action

In preferential looking studies, infants are presented with a visible object that moves on a straight line and moves out of view behind a visible occluder. The occluder is then removed to reveal the object at rest in one of several positions. Under certain conditions 6-month-old infants look reliably longer than baseline at outcome displays that present the object in a position that it would not have entered if it had continued to move naturally behind the occluder. It was claimed that infants make inferences about object motions behind the occluder and infants can represent object motion on a connected unobstructed trajectory in accordance with the principle of continuity (Spelke, Breinlinger, Macomber, & Jacobson, 1992, Spelke, et al. 1994). In other words, in preferential looking studies, infants' inferences about object motions appear to be guided primarily by a principle of continuity (Spelke, et al. 1992). In a number of preferential studies, infants' inferences failed to accord with inertia. In contrast, in predictive action studies, infants' anticipation of object motion appears to be guided primarily by a principle of inertia, or smoothness of motion (Study I).

It was reported that when presented repeatedly with a linearly moving object that was occluded very briefly by a small screen before entering reaching space at the center of the field of view, 11-month-old infants showed evidence of long-range extrapolations of object motion but 5- month-old infants supply no evidence of such prediction in the same experimental setting (van der Meer, et al, 1994). However, predictive action studies suggest that 5-month-old infants do reach predictively for moving objects that are continuously visible (von Hofsten 1980) which suggests that a short-range, continuous extrapolation process guides infants' reaching. So, it is possible that the reduction in reaching in Van de Meer et al's (1994) experiment happened because the occluder's placed position was within the infants' reaching space and so constrained the reaching movements of the infant..

The present thesis (Study II) then was undertaken to examine, in part, the nature and limitations on infants' extrapolations of object motion by investigating the predictive action (reaching and head turning) on moving objects whose paths are fully visible as in Study I or partially occluded as in Study II. The setting of Study II was the same as in Study I but with one exception: a small occluder was introduced and positioned in front of a portion of the object's path of motion just before the object entered the infant's optimal reaching space. Because the occluder was placed in the location without intruding into the optimal reaching area, it posed no barrier to obtaining the object. Also, because the occluder was just at the border of that space, it just occluded the object during the critical time when the infant initiated their predictive reaches.

Learning in anticipation

Another question investigated in the present thesis (Study II) concerns infants' ability to learn to anticipate upcoming object motions.

In previous predictive reaching experiments infants have shown little change in their behavior over the course of an experiment, despite repeated encounters with an object that moved on a single trajectory. For instance, when an object that moves smoothly on a semi-circular path or linear path is presented repeatedly, infants' aiming for the object is as accurate on their first reach as on later reaches (von Hofsten, 1983; Study I). Moreover, when infants are presented with an object that turns abruptly and repeatedly on the same path, they show no signs of learning to reach for it or to track it with head turning (Study I). Thus, no evidence was found that infants learn to anticipate abrupt turns of an object, and no evidence that such learning can guide predictive reaching or head turning.

In preferential looking studies, experiments with partially occluded linear and nonlinear motion also provide no evidence of infants' learning to anticipate object motion. For instance, 6-month-old infants failed to extrapolate linear motions, despite repeated experience of viewing an object moving at a constant velocity (Spelke et al., 1994, 1995a) or of a single linear motion behind an occluder (Spelke, et al., 1994). In these studies, no abrupt turn of object motion was presented. Thus, there is no direct evidence supplied that infants learn to anticipate abrupt turns of an object, and no evidence supplied that such learning can guide predictive reaching or head turning.

Both previous predictive action studies and preferential looking studies provide little evidence that infants learn to extrapolate object motions over periods of no-visibility such as when the object is behind an occluder during its motion trajectory. This finding is perplexing when we consider the wealth of evidence for rapid learning about objects in other contexts (Haith, 1998). Do infants truly fail to extrapolate object motions, or do they learn successfully but fail to show the fruits of this learning by means of head-turning and reaching? In preferential studies infants may have learned to extrapolate linear motions on the basis of their prior experience with objects or on the basis of their observations during the experiment. This learning, however, may have been too weak to guide extrapolations over the large regions of the scene that were occluded (Munakata, McClelland, Johnson, & Siegler, 1997). Learning to extrapolate object motion may be manifested only in a situation involving a moderate amount of occlusion, because effects of inertia on infants' extrapolation may be too strong when the trajectory of object motion is fully visible and too weak when it is fully occluded. Infants' capability to learn about both linear and nonlinear motions in a situation that might be more favorable to the expression of such learning was investigated in Study II.

Lateral asymmetry in reaching

Prospective action is a central process of perceptual, motor, cognitive development from birth (Rochat, 1999; von Hofsten 2004). It was a well acknowledged that infant reaching movement has played a valuable role in probing the early prospective actions that are vital to surviving and learning. However, despite the fact that a large number of studies devoted to describing human handedness and its origin as well as the relationship with the lateralization of the brain, we still lack the substantive knowledge about the development of hand preference during the first year of life (Rönnqvist & Domellöf, 2006). The literature documenting hand preference in reaching activities for moving objects in the course of the first semester of life remains sparse.

When many studies agreed that the use of a moving object was an effective tool to be adopted to investigate infant predictive behavior such as hand reaching, head turning and gaze control etc. (e.g., von Hofsten et al 1998, 2000; Jonsson, & von Hofsten, 2003, von Hofsten Rosanders, 1996, 1997; Rosanders, & von Hofsten, 2004; Gredebäck, et al , 2005), very few, if any, studies of lateral asymmetry involved a moving task in infant reaching (Robin, Berthier & Clifton, 1996) or studies of lateral asymmetry characters in infant prospective action were reported, though it was claimed prospective action is pivotal in the process of development. This thesis is making such an effort.

Although for neurologists and most medical professionals, the crossing of nerve tracks from one hemisphere of the brain to the contralateral side of the limb is a common pattern through the CNS (Vulliemoz, Raineteau & Janaudon, 2005), to the general public, the study of human handedness would seem, at first sight, quite straightforward as most people are able to claim whether they are right- or left-handed. However, when we try to move beyond that first stage of self-classification, the study of handedness becomes fraught with difficulty, ambiguity and controversy (Annett, 1972, 1985, 1998). The most notorious problem is that there is no agreement as to the essential definition of the concept- Handedness. Nevertheless, the nature and the relationship between the development of functional asymmetry in the brain and hand preference remains as the most interesting puzzle about handedness (Rönnqvist & Hopkins, 1998). Though with limitations, human handedness and other functional laterality remain very interesting and important because laterality is closely related to differences in the organization of our brain (Bishop, 1990).

Traditionally, handedness was typically taken to be synonymous with hand preference, though it was suggested there are distinctions between hand preference and hand proficiency, and between hand preference and manual specialization. By defining handedness as the preferred or consistent use of one hand on unimanual tasks, the hand is then labeled the dominant hand. Under this frame, contemporary estimation of right-handedness in the adult population is about 70% to 90%, with respect to different criteria used to determine the preferred hand (Porac & Coren, 1981, Porac, 1993; see also Hopkins & Rönnqvist, 1998, Previc, 1991; Provins, 1997, for reviews). A handedness questionnaire or a kinematical analysis of drawing movement so often used for assessing handedness in adult and older children are naturally not possible to apply to infants (Blank, Miller & von Vob, 2000). Instead, in human infant, hand preference and development of handedness have often been investigated by employing tasks for goal-directed reaching, (Bresson, Maury & Pieraut-Le-Bonniec, 1977; Ramsay & Willis, 1984, Fagard & Jacquet, 1996; Fagard & Lockman, 2004). During the first year of the human life hand preference has been found to be inconsistent and fluctuating, both within and between infant subjects (e.g., Corbetta & Thelen, 1996). When hand preference was considered as the consistent use of one hand rather than the other in a given task, the lateral placement of the test object had an important impact on hand use (Perris & Clifton, 1988; Carlson & Harris, 1985; Harris & Carlson, 1993; Morange & Bloch, 1996; Cornwell, Harris & Fitzgerald, 1991). One common phenomenon was that whenever the object was presented in an off-midline position, the previous hand preference diminished. Instead, the ipsilateral hand became the dominant one for reaching. According to Carlson and Harris (1985) and Harris and Carlson (1993), the disappearance of the infants' hand preference in reaching for an off-midline positioned object could be explained by the principle of "minimal effort". For instance, in order to pick up an object positioned to the right, a reach with the right hand requires less effort than a reach across the body midline with the left hand, given other things being equal. Nevertheless, it has been reported that when a stationary object is presented at the midline position in relation to the infant, the majority of infants at the age of 6-7 months then will use their preferred hand to reach for the object. However, mixed results of "preferred hand use" were reported, supporting either the left-biased theory (e.g., Perris & Clifton, 1988) or the right-biased theory (e.g., Carlson & Harris, 1985; Harris & Carlson, 1993; Morange & Bloch, 1996). Furthermore, other studies with stationary task-constraints reported fluctuations in handedness at an early age (e.g., Gesell and Ames, 1947, Thelen, Corbetta, Kamm, Spencer, Schneidr, & Zernicke, 1993; Thelen, Schöner, Scheier, & Smith, 2001). However, when the moving object was introduced, it was reported that 5 to 7-month-old infants demonstrate their anticipation of a moving object by increasing the use of the contralateral hand to intercept the object (Robin, Berthier & Clifton, 1996). Further, von Hofsten (1980, 1983) noticed, by studying infant's reaching trajectory, that infants from 18 to 36 weeks of age showed a somewhat more stable right-hand preference, thus, by means of using their right hand in more than 70% of the reaches, a much more salient preferential rate than data reported in stationary object studies (e.g. Perris & Clifton, 1988; Morange & Bloch, 1996).

Could it be the case that the above reported differences represented a picture of task sensitive phenomenon? Given that humans are evolved to deal with a moving world of constant change, we may ask if it is true that young infants show consistency in hand preference in predictive reaching for moving objects, but show fluctuation in hand preference when reaching for stationary objects. We may also ask, if this is the case, whether using a moving task which generates the infant's prospective action on it, would be a more logical, appropriate and effective task to investigate hand preference in young infants than a traditional stationary task. Study III made an attempt to investigate this question.

At many levels of motor control and coordination, timing and temporal coupling are important (Fagard, 1994; Fagard & Pezé, 1997). Yet, most of the work on timing in control and coordination comes from adult studies (e.g., Fitts, 1959; Peterson, 1965; Kelso, Southard & Goodman, 1979, 1979b, Kelso, Putman & Goodman, 1983, Marteniuk & MacKenzie, 1980; Marteniuk, MacKenzie & Baba, 1984). Little knowledge is available for the temporal characteristics underlying the interlimb coupling of an infant's arm movement. Thus the development of interlimb coordination has recently received renewed focus (Corbetta & Thelen, 1996; Fagard, 1994; Fagard & Pezé, 1997; Fagard & Lockman, 2005; Gabbard & Rabb, 2000). Corbetta and Thelen (1996) studied the infants' upper-arm coordination patterns associated with reaching movements during the first year of life. According to Corbetta and Thelen (1996), infants at 3 to 4 months of age begin to present two basic forms of goal-oriented interlimb coordination: reaching with one arm or reaching with both arms. The organizational characteristics underlying the temporal coupling of infant reach remain to be elucidated. Study III of this thesis analyzed some of the main characteristics embedded in the temporal coupling of the arm/hand movement associated with reaches for moving objects. Furthermore, we looked at the temporal pattern of the arm/hand movement and tried to probe whether there is feature of lateral asymmetry in temporal coupling of goal-directed reaching at early ages.

As stated above, studies suggest that 5 to 7-month-old infants demonstrate their anticipation of a moving object by increasing the use of the contralateral hand to intercept the object (Robin, Berthier & Clifton, 1996). Berthier and Robin (1998) showed that when the location of a target object was shifted, infants of 7 months of age are able to correct their hand-direction in mid-reach after a reach has been launched. Thus, Study III investigated when the immediate perception of an object contradicted the infant's prior prediction of it, whether infants are able to adjust their strategy or correct their reaching midway.

METHODS

The method adopted in this thesis was generally summarized in the following. More detailed descriptions can be found in the respective study listed in this thesis.

Subjects

All infants studied were normal, full time born, and with no known medical problems. At the time of observation their mean age was approximately 6-month (the age range was: 23 – 26 weeks in Experiment 1 of Study I; 24 – 26 weeks in Experiment 2 of Study I; 24-27weeks in Study II and 23 – 26 weeks in Study III).

Apparatus and displays

The apparatus used in all three studies for producing the object motion consisted of a large computer-controlled plane plotter (Roland DPX-4600), originally designed for producing precise technical drawings, whose pen was replaced with a small magnet. The 98 x 130 cm plotting area was topped with a sheet of aluminum that was painted white, coated with a silicone lubricant, and placed in a supporting structure such that it tilted 15° forward from the vertical. The aluminum sheet served as the background for an object that served as the attractive stimulus. The object was supported by a 12-cm wooden dowel rod, which was attached firmly to a second magnet. When the magnet on the object's supporting rod was placed on the aluminum sheet directly over the plotter magnet, the combined attraction held the object in place and caused it to undergo whatever motion was produced by the plotter. By using the commands originally intended to direct the motion of the plotter pen, this apparatus enabled us to direct the motion of any small object very precisely, anywhere along the surface of the plotter, and at any velocity up to 60 cm/s.

A small stuffed yellow teddy bear, 8 cm in length, served as the object for most infants on most trials; if infants displayed no interest in reaching for this toy, a stuffed blue bird of approximately the same size was substituted. Each object contained a small rattle to enable the experimenter to attract the infant's attention by tapping on it. The rattle was not activated during the motion of the object (see Figure 1). Throughout the study, soft classical music provided a soothing background sound to the more abrupt, distinct sounds produced by the plotter (details see also von Hofsten et al, 1998).

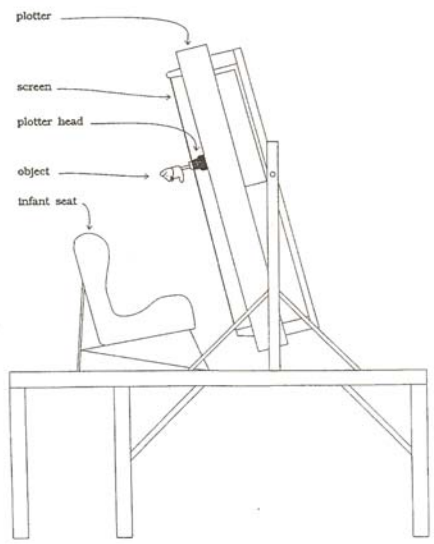

Figure 1. A side view of the experimental apparatus.

On any given trial, the object followed one of four paths of motion presented to the infants. Object motion started either from the left or from the right, either moved linearly along the full length of the diagonal (linear motion), or abruptly turned at the intersection (see below) of the two diagonals and continued along the other diagonal (nonlinear motion). The infant chair was centered between the two diagonal paths, supported on a platform. The object motion speed was predefined to 40 cm/s in Study I and 30 cm /s in study II and III (see Figure 2).

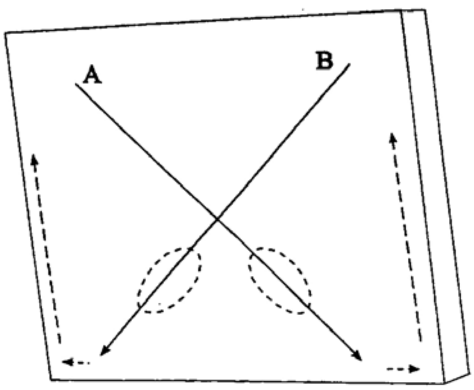

Figure 2. A schematic view of the display screen showing the four different motion trajectories used in the experiments. The dashed ellipses indicate the reaching areas for each trajectory.

Design and procedure

Infants were presented with four blocks of trials (two linear and two nonlinear motion blocks), each block consisting of 6-9 trials (see Figure 2). The order of the four blocks of trials was presented randomly (Experiment 1 of Study I) or in a counterbalanced ABBA order (Experiment 2 of Study I, Study II and Study III). Because of the nature of the hardware control unit, there was a delay of approximately 100 ms between the stopping of the first motion and the start of the second one on the nonlinear motion trials. All four motions were therefore equalized (except in Experiment 1 of Study I) by means of having the same interruption time at the intersection.

The infants were placed in an infant chair (Mothercare ©) with a secure belt fixed around the stomach. Before the test trials, the infants were encouraged to reach for the object when it was stationary and when it was moving in front of them to the left and right. This warm up procedure was intended to accustom the infant to the surroundings and encouraged reaching for and grasping the object.

After the warm up period, the object was placed at the upper left or right corner of the screen and the infant's attention was called. When the infant was visually attending to the object, the experimenter triggered the motion of the object by pressing a key on a computer keyboard. The object moved downward past the infant along the pre-defined trajectory. If the object was not grasped and pulled from the screen by the infant, it continued to move along the edges of the screen and back to the starting position of next trial. If the object was successfully grasped and pulled off the screen, the experimenter would gently take it away and manually reposition the object at the next starting position.

After half of the test trials, the chair was turned around and the infant was given a short break. If the infant became fussy or lost interest during the test session, a short break was also given. The entire session took about 15-20 minutes.

Data extraction and coding

All data collection was based on video recordings from two cameras mixed onto one single screen. One camera provided an overhead view (x- and z plane) and the other a side view (z- and y plane) of the infant. The overhead view enabled the extraction of the arm/hand and head movements in relation to the moving object. The side view served to clarify any ambiguities in the overhead view. The two cameras also provided information as to whether the infant was looking at the display or not. A timer was superimposed onto the video screen and gave the time in ms on each video frame. The video system was PAL, which produces 25 frames/s, in contrast to the 30 frames/s produced by NTSC.

The data from each infant were scored in two phases. For the first phase, the coding, judgment was made by two coders on whether the infant was visually attending to the object at the position of its motion onset and continually attending to it for at least 2/3 of the entire motion trajectory. Only trials that met this criterion were chosen for further analysis. The second phase of coding involved tracking the motions of the infant's head (Study I & II) or hand (Study I & III) during each trial at the designed codable points in time (ms) during a reach. Nine codable points (–133, -67, 0, 67, 133, 200, 267, 333 and 400 ms) were used for Experiment 1, seven codable points (-100, 0, 100, 200, 300, 400, and 500 ms) were used for Experiment 2 of Study I, Experiment 2. A regression analysis was adopted to assess whether infants reaches showed appropriate aiming to any position and velocity of the hand at each of the codable points in time. Data coding and analysis were carried out with respect to the specific questions of interest to be studied in Experiment 1 and Experiment 2 of Study I and the other two studies (Study II, III). Further details can be found in each article (Study I-III).

OVERVIEW OF THE EMPIRICAL STUDIES

Study I (Von Hofsten, Vishton, Spelke, Feng & Rosander, 1998)

This study examined the principles underlying early predictive actions, how infants generate their prediction of the future target and how infants organize their prospective action on it, by investigating both goal-directed head tracking and reaching for a moving object. Two experiments were conducted in this study.

In Experiment 1 of Study I, infants were presented with four different paths of object motion in random order, such that the motion of the object at the mid-point was unpredictable. To track and reach appropriately for the object infants' head and arm movements had to be based on an extrapolation of the object's motion beyond the center of the display. Both head turning and reaching movements were measured before, at and after the object's arrival at the midpoint. In this way, whether infants show extrapolation to the object motion and whether this extrapolation was in accord with the linear motion path can be tested. Since equal numbers of linear and nonlinear motion trials were presented in a random order, the motion of the object at the intersection was inherently unpredictable. This situation allows investigating about how principle constraints guide infants' action. The logic comes from the following: if infant's predictive actions are in accord with the principle that a linearly moving object will continue moving on a straight path, then this tendency reflects pre-existing assumptions about object motion rather than learning based on specific experience with the object during the experiment (detailed illustration see Study I).

Analysis showed that there was no difference in looking rates for linear or nonlinear motion trials. However, for the head tracking, the mean lateral velocity of head movement showed a linear extrapolation of object motion. The head position continued to track the motion in accord with linear motion even in nonlinear trails for at least 200 ms after the object motion was interrupted. Furthermore, no differences in head velocity patterns were obtained between the first and second halves of the experiment for either the linear or the nonlinear trials, providing no evidence of learning effects. For reaching, since the variability in the depth dimension (vertical axis) is not informative about the predictive nature of infants' reaching, the reaching movement was measured by analyzing the relationship between the lateral positions and velocities of each hand during the reach (horizontal axis). It was showed that infants tend to aim their reaches toward the contralateral side of reaching space, in accord with the principle of inertia. Furthermore, by analyzing the convergence patterns of different reaches at each measured point in time during the reach, infants' timing of convergent aiming at the object was assessed. A negative correlation was found between the position and velocity of the hand contralateral to the initiating point of the object motion. These findings showed that convergent reaching is present in all instances to a position on the side to which the object would have moved if it had continued along a path of linear motion, whether the object continued on the linear path or not. On the contrary, no correlation was found for the hand was ipsilateral to the origin of the object motion. Data indicated the ipsilateral hand only rarely exhibited convergence on a spatial location (2%). Taken together, when infants were presented with an object that moved either on a continuous linear or a nonlinear trajectory, analysis for the movement of both head turning and reaching suggested that infants do show extrapolation for the object motion on a linear trajectory.

In Experiment 2 of Study I, the design and procedure was basically the same as in Experiment 1 except two differences. First, four object motions were presented in an ABBA block of six to nine trials instead of in a random order. Second, both linear and nonlinear motions were stopped for 100 ms at the intersection so as to equalize them (detailed illustration see Appendix I). By examining the mean lateral head velocity at each time-interval during the motion path, it was found that the head movement was in accordance with a constant velocity of the target up to 200 ms after the target had stopped. Then during the next time interval the head movement decelerated and nearly stopped. Finally, the head started to move either in the same direction as before (in linear trials) or in the opposite direction (in nonlinear trials). At about 300 – 400 ms after the intersection, head velocity differed significantly between the linear and the nonlinear motion conditions. Furthermore, a comparison was made for the head velocity of the first three trials and later trials of each block. For reaching, as in Experiment 1, a convergence pattern was investigated by computing the regression analysis of hand position against velocity for each hand, each time point, and each motion condition. The result, in agreement with Experiment 1, indicated that the contralateral hand showed convergence on a position on the linearly extrapolated path of object motion, both when the actual motion was linear or not. Although the convergence effect was less straight than it was in Experiment 1, the pattern of convergence on spatial locations was nevertheless the same.

The learning effect on predictive reaching was also assessed in both Experiment 1 & 2; no evidence was found that infants' predictive action was influenced by learning in Study I, because there are no signs of learning to anticipate motions in violation of inertia, either within a block or over the whole experiment.

Taking together the findings from Experiment 1 and 2 of Study I, it was found that 6-month-old infants act (head tracking and reaching) prospectively on linear moving objects by extrapolating the object's motion paths. Because linear and nonlinear motions were presented with equal frequency in both experiments, this extrapolating ability cannot be explained by a learned expectation, developed over the course of the experiment. Because these motions were repetitive, however, it is unclear whether infants extrapolate such motions the first time they are presented, or if infants are truly unable to learn new rules for predicting object motion. It is possible that the direct visual guidance available in the current studies prevented the infants from using their earlier experience with the object in order to predict its future position. If performance was limited by this "visual capture" then occluding the middle part of the object trajectory might facilitate learning about nonlinear motion. Therefore Study II was carried out to investigate these possibilities.

Study II (Von Hofsten, Feng & Spelke, 2000)

Study II was set out to assess whether the differences in the tasks, or the visibility of the object account for infants' ability to extrapolate object on linear path. The nature and limitations on infants' extrapolations of object motion were studied by means of investigating predictive actions on moving object whose motion paths were partially occluded. Since no learning effect was found in either experiment of Study I, to investigate infants' capability to learn about both linear and nonlinear motions was the second aim of Study II. Because in Study II the object was occluded at the point at which it either continued to move straight or turned, thus eliminating any prepotent effect of a short term extrapolation mechanism on infants' predictive actions, a situation that might be more favorable to the expression of such learning. Predictive actions were measured on the first trial of each block, across the trials within a block and across successive blocks. If infants learn to anticipate linear or nonlinear object motion, then their actions should accord better with those motions on later trials within a block and should further influence performance on the next block of trials, In other words, a learning effect should present.

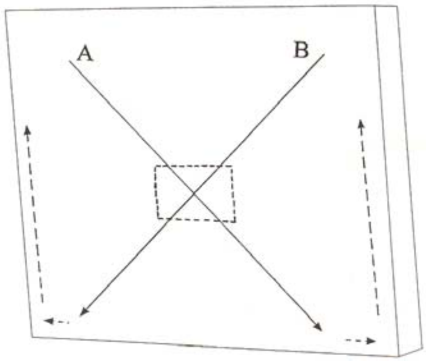

Figure 3. A schematic view of the display screen showing the position of the occluder (rectangle formed by broken lines) and the four motion trajectories (solid lines) used in the experiment.

The design and the apparatus was as same as in the Experiment 2 of Study I, except that a rectangular occluder was attached symmetrically over the central part of the object motion trajectories including the intersection between them (see Figure 3, more detailed illustration see Appendix II). The motions were, as in Experiment 2 of Study I, presented in blocks of linear and nonlinear trials in an ABBA order, starting either with the linear or with the nonlinear motion. On each trial, the object started to move at one of the upper corners of the display, and then moved on a predefined trajectory. The object disappeared behind the occluder just before the center of the display and reappeared just below the center of the display. Dependent on which trial, the object moved either to the diagonally opposite lower corner (i.e., on the extension of its linear path) or to the lower corner below its entrance point (i.e., in nonlinear trial).

Two main questions were asked. First, how do infants anticipate, by reaching and head turning, the repeated number of trials? More specifically, are head movements guided by an expectation of linear object motion? Second, how do infants' anticipations, investigated by predictive head tracking, change over the course of repeated exposure to linear or nonlinear motion?

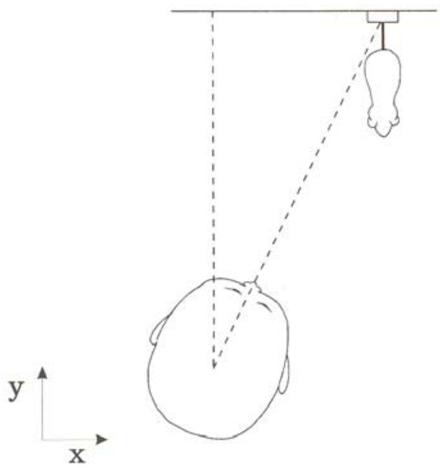

Figure 4. A top view of a subject at the object showing the axes of the coordinate system used to analyze the results.

The analysis of head turning was based on the lateral position of the nose (the x-axis in Figure 4.). The mean head position was measured at the ten coded time frames, from 500 ms before the object's disappearance to 600 ms after its reappearance, for the first, third and fifth trials of each motion condition.

The result confirmed the findings from Study I (von Hofsten, et al, 1998) that infants anticipate prospectively on moving objects by extrapolating object motion on linear paths. On subsequent trials of the linear motion, the infants came to look toward and beyond the far side of the occluder, where the object was expected to reappear. The effect of the trial on head position was significant for linear motion. On the contrary, in the nonlinear motion trials infants showed no consistent changes in head turning pattern over trials. For the learning effect, the result showed that the first time infants viewed an object's motion, their head movements did not anticipate either linear or the nonlinear motion path. However, infants quickly learned to anticipate linear motion on successive trials. Infants also learned to anticipate nonlinear motion, although this learning, compared to the learning connected to the linear motion, was slower and less consistent. Learning in all cases concerned the trajectory of the object, not the specific locations at which the object appeared. These results were interpreted as in accord with the theory that a single system of representation underlies both predictive action and perception of object motion, and that occlusion may play the role of reducing the precision of object representations.

Study III (Feng & Rönnqvist, 2006)

Study III focused on investigating whether infants of 6 months present hand preference in their reaching behavior, particularly whether there is lateral asymmetry embedded in infant predictive reaching for moving objects. Additionally, the aim was to investigate whether infants at the age of 6 months are able to monitor their reaching strategies when the immediate perception of an object contradicts infants' earlier prediction of its motion.

The design and the apparatus was the same as in Study II, except there was no occluder. Infants were presented with four blocks of trials (two linear and two nonlinear motion trials) in a counterbalanced ABBA order. By analyzing reaching movements in relation to the intersection of object motions, it was found that infants at 6 months of age are already able to adjust their reaches to anticipate the change in object motions. Infants did so even when the change of object motion direction was contrary to their prediction of the object's future position, as shown in Study II. These adjustments enable the infant to place the hand in the prospective location of the reaching space. Consequently, such adjustment on the infant's reaching strategy leads to a greater chance for the infant to catch the moving object.

This result was explained partly by infant's ability to predict the object's future position. Further, an online adjustment based on perception of the current change of the object motion, object's heading direction, and spatial location, must also be accounted for. It was argued that if the "inertial principle" was the internal working model for the spatial relationships of a moving object's locations at present and in future, then immediate visual perceptual input would be essential to calibrate the model when it is violated, which was the case in the nonlinear trials of Study III.

It was found that the rate of hand-object touch was more evident in right hand than left hand. However, when assessing the total number of reaches, although unimanual reach was dominant, no evidence was found that consistent use of one hand over the other, independent of the motion condition (linear vs. nonlinear) or the object motion direction (left vs. right), a result divergent from the earlier findings by von Hofsten (1980).

For temporal characters of the arm/hand movements, two parameters were adopted for further investigating: latency and duration of reaching. Results showed a left-right asymmetry in the temporal coupling by means of a significantly shorter latency. Furthermore, a longer duration of the left hand movement was found in comparison with the right hand movement. A relationship between latency and duration of reaching movement was also evident. Thus, the longer the latency was, the shorter the duration. The same pattern has also been reported by Morange-Majoux (2000), which suggested that as longer the reaction time, the shorter the total movement time. It was also found that both latency and duration were shorter for bimanual reaches than for unimanual reaches. One possible explanation is that young infants may lack the inhibitory control of the prepotent response due to the immaturity of the prefrontal cortex, according to Diamond (1988, 1991).

GENERAL DISCUSSION

Traditionally, researchers believed, when we were as young as a few months old, we understand very little about our physical world and actions are mostly just reflexes to the environment we live in. We did not open our minds enough to welcome a new image of how much we know and can do until pioneers like J. Piaget (1953, 1954), N. A. Bernstein (1967), J. J. Gibson (1966) etc. shed light on the road to self-understanding.

A note about infant perception, action and cognition

Since Piaget (1953, 1954), researchers have made stunning progress in understanding the early development and the interaction of visual perception, action and cognition. To a large extent, this progress is based on the understanding of infant's reaction to currently available input. However, without the understanding of infant's reaction to future oriented input, our progress in answering "how do we make sense of our world?" is less satisfying.

One of the essential questions concerning infant perception, action and cognition has been rooted upon how infants organize their current activity around a future event (e.g., Haith 1993; Haith, Hazan & Goodman, 1988; von Hofsten, 1983; von Hofsten & Rönnqvist, 1988; von Hofsten et al 1998, 2000; Spelke & von

Hofsten, 2001; von Hofsten, Kochukova, & Rosander, 2007; Kochukova & Grebäck, 2007; see also, Haith, 1993; Rochat, 1999, von Hofsten, 2004, 2007 for reviews). Life without future oriented perception and action does not exist in the human world, as long as time is a non-excludable parameter in life (see also Adolph, 2008).

Over the last three decades, with the keen interests in human perception, action and cognition, converging evidence from different perspectives suggested that many human movements are organized action, not reactions or reflexes, because they are initiated by motivation, with a plan to attain a goal (see von Hofsten 2004, for a review). How about our movement in infancy? Given the evolutionary history of the human being, is the infant born with the inherent capability to act predictively on the environment? (e.g., Spelke et al, 1992, 1994; Baillargeon, 1986, 1987; Baillargeon & Graber, 1987, see also Hauser, 2003, for a review), or is infant action guided by experiences gained through interaction with our environment (e.g., Piaget, 1953, 1954; Thelen et al, 1999, Smith & Thelen 2003).

Researchers from different theoretical and methodological approaches answer this question in different ways.

Empiricism is the discipline that generally favors knowledge spurred from experience of practice (e.g. Piaget 1953, 1954, Thelen et al, 1999, Smith & Thelen 2003). For Piaget (1954), children construct an understanding/knowledge of the environment by acting upon it. Action underlies much of the child's developing knowledge of how their world works. Almost all of Piaget's studies involved reaching for and acting upon an object (Piaget 1953, 1954). For instance, with his curious subject Piaget played one of his famous games like this: Show a 6-month-old infant a novel toy and she will reach for and play with it. Then take the toy back and place an opaque screen between the toy and the infant. The infant stops reaching. This led Piaget to conclude that: out of sight is out of mind, that infant's capacity to keep the toy in mind, object permanence, emerges at a later age largely due to the infant's sensorimotor experiences with objects. When a child starts reaching for a hidden object at around 9.5 months (Piaget, 1954), Piaget played a different game with his subject. The game was like this: Show the infant two opaque screens such as two cloths (A and B), and hide the toy behind/under A. Once the infant successfully and repeatedly retrieves the toy behind/under A, switch sides and hide the toy behind/under B. Although the hiding game is the same, although the infant is watching while the toy is placed under B, she searches behind/under A, and this error reoccurs over many trials. Piaget concluded that to understand how the world works and to organize action upon the world, infants and young children must go through a progressive and stage wise process that is restrained by and dependent on sensorimotor development.

Another significant voice from the empirical domain is the dynamic system theory or embodied view by Thelen and co-workers (e.g., Thelen et al, 1993, 2001, Smith & Thelen 2003). As a psychologist with strong biology background, Thelen and her team approached this question in a more descriptive way. Their approach is one of the few that demonstrated the early development with multileveled and multirelational patterns across different areas of infant studies (Thelen et al, 1993; Smith 2006). Dynamic theory claims that action is the source of developmental change and spontaneous sorts of movement and behaviors are essential in creating both tasks and opportunities for young children to learn and to mature their minds. Dynamic theory views "cognition as embedded in, distributed across, and inseparable from the processed of perception and action" (Smith, 2006). Full understanding of knowledge formation cannot be separated from its sensory, motor, real time, and embodied development (Thelen, 2000). In other words, development changes occur under the control of numerous variables within the complex dynamic system.

Opposite to Empiricism, the core principles hypothesis proposed by Spelke and co-workers (e.g., Spelke, 1994, Spelke et al, 1992,1994, 1995a, 1995b) suggested that infants are born, through evolution, with certain mature and commonsense core principles which were referred as innate knowledge (e.g., Spelke, 1994) that funded the infant with capacity to reason and to represent the world beyond immediate perception experience (e.g. Baillargeon, 1986, 1987, 1993; Baillargeon & Graver, 1987; Spelke et al, 1992. Spelke 1994). This innate knowledge includes a few basic rules related to objects. For instance, it was suggested that young infants are sensitive to a number of mechanical constraints, such as continuity (they extrapolate motion on connected paths), solidity (they extrapolate motion on unobstructed paths), contact (they extrapolate independent motions of distinct objects unless the objects come into contact) and support (they extrapolated downward motion in the absence of support) (Spelke et al, 1992; Spelke 1994). The advantages of the nativist domain, according to Spelke and associates, is that these innate core principles are needed to efficiently limit the difficulties in interpreting possible external events in the world (e.g., Spelke et al, 1992; Spelke, 1994).

One of the criticisms on the above nativism's argument is targeted on the use of the preferential looking paradigm. Preferential looking has been the method of choice partly due to the minimum technical demand required on the researcher's side. However, it is argued that this methodology was initially designed to address sensory and perceptual questions, not aimed to answer questions of high-level cognitive processing that underlies those competencies (Haith, 1998). "We have evidence of adaptive evolution, inasmuch as expectations for future spatial locations are important in survival both for predator and for prey… because we have no indicators of belief, inference, reasoning, counting symbolic representation, or surprise" (Haith, 1998, p. 169). Furthermore, perception and knowing are not the same thing (e.g., Butterworth, 1996). For instance, a person can regard an event as odd without knowing why or acting upon it (Haith, 1998).

Criticism targeted also on the low correspondence reported by some of the preferential looking studies. In case of the A-not B task, for instance, it was challenged by Hood and colleagues (Hood, 1995, 2001, Hood, Carey & Prasada, 2000): how can a mere 6-month-old baby know that a solid ball can't travel through a solid table or screen, while a 2-year-old thinks that this kind of physical event is not only possible but the way the world works? If knowledge is task dependent, then we must argue that we have to be clearer about what we mean by the term of "knowledge" (e.g., Haith, 1998, Hood et al, 2000, Butterworth, 1996).

Research based on action performance is different. Because action is the only media through which our thoughts can have an effect on the outside world. However, it is not always recognized that the questions we can ask about our knowledge in the nature of movement and actions are similar to those we can ask about other kinds of knowledge (Smyth, Collins, Morris & Levy, 1994). Reaching out for a coffee cup, for instance, is one of the simplest actions we do on daily basis but many of us take it for granted, without being aware of the plan and control perspective embodied in this well-organized action.

Under the framework of perceptual guided actions and their role in cognition, findings of infants' head tracking and reaching are discussed in the following.

Head tracking

In Study I, when infants of 6-months were presented with an object that moved on a predefined trajectory, either linear or nonlinear, data of infants' head tracking showed that infants at this age were already able to extrapolate the object motion on the linear path. Infants' head movements followed the object smoothly on linear trials. The head turning analysis for both linear and nonlinear trials revealed that infants showed a pattern of continuing tracking the moving object, whether it turned or not, at the same speed with no deceleration, for 200 ms after the object turned (in nonlinear trails) or stopped (in linear trials) at the intersection. This pattern suggested that infants moved their head tracking of the object motion on a linear path at least 200ms into the future. This evidence supported the future oriented perception-action claims. It also suggested that this movement is guided by a linear extrapolation, a notion of inertia to predict the future location of a fully visible object (Study I), thus data from this thesis supports the core knowledge account of Nativist approaches (Spelke, 1994, Spelke et al, 1992). In both Experiment 1 & 2 of Study I, infant's head tracking provided evidence of an extrapolation of the object motion on a linear path, in accord with principle of inertia. Further analysis of the head tracking speed vs. object velocity showed that infants extrapolated the external velocity very well on linear trials. The head sped up as the object passed the subject and reached its maximum velocity at the point where the object was closest to the infant. There was no indication of systematic lag found. These findings suggested that infants' head tracking was based on the spatial properties of the object motion, not on properties of the infants' sensorimotor systems.

The same setting and motion trials as in Study I were adopted in Study II where object motion was partially occluded by introducing a small occluder into the place where the four trajectories intersected. An effect of the trials on head position was found to be that, at the reappearance of the object, infants turned their heads significantly more towards the far side of the occluder, on the 3rd trial than on the 1st trial; furthermore, by the 4th linear trials, all subjects increased their head turning significantly for linear motion condition toward the far side of the occluder. This learning effect was slower and less consistent in nonlinear conditions. It was suggested that infants may anticipate neither linear nor nonlinear motion the first time they viewed a partially occluded object's motion, but they quickly learned to anticipate linear motion on successive trials. It was claimed that, by this evidence, infants showed a capacity and tendency to anticipate the upcoming motion in accord with principle of inertia. However, this capacity is weak, though present, in infancy. Although in previous predictive action studies (von Hofsten 1983, Study I), very little evidence of learning effect is reported. Study II supplied strong and clear evidence for the infants' ability to learn and learn quickly. This finding is in agreement with the rapid learning effect reported in studies that tested young infants by using a corneal-reflection eye-tracking technique (Gredebäck & von Hofsten, 2004, Kochukhova & Gredebäck, 2007). Furthermore, data from Study II showed that infants at 6-months of age learn to predict how the object will move, not where it will appear, especially in linear conditions.

Reaching

The present thesis provides evidence that infants as young as 6-months-old reach prospectively on moving objects. In other words, the reaches predict future positions of the target and were not just on-line extrapolations bridging the sensorimotor delay. The linear extrapolation of object motion came from the analysis of the relation between the position and velocity of each hand during the trials when infants attended to the object and the hand moved (Study I). It was suggested that planning of predictive reaches evidently is determined by the seen object motion and not by remembered object trajectories.

In Study I, infants' continued tendency to reach predictively in accord with a linear prediction throughout the study, despite the fact that the object changed its motion midway (nonlinear motion), either randomly or block wise, may indicate the robustness of this property of the reaching system.

This thesis claims that, the predictive reaching as well as head tracking may be attributed to a set of perceptual, cognitive and action systems in the infant for: 1) representing the distal velocity of a moving object (speed and direction); 2) representing the catching space around the infant (environment factors); 3) extrapolating the objects motion into the catching area and 4) guiding the hand and head to this area. All of these have several important implications and consequences: infants' reaching and head tracking are organized prospectively, reciprocally and with a purpose to attain the desired object.

This is not only important in understanding the mechanism of motor development, but also for the understanding of many other aspects of human development (von Hofsten 2004). Perceptual development in the child is determined by the capability of acting on their environment (people, object, space, number, event, motion etc.), which affords the child the necessary information (Gibson & Pick, 2000). Prospective control of the information available impacts the development of cognition by relating our action to our environment. During the last few decades, much progress has been made in understanding the development of perception, cognition and action; still, many questions need to be addressed (von Hofsten, 2004, for a review)

Learning effect

Learning effect on predictive reaching was not found in either Experiment 1 & 2 of Study I, as there are no signs of learning to anticipate motions in violation of inertia, either within a block or over the whole experiment.

In contrast, in Study II, the analysis of infants' head tracking for partially occluded object motion between the trials indicated an effect of learning and that infants learn more readily about linear than about nonlinear motions. The slow and less consistent learning to anticipate nonlinear occluded object motion suggested that the capacity to anticipate object motion in accord with inertia is weak, though present, in infancy. It was also suggested that task difference might influence infants' representations of the object (see also, Jonsson & von Hofsten, 2003). By measuring gaze tracking, Gredebäck and co-workers suggested that successful predictions are depends on strong representation, which are themselves depend on the richness of information available during encoding and graded representation (Gredebäck & von Hofsten, 2004, Kochukhova & Gredebäck, 2007). Findings of this thesis contribute to the claims that infants may have a single system of object representation that behaves differently in different task contexts (e.g. Munakata et al, 1997, Munakata, 1998, 2001), namely infants' knowledge underlying their performance is graded in nature, it evolves with experience, and is embedded in the specific processes that control the behavior at hand. This is a claim standing between the empiricist domain and the pure nativist domain. It suggests that no single method can uncover the whole range of complexity of any human ability, and that we should not generalize method specific performance to tasks-independent knowledge. This is especially true when we consider methods such as the preferential looking method that was initially designed to answer yes/no questions and to discover competencies, not the higher-level cognitive processes underlying those competencies (Heith, 1998). It seems to me, all of the above theories have contributed their part in understanding the early development of perception, action and cognition, however, without thorough, continuous observation involving longitudinal design, these theories can be neither validated nor falsified.

Lateral asymmetry in reaching

Study III focused on lateral asymmetry embedded in infant predictive reaching for a moving object. Though a higher rate of hand-object touch was found in the right hand, analysis of the total number of unimanual reaches showed no consistent hand preference in young infants, in contrast to a previous observation of moving tasks (von Hofsten, 1980, 1983), which claimed that infants at a similar age demonstrate a strong and stable hand preference when reaching for a moving object. When considering the conflicting observations from infants reaching for stationary objects (e.g., Perris & Clifton, 1988, Carlson & Harris, 1985; Harris & Carlson, 1993; Morange & Bloch, 1996), this result may suggest that no matter if it's a stationary or a moving object involved, provided that the hand preference was defined as the consistent preferred hand in reaching, the reaching paradigm may not be a reliable index to test the early sign of handedness in infancy. Nevertheless, a left-right asymmetry was found in the temporal coupling of infants reaching, evidenced by two main accounts: first, a left-right asymmetry was indicated by the significantly shorter latency and longer duration for the left hand than for the right hand in bimanual reaches for all four object motions; second, a shorter latency and duration in bimanual reach than unimanual reach, a result in agreement with earlier findings in studies of adults (Fitt, 1959; Peterson, 1965). In agreement with previous studies in human infants (e.g. Goldfield and Michel, 1986b; Diamond 1988), movement of two hands seems more often temporally linked at early age. It was argued that infants' difficulty to separate their two hands in bimanual reaching may due to the immaturity of the prefrontal cortex, especially the dorsolateral region (Diamond, 1988, 1991, Fagard & Pezé, 1997).

Taking into consideration the impact of context (e.g. Hopkins and Rönnqvist, 2002) and task scale (e.g. Jensen, 2005) on the action of infant's, studies with measurements of kinematics parameters are needed. As a matter of fact, Rönnqvist & Domellöf (2006) have just demonstrated this in an effort of combining quantitative measurement in a longitudinal study for 6 to 36-month-old infants, which has led to a further understanding of the development of human handedness in the first year and the organization of our brain.

Concluding remarks

The perception guided action approach stresses three aspects of human motor behavior rooted in early age. First, it stresses that motor behavior has to be afforded by a perceptual system. Motor behavior is as much an accomplishment of the muscles as it is an accomplishment of the perceptual system. Perception has evolved to serve action and is a necessary part of any action system (Gibson, 1950, 1966; von Hofsten, 2004). Second, with focus on the tight coupling between motor development and perceptual development, the perception guided action approach stresses the point that movements are inherently purposeful. Purposefulness is seen as a basic irreducible aspect of all action (Rochat 1999). Although triggered movements have commonly been the subjects of intensive study in attempts to understand motor control, such movements are rare in our everyday life (Reed, 1982). By evolution, the designs of our body's systems (perceptual system, CNS, effectors system etc.) have been tailored to each other for optimal function (Vulliemoz, Raineteau & Janaudon, 2005). In motor development our movements are wired by our plans and executed for certain purpose. Purposeful movements do not rely on reflexes, i.e., even at a very early age infant's reaching movement is prepared beforehand (e.g. von Hofsten & Rönnqvist, 1988). Third, to adapt adequately to an often-changing environment, our movement has to be prospective. Such prospective control may be based on knowledge about rules and regularities that govern events in the world, and may be also based on the ability to extract future-orientated information (Melzoff and Mooor, 1998; Spelke, 1994, Spelke et al, 1992; see also, Haith, 1993; von Hofsten, 2004, for reviews).

The studies of this thesis shed light on the nature of infants' representation of object, also revealed the infants' ability to learn to extrapolate object motion (Study I & II). Study II also argued that the successful predictions in infant reaching may depend on representations, which are themselves dependent on the affordances available during information encoding and graded representations (see also, Gredebäck and Von Hofsten, 2004; Kochukova & Grebäck, 2007).

Study II raises questions about the nature of the mechanism that accounts for anticipations of object motion in accord with the principle of inertia. These considerations suggested that a perceptual system underlies infants' anticipations of object movement, but more thorough understanding of the nature of these systems needs further studies.

The challenge confronting anyone trying to understand handedness is that of definition and measurement (see Annett, 1985, 1988; Hopkins & Rönnqvist, 1998, for reviews). Yet human handedness and other functional asymmetries retain their important role in the understanding of the organization of the human brain. Though questionnaires and kinematics analysis tests for drawing tasks are often used for adults and older children, they are not adequate for young babies. Instead, hand preference is often tested by the infant's goal-directed reaching activities.

When hand preference was defined as the consistent preferred hand use in reaching, Study III did not find a significant sign of human handedness at 6-months; nevertheless, a lateral asymmetry was evident in the temporal characters in the organization of infants' reaching, evidenced by the asymmetry in both latency and duration. Results also suggested that our two hands are more temporally linked to each other at this age. As stated above, to gain a more thorough and clear picture of the handedness as early as a few month of life, longitudinal design combined with measurements of kinematics data should be adopted.

The introduction of this thesis gave a short briefing of the ecological perspective of human perception. Gibson's insight of affordances is of great value and importance to early perception and movement and it depicts a fundamental aspect of human cognition (von Hofsten & Lindhagen, 1979). Neisser (e.g. 1988, 1991) and Shepard (1984) were among the first who tried to reconcile Gibson's ecological psychology that emphasizes the information in the environment and cognitive psychology that emphasizes internal representations. According to Shepard, instead of picking up the invariants that are wholly present in the sensory arrays, as a result of biological evolution and perceptual and cognitive learning, an organism is tuned to resonate to the invariants that are significant for it (Shepard, 1984). It was suggested that from birth, human infants demonstrate goal orientation and anticipation that implies some rudiments of representation in addition to finely tuned perception-action coupling and the direct perception of what objects afford for action (Rochat 1999). Human cognitive development has intimate relationship with expanding the prospective control of action. Action must be planned and cannot be constructed ad hoc (von Hofsten, 2007). The present thesis supplied further evidence to support this view: much information needed for perception and action is in the environment as invariants which can be picked up directly and quickly by infant as early as 6-month old. "Direct perception and representation are facts of the mental life of babies, as they are part of our adult life" (Rochat, 1999, pp 28).

Methodological considerations

Recent studies raised questions concerning the definition of infant predictive vs. reactive tracking in occluder context. One aspect of such questioning was concerning the temporal criterion in relation to this matter (e.g., Gredebäck and Von Hofsten, 2004). However, it seems that, although with different methodological applications, the temporal criteria still remain as a good choice to approach this matter, and the results from a number of current studies are pointing to the same direction, no matter if the infant head/eye tracking was tested on linear trajectory tasks or circular trajectory tasks (e.g. Grebäck., von Hofsten & Boudreau, 2002; Gredebäck and Von Hofsten, 2004; Spelke & von Hofsten, 2001; Study II).

By focusing on gaze tracking, Gredebäck and co-workers (Grebäck et al., 2002; Gredebäck and von Hofsten, 2004) adopted systems with customized set-up (a remote ASL 504 eye-tracker) that can simultaneously record the stimuli projected on a computer screen and the gaze based on the reflection of near infrared light from pupil and cornea of the infant, so that the gaze and target related information were sampled simultaneously. Although it was claimed that 3D real life object, like the one used in this thesis, appeared more interested than the 2D image projected on the monitor to young infants (Gredebäck and Von Hofsten, 2004), such methodology system did give great advantages of accuracy in data collection at the researcher's end, compared to the frame by frame film coding method used in this thesis (Study I, II, III). Further more, the device Grebäck and coworkers used can provide circular motion stimuli (Grebäck el at, 2002; Gredebäck and Von Hofsten, 2004) while the device of the current thesis cannot, due to the step engine's mechanical limitation (Study I, II, III).

By using a corneal-reflection eye-tracking technique (Tobii remote eye tracker), Kochukova & Grebäck (2007) reported that 6-month-old showed a learning effects during an occlusion task. This observation is in agreement with the learning effect reported in Study I & II of this thesis. Furthermore, with the advantage of high accuracy coordinates in gaze tracking, Kochukova & Grebäck (2007) were also able to advocate that these effects demonstrate a robust memory effect extending in excess of 24 hours, a memory competence that previous has only been reported in 14-month-old (Moor & Meltzoff, 2004).

Consequently, the use of a system integrating eye tracking and target dynamics such as the ones used in the studies referred to above (Grebäck et al, 2002; Gredebäck and Von Hofsten, 2004; Kochukova & Grebäck, 2007) provided a unique combination of accuracy, non-intrusiveness, easy calibration and fully automatic recording. Specially the Tobii eye tracker, which stores coordinates of gaze from both eyes, provides more prominent features: calibration and recording are very straight-forward than any other system; very easy in stimuli (audio & video) set up and large volumes of high quality data (Kochukova & Grebäck, 2007; also see von Hofsten, www.tobii.se).

Indeed, the use of a combination of a computer-based object motion displays and new recording methods has yielded new insights into the understanding of infant's early perceptual abilities. Still, the strength by using real-life 3D target objects to investigate infants' perceptual guided actions and abilities may still remain the ecological validity.

Future Directions

The three studies included in this thesis contributed evidence to this recognition: infant's movements are organized as actions and not reactions in the way they are goal-orientated and are directed to what's going to happen in the future. Infant's perception and motor planning seem to follow similar principles as those of adults (see also, von Hasten, 2004, for a review). These findings have meaningful consequences not only for our understanding of motor development, which is not just a question of gaining control over muscles; but for the understanding of the development as an integrated whole, because motor development is at the heart of development and reflects the whole spectrum of development. Yet, there are many questions waiting for us to search for answers in the future. Here are a few of them:

- Study I and II suggested that perceptual or cognitive systems underlie infants' anticipations of object motion. Understanding the nature of these systems is very important, however, it requires further systematic untangling of
  - what processes are exactly involved,
  - how the mechanism works between systems and
  - how early can these emergings be identified in the development scale.
- In the case of the A not B problem, Piaget generated the largest range of research trying to figure out the cause of a baby game for over 50 years in the history of developmental science. Did this tell us something valuable? According to Piaget, the use of longitudinal study is essential given that the individual differences in developmental transition do happen fast and unsynchronized. I personally believe that unless we engage longitudinal design with systematic observation and measurement, much of the effort would end up like the Blind Man and the Elephant, especially when researchers use paradigms like preferential looking in which any discrepancy from baseline can result in increased looking time (e.g., Haith, 1998; Hood, 2001). Given the divergence from different theoretical domains described above, our studies, based on a predictive action paradigm, provided further evidence in support of the core principles suggested by Nativists. An innate knowledge system seems to hold an advantage in explaining development, however, due to the lack of longitudinal studies, this account often fails to supply further consistent data to supply solid evidence for its claims (Haith, 1998). The reason, as stated above, is partly due to the technical difficulty or practical challenges from the experimenters' side in studying infant's activity during the very first few months of life. Yet, all the theory mentioned in this thesis has played a common role - to urge the use of the possible solution – more studies with longitudinal design.

- Furthermore, given the low correspondence among preferential studies between infant performance and interpretations, between looking time and attributed cognitive process; further studies need to call more attention to infant prospective action because cognitive development has to do with expanding prospective control over and above the information available at any point of time.
- Although some of the brain areas responsible for the control of adult motor performance have been revealed, how the prospective control is related to early brain function is yet an unclear picture. The same question also underlies infant handedness research. One of the probing efforts to these questions may have to involve brain-imaging study in parallel with measurement in infant behavior performance.

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