Development of Prospective Control of Reaching in Infants

by

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Declaration

I declare that this thesis has been composed by myself and that the work in it is my own.

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Abstract

The emergence of reaching and grasping behaviour in infants is an important occurrence in perceptuo-motor development. Traditionally, this behaviour has been described as a discrete achievement in development, emerging suddenly at about five months of age. This hypothesis was investigated in the first experiment of this thesis. It examined the role of spontaneous arm movements in young infants under six weeks of age for later reaching and grasping. Results showed that the infants moved the arm they were facing up and down in the same region despite added weights that pulled on the hand in the direction of the toes - but only if they could see the arm. The experiment suggests that when watching their arms moving young infants might be setting up a stable frame of reference for action.

Until recently, reaching behaviour has mostly been used as an indicator behaviour for the infant's underlying perceptual abilities. As a result, the skill itself has not received the attention it deserves. The remaining three experiments of this thesis examined what information infants reaching for moving toys were using so as to catch successfully. Catching a moving toy requires the ability to predict a toy's future trajectory. In a cross-sectional experiment, reaching for a toy moving at different speeds was investigated in 11-month-old infants. The toy was occluded from view by a screen during the last part of its approach. The results showed that gaze arrived at the exit side of the screen and the hand started to move forward before the toy had disappeared behind the occluder, and that these actions were prospectively geared to certain times before the toy would reappear. In two longitudinal studies, the development of predictive reaching was investigated in healthy, full-term infants and in infants classified neurologically at risk of brain damage because of low birthweight and prematurity. At each infant's first reaching session, gaze anticipated the reappearance of the moving toy. However, onset of reaching, prospective control of gaze and hand, and timing strategy varied considerably in the premature group and an attempt was made to correlate a deficiency in the ability to extract predictive information for action with mild or moderate perceptuo-motor problems later on in life.

Table of contents

Chapter Three: Prospective Control in Catching by Infants

Chapter Four: Development of Prospective Control of Reaching in Premature At-Risk Infants

Chapter Five: Summary and Conclusions

CHAPTER ONE

A Differentiation Approach to Perceptuo-Motor Development

(With F.R. van der Weel; In press in V. Pouthas and F. Jouen (Eds), *Les comportements du bébé: expression de son savoir?*)

1.1 Introduction

The development of reaching and grasping has received a lot of attention in the literature over the past twenty years. According to the literature, roughly three phases in the development of reaching can be distinguished (for an overview: see Van der Meer, 1988). Firstly, neonates have been observed to exhibit behaviours that look very much like intentional reaching for objects (Bower, Broughton, & Moore, 1970a, 1970b; Bower, 1972; Trevarthen, 1974; Von Hofsten, 1982). *Neonatal reaching*, however, is far from obvious and as a result the literature on infant reaching during the neonatal period is by no means in agreement (Dodwell, Muir, & DiFranco, 1976; Ruff & Halton, 1978; Rader & Stern, 1982). Much clearer is the reaching behaviour which emerges at about 4 months of age. A major feature of the reaching at this age is the important role visual control plays. While neonatal reaching is said to be visually elicited (or triggered, or initiated), *visual guidance* of arm and hand movements is thought to be essential in the second stage of development of infant reaching (Halverson, 1931; Piaget, 1952; Bower, 1976; McDonnell, 1975; Lasky, 1977). Finally, the third phase, in which the reaching becomes more or less adult-like, can be characterized by a decline of visually guided reaching. As the infant approaches 9 months of age the reaching is alleged to become more and more *preprogrammed* or *automatic* (Bushnell, 1985; McDonnell, 1979).

An analysis of the literature of infant reaching shows that different researchers are working in the above three domains, laying stress on only one developmental stage of infant reaching (Van der Meer, 1988). There are hardly any researchers who try to give a complete picture of the perceptuo-motor development of reaching for objects. The reason for this may simply be that one experimental psychologist is interested in the prehensile behaviour of very young infants, while the other is more interested in the reaching and grasping activities of slightly older infants. The question is, however, whether this explanation is sufficient.

In this Chapter it will first be shown that most of the research carried out in the field of infant reaching serves to confirm different theoretical positions on *perceptual* development. The development of reaching for objects as a *perceptuo-motor skill* has therefore not received the attention it deserves. By using reaching as an indicator behaviour of perception, developmental psychologists have tried to determine which perceptual abilities are present at birth and which perceptual abilities have to be acquired during infancy. However, although nativistic and empiricistic theories of perceptual learning seem diametrically opposed, they have one feature in common. Namely, they are both based upon the assumption that the "stimulus input" is poor and lacks meaning. Therefore, these stimuli have to be *enriched* by a creative mind which adds - either learned or unlearned - form, depth, or meaning to previously formless, depthless, or meaningless stimuli.

Some of the problems of the underlying assumptions of the enrichment theories of perceptual learning and development will be discussed. It will then be argued that the differentiation theory of perceptual learning with its different concept of information offers us a third, inherently non-dualistic way in which to discuss perceptual learning and development. Finally, in the last section, an overview of the remaining experimental chapters of this thesis will be given, in which the perceptuo-motor development of reaching from birth to one year of age will be discussed from a differentiational point of view.

1.2 Reaching as indicator behaviour of perception

The emergence of reaching and grasping has long been recognized as an important occurrence during infancy. However, reaching behaviour as a perceptuo-motor skill has not been the main interest of most developmental psychologists. Instead, over the past twenty years reaching for objects has been used predominantly as an *indicator behaviour* of perception (see also Bower, 1974). Thus, by investigating the overt reaching behaviour of young infants, psychologists tried to cast light upon the apparent sophistication of the infant perceptual system. More specifically, they tried to determine which particular perceptual abilities are evident at birth (and which therefore were said to be innate) and which perceptual abilities are not evident at birth (which therefore apparently had to be learned during infancy). In other words, most of the research carried out in the field of infant reaching was and still is concerned with the different theoretical developmental positions of perception, i.e., learning and maturation positions, or a combination thereof.

A well-known controversy in the literature of infant reaching, where reaching is used as an indicator of underlying perceptual abilities, stresses this point. Bower and his associates (1972; Bower, Dunkeld, & Wishart, 1979) reported that newborn infants reached for a solid, three-dimensional object, but not for the two-dimensional picture of that object. From this result it was concluded that the child possessed the innate ability of the mind to add the third dimension to the logically two-dimensional picture of the flat, retinal image. However, other investigators, who tried to replicate Bower's results, failed to find evidence that neonates could differentiate between a solid object and a representation of it (Dodwell, Muir, & DiFranco, 1976, 1979;

DiFranco, Muir, & Dodwell, 1978; Rader & Stern, 1982). This was taken as evidence that the ability of the mind to add the third dimension (which was assumed to be in the environment in the first place, but had been lost in the retinal image) developed only gradually in ontogenesis via an active learning process.

1.3 Descartes' heritage

The controversy between nativists and empiricists is philosophical in origin and goes back as far as Descartes (1637). Descartes' most important idea is called his "corporeal ideas hypothesis" (Reed, 1982). This hypothesis is the claim that the mind is directly aware only of the body, that it is aware of things by means of the body. The mind, Descartes argued, operates on the deliverances of the senses. Three grades of sense can be distinguished.

First, there is the essentially physical grade of sense. Grade one of sense involves nothing like awareness, but does involve some kind of movement, such as respiration, or movements which we would now call reflexes. Descartes' second grade of sense involves awarenesses which have the body as their (main) cause, such as pain and hunger. Finally, grade three of sense is perception which has the soul as its cause. When the soul actively interprets the bodily data, primary (objective) qualities which are truly in the world are perceived. The perception of primary qualities, according to Descartes, requires a *ratiocinative comparison of ideas* belonging to the second grade of sense.

Descartes' theory of the third grade of sense has been popular ever since in theories of perception - perceptions were and often still are said to be the result of ratiocinative or other mental operations on sensations. What is more, his theory was the first to explicitly hold that not all knowledge comes through the sense organs, but that some knowledge is contributed by the mind itself. Even in the present days, the influence of Descartes is apparent in theories of perception and perceptual learning. It has been argued that Descartes' corporeal ideas hypothesis induced so-called theories of indirect perception (see Gibson, 1979), of indirect knowledge (see Shaw & Bransford, 1977), and of indirect action (see Reed, 1984). Further, it can be argued, it was Descartes in the seventeenth century who had opened the way for nativists and empiricists to start arguing at the beginning of the nineteenth century whether the ability to account for the "mental surplus" is an ability that is present at birth or whether it is something that is established through experience.

1.4 Enrichment or differentiation?

As described above, Descartes' heritage gave rise to numerous 'indirect' theories of knowledge, perception, and action. Those theories hold that we do not experience the world and its contents directly, rather that we sense something else in its place, such as sense-data or our own retinal images, from which we then infer the world. The ecological approach (Gibson, 1979; see also: Shaw & Turvey, 1981) disagrees with the hypothesis that perception is indirect whereas most information-processing theories agree with it.

Traditionally, the problem in perceptual learning has been the issue of *how much* of perception is learned. Nativistic, interactionistic, and empiricistic theories agree that our perceptions of the world are indirect. As a consequence, incomplete sensations - aroused by stimuli - have to be turned into perceptions by a creative brain. Therefore, mental or psychological activities have been postulated to supplement the incoming sensations. Thus, sharing the assumption that we must go beyond the information given to the senses, nativists, interactionists, as well as empiricists have argued whether the enrichment we provide for the meagre sensory inputs is primarily innate or acquired, and thus whether much or only a little of perception is learned.

The Gibsons (1955) argued against the three types of enrichment theories, proposing a radically different specificity or differentiation theory according to which the information available for perception is infinitely rich and detailed and the 'sensory input' contains within it everything that the percept has. Therefore, there is no need for a creative mind to add - either learned or unlearned - form, depth, or meaning to previously formless, depthless, or meaningless stimuli. Instead, the information for affordances is in the ambient light (Gibson, 1979), and the child learns to differentiate more and more perceptual information for action.

1.5 Anthropological criticisms of dualism

The differentiation theory of perceptual learning is inherently non-dualistic, as opposed to the enrichment theories of perceptual learning which are based upon a theory which separates minds from bodies and organisms from their environments.

The breaking up of entities into their component parts and the reducing of the components to simpler elements has, since Descartes, been a feature of the Western mind. This analytical, detached thinking, 'la pensée analytique', as Merleau-Ponty (1945) calls it, is a result of the requirement of methodology that cause and consequence have to be able to be defined independently of one another in a conditional relationship. From an analytical perspective, man is transformed into a complex of mutual (logical) independent factors. If we consider that result as real man, it is very easy to get absorbed in a form of metaphysics with all its (seeming) problems. To give an inkling, a sketch of such a vision adapted from De Boer (1980) will be given below.

Imagine an infant reaching for and grasping an object. From the analytical point of view, there are three independent events: a physical, a perceptual and a mental event. The first, the reaching behaviour, is visible, but there must be a perceptual cause at the bottom of it. However, the perceptual event and the mental event which, in its turn, causes sensations to be turned into perceptions, are invisible, and only accessible to introspection. This gives us three trains of events, each with its own access route. A problem that arises is this: When we have to assume a separate mental entity to explain perception, what explains that mental entity? Do we not have to assume a new mental entity which causes that mental entity? This leads, as Ryle (1949) argues, to a *regressum ad infinitum*. What is more, the insolvable problem arises how these events, the external and the internal, relate to each other. Subsequently, nativists and empiricists argue furiously whether the ability of the mind to turn the incoming sensations into perceptions is innate or has to be acquired during infancy. But they seem to have forgotten that their whole problem arises because of one communal *a priori*: the ontological axiom - instead of merely a rule or model - that reality consists of logically independent events. Under pressure of this axiom, human beings become hybrid entities of physical and mental factors. Modern philosophical anthropology tries to break away from this dualism. An unprejudiced look at man shows how he manifests himself as an entity in which perception and action are internally related instead of two causally related factors.

According to Gibson and Gibsonians like Reed, Shaw, Turvey, Warren, and others, the nature of humans is inextricably intertwined with the nature of a world in which they live, perceive, move, and have their being. Similarly, when introducing the concept of the "body-subject", with its emphasis on man's primordial being-in-the-world, Merleau-Ponty (1945 & 1962) argued that all views dichotomizing sensations from perceptions, the person-as-perceiver from the environment-as-perceived and the act of perceiving from the act of knowing, create an *unnecessary* dualism between human/organism and environment and between body and mind.

In the theory of perceptual differentiation, form, distance, size, solidity, and depth are all specified in the optic array to begin with. The problem is thus no longer, as for the enrichment theories of perception, one of explaining how the organism turns meaningless stimuli into meaningful percepts. In order to increase our understanding of perceptual learning and development, we should stick as closely to perception as we can. Because of the *a priori* that the stimulus input cannot account for the ultimate percept, the enrichment theories of perception are forced to explain the difference as if it were the product of some mental chemistry. In this way, a distance in relation to perception in the form of 'indirect perception' is unnecessarily created. If on the other hand we admit that the meaning of an object is based on some intrinsic characteristic of the object, perceiving ceases to be a creative process and becomes once more what it really is, the experiencing of things, rather than the having of experiences (Gibson, 1979).

1.6 The present thesis

The differentiation theory of perceptual learning and development presupposes that the information for perception is already intrinsically meaningful. Thus, perceiving is a matter of differentiating what is outside in the available information. As a consequence, in this theory there is no need for a mental entity - either learned or innate - to construct percepts out of bare stimulus input. Thus, the learning-maturation dichotomy of perception inevitably becomes redundant. A second, related advantage of assuming that the information for perception is rich and detailed so that no mental operation is needed, is that it preserves the theory from the fallacies of traditional dualism.

From a differentiational point of view, however, fundamentally different questions will have to be asked. For the question whether much or only a little of perception is learned does not apply to this theory. Therefore, it becomes unnecessary to use reaching as an indicator behaviour to find out what perceptual processes produce the ultimate percept, or, in other words, what it is that the organism contributes or adds in forming the percept. Instead, the questions become how much and what kind of information must be specified for a defined population to be able to perform a certain task successfully.

The remainder of this thesis will consider how the differentiation theory can be used to study infant reaching as a perceptuo-motor skill in terms of the information used by an infant. Chapter 2 focuses on one aspect of early skill acquisition: how young infants' arm movements can be described in terms of establishing a stable bodily frame of reference for action. Chapter 3 reports cross-sectional and longitudinal data on the development of prospective control of gaze and hand during infant reaching. Chapter 4 presents results of a longitudinal study on the development of predictive reaching in premature, low-birthweight infants who are neurologically at risk of brain damage. Finally, Chapter 5 provides an overall summary and a discussion of the findings.

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CHAPTER TWO

Arm Movements in Very Young Infants: Establishing a Frame of Reference for Reaching

(With F.R. van der Weel and D.N. Lee; Paper under review in *Journal of Experimental Psychology: Human Perception and Performance*)

Abstract *To test whether very young babies take account of gravitational forces in moving their limbs, spontaneous arm-waving movements were measured while the baby lay supine with its head turned to one side. Free-hanging weights, attached to each wrist by strings passing over pulleys, pulled on the arms in the direction of the toes. The results showed the babies applied compensatory forces to keep the hand they faced moving in the same region. In contrast, the (invisible) contralateral hand was pulled down by the weights. In a second experiment, where the arms were occluded, both arms were pulled down, indicating that sight of the arm was necessary in compensating for the weight. The results challenge the general view that spontaneous arm movements of young babies are purposeless and either reflexive or due to spontaneous patterned efference to the muscles. Instead, the findings suggest that in waving their arms, very young infants are establishing a frame of reference for reaching, grasping, and other actions.*

2.1 Introduction

Moving a limb or the whole body in a controlled manner requires acting hand-in-hand with gravity and other external forces. Every limb movement is executed under the force of gravity and the effect of the force on limb movement can change considerably as the orientation of the limb to the direction of gravity changes. For example, if the forearm is raised from horizontal to vertical with the elbow supported, the gravitational torque about the elbow will change from maximum to zero during the movement. This changing external torque has to be taken into account and the internal muscular torque regulated appropriately in order to achieve an intended movement of the arm.

Bernstein (1967) was the first to draw attention to the fact that gravity and other non-muscular forces such as the drag of clothing and stiffness of the joints all must be taken into account in controlling the movement of a limb. The consequence, as Bernstein put it, is that an unequivocal relation does not and cannot exist between the pattern of excitation to the muscles and the form of the resulting movement (p. 21). In other words, movements cannot be represented simply as patterns of efference to the muscles nor in any preprogrammed context-insensitive way. Accurate control requires on-line regulation of muscular activation based on perceptual information about the dynamics of the limb movement and the external force field, as well as about the movement of limb relative to objects or surfaces to which it is being guided.

Are very young infants capable of such perceptuo-motor control or are their movements to be seen as simply reflexive or due to spontaneous patterned efference to the muscles as is commonly believed? The question whether newborns are capable of directed reaching has been addressed in several studies. Twenty years ago, Bower, Broughton, and Moore (1970) and Trevarthen (1974) reported evidence of coordination between eye and hand in the newborn. Up to then established opinion had denied the existence of any such behaviour: the eye and the hand were thought to be unconnected at birth (e.g. Gesell & Amatruda, 1941; Piaget, 1952). Bower *et al.* (1970) presented neonates with a small object in five different positions and reported that 70% of arm extensions were within five degrees of the object; later Bower (1974) reported that the infants actually touched the object on 40% of their arm extensions. However, there have been some failures to replicate Bower's observations (Dodwell, Muir, & DiFranco, 1976; Ruff & Halton, 1978). More recently, Von Hofsten (1982) made precise, three-dimensional measurements of newborns' arm movements and their direction of gaze when presented with an attractive object. He found that their hands got closer to the object if they were looking at it, which indicated a rudimentary form of eye-hand coordination in the newborn.

Analysis of spontaneous arm and hand movements in newborn babies revealed further that neonates can move the hand to the mouth from an indefinite number of starting positions and that the mouth anticipates arrival of the hand before the hand starts to move (Butterworth & Hopkins, 1988). It was concluded that reaching for the mouth has all the characteristics of a goal-directed act which only occasionally fulfills its intended outcome because it is unskilled.

There is thus some evidence that very young babies are able to move their arms and hands in a purposeful way. However, their movements are not sufficiently precise to be able to tell from the reaching data whether or not, or to what extent, their movements take into account the gravitational and other external forces acting on the limbs. Thelen (1990) addressed this question with regard to spontaneous kicking. Three-month old infants were placed in three different positions (supine, seated at 45 degrees, and held in a vertical position) and were found to produce similar movements of the legs under those different circumstances. It was concluded that spontaneous kicking movements cannot be characterized as stereotyped because they are sensitive to different gravitational contexts.

The aim of the present study was to test whether very young infants take account of gravity when making arm movements. We chose spontaneous arm movements to study because we were also interested in their possible functional significance. The movements do not look nearly as controlled and coordinated as the reaching behaviour that emerges at about 4-5 months of age, and they have been dismissed as merely excited thrashing (White, Castle, & Held, 1964), showing no evidence of intentionality and control. This view still prevails, going along with the general tendency to consider newborns as immature, reflexive organisms whose actions are best characterized as involuntary responses to gross aspects of physical stimulation. If, however, spontaneous arm movements were shown to be under perceptual control, this would raise the interesting question as to how these imprecise movements turn into the coordinated reaching behaviour which emerges at around 20 weeks of age.

2.2 Experiment 1

The first study investigated the effect on spontaneous arm movements of applying a force to the babies' wrists. The question was would they try and move the hand they were facing in the same region despite the force that was tending to pull it away.

2.2.1 Method

Subjects. Twelve full-term, normal babies served as subjects, six boys and six girls, with gestational ages between 38 and 42.3 weeks (M = 40 weeks, sd = 8 days) and postnatal ages ranging from 10 days to 6 weeks (M = 32 days, sd = 10 days).

Apparatus & procedure. The infants were placed on their backs on a special baby bed tilted at about 20 degrees to the horizontal and were comfortably secured with a standard baby harness which allowed free movement of the head, arms, and legs (see Figure 2.1). A tilted bed was used because newborns are known to be visually more alert in the semi-upright position than when horizontal (Casaer, 1979; Korner & Thoman, 1970). The infants spontaneously adopted a posture with the head to one side, in which position they could see only one arm.

Infrared light emitting diodes (LEDs) were fastened onto soft bands around the baby's wrists. The LEDs were viewed by an overhead Selspot camera, with optical axis vertical, from a distance of 1.5m. The x-axis in the camera's view was lined up perpendicular to the infant's body axis. A third LED which marked the umbilicus was fastened on to the baby harness and acted as reference LED for the analysis. The Selspot data were recorded on a computer at 62 frames per second. Two video cameras viewed the infant, one from above and one from one side, with a mirror facing the lateral camera. Using a split-screen video mixer a complete record of the infants' spontaneous activity was obtained.

Strings were attached to the baby's wristbands. The strings passed over pulleys at the foot of the bed and could have weights attached to their ends. The weights used were 0%, 10% and 25% of the estimated weight of the baby's arm. Winter's (1979) formula was used to estimate arm weight as a proportion of body weight, as reported by the parents, based on the latest weekly visit to the Health Clinic. By assuming the arm was a cylinder with the height determined by arm length (from the acromion to the first knuckle of the middle finger) and a circumference estimated by the average of the right and left upperarm and forearm measurements, it was confirmed that Winter's formula also applied to babies. With weights added, the string exerted a pull on the baby's wrists approximately parallel to its body axis in the direction of its toes (see Figure 2.1).

Figure 2.1. A three-week-old baby taking part in the experiment.

Each infant was tested for a total of 12 minutes in three experimental conditions, with 0%, 10% or 25% of arm weight pulling on each wrist. The experiment comprised six blocks of four 30s trials over which the three experimental conditions were randomly distributed. This resulted in a total, for each infant, of eight 30s trials with each weight.

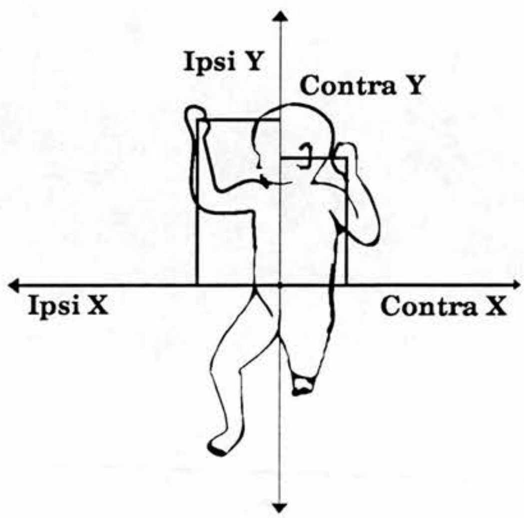
During the experiment care was taken that the infants fulfilled the following behavioural state requirements. They had to be alert, with their eyes open, and be lying either quietly or making gross movements with the arms and legs (states 3 and 4 as described by Prechtl, 1977). Parents were asked to bring their infants to the laboratory when the infants were awake, but not extremely hungry. When the baby fell asleep or started crying during the experiment attempts were made to wake the baby up or to calm her down. In the event of crying, this usually involved feeding the baby for a short while half-way through the experiment. Occasionally, the infant failed to settle and, as a result, the data were severely compromised by interruptions. In such cases, the data were discarded and the parents were asked to bring their baby in later that week for a completely new session of 24 trials.

Measures. The Selspot y-coordinate of the reference LED was subtracted from the y-coordinate of each wrist LED to give y-coordinates of the wrists with a body-centered origin. On each 30s trial, these transformed y-coordinates were used to calculate two performance measures: (1) the mean y-coordinate, a measure of the average location of the wrist in the direction of pull of the string; (2) the standard deviation of the y-coordinate, a measure of the range of the movement along that axis (see Figure 2.2a). Figure 2.2b shows a typical y-coordinate record of a young baby waving both arms with no weights attached.

The video record was inspected to determine which way the baby was facing during each trial of the experiment. The hand the baby was facing was called the ipsi-lateral hand; the opposite hand, which the baby was unable to see at all times, was called the contra-lateral hand. Occasionally, one of the older babies actively changed head position during a trial. In these cases, the mean and standard deviation of y-coordinates were measured over the longest period the baby was facing a particular direction.

Thus, there were 8 trials in each condition. Each trial yielded two basic measures: the average y-coordinate, measuring the average position of the hand and the standard deviation of the y-coordinate, measuring the amplitude of the movement

(a)



(b)

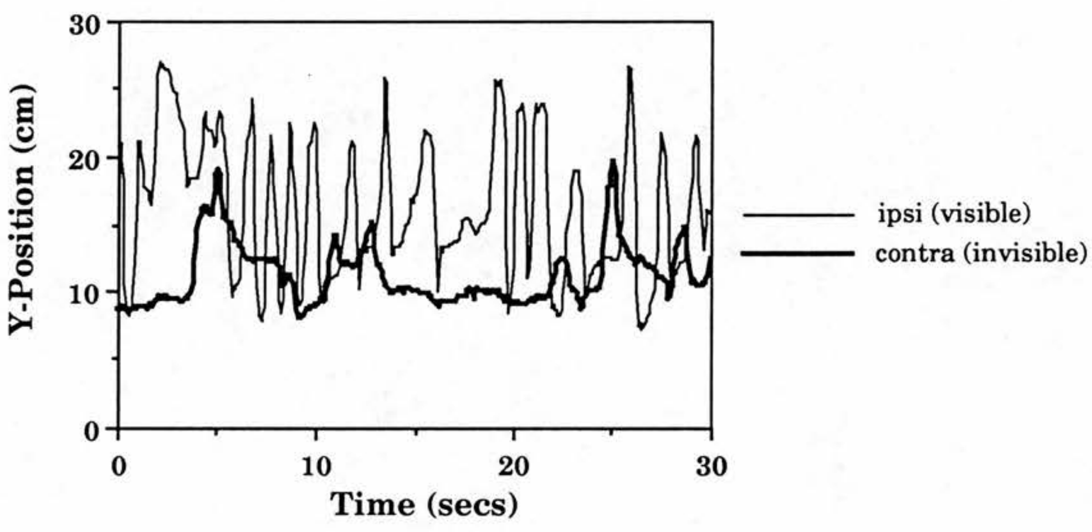


Figure 2.2. (a) Schematic representation of how the y-coordinates of the hands were measured. (b) Typical y-coordinate record of a very young baby waving both hands without weights attached during the 30s recording period. The thin line represents the visible ipsi-lateral hand; the thick line represents the invisible contra-lateral hand.

of the hand. The means and standard deviations of these two basic measures across the 8 trials were then computed for each infant, each hand and each experimental condition.

2.2.2 Results and discussion

Figure 2.3 shows exemplar phase plane plots for movement in the y-direction of the visible ipsi-lateral hand (a and b) and the invisible contra-lateral hand (c and d), both without and with weights attached. The phase planes for the visible ipsi-lateral hand show much movement, with equal range in y-position for the unweighted and weighted condition. In the weighted condition, range in positive velocity (opposing the pull of the string) of the visible ipsi-lateral hand is smaller than in the unweighted condition. The phase plane plots for the invisible contra-lateral hand look very similar in the two weight conditions and are concentrated around zero velocity with occasional outbursts of action.

Difference between hands in average y-position. The means of the average y-coordinates of the infants' wrists in each condition are presented in Figure 2.4. The average y-coordinates of the visible ipsi-lateral hand were significantly greater than those of the invisible contra-lateral hand in the two "weight" conditions (10% arm weight: $F(1,11) = 7.32$, $p < .02$; 25% arm weight: $F(1,11) = 11.23$, $p < .006$). However, in the "no weight" condition there was no significant difference in average y-coordinates between the two hands, $F(1,11) = .06$, *ns*. A repeated measures analysis of variance (Hand x Weight) produced a significant two-way interaction effect, $F(2,22) = 12.85$, $p < .0002$. Thus, adding weights only had an effect on the y-coordinates of the invisible contra-lateral hand.

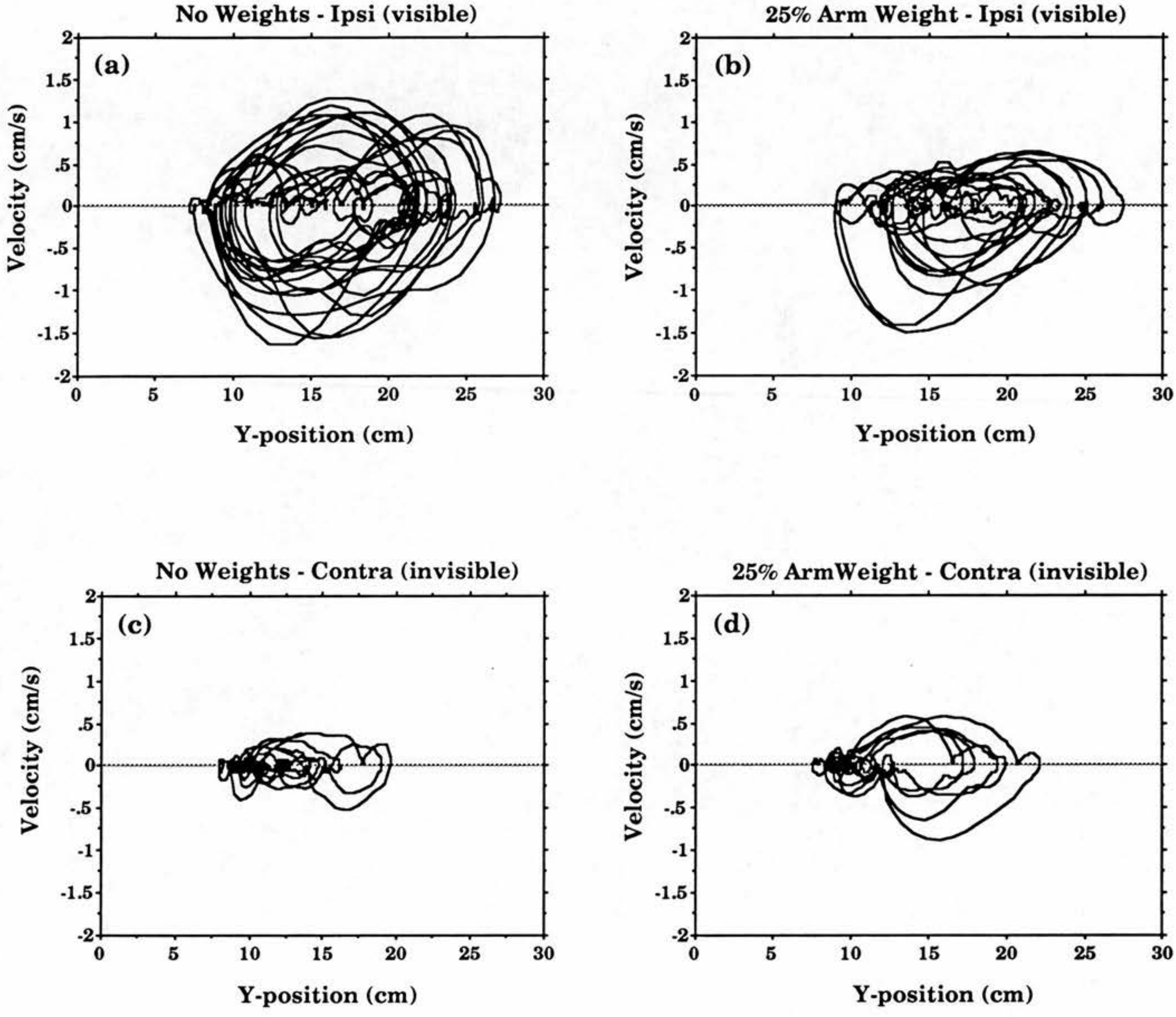


Figure 2.3. Typical phase plane trajectories of wrist position against velocity in y-direction during the 30s recording time. (a) Unweighted ipsi-lateral hand (visible). (b) Ipsi-lateral hand (visible) with 25% arm weight attached. (c) Unweighted contra-lateral hand (invisible). (d) Contra-lateral hand (invisible) with 25% arm weight attached.

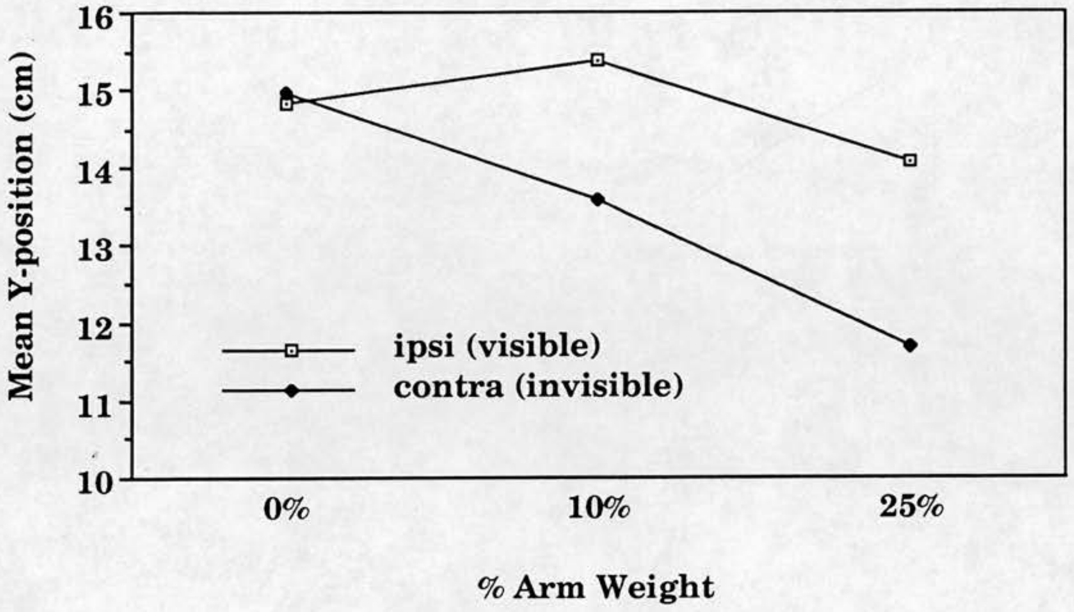


Figure 2.4. Means of the average y-coordinates of the infants' wrists in the "no weight", "10% arm weight", and "25% arm weight" conditions for the twelve young babies for the visible ipsi-lateral hand and the invisible contra-lateral hand. Each data point represents the mean of 96 trials.

To test whether the hands were systematically displaced by the pull of the string on the wrists, linear trend analyses were performed on the average y-coordinates of each hand. There was a significant linear trend for the invisible contra-lateral hand, $t(11) = -7.35$, $p < .0001$, but not for the visible ipsi-lateral hand, $t(11) = -1.46$, *ns*. Additionally, it was shown that the two trends were also significantly different from each other, $t(11) = -4.27$, $p < .0015$.

Difference between hands in variability in y-position. The variability in y-position of the hand, as measured by the standard deviation of the y-coordinates of the wrists on each trial, is shown in Figure 2.5. An ANOVA (Hand x Weight) showed a main effect of hand, $F(1,11) = 9.63$, $p < .01$, indicating that the visible ipsi-lateral hand moved more than the invisible contra-lateral hand in all three weight conditions. Further, there was a significant linear trend with weight for the invisible

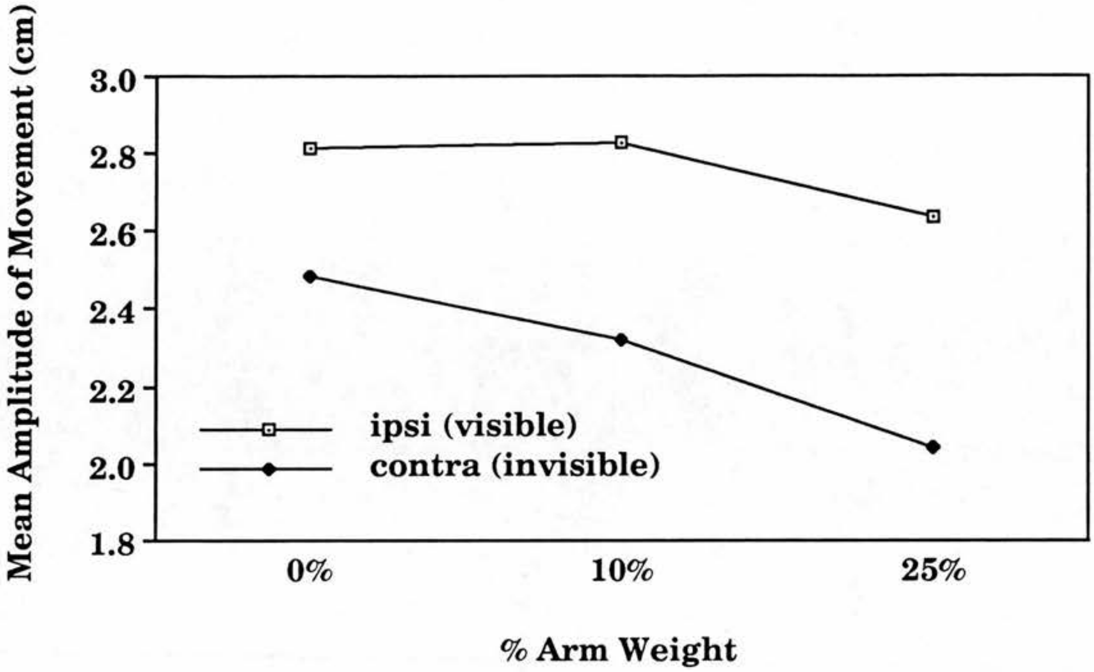


Figure 2.5. Mean amplitudes of hand movement (standard deviations of y-coordinate of wrist on a trial) in the y-direction in the "no weight", "10% arm weight", and "25% arm weight" conditions for the twelve young infants for the visible ipsi-lateral hand and the invisible contra-lateral hand. Each data point represents the mean of 96 trials.

contra-lateral hand, $t(11) = -2.43$, $p < .03$, but not for the visible ipsilateral hand, $t(11) = -1.18$, *ns*: the more weight was added, the less the invisible contra-lateral hand moved in the y-direction. Adding more and more weights to the visible ipsi-lateral hand, however, did not reduce its amount of movement in the same linear way.

Difference between hands in average x-position. An ANOVA (Hand x Weight) was performed on the subjects' average x-coordinates of the wrists on the trials. This revealed an effect of hand, $F(1,11) = 12.482$, $p < .005$, indicating that in all three weight conditions the visible ipsi-lateral hand was farther from the body in the x-direction than the invisible contra-lateral hand. Thus, from a biomechanical point of view, it should have been easier for the babies to keep their contra-lateral hand in the same y-position, because the moment of the pull of the string about the shoulder was less than for the ipsi-lateral hand. However, it was the contra-lateral hand that was pulled down by the weights, not the ipsi-lateral hand.

2.3 Experiment 2

Experiment 1 showed that the very young babies could move their visible ipsi-lateral hand up and down in the same place despite the pull of the string on their wrist. In contrast, the invisible contra-lateral hand was pulled down by the string. The amplitude of movement of the contra-lateral hand was also significantly smaller than that of the visible ipsi-lateral hand in all three weight conditions. Since only the visible hand to which the baby's head was turned showed adaptation to the pull of the string, this raises the question: Was *sight* of the arm necessary for the adaptation, or was *facing* the arm sufficient?

Experiment 2 addressed this question. It was a repeat of Experiment 1, except that occluders at the sides of the head prevented the baby from seeing either arm, while allowing the baby to see elsewhere (see Figure 2.6). Thus, if *sight* of the limb is necessary for its adaptive control, the ipsi-lateral arm should be pulled down by the string like the contra-lateral arm is. On the other hand, if *facing* the arm is sufficient and sight of the arm unnecessary, the results of the experiment should be the same as in Experiment 1.

The latter is also what would be expected if the results of Experiment 1 were a consequence of the asymmetric tonic neck posture (ATNP). In the ATNP, the side of the body to which the face is turned is more tonic, with the leg and arm in extension; on the contralateral side, the arm and leg are less tonic and in flexion (Bullinger, 1990). Therefore, if the infants in Experiment 1 had been in ATNP, the concomitant difference in tonus between the two arms could explain why the contra-lateral arm was pulled downwards more easily than the ipsi-lateral arm. However, several studies have noted that although the ATNP is frequently observed in full-term newborn babies, it is a transitory phenomenon which is easily interrupted by, and does not affect, the free movement of arms and hands to the mouth or chest (Bobath, 1980; Casaer, 1979; Gesell & Halverson, 1942; Peiper, 1963; Touwen, 1976). In fact, in Experiment 1 the infants did not adopt a rigid posture, but moved their arms continuously. Therefore, if the ATNP had still been exerting an influence its effect should have been small. In all events, simply occluding the arms should not change the effect of the ATNP.

2.3.1 Method

Subjects. Six full-term, normal babies who had not participated in Experiment 1 took part in the experiment, five boys and one girl. Their gestational ages were between 38 and 42.3 weeks ($M = 40$ weeks, $sd = 11$ days), with postnatal ages ranging from 3 to 6 weeks ($M = 31$ days, $sd = 10$ days).

Apparatus, procedure & measures. The apparatus was the same as in Experiment 1, except that a small vertical cardboard sheet 15cm high was placed on each side of the head which prevented sight of both arms, but allowed free movement of the head and arms (see Figure 2.6). The baby in Figure 2.6 is slightly older than the infants used in the present sample, and therefore shows better head control. The cardboard surround had no effect on the head turning and the young infants in the present experiment turned their heads as much to the side as the ones that participated in Experiment 1. The procedure and measures taken were identical to Experiment 1.

Figure 2.6. An infant taking part in the experiments.

2.3.2 Results and discussion

Difference between hands in average y-position. The means of the average y-coordinates of the infants' wrists of each hand in each weight condition are presented in Figure 2.7. The average y-positions of the two hands did not differ significantly in any of the weight conditions (0% arm weight: t(5) = .646, *ns*; 10% arm weight: t(5) =

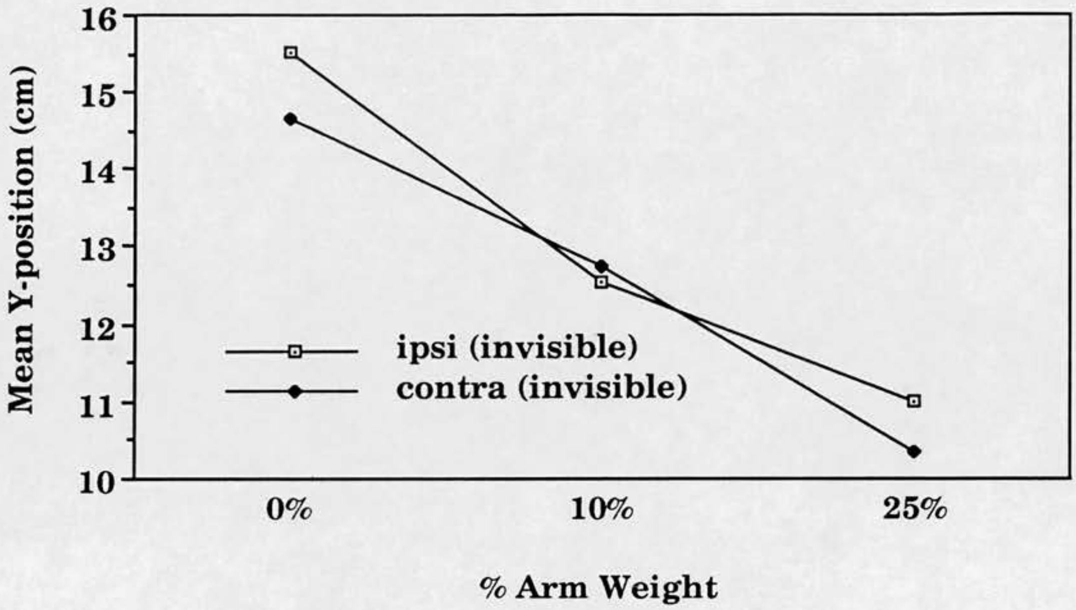


Figure 2.7. Means of the average y-coordinates of the infants' wrists in the "no weight", "10% arm weight", and "25% arm weight" conditions for the six young babies for the invisible ipsi-lateral hand and the invisible contra-lateral hand. Each data point represents the mean of 36 trials. See Figure 2.4 for a comparison.

.17, *ns*; 25% arm weight: $t(5) = .439$, *ns*). A repeated measures ANOVA (Hand x Weight) produced a main effect of weight, $F(2,10) = 11.83$, $p < .0025$. Thus, adding weights decreased the average y-position of both hands.

To test whether the hands were systematically displaced by the pull of the strings, linear trend analyses were performed on the average y-coordinate of each hand. This resulted in significant linear trends both for the invisible contra-lateral hand, $t(5) = -2.811$, $p < .04$, and for the invisible ipsi-lateral hand, $t(5) = -3.736$, $p < .015$.

Difference between hands in variability in y-position. The variability in y-position of the hand, as measured by the standard deviation of the y-coordinates of the wrists on each trial, is shown in Figure 2.8. There were no significant differences between the hands in variabilty in y-position. An ANOVA (Hand x

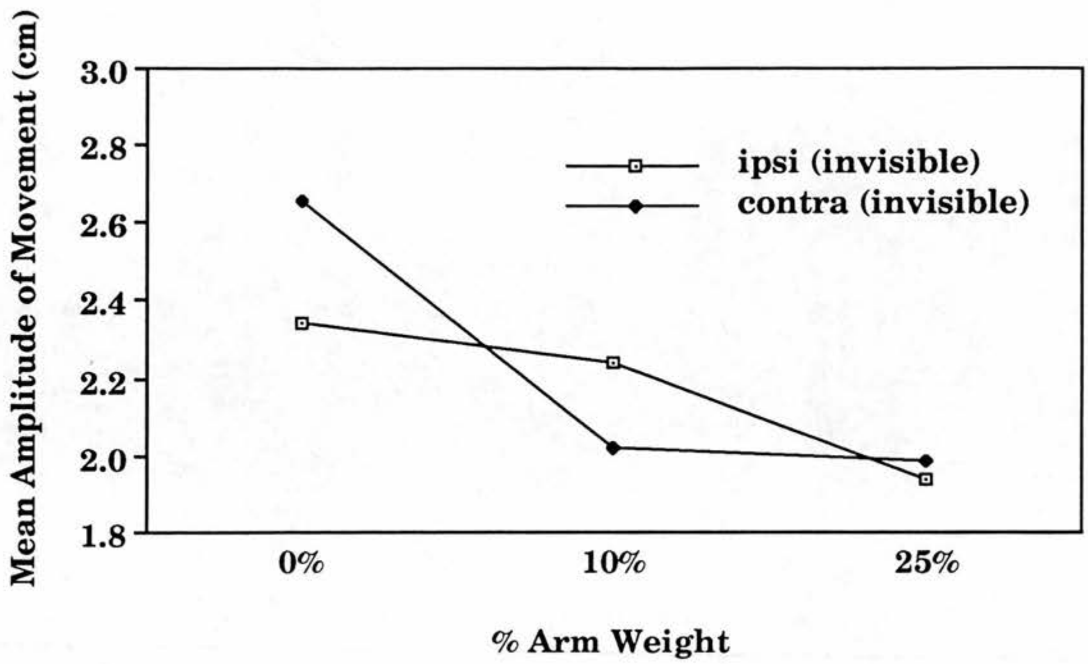


Figure 2.8. Mean amplitudes of hand movement (standard deviations of y-coordinate of wrist on a trial) in the "no weight", "10% arm weight", and "25% arm weight" conditions for the six young babies for the invisible ipsi-lateral hand and the invisible contra-lateral hand. Each data point represents the mean of 36 trials. For a comparison see Figure 2.5.

Weight), which produced no significant effect of hand or weight nor a two-way interaction, confirmed this result.

Difference between groups. Two separate mixed measures ANOVA's (Group x Hand x Weight) were performed on the subject average y-positions and amplitudes of movement of the ipsi- and contra-lateral hands. For this procedure a total of twelve babies were used; six infants selected randomly from Experiment 1 (group 1: 4 boys, 2 girls) and the six infants who participated in Experiment 2 (group 2: 5 boys, 1 girl).

The analysis on the average y-position revealed a significant three-way interaction, $F(2,20) = 8.913$, $p < .002$, indicating that adding weights made the invisible contra-lateral hand of Experiment 1 and the invisible contra- and ipsi-lateral hands of

Experiment 2 drop in the direction of the toes, while only the visible ipsi-lateral hand of Experiment 1 remained in the same y-position regardless of the weights.

The ANOVA on the amplitude of movement produced a significant interaction of Group x Hand, $F(1,10) = 7.932$, $p < .02$, implying that the visible ipsi-lateral hand of Experiment 1 moved more in all weight conditions than the invisible contra-lateral hand of Experiment 1 and the invisible ipsi- and contra-lateral hands in Experiment 2.

2.4 General discussion

The results indicate that very young babies can counteract external forces applied to their wrists so as to keep the hand in their field of view. This finding counters the general view that spontaneous arm movements in young babies are purposeless and are either reflexive or due to spontaneous (patterned) efference to the muscles.

What functional significance might arm waving in young infants have? In order to be able to successfully direct behaviour in the environment, the infant needs to establish a bodily frame of reference for action. Since actions are guided by perceptual information, setting up a frame of reference for action requires establishing informational flow between perceptual input and motor output. It also requires learning about body dimensions and movement limitiations. Vision plays an important role in all of this. Held and Bauer (1974) reported that infant monkeys deprived of sight of their hands and bodies during the first few weeks after birth appeared deficient in accuracy of reach. They also tended to watch their hands incessantly when the hands were eventually revealed. An opaque shield with a cloth bib fitted tightly around the monkey's neck had eliminated visual proprioception and had thus prevented the development of visual control of reaching and grasping.

As a basic part of development, infants - both monkey and human - need to see objects and their hands in conjunction. Gibson (1979) proposed that the shapes and sizes of objects are perceived *in relation* to the hands, as graspable or not graspable, in terms of their affordances for manipulation. Infants are not born with this kind of relational knowledge, and can frequently be observed looking at their hands. This is hardly surprising, as many lessons in practical optics have to be learned in those early weeks before reaching for objects can emerge. Infants also have to learn, for example, how long their arms are, in order to be able to perceive what is within reach, and what is out of reach.

In studies of blind children, Fraiberg (1977) and Warren (1977) found that problems in perceptuo-motor development are encountered at four to six months, the age at which sighted babies are first successful in reaching for and grasping objects. Blind babies often suffer from acquired hypotonia, caused by lack of movement of the limbs (Jan, Robinson, Scott, & Kinnis, 1975). Apparently, being unable to see the hands reduces the amount of arm movements, which, in the long term, causes the tonus of the muscles in the arms to decrease. One intervention aimed at helping blind babies involves bringing the hands to midline to encourage hand play (Fraiberg, 1977) - a non-visual way of exploring one's hands.

The bodily frame of reference for action has been investigated in hemiparetic cerebral palsied children (Van der Weel & Van der Meer, 1991). They were tested on a timing task in which they had to reach out and strike a bat to hit a moving ball. The CP children started moving earlier when using their affected hand, thus allowing for its relative slowness, and timed the hit as accurately as with the unaffected hand. However, when the children had to make the much shorter movement of pressing a button to activate the bat, the affected arm did not start moving appreciably earlier and timing accuracy was again the same as with the unaffected arm. The children were able, therefore, to take into account the limitations of their affected arm in adapting to the different tasks.

Thus, knowledge of one's action capabilities and bodily characteristics plays an important role in perceptuo-motor behaviour. The knowledge has to be incorporated, very early in life, in a bodily frame of reference for action. In general, the bodily frame of reference has to be updated during life, to accommodate changes in action capabilities and body characteristics. Sudden changes in action capabilities, as after a stroke, show this very clearly, as do rapid changes in body size in pregnancy and adolescence. Teenagers, for example, can be notoriously clumsy; they undergo such sudden growth spurts that their bodily frames of reference need to be updated nearly daily.

It, therefore, seems very plausible that the spontaneous arm waving of very young infants of the kind measured in our experiments is helping them set up a frame of reference for action. This being so, our findings could have practical implications for the early diagnosis of children at risk of brain damage. If early arm movements have an important function for later reaching, then infants with signs of hypo-activity of the arms should be monitored closely with respect to retardation in developing reaching, and possibly other perceptuo-motor skills too. In such cases, early intervention should concentrate on improving hand awareness.

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CHAPTER THREE

Prospective Control in Catching by Infants

(With F.R. van der Weel and D.N. Lee; Paper under review in *Perception*)

Abstract. *Catching a moving object requires the ability to predict an object's future trajectory. To test whether infants can use visual information predictively, reaching for a toy moving at different speeds was investigated in six infants around 11 months of age. The toy was occluded from view by a screen during the last part of its approach. The results showed that gaze arrived at the exit side of the screen and the hand started to move forward before the toy had disappeared behind the occluder, and that these actions were prospectively geared to certain times before the toy would reappear. In addition, it was shown that movement duration was related to the time of reappearance of the toy - the information used to regulate duration of hand movement being picked up before the toy disappeared behind the occluder. In a longitudinal study, the development of predictive reaching was investigated in two infants between 20 and 48 weeks. At all ages studied, gaze anticipated the reappearance of the moving toy. However, anticipation with hand movement of toy's disappearance and the ability to gear actions prospectively to the time (instead of distance) the toy was away from certain points on the track developed relatively late and marked the transition to successfully catching faster moving toys.*

3.1 Introduction

The timing and coordination of movements involved in catching fast moving objects has traditionally been considered an advanced perceptuo-motor skill that develops late. Catching requires accurate positioning of the hand and precise timing of the grasp (Alderson, Sully, & Sully, 1974). It thus requires calibrating both the spatial and the temporal information that is available through vision against the motor actions of reaching and grasping.

A number of studies have shown that around 4 months of age, when infants start reaching for stationary objects, they can also catch moving objects quite well (Von Hofsten, 1979; Von Hofsten, 1983). When reaching for a moving object, the hand will ideally be aimed at the point where it will meet the object rather than the point where the object is seen when the reach is initiated. This means prediction of the object's future location, which in turn requires prospective control of head, eye, and arm movements.

Recent work has shown that the head-eye coordination system is well developed at about 5 months of age (Daniel & Lee, 1990). In that study the development of gaze stabilization in infants 11-28 weeks old was investigated, both when looking at a moving toy and when looking at a stationary toy while compensating for body movement. It was found that all infants showed development in prospective control of the head and reached about adult level of control at 20 weeks. Von Hofsten (1980) made precise, three-dimensional measurements of infants' arm movements when reaching for fast moving objects. Each reach was divided into movement units comprising an acceleration followed by a deceleration and the aiming at the beginning of each unit was calculated. Von Hofsten found that even 18 week old infants aimed ahead of the moving object in a predictive way. He did not find evidence of any increase in predictive skill over age.

Recently, Mathew and Cook (1990) criticised Von Hofsten's (1980) conclusions about predictive reaching. They found that infants reaching for stationary objects made directional changes in their movement path not only between but also *within* movement units. Previously, it was assumed by Von Hofsten (1979; Von Hofsten & Lindhagen, 1979) that corrections to the movement path were restricted to the boundary points between movement units. Mathew and Cook (1990) suggested that rather than aiming ahead in reaching for moving objects, infants could simply be aiming their reaches at the current object position and continually adjust the direction of reach en route. However, their claim is not supported by Von Hofsten's (1980; 1983) results.

The present study was undertaken in order to clarify the nature of prospective control in reaching for moving objects by young infants. The visual information available to the infant was manipulated to force the infant to make use of predictive information. What type of information do infants use in controlling their reaching actions and how does prospective control of reaching develop? These are the questions addressed in the present paper.

3.2 Cross-sectional study

The first study investigated the effect on the catching behaviour of 11 month old babies of having an occluder obscure the last part of a moving toy's approach. The question was would the babies anticipate the toy's arrival with their gaze and hand, and if so on the basis of what information.

3.2.1 Method

Subjects. Six normal and healthy, full-term infants served as subjects, two girls and four boys. The infants ranged in age from 43 to 50 weeks (mean 47.5 weeks, sd 2.2 weeks).

Figure 3.1. An 11 month old infant taking part in the experiment.

Apparatus & procedure. The baby sat in an adjustable infant seat facing the middle of a 95cm long horizontal track (see Figure 3.1). Within reaching distance, small attractive toys, about 5cm across, were placed on a rod that moved on the track at shoulder-level to and fro in a frontal plane. Two perspex transparent screens (25cm high, 55cm wide, 18cm apart) were placed in a frontal plane between the infant and the track. The infant had to reach through the gap between the screens so as to catch the moving toy. The last part of the toy's approach was obscured by an occluder (7.5cm wide) attached to the screens on each side of the gap. There was one occluder for when the toy was moving from the infant's left and one for when it was moving in the opposite direction. The toy travelled 47.5cm before it reached the middle of the track.

A Selspot opto-electronic system monitored the motion of the toy and the infant's arm movements. Movements of the arms were recorded by two infrared light emitting diodes (LEDs) fastened onto soft bands around the baby's wrists. The motion of the toy was recorded by one LED mounted on top of it. When the toy passed behind one of the occluders, its LED was obscured by a small piece of material the same width as the occluder. The LEDs were viewed by an overhead Selspot camera, with optical axis vertical, from a distance of 1.5m. The y-axis in the camera's view was lined up perpendicular to the track. The Selspot data were recorded on a computer at 62 frames per second. Each session was also videotaped, using two videocameras and a split-screen video mixer to obtain a simultaneous image of the front and top views of the infant. Thus, information about the infant's field of view, arm and eye movements was obtained.

An experimental session lasted about 30 minutes. The aim was to provide sufficient data for statistical analysis within the time-span of attention of a young infant. Each infant was tested with four object speeds (6.5cm/s, 8.0cm/s, 11.5cm/s, and 13.0cm/s) presented in random order in blocks of eight trials. There were two trials at each speed, one trial with the toy moving from the infant's left and one moving from the infant's right. At these speeds the toy was behind the occluder for respectively 1.15s, 0.94s, 0.65s, and 0.58s. The experiment consisted of 24 to 32 trials. This resulted in a total, for each infant, of between six and eight trials at each speed. One of the infants had difficulty with the highest speed, achieving only one catch. Because of the low incidence of missed catches, only trials where the infant caught or touched the toy were saved on the computer for further analysis.

Measures. The following times were taken on each trial: when (1) *toy starts* moving; (2) *toy disappears* behind occluder; (3) *toy reappears* from behind occluder; (4) *gaze arrives* at point where toy will reappear; (5) *hand starts* moving forward, as indicated by a systematic increase in the y-coordinate of the hand; (6) *hand arrives*, as indicated by a levelling off of the y-coordinate of the hand; and (7) *catch*: hand contacts toy (see Figure 3.2). All measures were Selspot measures, except for the time the gaze

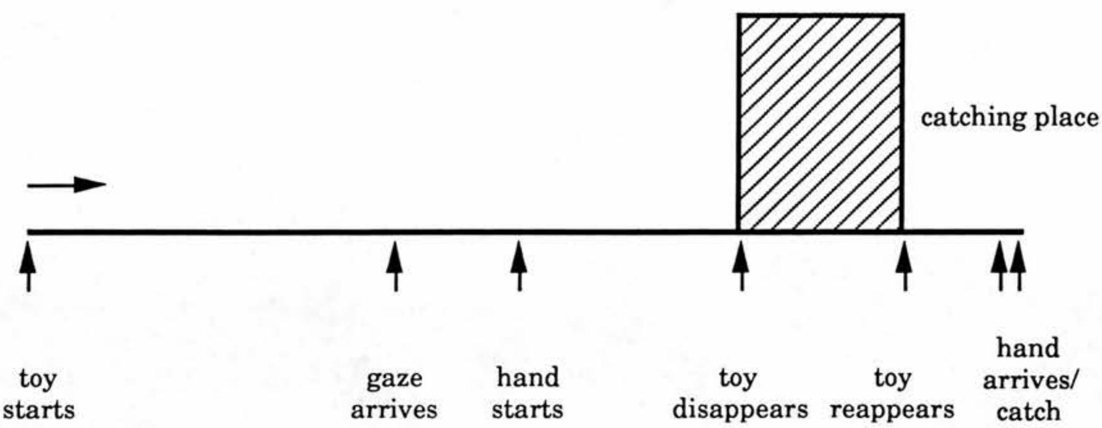

Figure 3.2. Schematic representation of the seven different times measured. The order of the action events is based on the results found in the present experiment.

arrived at the reappearance point, which was obtained from the video record. From the basic measures were computed:

ΔT(toy disappears, gaze arrives)	time gaze arrives - time toy disappears
ΔT(toy reappears, gaze arrives)	time gaze arrives - time toy reappears (negative value if anticipation)
ΔT(toy disappears, hand starts)	time hand starts - time toy disappears
ΔT(toy reappears, hand starts)	time hand starts - time toy reappears (negative value if anticipation)
ΔT(catch, hand arrives)	time hand arrives - time of catch (negative value if hand arrives before making contact with toy)
ΔT(gaze arrives, hand starts)	time hand starts - time gaze arrives

The means and standard deviations of both the basic times and the derived time intervals were then calculated for each infant and each experimental condition. Each mean and standard deviation was computed over six to eight values.

3.2.2 Results and discussion

A total of 152 reaches where the infant touched or caught the toy were analysed. Twelve missed catches occurred (KC: 3, IC: 9), but these were not saved on the computer for further analysis. Some instances of the behaviour on which the measures are based are shown in Figure 3.3. The results indicated that all the infants showed prospective control of gaze and hand on the basis of perceptual information.

Anticipation with gaze. All infants arrived with their gaze at the point where the toy would reappear even before it had disappeared behind the occluder (see Figure 3.4a). The Figure shows negative mean ΔT(toy disappears, gaze arrives) values across speeds for each subject ($t(5) = -4.16$, $p < .01$). The infants were thus showing prospective control of gaze, indicating they were preparing themselves with their gaze to catch the moving toy at the catching place. Research with adult subjects has shown that during reaching eye movements always precede hand movements, even though EMG activity typically begins first in the limb muscles (Biguer *et al.*, 1982).

Anticipation with start of hand movement. The infants all started to move their hands forward before the toy had disappeared behind the occluder, as shown in Figure 3.4b by negative mean ΔT(toy disappears, hand starts) values across speeds for each subject ($t(5) = -3.54$, $p < .02$). In prospectively moving their hands forward, the infants were thus anticipating the toy's arrival at the catching place with their hand. However, of the six subjects, the youngest infant, who was between four and

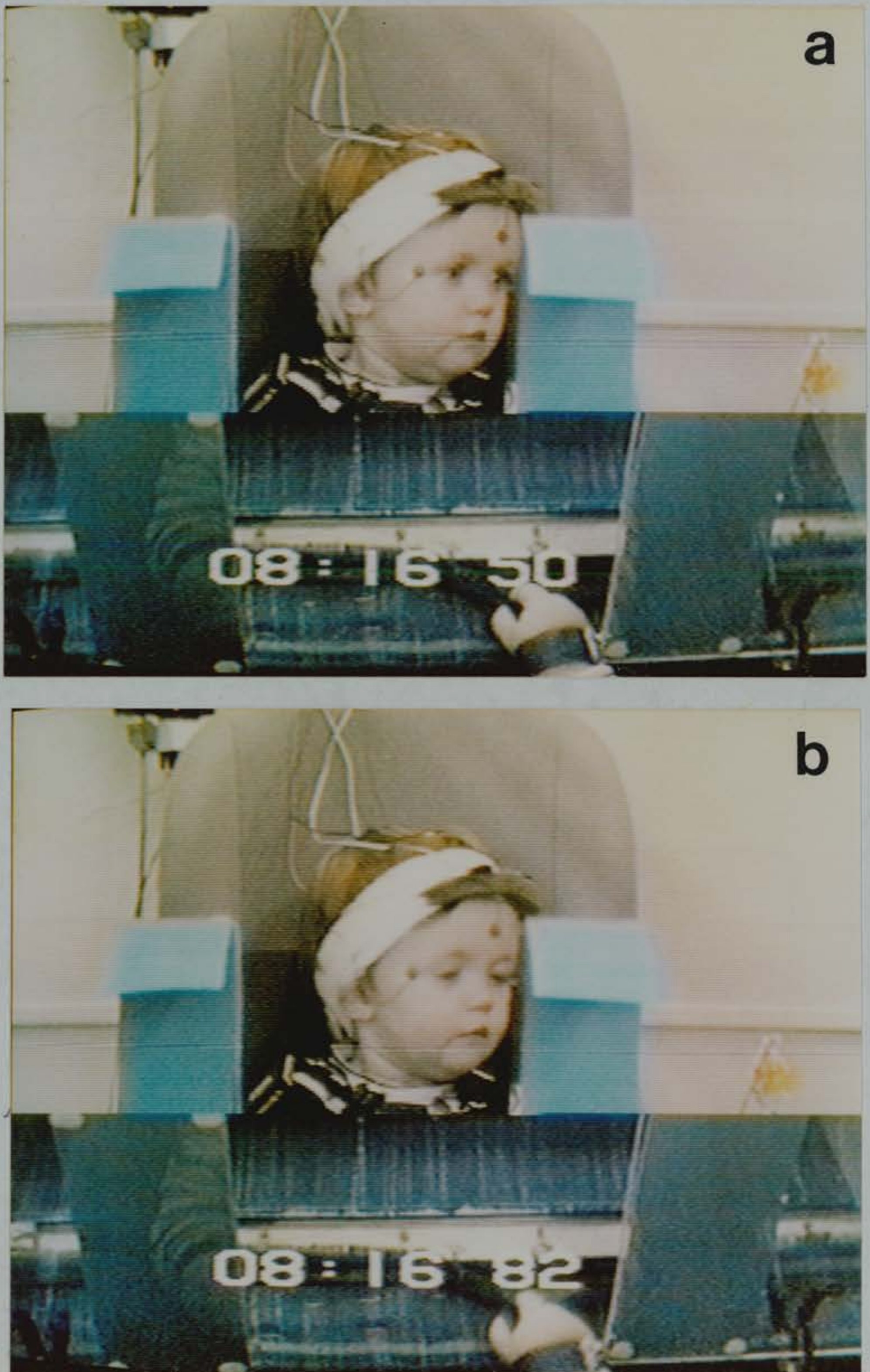

Figure 3.3a-f. Example of anticipation of the toy's arrival in action. The gaze arrives at the point where the toy will reappear (b and c) and the hand starts moving forward (d) even before the toy has disappeared behind the occluder. (continues)

(continued) A split-screen video mixer was used to obtain a simultaneous image of the front and top views of the infant. The infant is wearing a headband with two LEDs attached and three miniature e.o.g. electrodes to record head and (continues)

(continued) eye movements. However, these data were not included in the analysis and the video record was inspected instead to obtain direction of gaze.

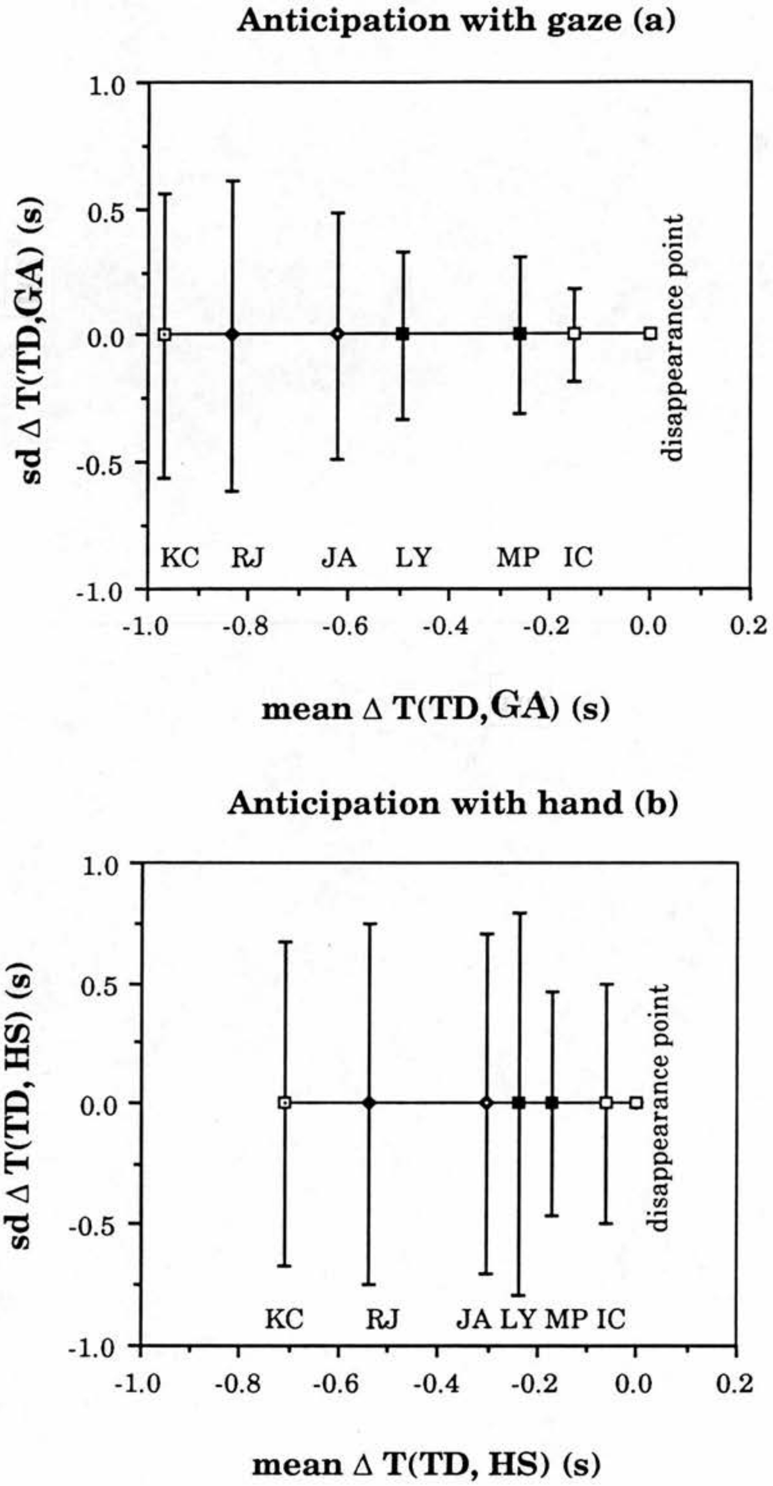

Figure 3.4. Anticipation of toy's arrival at the catching place (a) with gaze and (b) with hand is shown by negative mean values of ΔT(toy disappears, gaze arrives) and ΔT(toy disappears, hand starts). Means and standard deviations taken across speeds of toy are shown for each infant (KC, RJ, LY, JA, MP, IC).

seven weeks younger than the rest, often started to move his hand forward while the toy was behind the occluder (IC, 43 weeks). This behaviour caused him to have the largest number of misses over trials (9 misses out of 28 reaches) and he only managed to catch the toy moving at the highest speed once. The ability to control the movements of the hand prospectively is, of course, crucial at higher speeds. Seven out of the nine misses by the youngest subject occurred at the two highest speeds of the toy.

It should also be noted that, except on the rare occasion when the infants got excited and tried to grasp the toy through the perspex, they started to move their hand in the direction of the catching place rather than in the direction of the current position of the toy. This was very clear from the video records since the angle between the two directions was at least 45°. Thus the infants showed prospective control of the direction of hand movement as well as of its timing, as Von Hofsten (1983) found.

Sources of information. What information did the infants use to anticipate the toy's arrival with their gaze and hand? Three different strategies the infants might have used were tested.

Strategy 1: Actions geared retrospectively to start of toy's movement. We first tested whether the action events analysed occurred at fixed times after the toy started moving. The mean results in the four speed conditions for ΔT(toy starts, gaze arrives), ΔT(toy starts, hand starts), and ΔT(toy starts, hand arrives) and their standard deviations appear in Table 3.1. A repeated measures ANOVA (Speed) was performed on the subject means for the times ΔT(toy starts, gaze arrives). This revealed a highly significant effect of speed ($F(3,15) = 336.56$, $p < .0001$). In addition, there was a significant linear trend ($t(5)=-25.40$, $p < .0001$), indicating that the higher the speed the sooner after the toy had started did the infants look at the catching place. A repeated measures ANOVA performed on the subject means for the times ΔT(toy starts, hand starts) also revealed a highly significant effect of speed

toy's speed (cm/s)	**6.5**	**8.0**	**11.5**	**13.0**
gaze arrives	4.40 (.33)	3.35 (.34)	2.23 (.39)	1.62 (.34)
hand starts	4.69 (.25)	3.62 (.16)	2.32 (.32)	1.76 (.20)
hand arrives	6.44 (.19)	5.23 (.16)	3.83 (.06)	3.25 (.23)

Table 3.1. Means and standard deviations of ΔT(toy starts, gaze arrives), ΔT(toy starts, hand starts), and ΔT(toy starts, hand arrives) for six infants at four different speeds of the toy.

($F(3,15) = 869.27$, $p < .0001$), and a significant linear trend ($t(5)=-104.08$, $p < .0001$). This indicates that the higher the toy's speed the sooner after the toy had started did the infants start moving their hands. Finally, an ANOVA on the subject means for the times ΔT(toy starts, hand arrives) showed an effect of speed ($F(3,15) = 404.53$, $p < .0001$), and a significant linear trend ($t(5)=-30.23$, $p < .0001$), indicating that the toy was caught sooner after its start when it was travelling faster. Thus, none of the action events studied were geared to the start of movement of the toy.

Strategy 2: Actions geared to current position of toy. Next we tested whether the infants used the more sophisticated strategy of gearing their actions to certain positions of the toy on its trajectory. Figure 3.5 shows for each infant the toy's distance away from the reappearance point when the gaze arrived and when the hand started moving forward. Two repeated measures ANOVA's (Speed) on the subject means for toy's distance away from the reappearance point when the gaze arrived at the catching place and when the hand started to move forward revealed significant effects of speed (gaze arrives: $F(3,15)=20.95$, $p < .0001$; hand starts: $F(3,15)=108.22$, $p < .0001$) and significant linear trends (gaze arrives: $t(5)=5.65$, $p <$

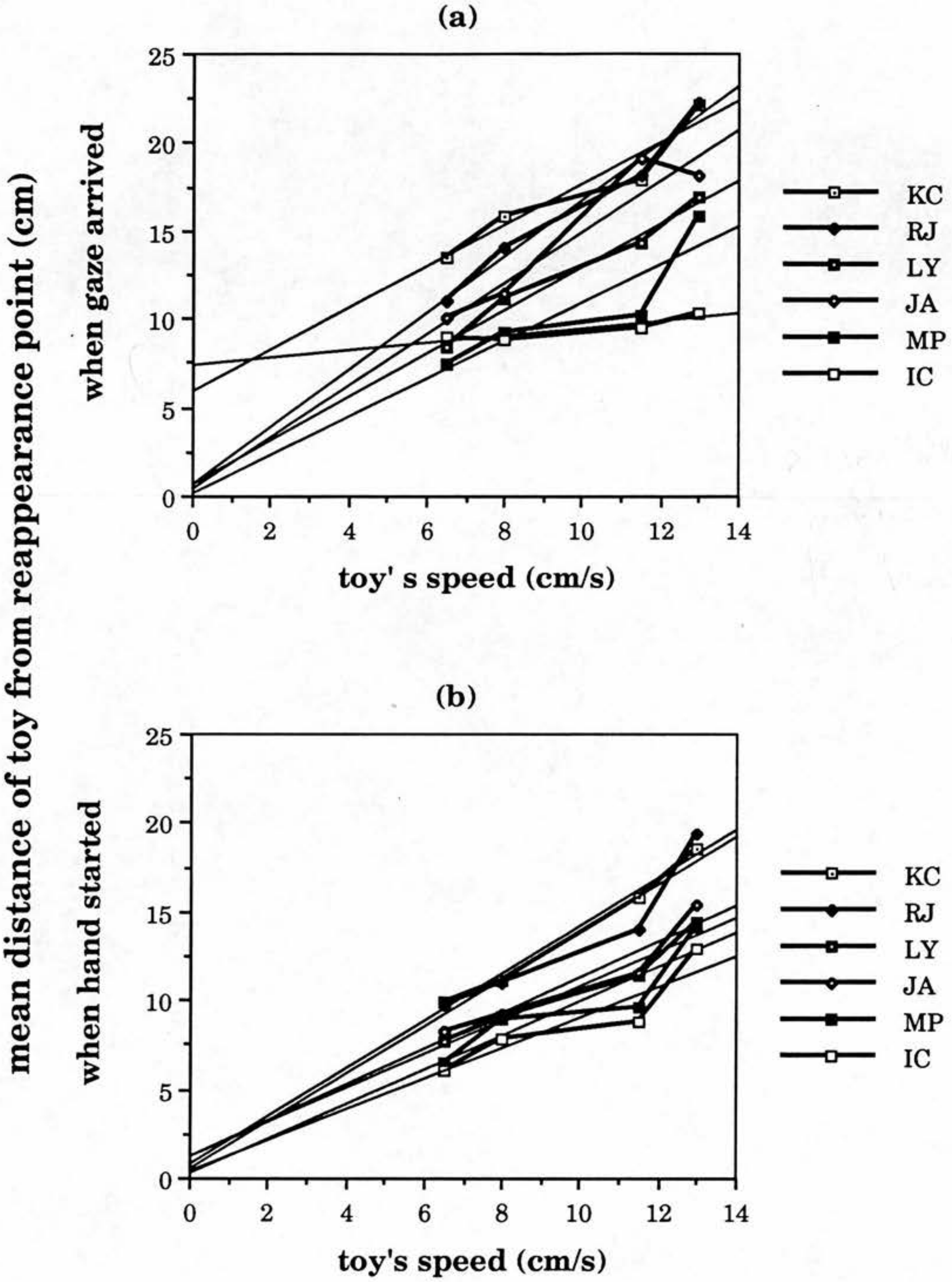

Figure 3.5. Mean distance of toy from the reappearance point when (a) gaze arrived at the catching place and when (b) hand started to move forward plotted as a function of speed of toy for each infant (thick lines). Thin lines represent regression lines for which the coefficients are shown in Table 3.2.

	GAZE			HAND		
	r^2	int.	slope/actual mean time ΔT(GA, TR)	r^2	int.	slope/actual mean time ΔT(HS, TR)
KC	0.914	5.93	1.17/1.66 (0.97)	0.988	0.84	1.34/1.38
RJ	0.975	0.68	1.60/1.67	0.896	0.49	1.34/1.37
LY	0.981	0.69	1.23/1.30	0.951	1.27	0.96/1.03
JA	0.913	0.48	1.45/1.32	0.911	1.28	1.00/1.10
MP	0.781	0.17	1.07/1.05	0.819	0.34	0.97/0.98
IC	0.788	7.47	0.19/0.97 (0.15)	0.829	0.35	0.87/0.88

Table 3.2. Coefficients (r^2, intercept, slope) of regression, for each infant, of toy's distance from reappearance point on toy's speed, when gaze arrived at catching place and when hand started to move forward. Also are reported the actual mean ΔT(gaze arrives, toy reappears) and ΔT(hand starts, toy reappears) values which would be equal to the regression slopes if the infants were gearing their actions perfectly to the toy's reappearance. In brackets are the actual mean ΔT(gaze arrives, toy disappears) values for KC and IC.

.003; hand starts: $t(5)=14.41$, $p < .0001$). These results indicate that when the gaze arrived at the exit side of the screen and when the hand started moving forward, the toy's distance from the reappearance point was longer the faster the toy's speed (see Figure 3.5)[1]. Thus, none of the action events studied were geared to a certain position of the toy.

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1 We also tested whether actions might have been geared to the toy's position, taking into account visuo-motor delay. Suppose an action were started a certain visuo-motor delay time, ΔT, after the toy (travelling at velocity v) had reached a certain distance x from the reappearance point. Then the toy's distance at the start of the action would equal ($x - v\Delta T$). Thus for higher speeds of the toy, the distance should be shorter not, as was found, longer.

Strategy 3: Actions geared prospectively to toy's future trajectory. Finally we tested whether the infants started their actions when the toy was certain times away from certain points on its trajectory. First we considered the reappearance point. If the infants were starting an action when the toy was a certain time away from this point, then the distance of the toy to the point would be longer the faster the toy's speed. This is indeed what was found in the two ANOVA's reported above under Strategy 2 (see also Figure 3.5). For each infant, we then did regression analyses of the mean distance of the toy from the reappearance point on the speed of the toy, for when gaze arrived at the catching place and for when the hand started to move forward. Figure 3.5 shows the regression lines and Table 3.2 shows the coefficients of the regression analyses. The high mean r^2 values of 0.892 for gaze and of 0.899 for the hand indicate that there was a good linear fit. If the infants were gearing their actions to when the toy was certain times away from the reappearance point then the intercepts would be close to zero. For the hand this was the case in all infants. KC and IC, however, seemed to gear their gaze to the toy's disappearance instead of its reappearance, indicated by intercepts of 5.93cm and 7.47cm, respectively (distance between disappearance and reappearance points was 7.5cm). This could explain why KC and IC were the only two infants with missed catches and why IC had problems with catching the toy in the fastest condition. Finally, the regression slopes give an indication of the times the infants were trying to keep constant when they started their actions. Thus, in general, the gaze arrived at the catching place and the hand started to move when the toy was certain *times* away from the reappearance point, independent of the toy's speed.

Anticipation with duration of hand movement. The results described so far indicate that the infants prospectively controlled the arrival of their gaze at the catching place and the start of hand movement to occur at certain times before the toy would reappear. The next question we asked was: Did the infants prospectively

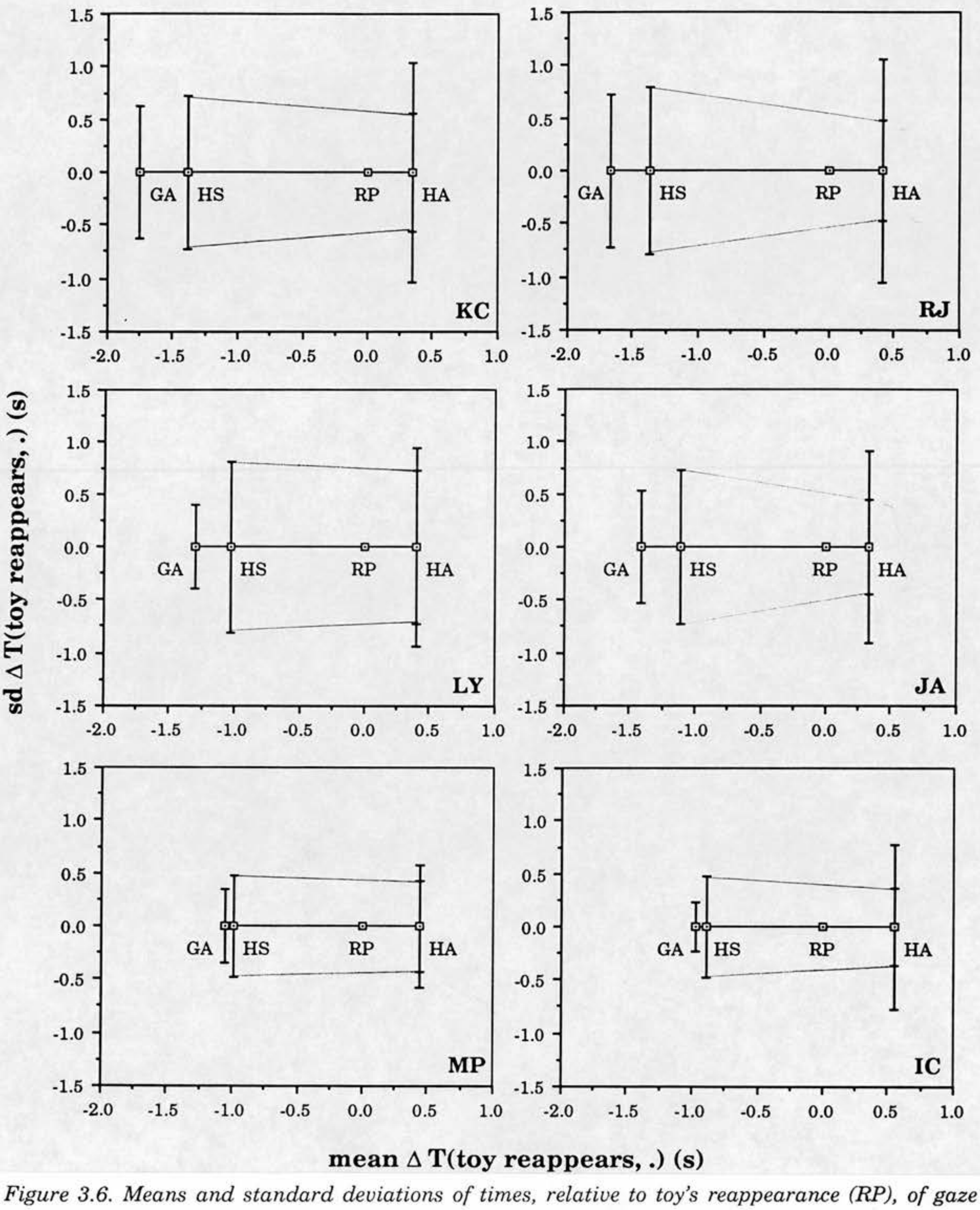


Figure 3.6. Means and standard deviations of times, relative to toy's reappearance (RP), of gaze arriving (GA), hand starting (HS), and hand arriving (HA) for each infant across speeds. Also plotted are the standard deviations of ΔT(toy reappears, hand arrives), which would be expected if information about the toy's arrival at the reappearance point had not been used.

Note that standard deviations are partly plotted with negative values. This was done for display purposes only. In all graphs, the larger standard deviation of hand arrives (HA) is the expected standard deviation if duration of hand movement were not based on visual information about when the toy would or did reappear from behind the occluder.

regulate the duration of hand movement on the basis of visual information about when the toy would or did reappear from behind the occluder, or was movement duration independent of such information. If the latter, then the expected standard deviation of ΔT(toy reappears, hand arrives) would be the square root of the sum of the variances of ΔT(toy reappears, hand starts) and ΔT(hand starts, hand stops). However, the obtained standard deviations across speeds for ΔT(toy reappears, hand arrives) were significantly smaller than the expected standard deviations ($t(5)=5.79$, $p < .003$). The expected values are plotted together with the obtained values in Figure 3.6.

Thus movement duration was related to the time of reappearance of the toy. It is most likely that the information about the time of reappearance was picked up when gaze was directed at the toy, i.e. either before gaze was turned to the catching place or after the toy had reappeared there. Mean values of ΔT(toy reappears, hand arrives) across speeds ranged from 350-550ms. Further, the hand always arrived before the toy had travelled 9cm from the reappearance point. If visual information picked up after the toy had reappeared from behind the occluder was used to regulate when the hand was stopped, then the longer the time interval ΔT(toy reappears, hand arrives) the smaller should be the absolute value of the timing error, ΔT(catch, hand arrives). However, there was no evidence of negative correlations between these two variables. It therefore appears that the information used to regulate the duration of hand movement was picked up *before* gaze was turned to the reappearance point - and, in fact, before the hand started to move. Figure 3.6 shows for each infant the means and standard deviations of the time intervals with respect to toy's reappearance of gaze arriving and of hand starting and arriving. The standard deviations of the time intervals for the anticipatory actions of gaze arriving and hand starting were only of the order 500ms.

	ΔT(hand arrives, catch) = timing error
KC	-.03 (.38)
RJ	-.01 (.27)
JA	-.13 (.33)
LY	.06 (.20)
MP	.07 (.23)
IC	.19 (.39)

Table 3.3. Mean ΔT(catch, hand arrives) values and their standard deviations, used as a measure of timing error for each infant.

Aiming and timing. Von Hofsten's evidence (1979; 1980) of predictive reaching has been criticised by Mathew and Cook (1990). The question is whether infants aim ahead of a moving target towards the meeting point or whether they just stick their hand in the trajectory of the toy and wait for it to reach the hand. The screens used in the study constrained the infants to catch the moving toy at a particular place and particular time, enabling us to investigate more precisely what strategy the infants adopted to catch the moving toy. Table 3.3 shows the mean time intervals ΔT(catch, hand arrives) for subjects across speeds. They were not significantly different from zero ($t(5) = .62$, *ns*). Thus, on average, the hand stopped moving toward the track at the same time as it contacted the toy, indicating that the infant was aiming at a perfect catch, as opposed to either chasing the toy or blocking it. Furthermore, the small standard deviations in Table 3.3 indicate the infants were quite accurate in catching the moving toy.

3.3 Longitudinal study

The cross-sectional study showed that 11 months old infants could anticipate the reappearance of a temporarily occluded moving toy with their gaze and hand, taking into account the speed at which the toy was travelling, but the youngest infant studied (43 weeks old) had difficulty in doing this. To examine how prospective control of reaching develops we ran a longitudinal study. It was a repeat of the cross-sectional study, except that the toy's speeds and the reaching gap were adjusted for the younger ages so that the task was interesting enough for the child to maintain attention for a fairly long period and keep on reaching.

3.3.1 Method

Subjects. Two normal and healthy, full-term infants completed the longitudinal programme, one girl and one boy. At the first session they were 16 weeks old and they were seen at 4-weekly intervals until the age of 32 weeks, and then at 8-weekly intervals until the age of 48 weeks. Both infants attended all seven sessions.

Apparatus, procedure & measures. The apparatus was the same as in the cross-sectional study, except that the reaching gap was widened to 22cm for the first four sessions. In each session, both infants were tested in four experimental conditions. At 16, 20, 24 and 28 weeks the toy travelled at 4.0cm/s, 5.0cm/s, 6.5cm/s, and 8.0cm/s, with a reaching gap of 22cm. At 32 weeks the toy's four speeds were 4.0cm/s, 6.5cm/s, 8.0cm/s, and 10.5cm/s, with a reaching gap of 18cm. At the 40 weeks and 48 weeks sessions the experimental conditions were the same as in the cross-sectional study, with the toy travelling at 6.5cm/s, 8.0cm/s, 11.5cm/s, and 13.0cm/s, and a reaching gap of 18cm. At all ages studied, pilot studies determined the reaching gap and the toy's maximum speed the infants were just able to catch. The procedure and measures taken were identical to the cross-sectional experiment.

3.3.2 Results and discussion

A total of 287 reaches were analysed across subjects and sessions. In all but the first two sessions both subjects made a minimum of 24 and a maximum of 28 reaches per session. This resulted in a total, for each infant, of between six and seven trials on each speed per session. At 16 weeks, neither subject anticipated or reached for the moving toy. Both infants watched the toy intensively and tended to bang their arm on the tabletop when the toy was in sight, but they did not seem to know how to move their hand to the toy. At 20 weeks, RW reached 16 times, but not at the toy's highest speed, while SF made only 5 reaches at the toy's lowest speed.

Anticipation with gaze. Figure 3.7 gives for each infant the mean ΔT(toy disappears, gaze arrives) and ΔT(toy reappears, gaze arrives) values across speeds at different ages. At 20 weeks, when the infants first reached, both infants anticipated the toy's reappearance with their gaze, as shown by the negative ΔT(toy reappears, gaze arrives) values for both subject means. From 24 weeks onwards, ΔT(toy disappears, gaze arrives) values were negative, indicating that both infants moved their gaze to the exit side of the screen even before the toy had disappeared behind the occluder. Both infants further showed longer anticipation with gaze as they got older, levelling off at about 40 weeks of age.

Anticipation with start of hand movement. Figure 3.7 also gives for each infant the mean ΔT(toy disappears, hand starts) and ΔT(toy reappears, hand starts) values across speeds at different ages. Each infant showed a clear trend with age towards anticipating with the hand. At 20 and 24 weeks both infants started moving their hand forward only after the toy had reappeared from behind the occluder. At 20 weeks the start of the hand movement could have been a reaction to the toy's

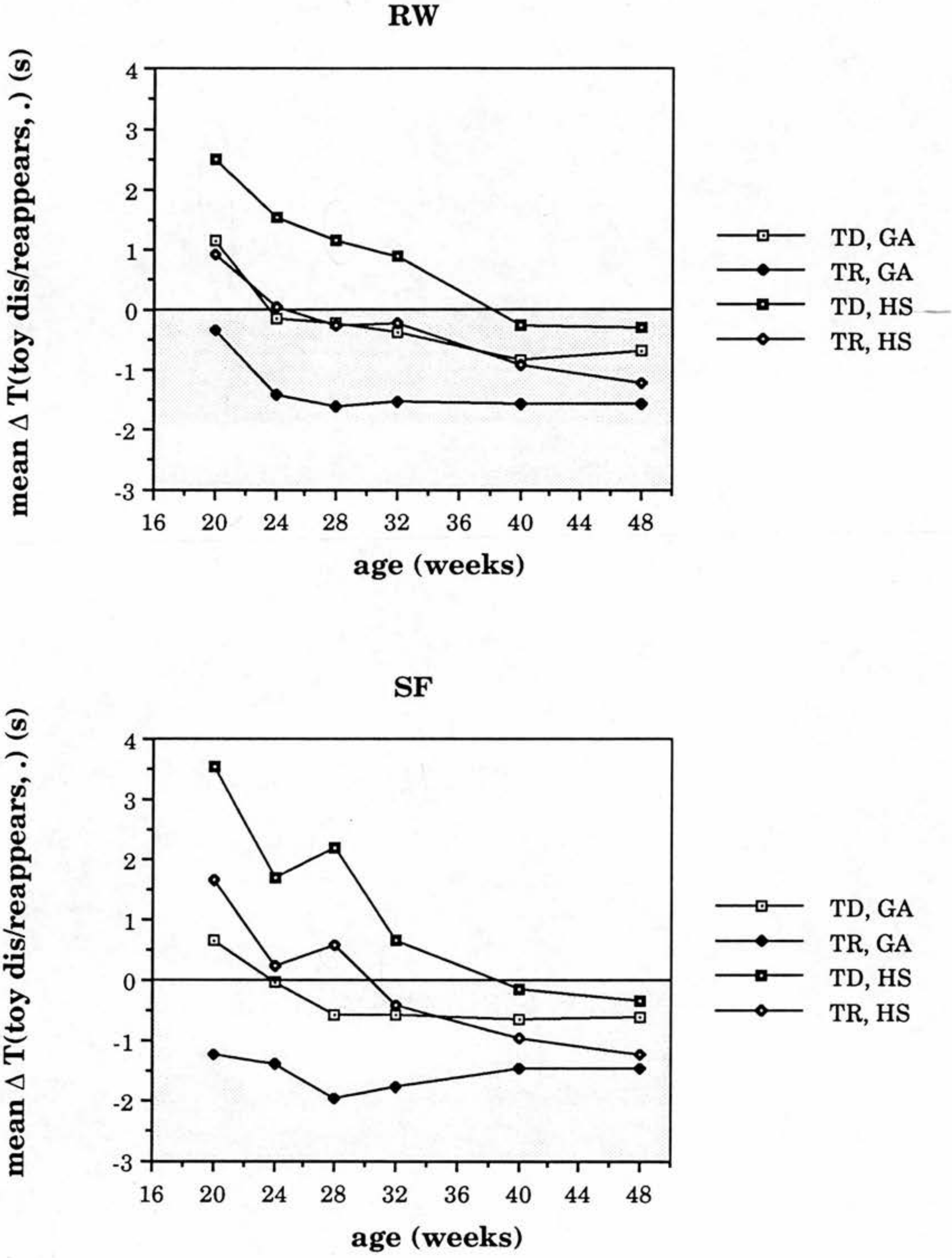


Figure 3.7. Mean ΔT(toy disappears, gaze arrives), ΔT(toy reappears, gaze arrives), ΔT(toy disappears, hand starts) and ΔT(toy reappears, hand starts) values across speeds for RH and SF at each age level studied. Shaded area indicates anticipation of toy's arrival at the catching place.

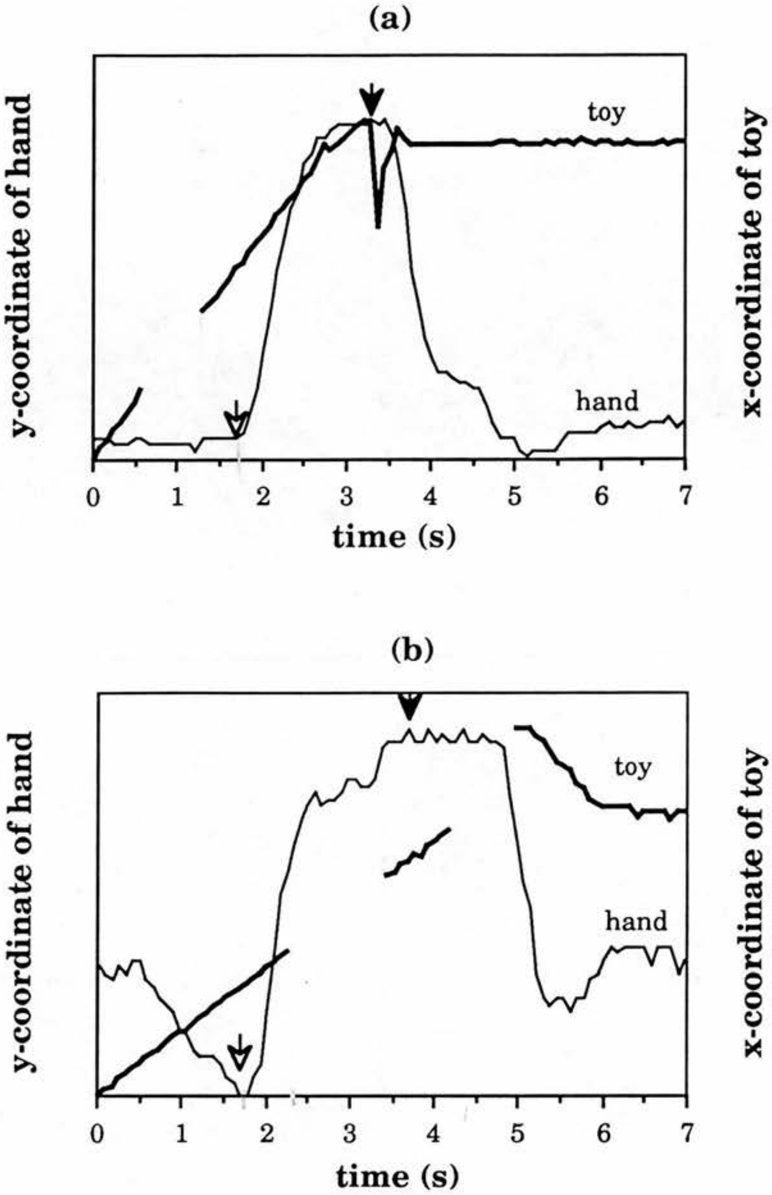


Figure 3.8. (a) Typical y-coordinate record of hand movement (thin line) relative to x-coordinate record of toy motion (thick line) in RW at 24 weeks of age with toy travelling at 8cm / s. The interruption in the toy record represents the period of time that the toy was behind the occluder. Note that the hand started moving forward (open arrow) about 0.4s after the toy had reappeared from behind the occluder. The closed arrow indicates when the toy was caught. (b) Typical y-coordinate record of anticipation in hand movement relative to x-coordinate record of toy motion in RW at 40 weeks of age, with the toy travelling at 6.5cm / s. Note that the hand started moving forward before the toy had disappeared behind the occluder.

reappearance, whereas at 24 weeks the shorter mean time intervals of 0.05s and 0.25s indicate anticipation of the toy's reappearance (see Figure 3.8a). At 32 weeks of age both infants clearly showed anticipation of the toy's reappearance, indicated by negative subject means for ΔT(toy reappears, hand starts) across speeds for both subjects. At 40 and 48 weeks, both infants initiated the movement of their hand before the toy had disappeared behind the occluder (see Figure 3.8b).

Sources of information. What information did the infants use to anticipate the toy's arrival first with their gaze and later with their hand? We first tested whether the infants started to move gaze or hand when the toy was at a certain position on the track. Figure 3.9 shows for each infant the toy's distance away from the reappearance point when the gaze arrived at the catching place and when the hand started moving forward. At 20, 24, and 28 weeks both infants geared their actions to a current position of the toy, since the toy's distance away from the reappearance point did not vary systematically with the toy's speed (see also Footnote 1). At 32 weeks, there is some evidence that both infants started to gear their actions prospectively to the toy's future trajectory. At 40 and 48 weeks of age the toy's distance from the reappearance point when gaze arrived at the catching place and when the hand started moving clearly increased with higher speeds (while the time intervals did not vary systematically with the toy's speed), indicating that both infants had switched from a distance strategy to a strategy which involved gearing their actions prospectively to the time the toy was away from the reappearance point.

Two separate mixed measures ANOVA's (Group x Speed) were performed on the subject means for toy's distance away from the reappearance point when the gaze arrived at the catching place. For this procedure a total of eight babies was used; the six infants from the cross-sectional study and the two infants who participated in the longitudinal study, using the data from the 40 and 48 weeks sessions. The analyses

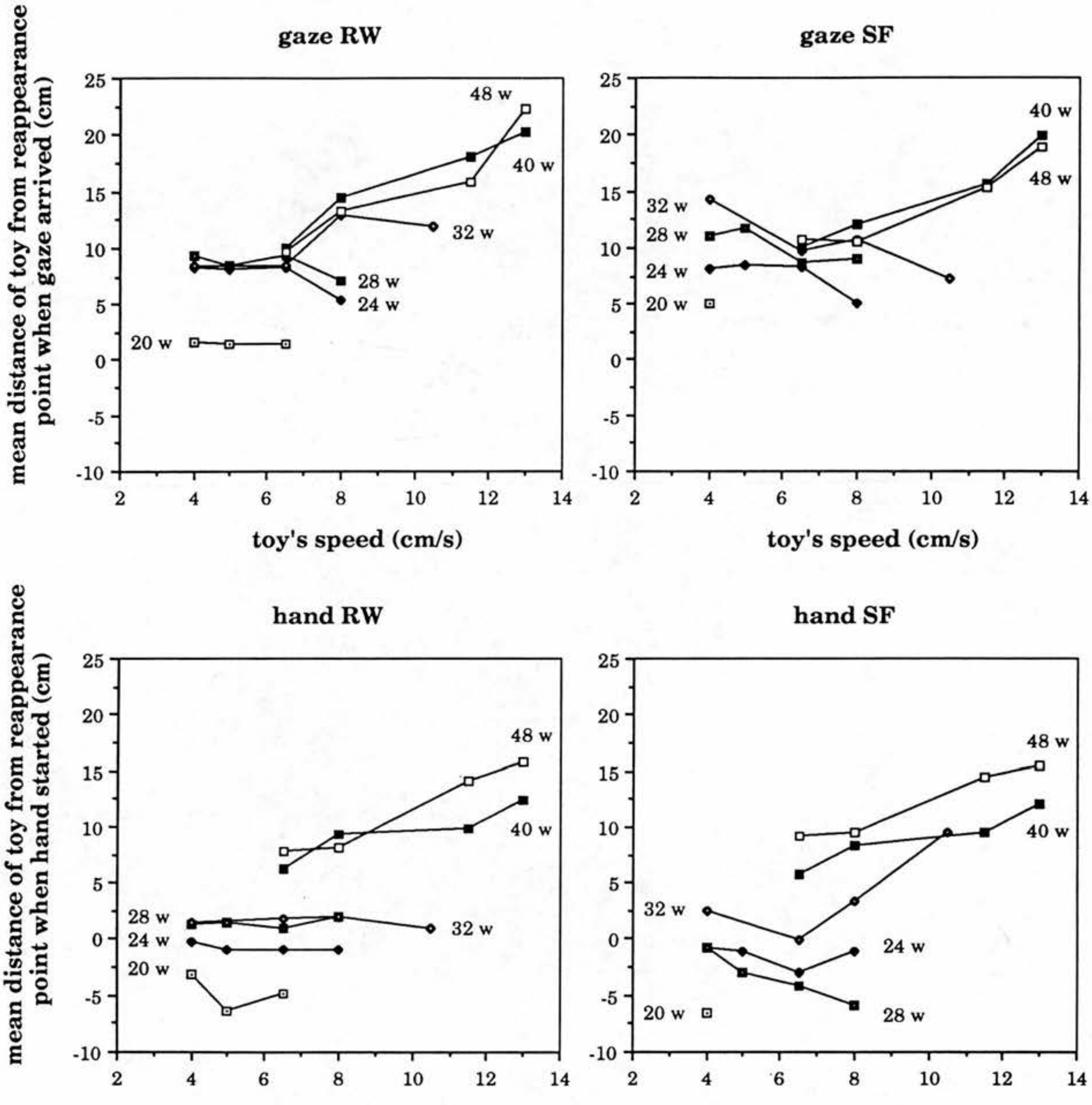


Figure 3.9. Mean distance of toy from the reappearance point, when gaze arrived at the catching place and when hand started to move forward, plotted as a function of speed of toy for RH and SF at each age level studied. Up to 28 weeks the infants appeared to use a distance strategy, gearing their actions to the toy's position on the track. From 32 weeks onwards infants geared their actions prospectively to the time the toy was away from the reappearance point.

revealed effects of speed at both age levels ($F(3,18)=31.01$, $p < .0001$ and $F(3,18)=30.70$, $p < .0001$, respectively), but no group effects nor any interaction effects. Two separate mixed measures ANOVA's (Group x Speed), performed on the subject means for toy's distance away from the reappearance point when the hand started to move forward, showed main effects of speed at 40 and 48 weeks ($F(3,18)=96.94$, $p < .0001$ and $F(3,18)=123.41$, $p < .0001$, respectively). There were no group effects nor any interaction effects. In addition, the time intervals for ΔT(toy reappears, gaze arrives) and ΔT(toy reappears, hand starts) did not vary systematically with the toy's speed. These results indicated that at 40 and 48 weeks of age the two longitudinal subjects anticipated with their gaze and hand the disappearance of the toy behind the occluder while taking its speed into account in the same way as the six 11 month old infants in the cross-sectional study.

Gaze and hand latency. We tested whether, in the course of the development of prospective control of reaching, the flicking of the eyes to the exit side of the screen and the start of movement of the hand became more synchronous. Research with adult subjects has found that the latency between eye and hand movements was about 100ms in an accurate pointing task (Fisk & Goodale, 1987). For each infant, mean time intervals ΔT(gaze arrives, hand starts) across speeds at different ages are shown in Figure 3.10. From 28 weeks onwards, both subjects showed clear developmental trends with age towards smaller time intervals (250-450ms).

Two separate mixed measures ANOVA's (Group x Speed) were performed on the subject means for ΔT(gaze arrives, hand starts), using the same procedure as above. The analyses showed a difference between the cross-sectional and the longitudinal group at 40 weeks ($F(1,6)=14.17$, $p < .01$), indicating that the time interval ΔT(gaze arrives, hand starts) was still relatively large at that age. At 48 weeks there was no such difference between the groups ($F(1,6)=.19$, *ns*). At both ages, there was no effect of speed, nor a Group x Speed interaction.

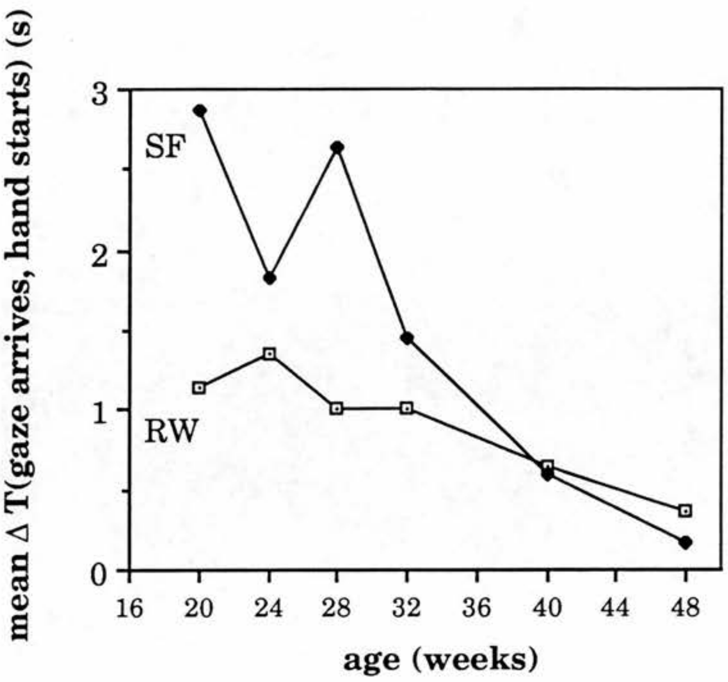


Figure 3.10. Mean ΔT(gaze arrives, hand starts) values across speeds for RH and SF at each age level studied.

3.4 Summary and discussion

To catch accurately a fast moving toy which disappears behind a screen and reappears only shortly before it can be caught requires prospective control of eye, head and hand movement. The hand has to be moving toward the future position of the toy while the toy is hidden and be ready to catch the toy as it comes into view. For precise visual control of the final phase of the catch, gaze has to be oriented to the toy and hand.

All the infants in the present study showed prospective control of both gaze and hand. Gaze shifted to the catching place even before the toy had disappeared behind the screen. In all but the youngest (32 week old) infants, the hand also started to move before the toy had disappeared. Furthermore, the records of the trajectory of the hand showed that, as soon as the hand started to move, it was aimed at the catching place rather than the current position of the toy. Thus, even a second or so before the catch, the direction of hand movement was geared prospectively to the *position* where the catch would be made.

The anticipation with gaze of the moving toy as soon as the infants started reaching suggests that this ability is a prerequisite for the onset of reaching for moving toys. However, this is not what Piaget (1952) argues, for he claims that the object permanence concept is absent in the first eight months or so in life. The present results corroborate more recent findings on this matter (Bower, Broughton, and Moore, 1971; Spelke, 1983).

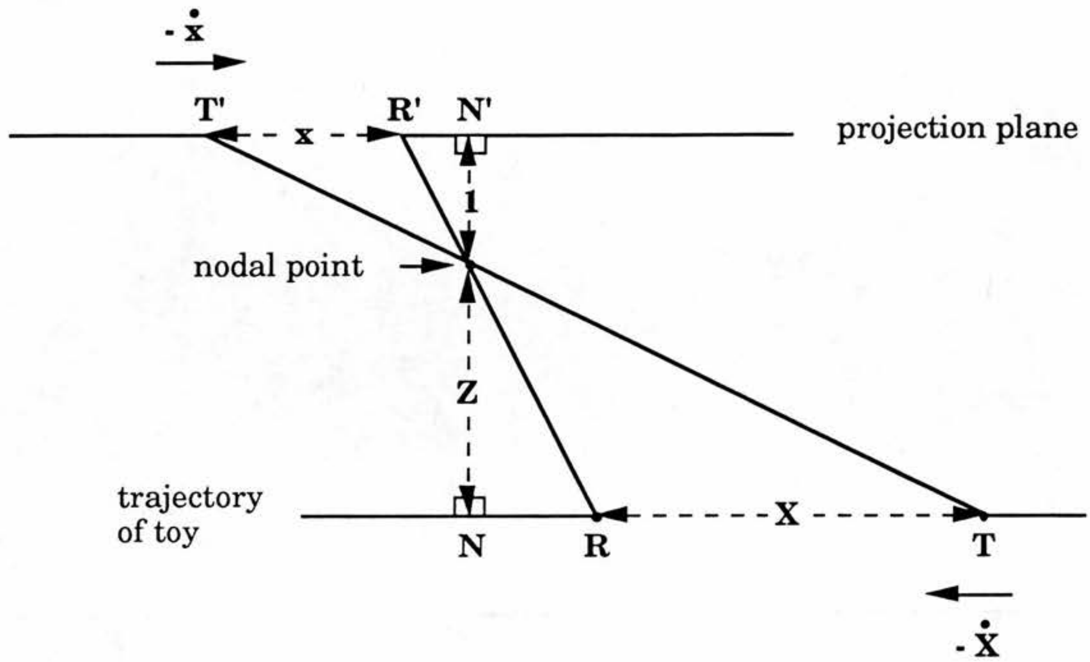
The information used by the infants for prospectively controlling the *timing* of shift of gaze and movement of hand appeared to change with age. None of the infants showed evidence of linking their movements to the start of movement of the toy - which would have not been efficient procedure since their hand would have had to move increasingly faster the faster the toy. However, infants up to 32 weeks of age did appear to use a procedure with a similar drawback - shifting gaze and starting to move the hand when the toy reached certain positions.

Older infants showed more skill. The results indicate that, from 40 weeks, infants shifted their gaze and started reaching when the toy was certain *times* rather than distances away from the reappearance point. They thus made available the same average time for the catching movement whether the toy was moving slowly or quickly.

Each infant naturally showed some variability in timing the start of hand movement. It is significant to note, however, that each showed evidence of taking actual start time into account, varying the *duration* of the reach to time the catch. The data further indicate that they controlled reach duration principally on the basis of visual information about the toy's arrival time picked up *before* the hand started to move.

Thus, the different aspects of the data all point to quite skilled timing of action with respect to the prospective time of arrival of the toy at the catching place. In conclusion, Figure 3.11 shows a model, adapted from Lee et al. (1991), which proposes how the infants might have perceived the time it would take the toy to reach the reappearance point[2].

[2] It may be noted that previous descriptions of the tau theory (e.g., Lee, 1976, 1980) were restricted to a special case of the more general approach situation described here (see also Tresilian, 1992). The restriction was that the destination point, instead of being a general point (R in Fig. 3.11) was always the point-of-nearest-approach (N in Fig. 3.11) of the trajectory to the nodal point. Also, previous descriptions of the theory used either a spherical projection surface (Lee, 1976) or a projection plane perpendicular to the trajectory (Lee, 1980), rather than, as in Fig. 3.11, a projection plane parallel to the trajectory. These different descriptions are, however, equivalent mathematically. The definition of tau of quantity x as $x/\dot{x}$, which equals 1/(rate of dilation of x), is the same throughout.



$$x/1 = X/Z$$

$$\dot{x}/1 = \dot{X}/Z$$

$$\therefore \quad \tau(x) = x/\dot{x} = X/\dot{X} = \tau(X)$$

Figure 3.11. Optical specification of time to contact of toy (T) with reappearance point (R). See text for details.

Figure 3.11 shows the nodal point of the infant's eye and the trajectory of the toy T. R is the reappearance point. At a certain time t, T is distance X from R and moving with velocity $\dot{X}$. With a visual frame of reference defined by a nodal point unit distance from a projection plane parallel to the trajectory of the toy, the images of T and R on the projection plane are T' and R' respectively. At time t, T'R' = x and T' is moving toward R' with velocity $\dot{x}$. From simple geometry, x/1 = X/Z, where Z is the (fixed) distance of the nodal point from the trajectory of T. Differentiating this equation with respect to time and then eliminating Z results in

$$\tau(x) = x/\dot{x} = X/\dot{X} = \tau(X) \qquad (1)$$

where $\tau(x)$ is the tau function of x.

Thus the value of the tau function of the distance X - which equals the time to arrival (at constant velocity) of the toy at the reappearance point - is given by the tau function of the optical distance x.

3.5 References

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CHAPTER FOUR

Development of Prospective Control of Reaching in Premature At-Risk Infants

Abstract. *Catching a moving object requires the ability to predict an object's future trajectory. Healthy full-term infants and infants classified neurologically at risk because of low birthweight and prematurity were tested longitudinally on the ability to use visual information predictively. Reaching for an object moving at different speeds was investigated from 20 weeks until the infants were 48 weeks old. The object was occluded from view by a screen during the last part of its approach. The results showed that at each infant's first reaching session, gaze anticipated the reappearance of the moving toy. However, onset of reaching and prospective control of gaze and hand varied considerably between the normal and premature group. In addition, it was shown that some premature infants used the less sophisticated timing strategy of gearing their actions not to the time but to the distance the toy was away from the catching place, causing problems with faster moving toys. Finally, an attempt was made to correlate a deficiency in the ability to extract predictive information for action with mild or moderate perceptuo-motor problems later on in life.*

4.1 Introduction

There is an extensive literature concerned with investigating the developmental outcome of children born preterm with low birthweight who are neurologically at risk of brain damage (Ellenberg & Nelson, 1981; Stewart, Reynolds & Lipscomb, 1981; Vohr *et al.*, 1989). In general, the lower the birthweight or the shorter the gestation, the poorer the child's overall outcome. Various studies have found that preterm, low birthweight infants are at greater risk for physical and neurological problems (Piper *et al.*, 1988; Saigal *et al.*, 1982; Sainte-Anne Dargassies, 1977; Williams *et al.*, 1987). Some of these problems are obvious at birth, whereas others are not detected until as late as two years of age.

Infants with severe forms of cerebral palsy are readily identifiable at birth or shortly thereafter because of obvious tone abnormalities and strong pathological patterns. In the infant with mild to moderate cerebral palsy, early diagnosis with standard neurological tests is more difficult and many infants go undiagnosed until they begin to show delays in some of the more important motor milestones such as sitting, crawling and standing. Early identification of cerebral palsy is important not only to establish a diagnosis, but also to allow for the start of early intervention programmes which may have a beneficial effect on the developmental outcome of the child (Burns, O'Callaghan & Tudehope, 1989; Ellenberg & Nelson, 1981; Harris *et al.*, 1984).

Since cerebral palsy is a developmental disorder, assessment and treatment need to be founded on principles of development of movement and postural control (Lee *et al.*, 1990). With early brain damage particularly, fundamental perceptuo-motor skills, such as looking, maintaining balance, and timing are likely to be affected, which could later affect the development of more complex skills such as reaching, walking and writing. It is therefore necessary to gain insight in the basic principles of development of movement.

Underlying all fundamental perceptuo-motor skills is the ability to use perceptual information predictively. When reaching for a moving object, the hand will ideally be aimed at the point where it will meet the object rather than the point where the object is seen when the reach is initiated (Von Hofsten, 1980, 1983; Van der Meer *et al.*, 1992; Chapter 3). This means prediction of the object's future location which in turn requires prospective control of head, eye, and arm movements. Recent work has investigated the development of prospective control of the head-eye-hand coordination system in healthy, full term infants while looking at a moving toy or while compensating for body movement (Daniel & Lee, 1990), and while reaching for a temporarily occluded moving toy (Van der Meer *et al.*, 1992). Prospective control of head and eyes developed early, and showed a surge around 4-5 months, which is the age when reaching normally starts to develop. Prospective control of the hand movement, however, developed relatively late (11 months) and marked the transition to successfully catching faster moving objects.

Gearing actions adequately to the environment requires perceiving the consequences of continuing the current course of action, so that adjustments can be made in time. And this requires the pick-up of predictive perceptual information. As the ability to use visual information predictively is fundamental to coordinating action, its disruption could have wide-reaching effects. (1) What are the differences in how well full-term, healthy infants and preterm, low birthweight infants can differentiate predictive elements in visual information for reaching and (2) Could a deficiency in the ability to extract predictive information for action be a precursor for mild or moderate perceptuo-motor problems? These are the questions examined in the present Chapter.

4.2 Longitudinal study

Catching a moving object requires the ability to predict an object's future trajectory. In Chapter 3 it was shown that 11 month old infants anticipate the arrival of a temporarily occluded moving toy with their gaze and hand, taking into account the speed at which the toy is travelling. In that study reaching for a toy moving at different speeds was investigated, where the toy was occluded from view by a screen during the last part of its approach. It was found that gaze arrived at the exit side of the screen and the hand started to move forward before the toy had disappeared behind the occluder, and that these actions were prospectively geared to certain times before the toy would reappear. To examine how prospective control of reaching develops in infants neurologically at-risk of brain damage we ran a longitudinal study identical to the one reported in Chapter 3, with normal, full-term infants acting as controls.

4.2.1 Method

Subjects. A paediatric consultant at the local maternity hospital referred to us ten infants, three boys (BC, JB and SB) and seven girls, classified neurologically at risk of brain damage. The infants had all been born within 32 weeks of gestation (M = 28.7 wks; sd = 2.3 wks; range = 25-32 wks) or had birthweights of 1500 grammes or less (M = 1178g; sd = 363g; range = 645-1694g), and had been on a mechanical ventilator for at least 48 hours. Two healthy, full-term infants served as normal controls, one girl and one boy (the control data are also reported in Chapter 3).

Testing started at 20 weeks of age (corrected gestational age) and after that the infants were seen at 4-weekly intervals until the age of 32 weeks, and then at 8-weekly intervals until the age of 48 weeks. Due to illness, two twin sisters (CB and RB) from the at risk group missed the 24- and 32-weeks session, and one girl missed the 20-weeks session. The two infants in the control group attended all six sessions.

Apparatus & procedure. The apparatus was the same as reported in Chapter 3. In each session, the infants were tested with four object speeds presented in random order in blocks of eight trials. There were two trials at each speed, one trial with the object moving from the infant's left and one moving from the infant's right. At 20, 24 and 28 weeks the object travelled at 4.0cm/s, 5.0cm/s, 6.5cm/s, and 8.0cm/s, with a reaching gap of 22cm. At 32 weeks the object's four speeds were 4.0cm/s, 6.5cm/s, 8.0cm/s, and 10.5cm/s, with a reaching gap of 18cm. At the 40 weeks and 48 weeks sessions the object travelled at 6.5cm/s, 8.0cm/s, 11.5cm/s, and 13.0cm/s, with a reaching gap of 18cm. Apart from some infants' first reaching session, each following session consisted of 24 to 28 trials evenly distributed over the toy's four speeds. This resulted in a total, for each infant, of between six and seven trials on each speed per session. At 28 weeks, CB only reached for the toy when it was travelling at its lowest speed. Because of the low incidence of missed catches, only trials where the infant caught or touched the toy were saved on the computer for further analysis.

Measures. The following times were taken on each trial: when (1) *toy disappears* behind occluder; (2) *toy reappears* from behind occluder; (3) *gaze arrives* at point where toy will reappear; and (4) *hand starts* moving forward, as indicated by a systematic increase in the y-coordinate of the hand (see Figure 3.2). All measures were Selspot measures, except for the time the gaze arrived at the reappearance point, which was obtained from the video record. From the basic measures were computed:

ΔT(toy disappears, gaze arrives)	time gaze arrives - time toy disappears
ΔT(toy reappears, gaze arrives)	time gaze arrives - time toy reappears (negative value if anticipation)
ΔT(toy disappears, hand starts)	time hand starts - time toy disappears
ΔT(toy reappears, hand starts)	time hand starts - time toy reappears (negative value if anticipation)

The means and standard deviations of both the basic times and the derived time intervals were then calculated for each infant and each experimental condition. Each mean and standard deviation was computed over six to seven values.

Neurological and ophthalmological measures. It was agreed with consultants at the local hospital that neuro-developmental assessments and ophthalmological data on the ten premature infants would be revealed to us after data analysis of the present study was completed.

4.2.2 Results and discussion

A total of 1370 reaches were analysed across subjects and sessions. Both normal controls started reaching at 20 weeks of age. As a group, the premature "at risk" infants started reaching significantly later (mean corrected age 22.8 wks, sd 3.8 wks) than the healthy, full-term infants ($t(9)=2.33$, $p < .05$). However, as can be seen in Figure 4.1, individual differences were pronounced in the premature group. Of the ten infants at risk of brain damage, six reached in the first session at 20 weeks (CB, JB, NG, RB, RH and SB), one started reaching at 24 weeks (MT), and three started reaching at 28 weeks (BC, DS and SP).

Anticipation with gaze. Figure 4.1 gives for each infant the mean ΔT(toy disappears, gaze arrives) and ΔT(toy reappears, gaze arrives) values across speeds at different ages. Regardless of age at onset of reaching, all infants anticipated the toy's reappearance with their gaze in their first reaching session, as shown by the negative mean values of ΔT(toy reappears, gaze arrives) for all subjects. This was true for both the 'early' and the 'late' reachers. The ability to anticipate the toy's arrival at the catching place thus seems to be a prerequisite for the onset of reaching for moving toys.

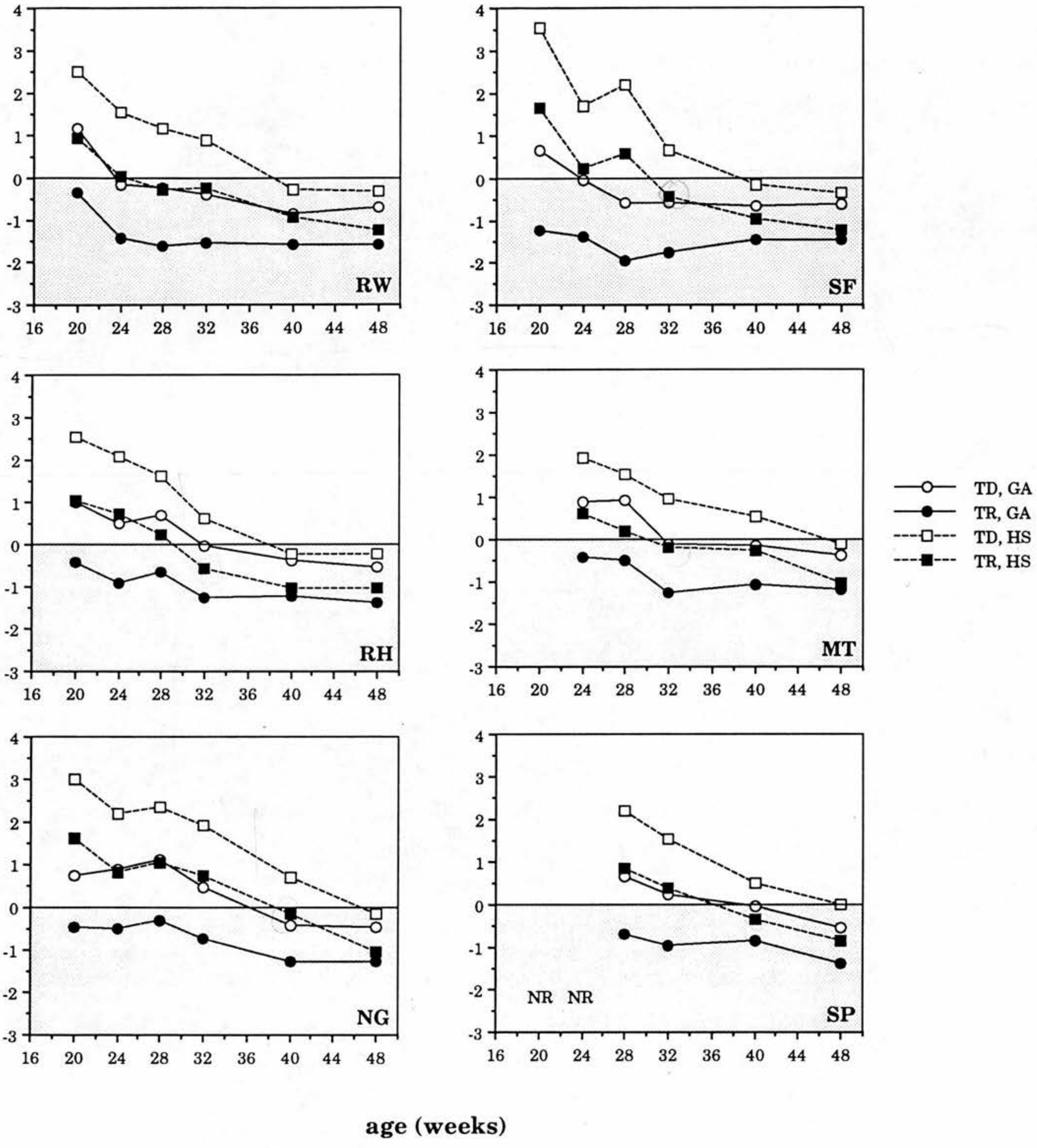
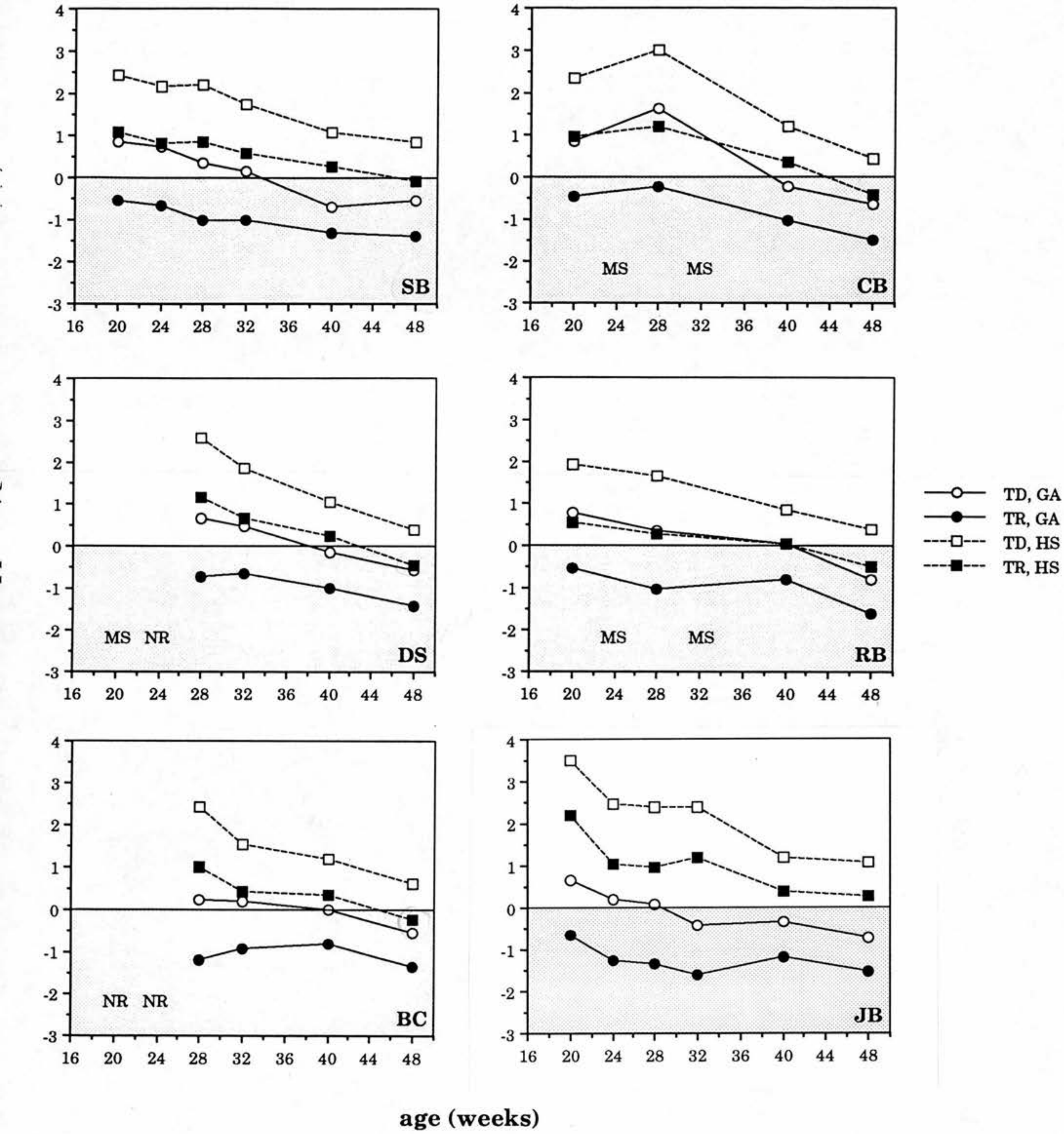


Figure 4.1. Development of anticipation of toy's arrival at the catching place with gaze and hand, shown by mean values of ΔT(toy disappears, gaze arrives), ΔT(toy reappears, gaze arrives), ΔT(toy disappears, hand starts) and ΔT(toy reappears, hand starts). Mean values taken across speeds of toy at each age level studied for two normal controls (RW and SF) and ten infants neurologically at risk of brain damage (BC, CB, DS, JB, MT, NG, RB, RH, SB and SP). Shaded area indicates anticipation. (continues)



(continued) The order in which the graphs are presented is from the infant showing the largest to the infant showing the smallest degree of anticipation, as indicated by the number of data points in the shaded anticipation area. Anticipation with start of hand movement was considered the more important form of anticipation for catching. NR stands for non-reaching session; MS stands for missed session due to illness.

From 24 weeks onwards, the mean ΔT(toy disappears, gaze arrives) values for the normal subjects were negative, indicating that both infants moved their gaze to the catching place even before the toy had disappeared behind the occluder. Both infants further showed longer anticipation with gaze as they got older, levelling off at about 40 weeks of age. In the premature group anticipation with gaze of the toy's disappearance was much delayed (from 32 weeks onwards in JB, MT and RH, and from 40 weeks onwards in CB, DS, NG, SB and SP), but had eventually developed in all infants by 48 weeks corrected age (BC and RB; $t(9) = -12.96$, $p < .0001$).

Anticipation with start of hand movement. Figure 4.1 also gives for each infant the mean ΔT(toy disappears, hand starts) and ΔT(toy reappears, hand starts) values across speeds at different ages. Both normal control infants showed a clear trend with age towards anticipating with the hand. At 20 and 24 weeks both infants started moving their hand forward only after the toy had reappeared from behind the occluder. At 32 weeks of age both infants clearly showed anticipation of the toy's reappearance, indicated by negative subject means for ΔT(toy reappears, hand starts) across velocities for both subjects. At 40 and 48 weeks, both infants initiated the movement of their hand before the toy had disappeared behind the occluder.

In the premature group anticipation of the reappearance of the object with the hand developed very late, with only MT and RH showing a similar developmental trend as the normal infants with negative mean ΔT(toy reappears, hand starts) values from 32 weeks onwards (see Figure 4.2a). By 48 weeks, however, all at risk infants anticipated the reappearance of the object ($t(9) = -3.75$, $p < .005$), except JB (see Figure 4.2b). Prospective control of hand movement before the disappearance of the object developed relatively late in the normal infants and turned out to be the cause of problems in catching faster moving toy's in the premature group. Of this group, only MT, NG and RH showed prospective control of hand movement at 48 weeks, indicated by negative mean ΔT(toy disappears, hand starts) values (see Figure 4.2c).

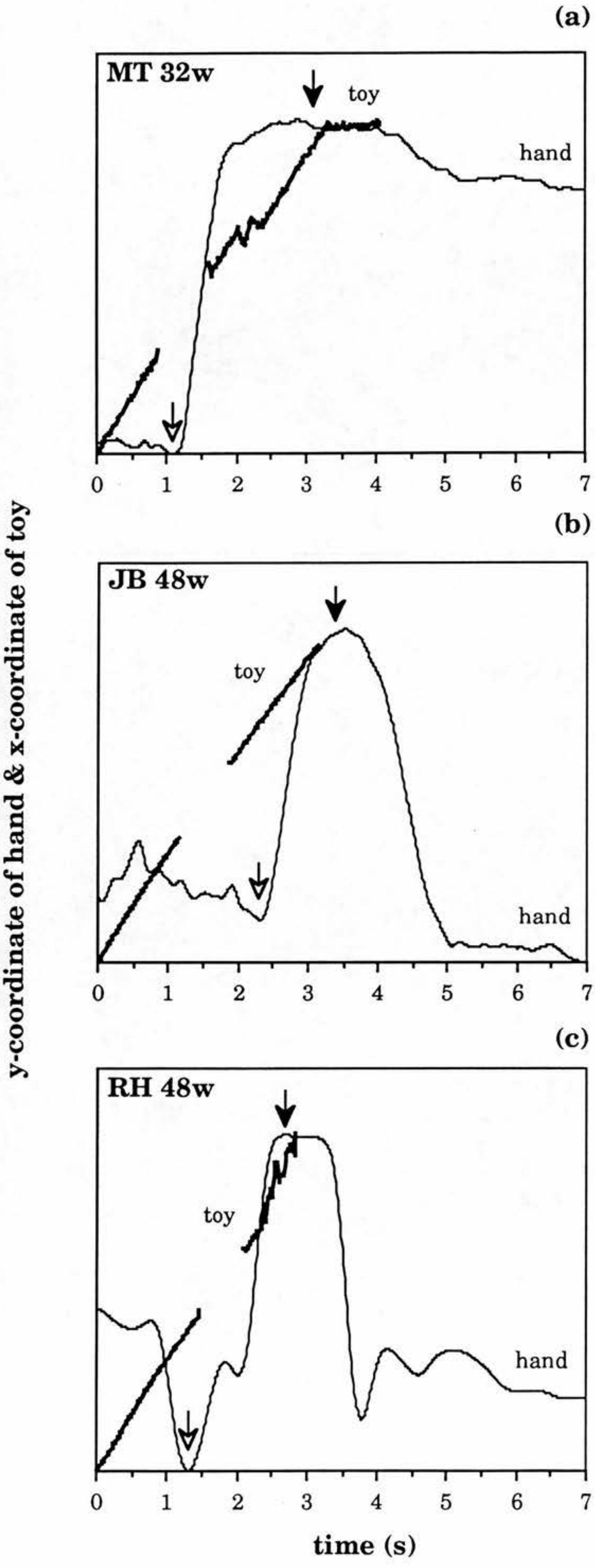


Figure 4.2. (a) Typical y-coordinate record of hand movement (thin line) relative to x-coordinate record of toy motion (thick line) in MT at 32 weeks of age with toy travelling at 10.5cm/s. The interruption in the toy record represents the period of time that the toy was behind the occluder. Note that the hand started moving forward (open arrow) about 0.45s before the toy reappeared from behind the occluder. The closed arrow indicates when the toy was caught. (b) Typical y-coordinate record of hand movement relative to x-coordinate record of toy motion (11.5cm/s) in JB at 48 weeks of age, not showing anticipation of toy's reappearance. Note that the hand started moving forward in reaction to toy's reappearance. (c) Typical y-coordinate record of anticipation in hand movement relative to x-coordinate record of toy motion in RH at 48 weeks of age, with the toy travelling at 11.5cm/s. Note that the hand started moving forward about 0.2s before the toy had disappeared behind the occluder.

Sources of information. What information did the infants use to anticipate the toy's arrival first with their gaze and later with their hand? And were the infants who did not show optimal anticipation perhaps using a less sophisticated timing strategy? Previously, it was found that 11 month old infants prospectively geared their actions to the time (instead of the distance) the toy was away from the reappearance point (Chapter 3).

We first tested whether the infants started to move gaze or hand when the toy was a certain distance away from the reappearance point. Figure 4.3 shows for each infant the toy's distance away from the reappearance point when the gaze arrived at the catching place and when the hand started moving forward. At 20, 24, and 28 weeks both normal control infants geared their actions to a current position of the toy, since the toy's distance away from the reappearance point did not vary systematically with the toy's speed. At 32 weeks, there is some evidence that both infants started to gear their actions prospectively to the toy's future trajectory, shown by longer distances of the toy from the reappearance point with faster speeds when RW arrived with gaze at the catching place and when SF started to move his hand forward. At 40 and 48 weeks of age the toy's distance from the reappearance point when gaze arrived at the catching place and when the hand started moving clearly increased with higher speeds (while the time intervals did not vary systematically with the toy's speed), suggesting that both infants had switched from a distance strategy to a strategy which involved gearing their actions prospectively to certain times the toy was away from certain points on its trajectory.

Repeated measures ANOVA's (Speed) on the premature group's subject means for toy's distance away from the reappearance point when gaze arrived and the hand started to move forward revealed significant effects of speed at 48 weeks (gaze arrives: $F(3,27)=6.01$, $p < .003$; hand starts: $F(3,27)=6.23$, $p < .003$) and significant linear trends (gaze arrives: $t(9)=4.24$, $p < .003$; hand starts: $t(9)=2.70$, $p < .03$), but not at 40 weeks (gaze arrives: $F(3,27)=2.13$, *ns*; hand starts: $F(3,27)=0.42$, *ns*). These

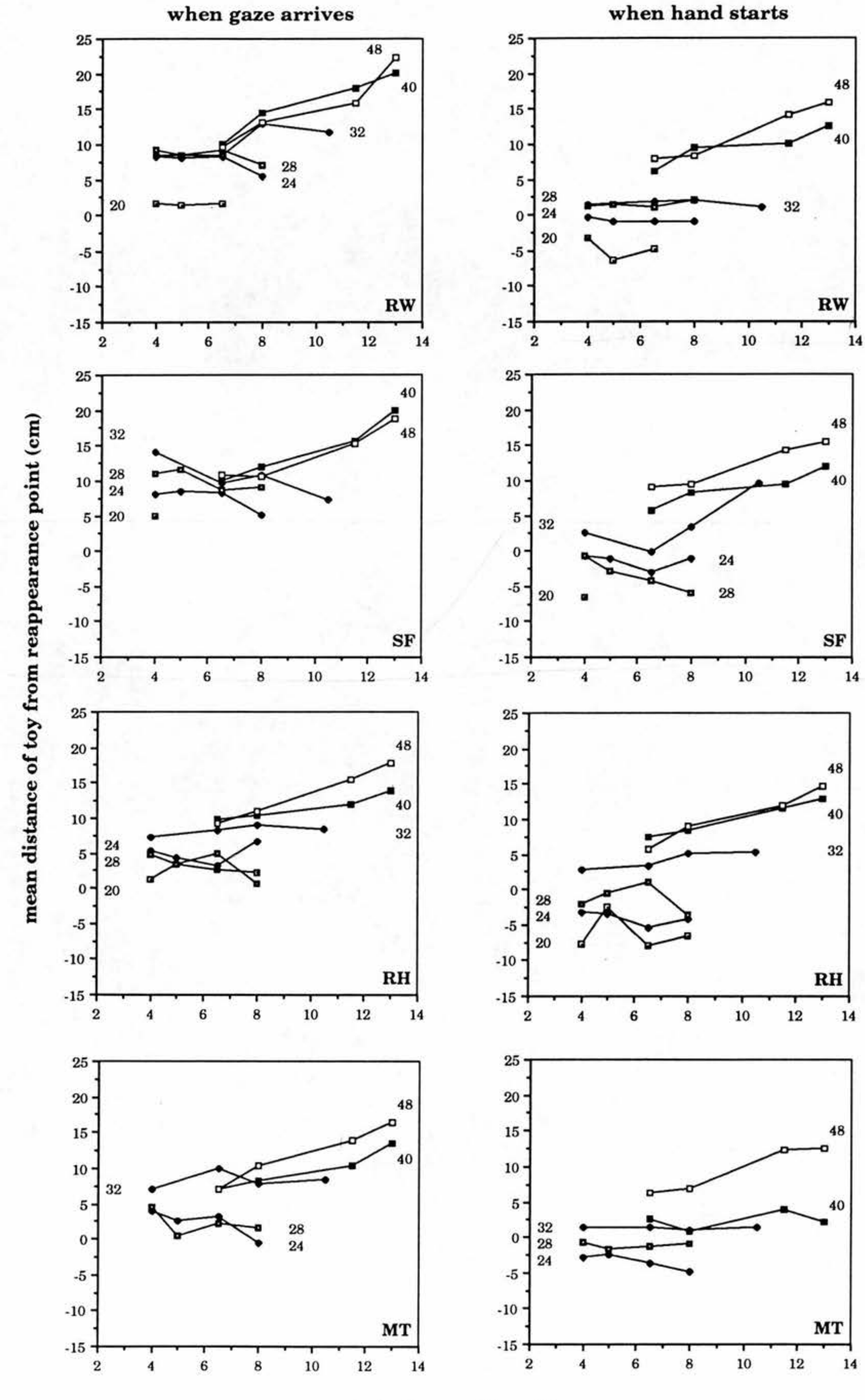
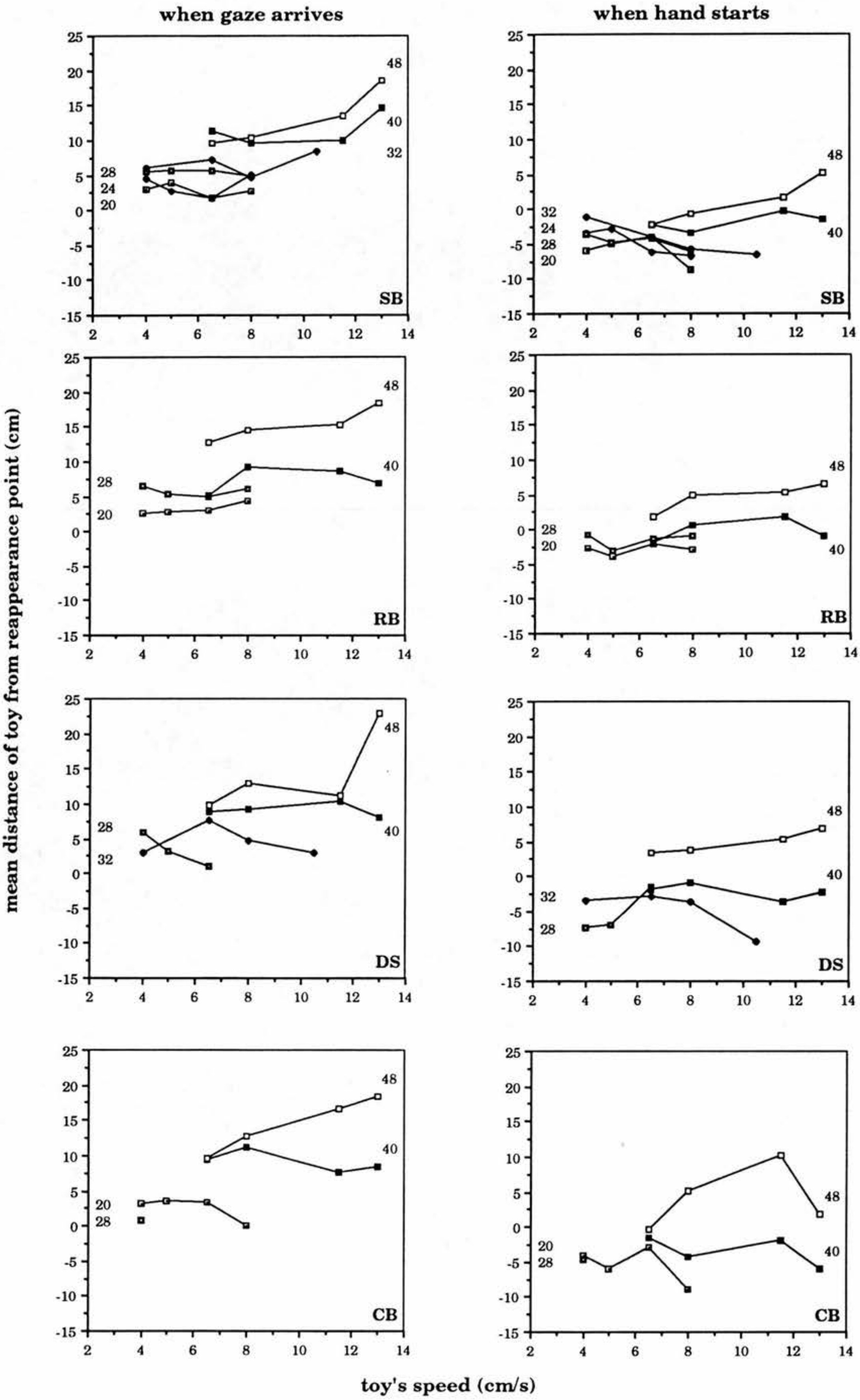
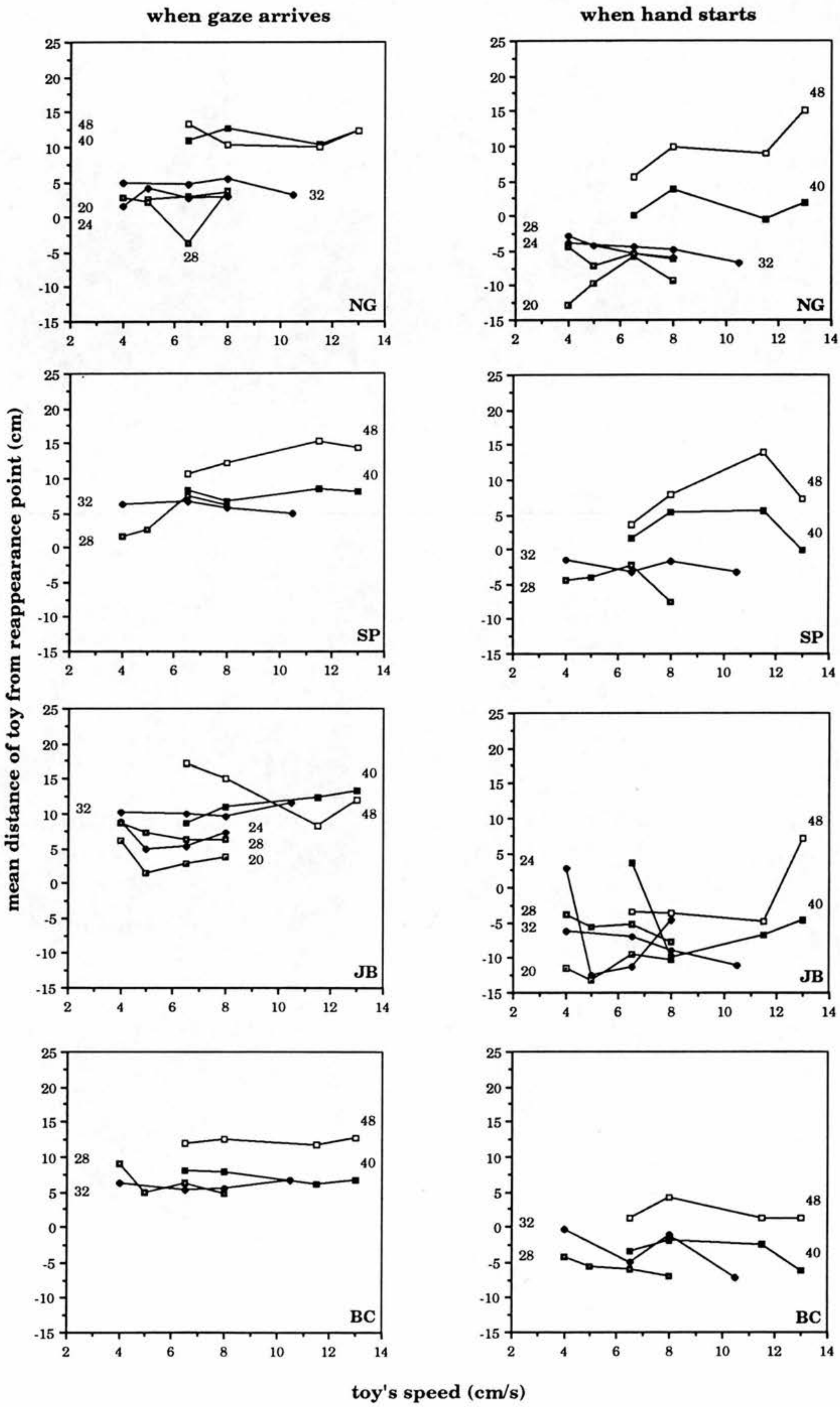


Figure 4.3. Mean distance of toy from the reappearance point when gaze arrived at the catching place and when hand started to move forward plotted as a function of speed of toy for two normal controls (RW and SF) and ten infants neurologically at risk of brain damage (continues)



(continued) (BC, CB, DS, JB, MT, NG, RB, RH, SB and SP) at each age level studied. The order in which the graphs are presented is from the infant showing evidence, throughout the period studied, of using a more sophisticated timing strategy at a younger age (i.e., keeping the time the toy is away from the (continues)



(continued) catching place constant so that the toy's distance from the reappearance point varies systematically with the toy's speed), to the infant continuing to use the less sophisticated distance strategy (i.e., shifting gaze and reaching out when the toy is a certain distance away from the reappearance point).

overall results at 48 weeks indicate that when the premature infants arrived with their gaze at the exit side of the screen and when they started to move their hand forward, the toy's distance from the reappearance point was longer the faster the toy's speed.

However, as can be seen from Figure 4.3, only RH showed the same development as the normal controls, using a distance strategy for gaze and hand until 28 weeks and then arriving with gaze at the catching place and moving her hand forward when the toy was certain times away from the reappearance point from 32 weeks of age. By 48 weeks, MT, SB, and RB had also adopted a time strategy with gaze and hand, and DS and CB with only hand and gaze, respectively. At 48 weeks, NG and SP still predominantly used a distance strategy, but there was some evidence that they geared their hand (NG) or gaze (SP) to when the toy was certain times away from the reappearance point while making mistakes in their timing. With the exception of JB at 40 weeks with gaze, BC and JB mainly used a distance strategy during the period studied and at 48 weeks did not show any evidence of the beginning of a strategy which involved gearing actions to the time the toy was away from the reappearance point.

Finally, we did regression analyses of the mean distance of the toy from the reappearance point on the speed of the toy, for when gaze arrived at the catching place and for when the hand started to move forward for those infants who were using a time strategy rather than a distance strategy. Table 4.1 shows the regression coefficients for two normal controls (RW and SF) at 40 and 48 weeks, for two premature infants at 40 weeks, and for seven premature infants at 48 weeks. The generally high r^2 values for gaze and hand indicate that there was a good linear fit. If the infants were gearing their actions to when the toy was certain times away from the reappearance point then the intercepts would be close to zero. This was usually the case. RH at 40 weeks and RB and SP at 48 weeks, however, seemed to gear their gaze to the toy's disappearance instead of its reappearance, indicated by intercepts of 5.66cm, 8.26cm and 6.77cm, respectively (distance between disappearance and reappearance points was 7.5cm). SB at 48 weeks did not appear to gear his start of hand movement to the toy's reappearance or disappearance, but to a point on the middle of the track 9cm after the toy had reappeared (catching window was 18cm). Finally, the regression slopes give an indication of the times the infants were trying to keep constant when they started their actions. Thus, in general, the gaze arrived at the catching place and the hand started to move when the toy was certain *times* away from the reappearance point, independent of the toy's speed.

Neurological and ophthalmological data. The results described so far indicate that at 48 weeks BC and JB showed suspicious performances regarding anticipation of the moving toy with the hand. Throughout the period studied, both infants also used a less sophisticated timing strategy of gearing their actions to when the toy was certain distances, instead of certain times, away from the reappearance point.

These results are confirmed by diagnoses of brain damage, that were blind to us, made by a paediatric consultant at the local hospital. At 18 months corrected gestational age, JB showed abnormal scores on standard neuro-developmental assessments with a delay in postural skills and was diagnosed as having mild diplegia. BC was diagnosed as suffering from moderate diplegia at 21 months, with all signs showing in the lower limbs. Cognitive and behavioural development as well as vision appeared to be normal at the time of diagnosis in both infants.

All other infants were normal on neuro-developmental testing (including vision) and have been discharged. RH and NG were declared completely normal before the age of 6 months; MT, CB, and RB before the age of one year; SB and SP before they were 18 months old; and DS before the age of two years (all ages are corrected for prematurity).

	GAZE			HAND		
	r^2	int.	slope/actual mean time ΔT(GA, TR)	r^2	int.	slope/actual mean time ΔT(HS, TR)
40 wks						
RW	0.952	1.62	1.44/1.59	0.829	0.64	0.94/0.93
SF	0.959	0.55	1.42/1.47	0.917	0.78	0.83/0.97
RH	0.946	5.66	0.60/1.25 (0.40)	0.997	1.78	0.86/0.97
MT	0.936	0.89	0.91/1.07	*	*	*
48 wks						
RW	0.897	-1.14	1.67/1.58	0.972	-1.56	1.33/1.22
SF	0.928	1.35	1.28/1.48	0.969	1.64	1.07/1.22
RH	0.997	0.63	1.30/1.38	0.972	-1.86	1.25/1.05
MT	0.979	-1.37	1.36/1.21	0.948	-1.16	1.09/1.03
SB	0.896	0.61	1.27/1.37	0.936	-9.27	1.05/0.06
RB	0.840	8.26	0.71/1.63 (0.79)	0.767	-0.92	0.57/0.50
DS	0.545	-0.18	1.46/1.42	0.951	-0.23	0.52/0.47
CB	0.984	1.64	1.30/1.48	*	*	*
NG	*	*	*	0.674	-0.62	1.07/1.03
SP	0.822	6.77	0.64/1.39 (0.55)	0.336	0.09	0.82/0.85

Table 4.1. Coefficients (r2, intercept, slope) of regression of toy's distance from reappearance point on toy's speed, when gaze arrived at catching place and when hand started to move forward. Results are for each infant who showed evidence of gearing their actions to certain times the toy was away from certain points on its trajectory at 40 and 48 weeks. Also are reported the actual mean ΔT(gaze arrives, toy reappears) and ΔT(hand starts, toy reappears) values which would be equal to the regression slopes if the infants were gearing their actions perfectly to the toy's reappearance. In brackets are the actual mean ΔT(gaze arrives, toy disappears) values for RH, RB and SP.

Ophthalmological data were collected on seven infants (all with birthweight ≤ 1250 grammes) at 38 weeks gestational age. Three infants suffered from retinopathy of prematurity (BC, DS, MT), but none required treatment. Probably related to this illness of the retina associated with prematurity is the fact that all three infants suffering from it started reaching late (BC and DS at 28 weeks, MT at 24 weeks).

4.3 Summary and discussion

To catch accurately a fast moving toy which disappears behind a screen and reappears only shortly before it can be caught requires prospective control of eye, head and hand movement. The hand has to be moving toward the future position of the toy while the toy is hidden and be ready to catch the toy as it comes into view. For precise visual control of the final phase of the catch, gaze has to be oriented to the toy and hand. By the age of 40 weeks, the normal control infants quite skillfully timed their reaching actions with respect to the prospective time of arrival of the toy at the reappearence point. As the ability to use visual information predictively is fundamental to coordinating action, its disruption could have wide-reaching effects. The differences in how well full-term, healthy infants and infants classified neurologically at risk of brain damage can differentiate prospective elements in visual information were investigated in this Chapter.

All the infants in the present study showed prospective control of both gaze and hand, except JB who at 48 weeks did not anticipate the reappearance of the moving toy with his hand. From 24 weeks onwards in the normal infants, gaze shifted to the catching place even before the toy had disappeared behind the screen. In the premature group, anticipation of the toy's disappearance with gaze was delayed in all infants, but was finally apparent in all infants by 48 weeks of age. At 40 and 48 weeks the normal infants also showed anticipation of the toy's disappearance with their start of hand movement. This form of anticipation was only achieved by three out of ten premature infants by the age of 48 weeks. However, all premature infants (except the aforementioned JB) anticipated the reappearance of the moving toy with their hand at the final testing session at 48 weeks corrected age.

The information used by the infants for prospectively controlling the *timing* of shift of gaze and movement of hand appeared to change with age. The normal infants up to 32 weeks of age seemed to use a procedure which involved shifting gaze and starting to move the hand when the toy reached certain positions. This is not a very sophisticated strategy since it entails moving the hand increasingly faster the faster the toy. Especially at higher speeds of the toy, the infant could run out of time and, as a consequence, the reach would result in a miss. From 40 weeks, the normal infants changed strategies and shifted their gaze and started reaching when the toy was certain *times* rather than distances away from the reappearance point. They thus made available the same average time for the catching movement whether the toy was moving slowly or quickly.

From the premature group, only one infant switched strategies at the same age as the control infants. However, by the age of 48 weeks another seven infants showed evidence that they geared their actions to when the toy was certain times away from the reappearance point. At 48 weeks, two infants from the premature group still seemed to use the less advanced distance strategy for when they shifted their gaze and started to move their hand. These infants also showed the smallest amount and no anticipation (BC and JB, respectively) of the toy's reappearance with their hand.

The neurological assessments conducted by a paediatric consultant at the local hospital pointed to the same children as having neurologically abnormal scores. At 18 months, JB was diagnosed as having mild cerebral palsy. At two-and-a-half years, he is still not able to walk unaided. BC was diagnosed as suffering from moderate CP at 21 months, with only the lower limbs affected. Thus, even though neurological problems in both infants were especially apparent in the legs, this longitudinal experiment showed that the underlying fundamental ability to use perceptual information in a predictive way was also affected.

Greater understanding of the normal and abnormal development of using perceptual information predictively might therefore have important diagnostic and therapeutic consequences. The sooner parents and neurologists know there is a problem, the sooner it can be tackled by relatively minor intervention because of the flexibility of the brain under the age of one year (Bobath, 1980). The mastering of reaching and grasping normally develops very early and it provides a foundation for more specific perceptuo-motor skills that rely on these abilities. Catching is such a case. It requires the pick-up of predictive information and quite advanced timing skills. If there is a problem on such a basic level, then more complex skills such as walking and speaking - skills that are highly dependant on correct timing - are also likely to be affected later on in life.

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CHAPTER FIVE

Summary and Conclusions

5.1 Development of prospective control of reaching in infants

In the old days of the nature/nurture debate, nature was identified with a set of internal, hereditary influences on perceptuo-motor development, nurture with a set of external, environmental influences. Depending which side of the debate you took, either the one or the other set of influences was supposed to prevail (Van der Meer & Van der Weel, 1992; Chapter 1). More modern psychologists say they dismiss the debate, claiming that perceptuo-motor development is the combined product of *both* innate *and* environmental factors , in proportions that are variable and to be determined empirically. But although the debate has been declared obsolete, the terms in which it was conducted obstinately persist. Organism and environment are still posited as independently given, endogeneous and exogeneous determinants of development.

As an alternative to the traditional, dualistic theories of perceptuo-motor development, this thesis adopted a differentiation approach to development in which perception and action are internally related and mutually dependant. In such an approach the environment can be no more regarded as the sum of exogenous preconditions than the organism be regarded as the sum of endogenous schemata, motor programs or perceptual abilities. Perceptuo-motor development is not a simple *effect* of exogenous and endogenous *causes*. Rather, it is a process within a relational field, whose *outcome* is the mutual complementarity of organism and environment, perception and action, and body and mind.

It is not necessary to endow the infant with some phylogenetically given endogeneous schemata . However, nature did provide babies with some very helpful equipment to start their long course of learning about themselves and the world. Infants are provided with an urge to use their perceptual systems to explore the world; and they are impelled to direct attention outward toward events, objects and their properties, and the layout of the environment. Babies are also provided with a few ready-to-go exploratory systems, but these change as the perceptual systems become more refined and as new action systems emerge. As new actions become possible, new affordances are brought about; both the information available and the mechanisms for detecting it increase.

Perceptuo-motor development can therefore best be regarded as a continuous process of perception-action loops (Gibson & Schmuckler, 1989; Thelen, 1990). Perceiving and acting go on in a cycle, each leading to the other. The process of skill acquisition requires not only knowledge of the outside world, but also knowledge of the capabilities and limitations of one's own body as it acts in a world of forces (Van der Weel, 1991). Indeed, it is the integration of the perceptions of affordances of the environment with the perceptions of the dynamics of the body which allow adaptive actions to emerge.

The development of reaching skills is one of the most remarkable perceptuo-motor achievements of the human child during the first year of life. Gearing reaching actions to the environment is a complex process. As shown in this thesis, a number of problems have to be solved before reaching and grasping can emerge and before moving toys can be successfully caught. The solution to each of these problems requires information about the infant's own action system, predictive information about the infant's actions and predictive information about the environment.

Very young infants under six weeks of age already seemed to be learning to cope with external forces on their arms and at the same time about their arms and hands themselves, the 'tools' for later reaching and grasping. When the infants' arms were weighted the hand, the face was turned to moved in the same region within the field of view, but only if the infants could see that arm. Thus, when watching their arms moving young infants seemed to be developing visual control of the arm. In the near future this idea will be tested further in young infants by manipulating where the infant sees its arm to be - by, e.g., using closed-circuit TV to present the baby with a video image of its arm while occluding sight of the arm itself. If shifting the video image causes the baby to shift its arm correspondingly this would indicate visual guidance of the arm.

As infants wave their arms and hands while supine, they thus seem to be learning about their own body-dimensions through vision and proprioception, as well as about the consequences of their movements on the environment, which, in turn, provides new information about the environment and the infant. Spontaneous self-initiated actions have consequences, and observation of these is extremely educational (Gibson, 1988). By 'looking' at their waving arms and hands young babies discover and learn about all the relationships essential for successful reaching and grasping: they are differentiating perceptual information about the body. This information can then be used to establish a frame of reference for reaching.

Once having established a stable bodily frame of reference for reaching and grasping, the infant can then tackle the problem of regulating his/her actions to fit in with the spatio-temporal structure of stationary or moving *objects*. This requires predictive control and entails differentiating other perceptual information. Once differentiated, this information can, in turn, be used for establishing a frame of reaching for a more coordinated form of reaching, and so on.

The mastering of reaching and grasping normally occurs around 20 weeks of age and it provides a basis for more specific perceptuo-motor skills that rely on these abilities. Catching is such a case. It is also one of the clearest and most striking examples of anticipation in infants' manual action. To be able to catch a moving toy, the infant not only needs to perceive the position of the toy at an instant but also where it is going and how quickly it will get there. A successful catch has to be aimed for some point ahead of the toy where the hand and the toy would meet and as the hand gets there it should close around the toy at the right time. Obviously, timing has to be extremely precise.

When eleven month old infants attempted to catch a moving toy that disappeared behind a screen for the last part of its approach they showed remarkable anticipatory skills. Not only did they anticipate the reappearance of the toy with their gaze and hand, but they prospectively shifted their gaze and started reaching when the toy was certain times rather than distances away from the reappearance point. They thus made available the same average time for the catching movement whether the toy was moving slowly or quickly. In addition, each infant showed evidence of taking actual start time into account, varying the duration of the reach to time the catch. Further, it was shown that the infants controlled reach duration principally on the basis of visual information about the toy's arrival time picked up before the hand started to move. Finally, the records of the trajectory of the hand showed that, as soon as the hand started to move, it was aimed at the catching place rather than the current position of the toy. Thus, even a second or so before the catch, the direction of hand movement was geared prospectively to the position where the catch would be made.

The development of predictive reaching was then investigated longitudinally in two infants between 16 and 48 weeks. At their first reaching session at 20 weeks, both infants showed prospective control when they anticipated the toy's reappearance with their gaze. From 24 weeks, gaze even shifted to the catching place before the toy had disappeared behind the screen. From 40 weeks onwards the hand also started to move before the toy had disappeared. The information used by the infants for prospectively controlling the timing of shift of gaze and movement of hand appeared to change with age. Infants up to 32 weeks of age used a distance strategy which involved shifting gaze and starting to move the hand when the toy reached certain positions on its trajectory. This is not a very efficient procedure, since their hand had to move increasingly faster the faster the toy. Older infants showed more skill. The results indicated that, from 40 weeks, infants used a time strategy which involved shifting gaze and starting reaching when the toy was certain times away from the reappearance point.

In the last experiment of this thesis, infants neurologically at risk of brain damage because of low birthweight and prematurity were tested longitudinally on their predictive reaching skills. Onset of reaching and the development of anticipatory gaze and hand movements were much delayed in some infants, and actions were geared to the reappearance point using a less efficient distance strategy rather than a time strategy until a higher age. Two infants did not anticipate the reappearance of the moving toy with their hand and still used the less sophisticated distance strategy for timing their actions at 48 weeks. At two years of age, these infants were diagnosed of mild to moderate diplegia by a paediatric consultant at the local hospital.

The results of this thesis could therefore have important consequences for early diagnosis of brain damage. Particularly with early brain damage, such as cerebral palsy, fundamental perceptuo-motor abilities are likely to be affected. To gain insight into the basic principles of movement, normal perceptuo-motor development needs to be studied in more detail. In particular, future research will concentrate on the development in infants of prospective control of different basic actions, such as looking, maintaining balance, and timing. Namely, all these actions are highly dependent on the correct pick-up of predictive sensory information. Looking, for instance, is a fundamental ability necessary for precise visual control of limb and whole body movements, and requires prospective control of head and eye movements. Detailed information about basic perceptuo-motor (dys)function could be used to develop tests to aid early assessment of infants neurologically at risk of brain damage.

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