

Looking with the Head and Eyes:

A Developmental Study

by

Brigid M. Daniel

Doctor of Philosophy

University of Edinburgh

1987



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

ABSTRACT

From a very early age, infants use their heads, eyes and hands to explore the world of objects around them. The infant therefore has to develop a hierarchy of stabilized systems: trunk, head and eyes must work in coordination to allow effective control of the arms and hands. In particular gaze has to be stable. Previous research into the stabilization of gaze has mainly concentrated on how eye movements compensate for head movements. There is little information on the role of the head in gaze stabilization, either for adults or for infants.

The head and eye coordination of a group of adults was tested under two situations; when tracking a moving target and when compensating for body movement while gaze was fixed on a stationary target. Movement of the target or subject could be either predictable or unpredictable. It was found that the head played an important role, whether the target or subject was moving. Head control was equally good under both conditions, but was superior when movement was predictable.

A group of infant subjects were tested longitudinally on the same tasks in order to chart the development of the role of the head in looking. Testing was at three week intervals between the ages of 10 and 28 weeks. As with the adults, the head was found to play an important role, control improved over the tested period, showing a surge around 16-20 weeks. Unlike adults, the performance of the infants was much better when they rather than the target were moving.

Deficiencies in the development of gaze stabilization would have serious implications for perceptuo-motor development. A brain-damaged infant was tested under similar conditions in an exploratory longitudinal study between the ages of 21-28 weeks. He was shown to be principally deficient in head rather than eye control, particularly in the visual tracking task.

Acknowledgements

I am extremely grateful for all the technical help and backup I received from J.Cuthbert, J.Duncan, J.Gordon, W.Robertson, R.Welensky and D.Wilkinson.

I would also like to thank Dave Young for providing invaluable computing, technical and experimental help, Colwyn Trevarthen for useful discussion and especially Dave Lee for the many hours of discussion, help and support with all aspects of the study.

Finally the whole project would not have been possible without the infant subjects and the enthusiastic and conscientious cooperation of their mothers who continued to turn up regularly for experimental sessions throughout the study.

TABLE OF CONTENTS

1 Introduction	1
1.1 Gaze Stabilization	3
1.2 Development of Gaze Stabilization	6
1.3 Aims of the Study	9
2 Method and Analysis	11
2.1 Schedule of Testing	11
2.2 Testing Session	11
2.3 Subjects	12
2.3.1 Infants	12
2.3.2 Adults	12
2.4 Apparatus and Data Recording	12
2.5 Procedure	14
2.5.1 Infants	14
2.5.2 Adults	16
2.6 Analysis	16
2.6.1 Target/shoulder angle	17
2.6.2 Head/shoulder angle	18
2.6.3 How much was the head used?	19
2.6.4 How well did the head movement link with that of the target?	19
2.6.5 How accurate was gaze?	20
2.7 Method of Statistical Analysis	22
3 Effect of Target/Chair and Predictable/Unpredictable Movement	23
3.1 Adult Summary Results	23
3.2 The Effects of the Two Experimental Variables on Adult Results	26
3.3 Infant Results	28
3.3.1 The Effect of Predictable versus Unpredictable Movement	29
Cross-Correlation	29
GVE	29
Proportion of Head/Target Movement	29
3.3.2 The Effect of Target Movement versus Chair Movement	38
Cross-Correlation	38
GVE	38
Proportion of Head/Target Movement	38
3.4 The Effects of the Individual Experimental Conditions	44
3.5 Summary	52
4 Changes Over Age	53
4.1 Zero-Lag Cross-Correlations	53
4.2 Peak Cross-Correlations	56
4.3 Lags Yielding Peak Cross-Correlations	59
4.4 Proportion of Head to Target Movement	62
4.5 Accuracy of Gaze - gaze velocity error (GVE)	65
4.6 Summary	69

5 Dysfunction in Head and Eye Control: a Case Study	72
5.1 Introduction	72
5.2 Testing schedule	73
5.2.1 Preliminary summary	74
5.3 Head and Eye Coordination	74
5.3.1 Results	75
5.3.2 Effect of the Experimental Variables	79
5.4 Summary	81
6 Summary and Discussion	82
6.1 Visual Control of Head Movement	82
6.2 Amount of Head Movement	82
6.3 The Effect of Predictable versus Unpredictable Movement	85
6.4 The Effect of Target Movement versus Chair Movement	85
6.5 Developmental Changes	87
6.6 In Conclusion	88
I References	89
II Appendices	98

CHAPTER 1
INTRODUCTION

"One sees the environment not just with the eyes but with the eyes in the head on the shoulders of a body that gets about. We look at details with eyes, but we also look around with the mobile head, and we go-and-look with the mobile body."
(Gibson, 1979, p222)

From a very early age infants use their heads, eyes and hands to explore the world of objects around them (Trevarthen, 1975; 1984b; Bullinger, 1981; von Hofsten, 1982). In order to do this effectively they must not only coordinate different parts of the body, but must also have a sense of the body in relation to the rest of the world so that objects can be located with respect to the self (Hein, 1974). The infant therefore has to develop a hierarchy of stabilized systems; trunk, head and eyes must work in coordination to be directed at interesting objects, forming a general, stable orientation to allow effective use of the arms and hands as part of the exploratory system (Trevarthen, 1984b).

In order to look and reach effectively, posture must be appropriate (Bower, 1974; Casaer, 1979). As Forsstrom and von Hofsten (1982) found, in neurologically-impaired children a common problem in reaching is abnormal postural fixation. Bullinger (1981; 1983) has described the developmental sequence from 2 to 17 weeks which shows the importance of postural control and stabilization for effective action. Early object tracking is achieved by rotation of the whole trunk; it appears that infants restrict the degrees of freedom by using a trunk-related frame of reference only. At the next stage the shoulders and arms move independently of the trunk and finally the head alone can be used "with the torso serving as a stable reference". By this stage then infants appear to be developing the ability to function within several frames of reference as an adult does. Early looking behaviour can therefore be relatively successful, albeit limited. Early in this period visual control of head posture is also apparent (Butterworth, 1983; Jouen, 1985).

At birth, the areas related to the trunk in the motor and sensory cortex are

most developed (Casaer, 1979). Although the brain contains the full complement of neurons at birth, brain development continues for several years (Bronson, 1965; Trevarthen, 1980; Williams, 1983; Hay, 1984). Subcortical systems are myelinated before cortical pathways and development proceeds according to two principles: 1) the cephalo-caudal principle with progressive mastery starting from the neck and proceeding to the legs and 2) the proximo-distal principle in which elements controlling proximal musculature develop before those controlling distal musculature (Peiper, 1963; McGraw, 1966; Casaer, 1979; Illingworth, 1983, Hay, 1984).

Early postural behaviour is often described as reflexive, with the emergence of controlled voluntary behaviour being attributed either to inhibition of infantile reflexes or their incorporation into controlled movements as the infant develops from a state of subcortical to cortical control (Twitchell, 1965; McGraw, 1966; McDonnell et al., 1983; Hay, 1984; Beek, 1986). But young infants exhibit patterns of coordination that are clearly not reflexive (Bower et al., 1970; Trevarthen, 1975, 84a). Different elements seem to be innately linked to form "prefunctional" units (Trevarthen, 1975). Coordinated head and eye movements have been observed as young as three days and several researchers have reported early arm movements under some degree of visual control (White et al., 1964; Bower, 1970; von Hofsten, 1982; Bullinger, 1983) The importance of visual control has also been demonstrated in very early balance (Lee and Aronson, 1974; Butterworth and Hicks, 1977; Pope, 1984). As Butterworth says:

"The optic flow pattern is not a stimulus that gives rise to a reflex response in the traditional sense. Rather it both provides a motive for corrective behaviour (by informing about loss of postural stability) and is also goal directed in that it specifies when a well controlled posture has been achieved." (1986, p27).

Nor is it the case that an infant behaves like an acortical preparation (Robinson, 1969; Bronson, 1974). Although the cortex is immature at birth and develops rapidly over the early months there is now increasing evidence for the existence of functional cortical connections very early in life (Maurer and Lewis, 1979; Atkinson and Braddick, 1982)

1.1. Gaze Stabilization

"The positions of the head and eyes may be the central part of a spatial reference system that is developed early in life and used extensively in everyday activities." (Martinuik, 1978)

It is clear that a vital requirement for the integration of the various elements involved in effective visually guided action is the stabilization of gaze, that is the ability to maintain visual contact with an object of interest.

Research into the control of gaze stabilization when fixating and compensating for body movement has, with some exceptions, been limited by the same preoccupation with reflex response. While it has long been recognised that vestibular information alone is not sufficient for gaze stabilization (Kornhuber, 1974; Schmid et al., 1985) research has nevertheless primarily concentrated on examining vestibularly driven "reflex" compensatory eye-movements for externally imposed head movements (Outerbridge and Melvill Jones, 1971, Melvill Jones, 1976; Barnes, 1980). This emphasis on vestibular reflex activity has two important shortcomings. First it presupposes that stabilization principally occurs at the highest level of the hierarchy (the eyes), and ignores the fact that the head compensates for a lot of the movement of the trunk. Second, it neglects the fact that vision is essential in stabilizing gaze.

When an object of interest appears beyond about 15 degrees to one side of the fixation point the eyes first make a saccade to look at the point, and shortly afterwards the head also turns in the same direction. The counter-rotation of the eyes that keeps the gaze on the target during head rotation is described as the vestibular-ocular-reflex (VOR) (Fuchs, 1981; Barnes, 1981). The VOR has received much attention as the primary system for gaze stabilization, but in everyday behaviour the relationship between head and eye movement is not as rigid as the term "reflex" implies. The ratio of eye velocity to head velocity in the dark, ie the VOR gain, can be increased by asking the subject to imagine a target in front of them (Barr et al., 1981); and work with left-right reversing prisms has shown that the gain can even be reversed (Melvill-Jones, 1977).

In addition, the vestibular information alone is not sufficient to specify exactly the amount of counter-rotation needed during head rotation (Biquer and Prablanc, 1981; Owen and Lee, 1986). Because the centre of rotation of the eye is not in the same place as the centre of rotation of the head, the angle by which the eye needs to counter-rotate in order to maintain fixation is greater than the angle of head rotation and further, the difference will increase the closer the target is to the subject (see figure 1.1). Only vision can provide the necessary information for fixation that accurate.

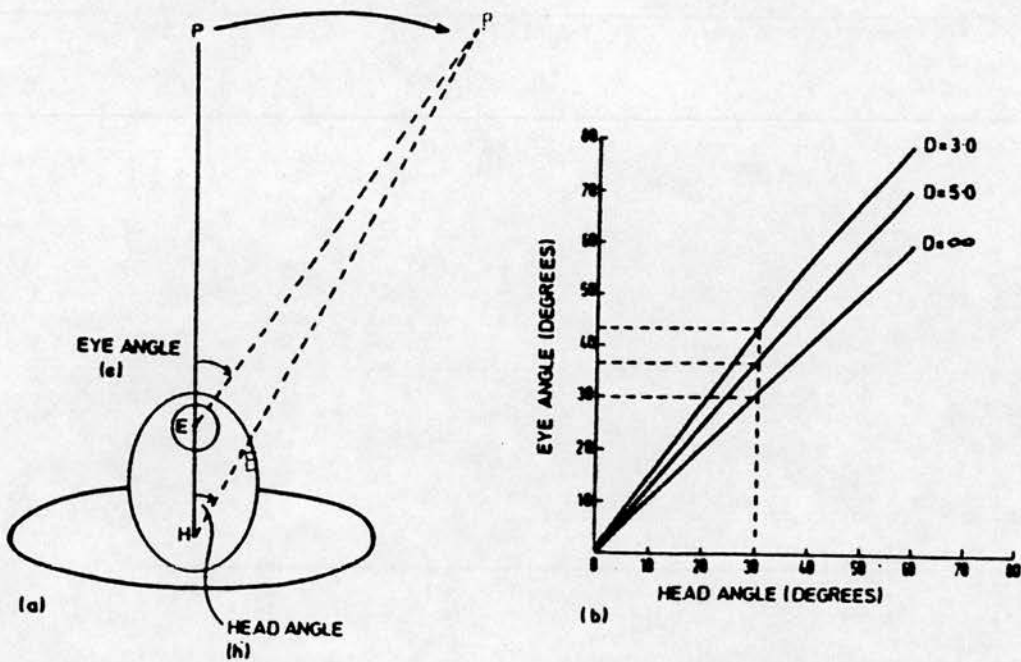


Figure 1.1 Showing how the eye movement required to compensate for a head movement does not depend simply on the head movement, but also on the distance of the target. In (a), E is the centre of rotation of an eye, H the centre of rotation of the head. The axes of rotation are taken to be vertical. Initially, H and E are aligned with target point P and gaze is directed at P. When the target moves to the right, first the eye turns through angle e to fixate the target and then, as the head turns through angle h to point at the target, the eye counter-rotates through angle e. Note that eye angle e will always be greater than head angle h. The difference between the angles is greater the closer the target and the larger the head or eye angles. This is seen by applying the sine rule to triangle HEP, which gives $\sin(e)/\sin(e-h)=HP/HE=D$ (say), where $e = \tan^{-1} (D \sin(h)/(D\cos(h)-1))$. This function is plotted in (b) for different values of D: D=3 corresponds to close reading distance, D=5 to comfortable reaching distance, D=∞ to the horizon.

When it is studied, the role of vision in gaze stabilization is normally described in terms of the optokinetic response (OKR): the pattern of eye movements shown when the whole visual field moves around the subject. The eyes track the moving field with smooth slow movements alternated with quick recentering movements. Although the OKR is often described as a system of eye movement it should be seen primarily as one of stabilization with respect to the stable world – it is “not to make the eye move but to hold it still” (Robinson, 1976; 1981). Recent work on visual stabilization of the eyes has demonstrated this system to be much more complex and flexible to everyday demands than had previously been believed (Miles and Kawano, 1987).

Optokinetic and vestibular signals are received in the vestibular nucleus (VN) (Dichgans et al., 1972) and a set of neurons in the monkey VN respond to head rotation in one direction and to optokinetic stimuli rotating in the opposite direction. Afferents from the neck also provide proprioceptive information about head movement (Tomlinson et al., 1980; Fuchs, 1981). But the tendency has been to regard vestibular information as somehow primary and open to “modulation” by visual information. The “modification” of the VOR is believed to be under the control of the flocculus of the cerebellum via a sidepath to the three-neuron VOR arc. The flocculus receives information about head rotation via collaterals from the VIIIth nerve and indirectly via secondary vestibular neurons, a visual input comes via climbing and mossy fibres, and eye-movement and neck afferent information comes from the VN (Barnes, 1980; Robinson, 1981; Fuchs, 1981; Ito, 1984). The fact that visual information alone can be used in maintenance of balance (Lee and Lishman, 1975), and can induce feelings of subjective movement (Dichgans et al., 1972; Wong and Frost, 1978) implies that vision is not just used in a modulatory role. Rather than seeing vision as modulating the vestibular response it would seem preferable to regard them both as important sources of concordant information for the stabilization of gaze.

The ability to smoothly track a small object as it moves with respect to the background has developed along with the evolution of the fovea (Robinson, 1976). Most of the research has again been limited by the concentration upon eye-movements with head fixed with respect to the body. The velocity of the eye in this situation is tightly linked to that of the target

and phase lag can be greatly reduced when target movement is predictable (Stark et al., 1962; Rashbass, 1971; Young, 1977; Becker and Fuchs, 1982). It has been suggested that the appropriate eye movement is produced both as a response to retinal slip velocity, and also in response to the position of the target with respect to the fovea. As well as these feedback mechanisms there must be a very important predictive element, possibly based on a central representation of target velocity, since accurate tracking can occur without any retinal slip, and on occasions eye velocity may be greater than that of the target (Robinson, 1965; 1981; Young, 1971; Lanman et al. 1978).

In a natural situation of course the head is not fixed with respect to the shoulders, and the movement of both the head and the eyes must be taken into account. When the head is free to move it takes up much of the tracking of a moving target and also allows better accuracy in pointing and aiming tasks (Ripoll et al., 1985; Bard and Fleury, 1986). If the VOR is described as a reflex then when the head is following a moving target the problem arises as to what occurs to the now inappropriate reflex to counter-rotate the eyes. The smooth pursuit system is described as suppressing the vestibular response in this situation (Herman et al., 1982). But the input from the vestibular system need not be seen as something that needs to be suppressed, rather as providing useful information about head rotation; for example Lanman et al. (1978) suggest that a central signal representing target movement relative to the trunk is used to drive both the head and eyes. Eye movements appear to be driven by a combination of this central command representing target motion and vestibular feedback from head movement.

1.2. Development of Gaze Stabilization

The first six months of life are characterized by tremendous advances in visual capacity. The development of different aspects is closely linked and is paralleled by improvements in control. Accommodation and convergence both improve rapidly during the first three months. Convergence to near targets is not consistent until 2 months and up until 3 months involves some delay in response (Aslin, 1977). During this time accommodation is also improving, especially during the first 2 months (Banks, 1980). There is also some delay in accommodative response and the large variations indicate a problem not of

muscular incapacity but of control. As the accommodative and convergence systems act synergistically, the maturation of the two is closely linked (Atkinson, 1984). Similarly the development of accommodation depends on the development of the ability to detect changes in the amount of blur, that is the depth of focus, and this in turn depends on acuity (Banks, 1980) which by 3 months is as good as 10 min of arc. The improvement in spatial resolution can be attributed both to anatomical differentiation of the retina and to development in central visual circuits. Myelination of the thalamic optic radiations is complete by the fifth postnatal month (Trevorthen, 1980). Binocular function is first evident on average at 12-17 wks (Braddick and Atkinson, 1983; Braddick et al., 1983) and stereopsis emerges at the end of the fourth month. By 21 wks stereoacuity is 1 min of arc or better (Held et al., 1980). By 3 months then acuity, accommodation and convergence are well developed and binocular function follows shortly after.

The development of these visual functions therefore reaches a peak just as reaching becomes very vigorous - at 20 wks (von Hofsten and Lindhagen, 1979; von Hofsten, 1980). Head control is also developing over this period. By 12 wks the head is mostly held up with some bobbing forward when in a sitting position; by 16 wks it is constantly held up but wobbles when the body is swayed. By 20 wks the head is held steady even when the body is swayed (Illingworth, 1983).

Developmental work on the control of gaze stabilization has also been limited by the concentration upon reflex response, and by the artificial restriction of head movements. Vestibular responses develop very young: within 20 to 30 days of age 84% of normal-birthweight infants show appropriate vestibular nystagmus in response to whole body oscillation, when blindfolded to eliminate visual information (Eviatar et al., 1974). By 3-6 months, vestibular responses are mature and parallel acquisition of head and postural control (Eviatar et al., 1979). The importance of vision in stabilization is demonstrated by the fact that in cases when vision is poor, even gentle head rotation will break fixation (Jan et al., 1986). Optokinetic following can be demonstrated in newborns (McGinnis, 1930) but is different from adult behaviour in two interesting ways. First, unlike adults the tonic ocular deviation is in the direction of field movement. This is a characteristic of adult behaviour under scotopic conditions or with a central scotoma and may

be attributable to foveal immaturity (Kremenitzer et al., 1979). Second, infants show asymmetrical monocular OKN, with the response to temporal-to-nasal field movement developing before the response to nasal-to-temporal movement. This asymmetry has also been observed in adults with binocular problems. The emergence of nasal-to-temporal OKN has therefore been related to the development of cortical binocularity (Atkinson and Braddick, 1981; Held, 1985). Smooth tracking of a moving target with the eyes only begins to emerge at 12 wks; before that, tracking is largely saccadic (Aslin, 1981).

At the level of head and eye coordination, those few studies which have not restricted head movement have shown a variety of patterns of coordination in which the head plays an active role. Two main findings emerge: head and eye movements are quite well coordinated in the infant and smooth looking patterns involving head and eyes occur before smooth pursuit with the eyes alone. Therefore there can be functional orienting by a relatively immature system. Tronick and Clanton (1971) described four different patterns of looking during free exploration of a static visual field. All the patterns involved smooth integration of head and eyes. They emphasized the importance of the head as part of the orienting system and described it as serving a place-holding function while the eyes explore small areas of the visual field, or as acting under visual guidance to shift the line of regard in the visual field. The imprecision of the calibration system used in this study has led to some doubt as to the exact descriptions of the different patterns (Maurer, 1975; Salapatek, 1975), but it does show the importance of the head both for tracking and for maintaining fixation. Trevarthen (1968) found an increase in the use of the head in tracking a moving target over the first six months, with a sudden improvement at four months accompanying the rapid maturation in muscular control of the head.

The stabilization of gaze then is not a passive reflex response, but is an active, flexible process, tightly linked to performance and action. The main problem for understanding how the system works is that the experiments have not been set in the context of functional tasks. Although it may be useful to know facts such as the gain of the vestibular-ocular reflex in the dark, the optimal velocity for optokinetic nystagmus, etc, these system specifications do not capture the essence of the overall functional process. Descriptions of eye

movements need to be set in the context of overall coordination during activities such as orientating, exploring, interacting and reaching.

Several studies have looked at compensatory eye movements incident on head movement (Goodkin, 1980; Roucoux et al., 1983; Regal et al., 1983), but none has investigated the pattern of compensation for externally imposed body movement. Much useful visual information would be lost if a baby were unable to use the visual system effectively while being carried, which for babies is a very common experience.

Although vestibular reflexes are present at birth (Eviatar and Eviatar, 1978; Eviatar et al., 1979; Herman et al., 1982), smooth visual control of the eyes improves between 8 - 12 weeks (Aslin, 1981). Coordinated movements of both head and eyes also occur from birth (Barten et al., 1971; Trevarthen, 1984b) but there is little information on the development of smooth control of the head in a visual tracking task. The fact that reaching becomes very prominent and accurate at 18-20 weeks (von Hofsten, 1980) suggests that by this stage gaze stabilization and postural control is adequate for localising objects with respect to the trunk. Therefore the indication is that important developments in the stabilization process will be occurring between 12 and 20 weeks.

1.3. Aims of the Study

The main aim of this study is to chart the development of looking behaviour from around 12 weeks, through the apparently crucial 20 week stage. The accuracy, and amount of relative head movement will be examined both when tracking a moving target and when keeping gaze fixed on a stable object when the body is moving. Although, as indicated above, visual information is essential for accurate target localization in both these situations, there are important differences between the conditions which would be expected to affect infant performance. When a target is moved the only information specifying that motion is the relative movement of the target with respect to the background and with respect to the subject. When the body is moved while the target is kept stationary however, there is also visual rotary flow and vestibular information specifying that rotation. It would be expected that infants, who have an immature fovea but mature vestibular responses, would be able to pick up and use the visual rotary flow and vestibular

information more efficiently than the relative movement between target and background. Performance would therefore be expected to be superior when the chair rather than target is moved.

In learning to reach and grasp efficiently infants must learn to take in and use information about the body, and about the conditions in the world (Trevvarthen 1984a). It would be expected that prediction in visual tracking would precede anticipatory reaching and Aslin (1981) provides some evidence for anticipatory eye-movements by 10 wks. The fact that infants can accurately intercept a moving object by 20 wks suggests that they can by this stage use visual information about object movement to guide action. Accurate looking with the head and eyes also depends on using visual information about target movement to guide action, and as discussed above, adult tracking performance is improved when target motion is predictable.

If tracking involves making predictions about target motion, then the simpler that target motion the easier it should be to track. In order to examine this, the accuracy of head movement in response to simple sinusoidal movement of the target or body will be compared with the response to irregular movement composed of more changes in direction - and consequently more changes in velocity. Both adults and infants would be expected to perform better in response to the simpler target movement. In addition it would be expected that as the ability to make long term predictions about target movement develops, a superior performance should emerge for regular, predictable movements of the target or body.

A final aim of the study is to describe the performance of adults under the same conditions, firstly to provide a comparison with infant behaviour; secondly to provide more information on the neglected role of the head in looking.

CHAPTER 2
METHOD AND ANALYSIS

2.1. Schedule of Testing

As changes in infant behaviour do not occur at exactly the same age in all babies, a longitudinal study was carried out so that developmental changes would not be blurred by averaging across subjects. The main interest was in the profile of change in individual infants. The number and spacing of visits had to be governed by practical considerations. To obtain data at each particular age it was necessary to allow for the possibility of two visits, since pilot studies had shown that due to a combination of technical problems and infant fussiness, data from two sessions close in time sometimes had to be combined. A longitudinal study is a heavy commitment for the parent and it was felt that they could not be asked to come in more frequently than once every three weeks, particularly if a repeat visit was going to be necessary. Testing each baby every three weeks between the ages of about 11 and 28 weeks gave a total of six to seven sessions per baby.

2.2. Testing Session

The design of the individual testing session had to be a compromise between statistical and human considerations and was based on the results of pilot studies. The aim was to provide sufficient data for statistical analysis within the time-span of attention of a young infant.

Either the target was moved (MT) or the chair was moved (MC) and in both cases the movement was smooth, but could be either approximately sinusoidal (PR), or more irregular (UP). (See Figure 3.1, p24, for an example of the two patterns of movement.) This gave four conditions – MTPR, MTUP, MCPR, MCUP – which were arranged in random order into a block of four 15 sec trials. Altogether in one session five blocks were presented, each arranged in a different random order. Thus each session comprised a total of 20 trials representing five presentations of each individual condition.

2.3. Subjects

2.3.1. Infants

After securing ethical approval, names of possible subjects were obtained from the birth records at the Simpson Memorial Maternity Pavilion, Edinburgh. The babies were all described as normal by routine neurological examination. A standard letter was sent to the mother's GP describing the study and asking for permission to approach the parents. If the GP approved, the parents were sent a letter asking if they were interested in the study. The parents were then phoned and the procedure was explained. If they were interested in taking part an arrangement was made for an initial visit on a trial basis on the understanding that they could withdraw from the study at any time. In this way six normal and healthy subjects were recruited, three girls (SB, AT, FT) and three boys (NH, SS, IB). None of the subjects was withdrawn from the study.

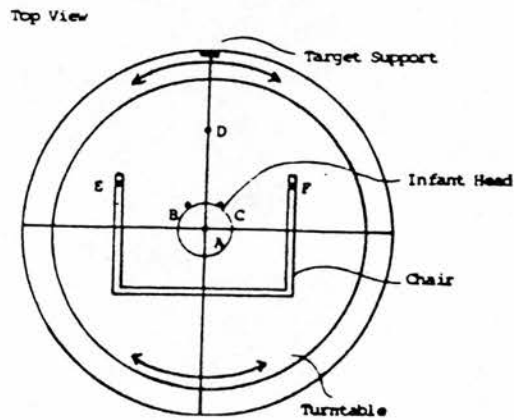
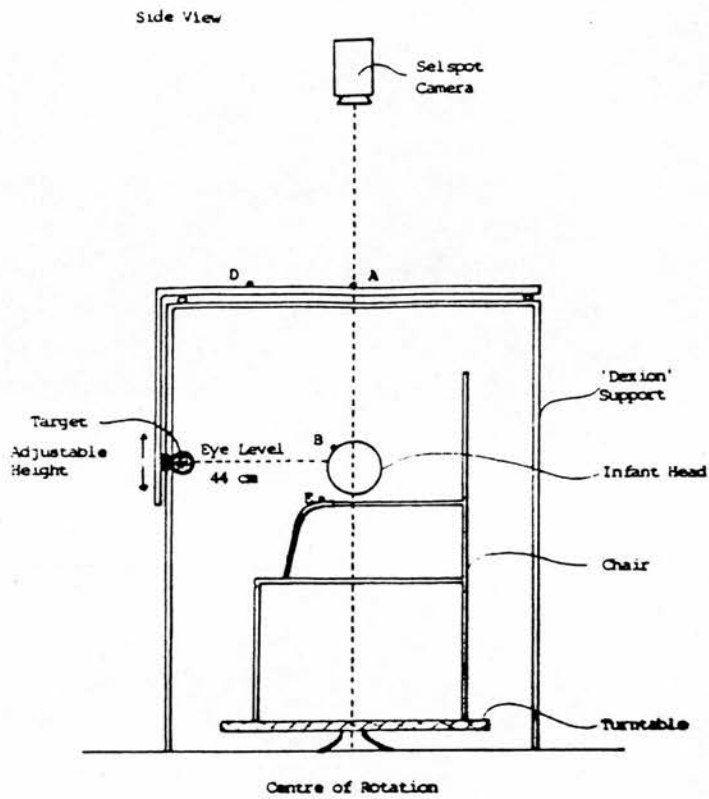
2.3.2. Adults

As indicated above, much of the relevant research both with infants and adults has concentrated on gaze stabilization under experimental conditions of restricted head movement. Some work has been carried out with monkeys tracking with head free (Lanman et al, 1978), but no comparison was made with the use of the head to compensate for body movement. Single session data was therefore also gathered from six adult subjects to compare with the infant data.

2.4. Apparatus and Data Recording

A chair was firmly fixed onto a turntable within a rigid Dexion surround that supported an adjustable strut that could be rotated in an arc around the chair, (see Fig 2.1). Small rotating toys acted as targets and could easily be attached to the end of the strut on the axis of a miniature motor pointing towards the subject from a distance of 44cm. Both the chair and the target could be turned by the experimenter : either the chair was gently rotated from

side to side $\pm 50^\circ$, and the target kept fixed (MC), or the target was moved $\pm 50^\circ$ and the chair was kept fixed (MT). (Freq about .2Hz, Peak vel. about 125 deg.s⁻¹)



- LED's
- A - Centre of Rotation
 - B } - Head Rotation
 - C }
 - D - Target Rotation
 - E } - Chair Rotation
 - F }

Figure 2.1 Side and top view of the experimental apparatus showing location of the Selspot leds.

All the movements were monitored by a Selspot movement monitoring system : infra-red light emitting diodes (leds) were mounted on the chair (leds E and F, fig 2.1) and were viewed by an overhead camera with its optical axis coincident with the vertical axis of rotation of the chair, which was indicated by another led attached to the top of the frame (led A). As the target was beyond the field of view of the camera its position was given by a reference led (D) attached to a cross-hair running from the centre of the frame out to the target. Rotations of the head and position of the eyes in a horizontal plane were recorded by two leds (B, C) mounted above the eyes on a soft headband worn by the subject. The orientation of the eyes in the head was recorded by electro-oculography (eog). Three miniature eog electrodes were attached, one at each outer canthus and one on the forehead to act as earth.

The positions of six leds were therefore recorded - one indicating the centre of rotation, one the direction of the target, two rotation of the chair and two rotation of the head and positions of the eyes. The DC analogue signal from the eog was passed through an optical isolator and a pre-amplifier, and digitized by the Selspot system. The led and eog data was sampled during a period of 3 ms, at a rate of 62.5 Hz (ie one 3 ms sample every 16 ms) giving a total of 966 points per trial, and was recorded by a PDP11/34 computer. The experiment was controlled from the lab by a BBC micro acting as a remote terminal. Each session was also videotaped.

2.5. Procedure

2.5.1. Infants

At the beginning of the session the skin around the eyes was washed and the miniature eog electrodes were attached. Once the headband and leds on the head were in place the mother sat in the chair with the baby on her lap (see fig 2.2). The trials were begun when the child's attention was fixed on the target. If the baby showed signs of distress or fussiness the session was stopped and, if possible, continued after a break. If this was not possible the mother was asked to come back within the next day or two to repeat the session.



Figure 2.2 Photo showing the positions of eeg electrodes, headband and Selspot leds on the arms of the chair.

Obviously many uncontrollable factors can affect infant behaviour. It is hard to predict exactly how alert they will be at any given test session. Every effort was made to arrange visiting times to coincide with the child's most alert state, but this was ultimately very much a matter of the mother's subjective judgement. The infants were on the whole very cooperative during the experiments. The targets used in the experiment were generally attractive to the infants, and could be changed several times during the session to maintain attention. Nevertheless there were occasions where the child would lose interest. Sometimes, the child was more interested in social interaction and this was exploited by using the experimenter as target, who would stand just behind the target, attract the infant's attention and act as target.

Table 2.1 shows the schedule of testing for each baby, the amount of data collected and the quality of the eog recording.

2.5.2. Adults

The procedure for the adults was very similar; all leds and the eog were recorded as for the infants. The subject sat on the chair and the target and chair position were adjusted so that the subject's head was over the centre of rotation of the chair and the eyes were level with the target. The subject was asked to fixate the target and to track it with whatever movements felt comfortable while keeping the shoulders fixed relative to the chair.

2.6. Analysis

The development of eye-movements in infancy has been well documented, but the use of the head in stabilizing gaze has not received the same attention. Pilot studies revealed that much of the target fixation was in fact performed by the head. Analysis of both adult and infant data therefore focussed largely on examining the role of the head in gaze stabilization when the target or subject was moving, and on charting the development of this head control in early infancy. All the analyses of head movement was based on a set of time series extracted from each trial, as described below.

Table 2.1 Schedule of testing. Showing the age in weeks and days at each session, the amount of data collected and the quality of eog recording: G - good, N - noisy, O - absent.

	SB	AT	FT	NH	SS	IB
Age	10,3	10,1	10,3	11,4	11,2	11,1
n	8	19	19	20	18	19
EOG	G	G	G	G	G	G
Age	13,6	13,1	13,3	13,3	13,4	13,2
n	20	20	19	20	20	18
EOG	G	G	G	G	G	G
Age	17,0	16,4	16,3	17,0	16,2	16,1
n	18	20	19	20	20	20
EOG	G	O	O	G	N	G
Age	19,3	19,2	19,3	20,0	21,4	18,1
n	20	20	20	20	20	20
EOG	N	G	G	G	N	G
Age	26,6	--	22,1	22,2	24,1	20,1
n	20	--	20	20	20	20
EOG	N	--	N	G	G	G
Age	28,6	26,0	25,3	28,0	29,2	24,4
n	20	20	19	20	20	20
EOG	G	N	G	G	G	G
Age	--	29,0	28,4	--	--	28,5
n	--	20	20	--	--	20
EOG	--	G	G	--	--	G

2.6.1. Target/shoulder angle

The target/shoulder angle was calculated as the angle between a line joining the centre of rotation (led A, fig 2.1) to the target reference led (D) and the line perpendicular to that joining the two leds (E, F) on the chair, ie the saggital plane (fig 2.3). When the target was directly ahead of the subject this angle was zero. While rotating to the left with respect to the subject it was negative; to the right it was positive. Fig 2.3 (i) illustrates the target at a positive angle in the moving target condition. In the moving chair condition, when the subject's shoulders were facing square onto the target the target/shoulder angle was zero. When the chair rotated to the left, the target

moved to the right with respect to the subject's shoulders and the target/shoulder angle was positive; when the chair rotated to the right the target/shoulder angle was negative. Fig 2.3 (ii), illustrates the chair rotating to the left thereby yielding a positive target/shoulder angle.

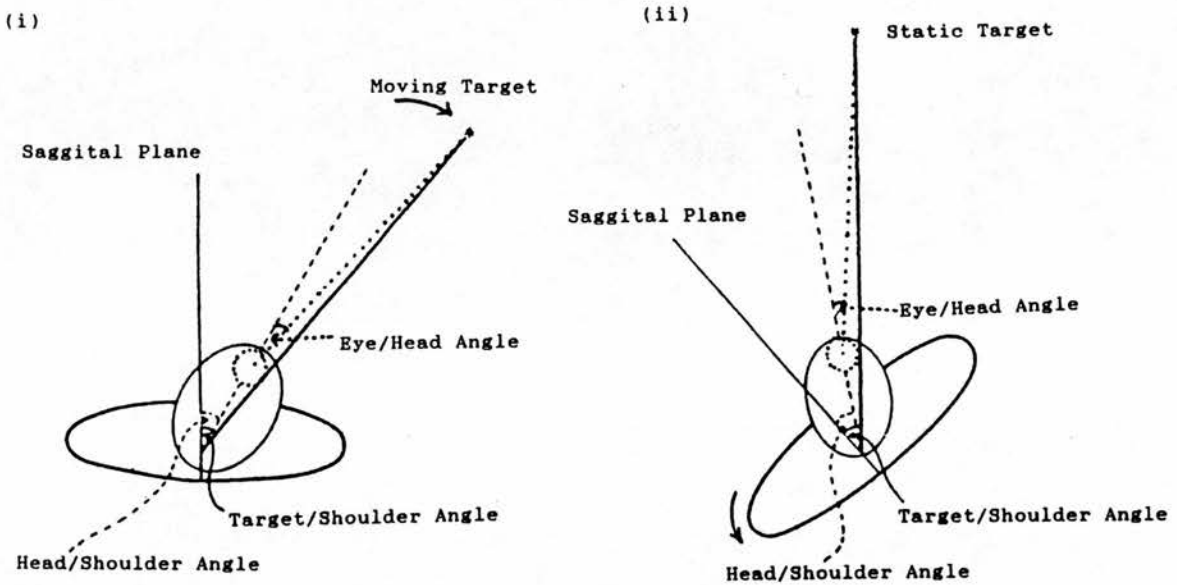


Figure 2.3 Showing a positive eye/head, head/shoulder and target/shoulder angle in (i) moving target (MT) condition and (ii) moving chair (MC) condition.

2.6.2. Head/shoulder angle

In both conditions the amount of head rotation was measured with respect to the shoulders. The head/shoulder angle was taken as that between the sagittal plane and a line perpendicular to the line joining the leds on the headband (B, C). When the head was turned to the left on the shoulders the head/shoulder angle was negative, when the head was turned to the right on the shoulders it was positive. Fig 2.3 shows the head at a positive angle to the shoulders under both conditions.

These represent the standard set of data used for all analyses of head movement. With the adults, it was possible to use all the data from each 15 sec trial. With the infants, on the other hand, only sections where the child

was fully engaged in the task could be selected, and these sections were analysed separately.¹ So, for example, the trial represented in Fig 2.4 (taken from the first session with NH) was analysed from 5 seconds to the end. The figures quoted in this section for infant head tracking apply to these sections.

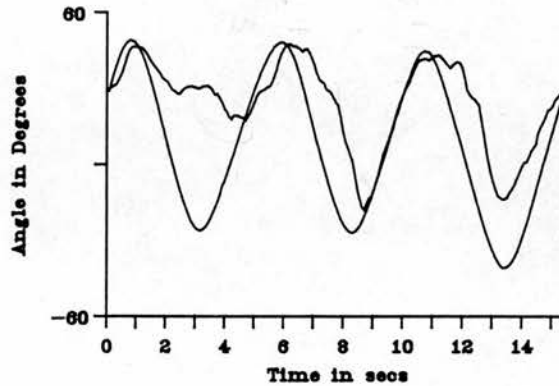


Figure 2.4 Illustrating how sections of infant records were chosen for analysis (see text for details).

2.6.3. How much was the head used?

The amount of head movement was calculated as a proportion of the target movement. For each trial the standard deviation of the time series of the head/shoulder angle was divided by the standard deviation of the time series of the target/shoulder angle ($sd\ head/sd\ target$). This gave a measure of the amount of movement of the head relative to the amount of target or shoulder movement, but made no statement about accuracy or absolute amplitude of head movement. (See appendix I for a copy of the program.)

2.6.4. How well did the head movement link with that of the target?

Two things are important in the maintenance of gaze when the target moves relative to the body: anticipation of the movement of the target and ability to match the shape of that movement. Matching of the target movement is mainly related to the movement that has to be performed, i.e., the shape of movement, whereas anticipation is more to do with synchronising movement with that of the target. These two aspects were measured by cross-correlation analysis.

For each trial, the zero-lag cross-correlation between the head/shoulder angle and the target/shoulder angle was calculated (head-target correl.). The time series were then shifted with respect to one another to find the peak cross-correlation (head-target peak corr.). If the correlation was above .50 (as it was in the majority of cases), the head was reckoned to be tracking the target and the shift between the two time series was taken as a measure of the amount that the head lagged the target (head-target lag). So, for example, if in the PR conditions both the target and chair were moving sinusoidally in phase at the same frequency, but not necessarily at the same amplitude, the cross-correlation would be perfect and there would be no lag. If they were out of phase, then the peak cross-correlation would be unity and the lag would correspond to the phase shift. (A copy of the program used for cross-correlation analysis is given in appendix II).

The lag times gave an indication of the amount of anticipation, the lower the lag, the higher the degree of anticipation. The peak cross-correlations gave a measure of the match between head and target movement irrespective of phase: the higher the peak cross-correlation, the better the match.

2.6.5. How accurate was gaze?

Conventionally, direction of gaze is taken as the sum of the head/shoulder and eye/head angles, and the gaze error is taken as the difference between this value and the target/shoulder angle. However, as indicated in chapter 1, this measure of gaze is accurate only when the target is a long way off (see fig 1.1). Since the target was only about 50cm away in the present experiments, an exact formula for the gaze error was used, ie, the angle between the direction in which the eyes were actually pointing and the direction in which they should have been pointing in order to fixate the target.

It is not easy to calibrate eog in the traditional manner with infants as they cannot be relied upon to fixate a static calibration point (Maurer, 1975). For this reason the eog calibration procedure was based on the information from the dynamic trials. The orientation of the eyes in the head (the eye/head angle) is a linear function of the eog voltage. The linear function was estimated by calculating the linear regression of eye/head angle on eog voltage over periods when the eyes were calculated to be fixating the target.

The procedure was as follows:

1. The 'ideal' eye/head angle (ie the angle required to fixate the target) was calculated at each sample point. This was taken as the angle between the line joining the target to the mid-point between the leds (B, C) over the eyes (the cyclopean eye) and a line perpendicular to BC (see fig 2.3). According to whether the eyes pointed left, straight ahead or right the angle was negative, zero or positive.
2. The time series for the eog and ideal eye/head angle were inspected and sections picked out where the series showed a matching pattern. The adults tracked in a consistent fashion and therefore most calculations were carried out over the complete trials. Infant tracking was more erratic and therefore more and smaller sections were picked out.
3. For each of these sections, the linear regression of ideal eye/head angle on eog was calculated. If the correlation coefficient was greater than 0.97 (indicating that the eyes were closely tracking the target), then the regression slope (m), and intercept (c), were accepted as estimates of the eog constants, ie

$$\text{eye/head angle} = m \times (\text{eog voltage}) + c \quad (1)$$

In the case of the adults the regression slope and intercept remained fairly steady (eg S1: when correlation coefficient was above .97: mean slope .26, sd .02; mean intercept 188, sd 17) The mean slope and intercept for the whole session could therefore be used to scale the eog time series for each trial for graphical purposes. With the infants, apart from occasional attempts to pull the electrodes off, other problems such as crying, yawning, and sweating all affected the eog recording, resulting in more drift which affected the stability of the intercept and to a less extent, the slope, (eg FT 2: mean slope .91, sd .16; mean intercept 430, sd 120).

4. In order to remove the effect of the drift of the intercept, the eye/head angle and eog time series were smoothed using a moving Gaussian profile filter spanning 36 data point (576 ms) and differentiated prior to regression. Theoretically, after differentiation the slope should be unchanged and the intercept should be zero. Results agreed well with this: (S1: mean slope .26, sd .02; mean intercept .02, sd .02; FT 2: mean slope .93, sd .06; mean intercept .03, sd .16). The mean slope from sections of high correlation between ideal eye/head angle velocity and eog velocity for individual trials in a session was used to calibrate the eog for the whole session. For the infants this

slope function was similar for many sessions and an estimated figure was used for those sessions where it was not possible to obtain sufficient sections of high correlation for calibration.

5. The root mean square of the difference between the ideal velocity record and the calibrated eog velocity record was taken as a measure of gaze velocity error (GVE). The GVE for each individual trial (not including large velocity differences attributed to blinks etc) was used to produce a mean GVE for each session.

2.7. Method of Statistical Analysis

The cross-correlations between head/shoulder and target/shoulder angles did not show normal distribution and therefore the non-parametric Mann-Whitney test was used. It was also used for the estimates of infant GVE. Parametric t-tests were used on the head/target ratio, on the lags and on the adult GVE. On the basis of pilot studies some predictions were made in advance and therefore the tests for predictability and effect of target versus chair movement were one-tailed, the prediction being made that in the PR and MC cases cross-correlations and proportion of head movement to target movement would be higher, lags shorter and GVE lower. As can be seen from table 2.1 not all the baby sessions produced the full 20 trials, so there were not enough data points to carry out ANOVAs and look for interactions. It was expected that all the measures would show improvements over age and so one-tailed tests were used to look for these. In order to pick up the exact points at which changes were occurring, separate tests were carried out between each of the sessions, rather than doing an overall trend test.

¹ In order to obtain a good measure of the optimal performance at each age, it was necessary to omit sections where the attention of the infant subjects was not on the target. The results of pilot studies and the videotapes indicated that when infants were tracking the target they actively used their heads and this was clearly reflected in the graphs by sections where the head/shoulder angle closely followed the target/shoulder angle; lapses in attention were conversely reflected as sections where the head/shoulder angle either went in a different direction to the target/shoulder angle or else remained relatively flat. Therefore the graphs from each trial were inspected and those sections where the head/shoulder angle closely followed the target/shoulder angle (regardless of any phase lag), were selected for analysis. In fact the findings from an analysis of the data with no sections omitted were not substantially different from those reported below.

CHAPTER 3

EFFECT OF TARGET/CHAIR AND PREDICTABLE/UNPREDICTABLE MOVEMENT

In this chapter, following a brief summary of the adult results, the effects on both adult and infant performance of the two variables - target/chair movement and predictable/ unpredictable movement - will be considered in detail and compared. A description of the main developmental changes found during the tested period of infancy will be given in chapter 4.

Although infant motivation in target tracking is likely to be very different from adult motivation, a picture of mature performance on the tasks will set the infant behaviour into context. While the information available for coordination of gaze would be the same for all subjects, it was expected that adults would use this information more efficiently.

3.1. Adult Summary Results

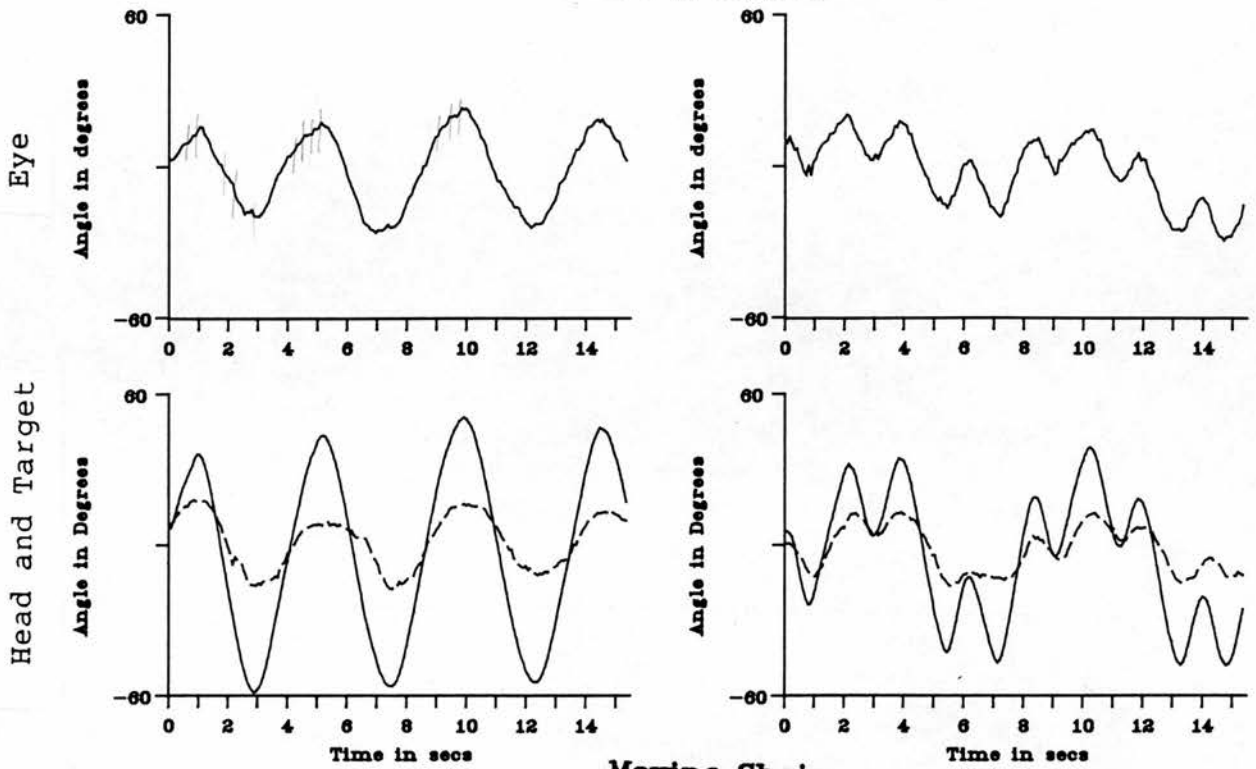
The typical adult response to each condition is shown in fig 3.1. The upper graph in each set represents the calibrated eog record (see Chapter 2). The solid line represents target/shoulder angle, while the dashed line represents head/shoulder angle.

Both the head and eyes were used smoothly to maintain fixation on the target in all conditions with an average of 61% of target movement being accounted for by the head. The average zero-lag cross-correlation between head/shoulder and target/shoulder angles (ie the head-target correlation) was .96 while on average, the head lagged the target by 45 ms. Table 3.1 shows the cross-correlations and lags; a positive lag indicates a real lag behind the target whereas a negative lag indicates anticipation. The coordinated action of the head and eyes resulted in a GVE that was on average only 2.88 degs.s⁻¹ while the mean rms target/shoulder velocity was about 40 deg.s⁻¹.

Predictable Movement (PR)

Unpredictable Movement (UP)

Moving Target



Moving Chair

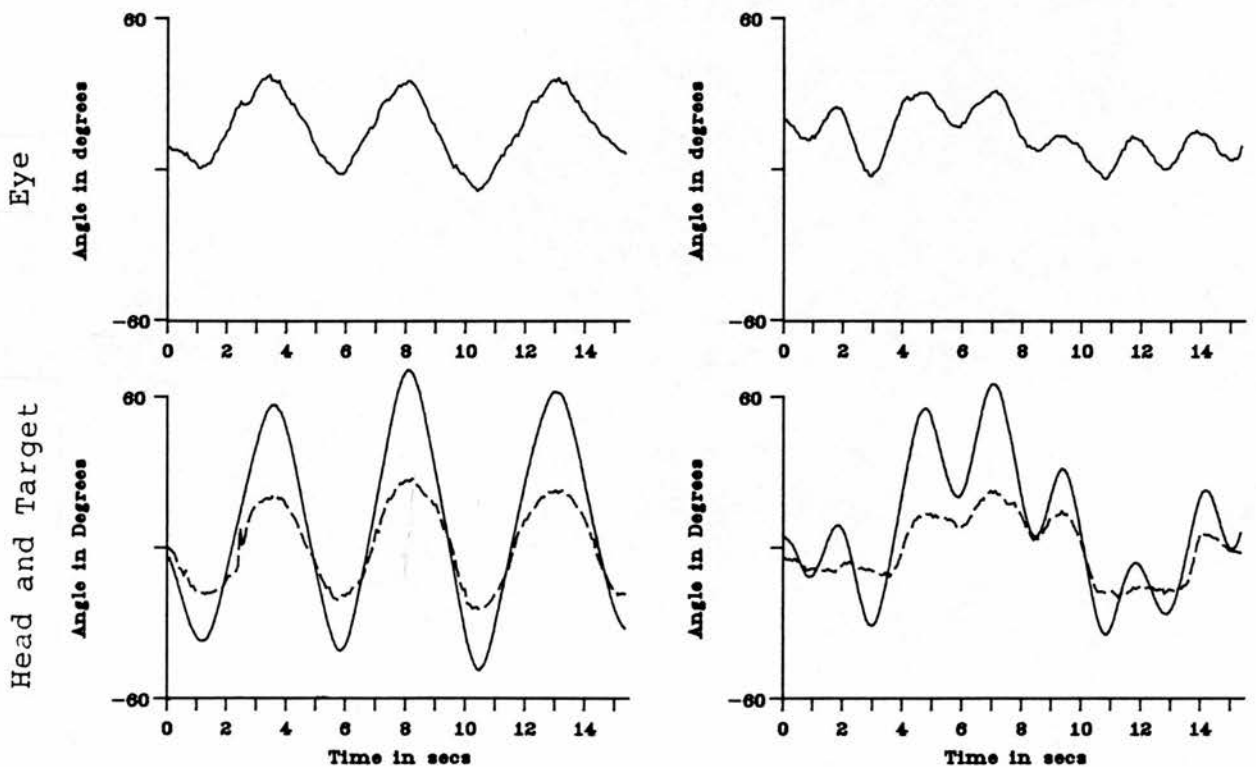


Figure 3.1 Graphs showing typical adult response (s1) on each of the conditions. Upper graph in each set shows calibrated eog (see text). Lower graph shows head/shoulder-----angle and——target/shoulder angle.

Table 3.1 Showing the mean and sd of adult results on the zero-lag cross-correlation, peak correlation and lag between head/shoulder and target/shoulder angles, the proportion of head to target movement and GVE.

Subj.	n	Head-Target correl.		Head-Target lag (ms)		Head-Target Peak corr.		SD head SD /tar		GVE deg.s ⁻¹	
		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
1	20	.95	.03	110	70	.96	.02	.39	.09	3.41	.54
2	20	.91	.01	123	155	.93	.08	.55	.29	2.62	.55
3	20	.97	.01	- 64	90	.98	.01	.78	.09	2.70	.98
4	20	.94	.06	89	48	.96	.05	.49	.12	3.00	1.13
5	20	.98	.01	- 22	29	.99	.01	.58	.06	3.12	.69
6	20	.99	.01	34	41	.99	.01	.87	.04	2.45	.68
Over subjects											
Mean		.96		45		.97		.61		2.88	
sd		.03		76		.02		.18		.36	

Although the performance of all the subjects was similarly accurate (all had high zero-lag and peak cross-correlations and low GVEs), table 3.1 shows that there was quite a lot of variation between subjects. The differences arose in the amount of lag between head and target and the proportion of head/target use. The amplitude of head movement would not affect cross-correlation; a low amplitude head movement could still produce a high correlation. It appears that different subjects were using different strategies to maintain gaze. Subject 6, for example, had a very high proportion of head use (.87) and very low head lag time (34 ms), while the opposite was the case for subject 1. Nor is it the case that the head lagged behind the target in all the subjects. In some subjects the head lagged behind the target, (Ss 1, 2, 4, 6); whereas the opposite was the case for others (Ss 3, 5) and the target/chair movement was anticipated. There was also a lot more within subject variation in lag time than in cross-correlations or in GVE, which indicates a large degree of flexibility in the successful response to the task. As the adults showed such high zero-lag cross-correlations with little possibility of a large increase to

peak cross-correlation, the lag times were taken from quite a flat curve, which may account for some of the variability.

The results were collapsed so that the two main variables were considered separately. Superior performance was expected both as a response to predictable movement whether MT or MC and as a response to chair movement whether PR or UP.

3.2. The Effects of the Two Experimental Variables on Adult Results

The results and statistics for each adult subject are shown in tables 3.2 and 3.3. Neither condition produced a completely consistent effect on any of the measures. Because of the intersubject variation no strong conclusions can be made about the effects of the variables on the pooled data, but table 3.3 shows that while none of the measures was significantly affected by the MT/MC variable, when measured by lags and cross-correlations a superior performance was produced when the target or chair movement was predictable. Looking at individual results, the GVE was most resistant to the effect of the conditions which suggests that the eyes were compensating for fluctuations in head accuracy. Only the proportion of head/target movement was significantly affected by MT/MC, but as two subjects showed a lower head/target proportion when the target was moving (S1, S4) and two subjects showed the opposite effect (S2, S3) the implication is again that this reflects individual strategy. The cross-correlations though, were more consistently affected, being higher when movement was predictable for every subject, with significant differences occurring for four of the subjects (Ss 1, 2, 4 and 6). Again, lags were lower in the predictable condition for every subject with two significant effects (Ss 1 and 6).

The adult picture is therefore one of variability in strategy resulting in a consistently low GVE. Head control was not significantly different when tracking a moving target or when keeping gaze fixed in compensation for body movement, but it tended to be superior for predictable movement - suggesting that the eyes may have been responsible for making up performance in the unpredictable situation.

Table 3.2 Table showing the mean and sd of adult results on the zero-lag cross-correlation, peak correlation and lag between head/shoulder and target/shoulder angles, the proportion of head to target movement and GVE for each conditon.

Subj.	n	Head-Target Correl.		Head-Target Lag (ms)		Head-Target Peak corr.		sd head /sd tar		GVE deg.s ⁻¹		
		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	
1	MC	10	.96	.03	70	50	.97	.02	.44	.04	3.44	.33
	MT	10	.93	.03	150	50	.96	.02	.33	.10	3.38	.72
	PR	10	.96	.02	110	20	.98	.01	.40	.07	3.50	.53
	UP	10	.93	.03	110	70	.95	.02	.37	.11	3.31	.56
2	MC	10	.85	.09	265	68	.88	.09	.29	.08	2.58	.64
	MT	10	.97	.03	- 19	34	.97	.03	.82	.10	2.65	.47
	PR	10	.94	.05	114	114	.97	.03	.55	.22	2.58	.57
	UP	10	.87	.01	132	132	.88	.09	.56	.36	2.65	.56
3	MC	10	.98	.01	30	49	.98	.01	.73	.08	1.89	.39
	MT	10	.97	.01	-130	70	.97	.01	.83	.07	3.52	.65
	PR	10	.98	.01	- 75	92	.98	.01	.79	.08	2.82	.96
	UP	10	.97	.01	- 53	91	.97	.01	.77	.10	2.59	1.05
4	MC	10	.96	.04	69	57	.97	.03	.58	.06	3.10	1.04
	MT	10	.93	.07	109	29	.94	.06	.40	.09	2.89	1.26
	PR	10	.98	.01	56	40	.98	.01	.53	.10	2.79	1.00
	UP	10	.91	.06	122	30	.93	.05	.45	.13	3.20	1.27
5	MC	10	.99	.01	- 23	21	.99	.01	.57	.06	3.15	.68
	MT	10	.98	.01	- 21	36	.98	.01	.58	.06	3.09	.73
	PR	10	.99	.01	- 31	30	.99	.00	.58	.05	3.33	.69
	UP	10	.98	.01	- 13	25	.98	.01	.57	.07	2.91	.66
6	MC	10	.99	.02	8	36	.99	.02	.88	.04	2.32	.74
	MT	10	.99	.01	61	27	.99	.01	.86	.04	2.59	.61
	PR	10	1.00	.01	18	31	1.00	.00	.88	.04	2.17	.45
	UP	10	.98	.02	51	45	.99	.01	.86	.04	2.74	.77

Over subjects

Mean (sd) MC	.96 (.05)	70 (102)	.96 (.04)	.58 (.21)	2.75 (.59)
Mean (sd) MT	.96 (.03)	25 (102)	.97 (.02)	.64 (.23)	3.02 (.38)
Mean (sd) PR	.98 (.02)	32 (76)	.98 (.01)	.62 (.18)	2.87 (.49)
Mean (sd) UP	.94 (.04)	58 (77)	.95 (.04)	.60 (.19)	2.90 (.30)

Table 3.3 Statistical differences between the conditions for the MT/MC and PR/UP variables for each individual adult subject and for all the adult subjects together.

Subj.		Head-target correl.		Head-target lag(ms)		Head-target peak corr.		Sd head /sd tar		GVE (deg.s ⁻¹)	
		U	p<	t	p<	U	p<	t	p<	t	p<
1	MC/MT	21.5	.025	3.115	.02	44	ns	4.075	.01	-.254	ns
	PR/UP	20.5	.025	.178	ns	11	.005	.966	ns	-.811	ns
2	MC/MT	1.5	.005	-11.520	ns	14	.005	-10.683	.001	.303	ns
	PR/UP	26.5	.05	.770	ns	14	.005	.177	ns	-.209	ns
3	MC/MT	38	ns	-4.54	ns	34.5	ns	-3.239	.01	7.801	.001
	PR/UP	38	ns	.793	ns	33.5	ns	.562	ns	-.873	ns
4	MC/MT	31.5	ns	3.062	.01	39.5	ns	5.526	.001	-.456	ns
	PR/UP	2	.005	4.708	.005	8.5	.005	-3.059	.02	.831	ns
5	MC/MT	43.5	ns	.173	ns	45	ns	.565	ns	-.186	ns
	PR/UP	34	ns	1.255	ns	32	ns	.330	ns	-1.480	ns
6	MC/MT	29	ns	3.861	.005	41.5	ns	-1.340	ns	-.783	ns
	PR/UP	13	.005	4.317	.001	9	.005	1.340	ns	1.643	ns
Over subjects											
	MC/MT	65.5	ns	-.967	ns	71.5	ns	-.780	ns	1.488	ns
	PR/UP	29.5	.01	2.530	.025	29	.01	1.130	ns	-.071	ns

For individual subjects, ttests df=9; Mann-Whitney tests n1,n2 = 10. For sum of all subjects ttests df=11; Mann-Whitney test n1,n2 = 12; (for overall tests the mean value for each cell for each subject was used).

3.3. Infant Results

In comparison with the adults both conditions had marked, if not entirely predicted effects on infant performance. The predictions were that performance would be superior in the PR and MC conditions. An increasing divergence between the predictable and unpredictable conditions was also expected.

3.3.1. The Effect of Predictable versus Unpredictable Movement

Cross-Correlation

The mean results for predictable and unpredictable conditions as plotted over age for each of the three measures (Figs 3.2 - 3.4, see appendix III for set of figures) show a mixed picture. For all the babies there was not one session where the predictable movement produced a significantly shorter lag, rather there were several cases of an apparently opposite response (table 3.4). Only IB showed predictability as a significant factor when all the sessions were considered together ($f=12.733$, $p < .01$).

On the other hand, apart from two sessions, (NH: 1; IB: 6), the cross-correlations were always higher in response to predictable rather than unpredictable movement with several of these differences being significant (fig 3.3, 3.4).

Performance by NH, IB and FT seemed to be particularly influenced by predictability, but even they did not show any evidence of a divergence of response with increasing age, as had been predicted.

GVE

Although the head/target cross-correlations were generally higher with the predictable rather than the unpredictable movement, GVE did not follow the same pattern (fig 3.5) and only one significant difference occurred (SS : 6). Certainly predictability did not have a striking effect on accuracy of gaze but it is possible that differences could have been picked up by more sensitive measures of gaze error.

Proportion of Head/Target Movement

As the graphs (fig 3.6) show clearly, this measure was the least influenced by whether target movement was predictable or not. There were only two significant differences in the expected direction (IB : 6, FT : 2), and if anything the larger differences tended to be in the opposite direction (NH : 6; AT : 2, 3; SB : 2, 3).

NH session	Head-Target Correl.		Head-Target Lag (ms)		Head-Target Peak corr.		SD head /SD tar		GVE deg.s ⁻¹	
	U	p<	t	p<	U	p<	t	p<	U	p<
1 MC/MT	16	.01	4.281	.005	27	ns	1.482	ns	17	.01
	PR/UP	-42.5	ns	-1.928	ns	48.5	ns	-1.004	ns	-33
2 MC/MT	17	.01	1.888	.05	19.5	.025	1.711	ns	-	-
	PR/UP	17.5	.01	-3.693	ns	26	.05	-.743	ns	-
3 MC/MT	43	ns	3.767	.005	-45	ns	-1.078	ns	31	ns
	PR/UP	17	.01	1.512	ns	19	.025	.664	ns	-34
4 MC/MT	30	ns	1.259	ns	49	ns	.185	ns	19.5	.025
	PR/UP	15.5	.005	1.032	ns	17	.01	.022	ns	-21.5
5 MC/MT	35.5	ns	5.406	.001	-47	ns	-1.157	ns	44.5	ns
	PR/UP	20	.025	-.371	ns	22	.025	.533	ns	46
6 MC/MT	30.5	ns	4.057	.005	36.5	ns	-1.248	ns	38.5	ns
	PR/UP	18	.01	.905	ns	11	.005	-2.965	ns	37

SS

session	Corrn		Lag		Peak		SD head /SD tar		GVE	
	U	p<	t	p<	U	p<	t	p<	U	p<
1 MC/MT	00	.001 ¹	4.170	.005 ⁴	14	.025 ²	.763	ns ⁶	31.5	ns ¹
	PR/UP	-38.5	ns ¹	-.181	ns ⁴	33.5	ns ⁴	-.868	ns ⁶	-41.5
2 MC/MT	19	.025	4.181	.005	24.5	.05	1.570	ns	24.5	.05
	PR/UP	39	ns	-1.747	ns	44.5	ns	-.886	ns	-48.5
3 MC/MT	10	.005	8.462	.001	-40.5	ns	-2.304	ns	-	-
	PR/UP	38	ns	-1.433	ns	42.5	ns	.927	ns	-
4 MC/MT	13	.005	5.057	.001	22.5	.025	-2.248	ns	-	-
	PR/UP	23.5	.05	1.250	ns	23.5	.05	1.531	ns	-
5 MC/MT	12.5	.025	7.134	.001	44	ns	-1.456	ns	20	.025
	PR/UP	-47	ns	-1.918	ns	40.5	ns	-.048	ns	-46
6 MC/MT	2	.005	7.967	.001	34	ns	1.407	ns	31.5	ns
	PR/UP	42	ns	-.600	ns	28.5	ns	-1.690	ns	20

Table 3.4 Showing the statistical differences between conditions for each infant. The tests were one-tailed and signs indicate whether differences were in the predicted direction: PR>UP, MC>MT. Mann-Whitney n1, n2 10,10; ttests df=9, except in the following cases: ¹-10, 9; ²-9,9; ³-9,8; ⁴-10,8; ⁵-11,9; ⁶-df=7; ⁷-df=8.

IB

session	Corrn		Lag		Peak		SD head /SD tar		GVE	
	U	p<	t	p<	U	p<	t	p<	U	p<
1 MC/MT PR/UP	-48	ns	-4.829	ns ⁷	23	.05	-.020	ns ⁷	26	ns ¹
	-46	ns	-2.985	ns ⁷	33.5	ns	-.261	ns ⁷	-34.5	ns ¹
2 MC/MT PR/UP	-29.5	ns ³	-.120	ns ⁴	-27.5	ns ³	.065	ns ⁴	33	ns
	30.5	ns ³	-2.310	ns ⁴	13.5	.025 ³	-.412	ns ⁴	-22	ns
3 MC/MT PR/UP	30	ns	1.590	ns ⁷	29	ns	5.411	.001 ⁷	12.5	.005
	10	.005 ⁵	-.263	ns ⁷	14.5	.005 ⁶	1.357	ns ⁷	38.5	ns ⁶
4 MC/MT PR/UP	32.5	ns	11.113	.001	-38.5	ns	-1.482	ns	19	.025
	30	ns	-2.034	ns	18.5	.01	.916	ns	39	ns
5 MC/MT PR/UP	7	.005	3.085	.01	17.5	.01	9.150	.001	-44	ns
	34	ns	-2.222	ns	19.5	.025	-.265	ns	-42.5	ns
6 MC/MT PR/UP	17.5	.01	2.334	.025	26.5	.05	3.243	.02	36	ns
	16.5	.01	.583	ns	26	.05	2.297	.05	-46	ns
7 MC/MT PR/UP	7.5	.005	4.131	.005	18	.01	5.216	.001	49	ns
	36.5	ns	-.784	ns	25	.05	-.038	ns	49	ns

AT

session	Corrn		Lag		Peak		SD head /SD tar		GVE	
	U	p<	t	p<	U	p<	t	p<	U	p<
1 MC/MT PR/UP	27	ns ¹	1.289	ns ⁷	38.5	ns ¹	.183	ns ⁷	-38.5	ns
	37	ns ¹	-1.012	ns ⁷	33	ns ¹	.445	ns ⁷	48.5	ns
2 MC/MT PR/UP	-41.5	ns	.453	ns	30.5	ns	-2.218	ns	17.5	.01
	40.5	ns	-.783	ns	31.5	ns	-2.280	ns	39	ns
3 MC/MT PR/UP	-41	ns	4.473	.005	-27.5	ns	-2.002	ns	-	-
	36.5	ns	-2.690	ns	29	ns	-3.438	ns	-	-
4 MC/MT PR/UP	-45	ns	2.924	.01	-30	ns	-1.775	ns	33	ns
	18.5	.01	-.107	ns	27.5	ns	.316	ns	40	ns
5 MC/MT PR/UP	-	-	-	-	-	-	.019	ns	-	-
	-	-	-	-	-	-	-	-	-	-
6 MC/MT PR/UP	45	ns	4.674	.005	48	ns	-.128	ns	-	-
	42	ns	-.637	ns	27	ns	-.426	ns	-	-
7 MC/MT PR/UP	17.5	.01	.318	ns	11	.005	-1.382	ns	18.5	.01
	30.5	ns	.843	ns	41.5	ns	.000	ns	28	ns

Table 3.4 (cont)

FT

session	Corrn		Lag		Peak		SD head /SD tar		GVE	
	U	p<	t	p<	U	p<	t	p<	U	p<
1 MC/MT	- 1	ns ¹	-		-		-3.340	ns ⁷	34.5	ns ¹
PR/UP	39.5	ns ¹	-		-		.203	ns ⁷	37	ns ¹
2 MC/MT	-13.5	ns ¹	-.847	ns ⁷	- 6	ns ¹	-.649	ns ⁷	-41	ns ¹
PR/UP	14	.01 ¹	.472	ns ⁷	17	.025 ¹	2.821	.05 ⁷	28.5	ns ¹
3 MC/MT	39	ns ¹	3.902	.005 ⁷	42.5	ns ¹	-1.529	ns ⁷	-	
PR/UP	26.5	ns ¹	-.496	ns ⁷	21.5	.05 ¹	-.849	ns ⁷	-	
4 MC/MT	42.5	ns	2.008	.05	-22	ns	-3.200	ns	26.5	.05
PR/UP	34	ns	-.635	ns	44.5	ns	.105	ns	-45.5	ns
5 MC/MT	44	ns	6.122	.001	-27.5	ns	-3.160	ns	32	ns
PR/UP	28.5	ns	-2.866	ns	26	.05	-.448	ns	48	ns
6 MC/MT	17.5	.025 ¹	5.598	.001 ⁷	-30	ns ¹	.381	ns ⁷	-22	ns ¹
PR/UP	20	.05 ¹	-.590	ns ⁷	13.5	.01 ¹	.863	ns ⁷	30.5	ns ¹
7 MC/MT	18.5	.01	6.948	.001	37.5	ns	-1.598	ns	10	.005
PR/UP	32.5	ns	.339	ns	29	ns	-.342	ns	47.5	ns

SB

session	Corrn		Lag		Peak		SD head /SD tar		GVE	
	U	p<	t	p<	U	p<	t	p<	U	p<
1 MC/MT	1.5	.005 ³	-		4.5	.01	.177	ns ⁷	10	.005 ²
PR/UP	17.5	.05 ³	-		15.5	ns	-.075	ns ⁷	33	ns ²
2 MC/MT	29	ns	3.638	.005	31.5	ns	.451	ns	25.5	ns ¹
PR/UP	43	ns	.368	ns	-49	ns	-1.415	ns	44	ns ¹
3 MC/MT	12.5	.01 ²	1.400	ns ⁷	28.5	ns ²	-1.872	ns ⁷	42	ns
PR/UP	25.5	ns ²	.761	ns ⁷	34	ns ²	-.358	ns ⁷	-43.5	ns
4 MC/MT	-40.5	ns	3.304	.005	-26.5	ns	.199	ns	-	
PR/UP	38	ns	-1.220	ns	34.5	ns	.202	ns	-	
5 MC/MT	-37	ns	1.949	.05	-37.5	ns	-.902	ns	-	
PR/UP	17	.01	-1.835	ns	17	.01	1.611	ns	-	
6 MC/MT	17.5	.01	3.145	.01	40	ns	-1.658	ns	12.5	.005
PR/UP	28.5	ns	1.762	ns	17	.01	-1.360	ns	-34	ns

Table 3.4 (cont)

Effect of Predictable/Unpredictable Movement : Lags

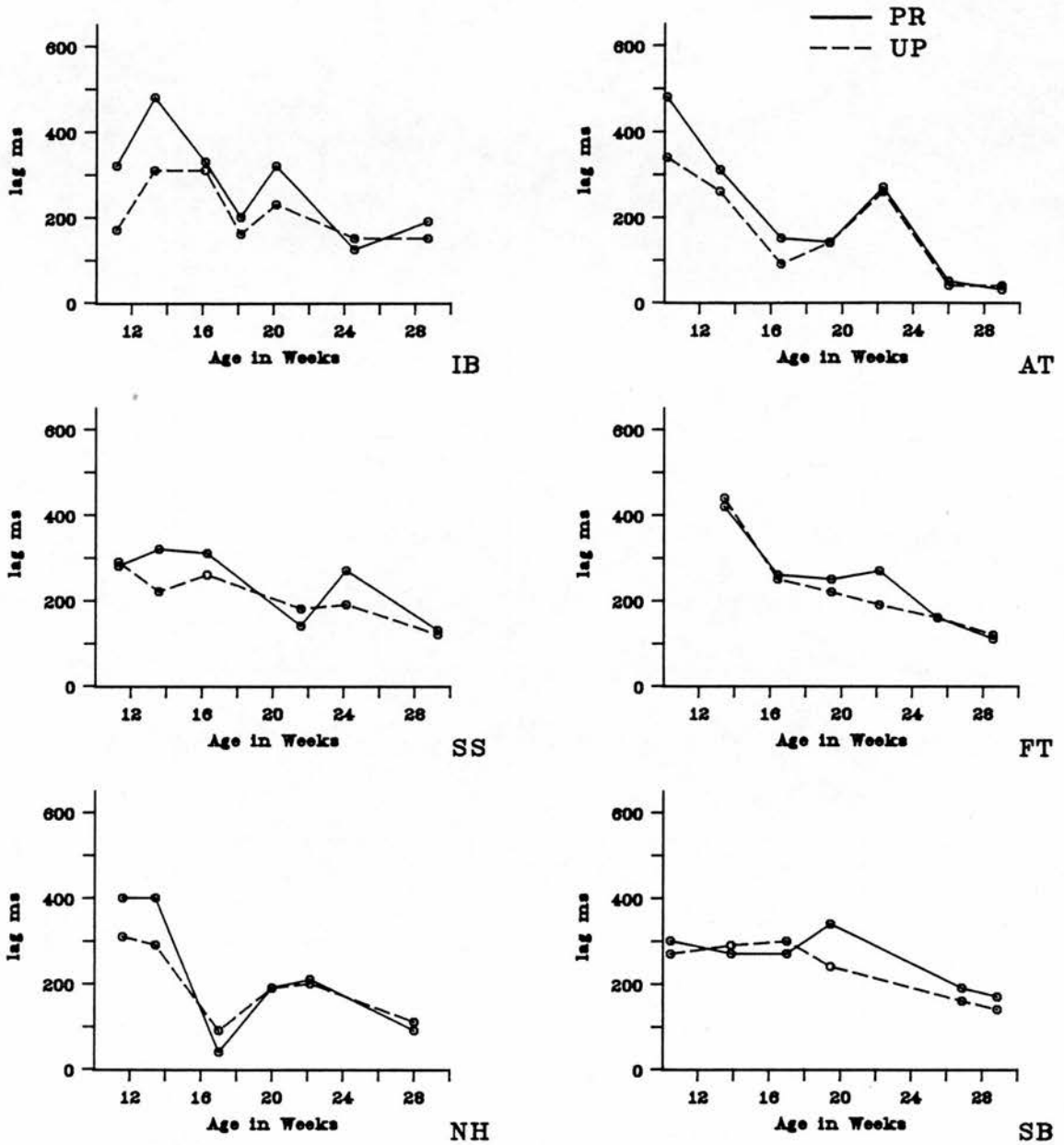


Figure 3.2 Lags between head/shoulder and target/shoulder angles for each infant. Broken down by whether target/shoulder movement was predictable or unpredictable.

——— Predictable Movement (PR)
 - - - - Unpredictable Movement (UP)

Effect of Predictable/Unpredictable Movement :

Zero-Lag Cross-Correlations

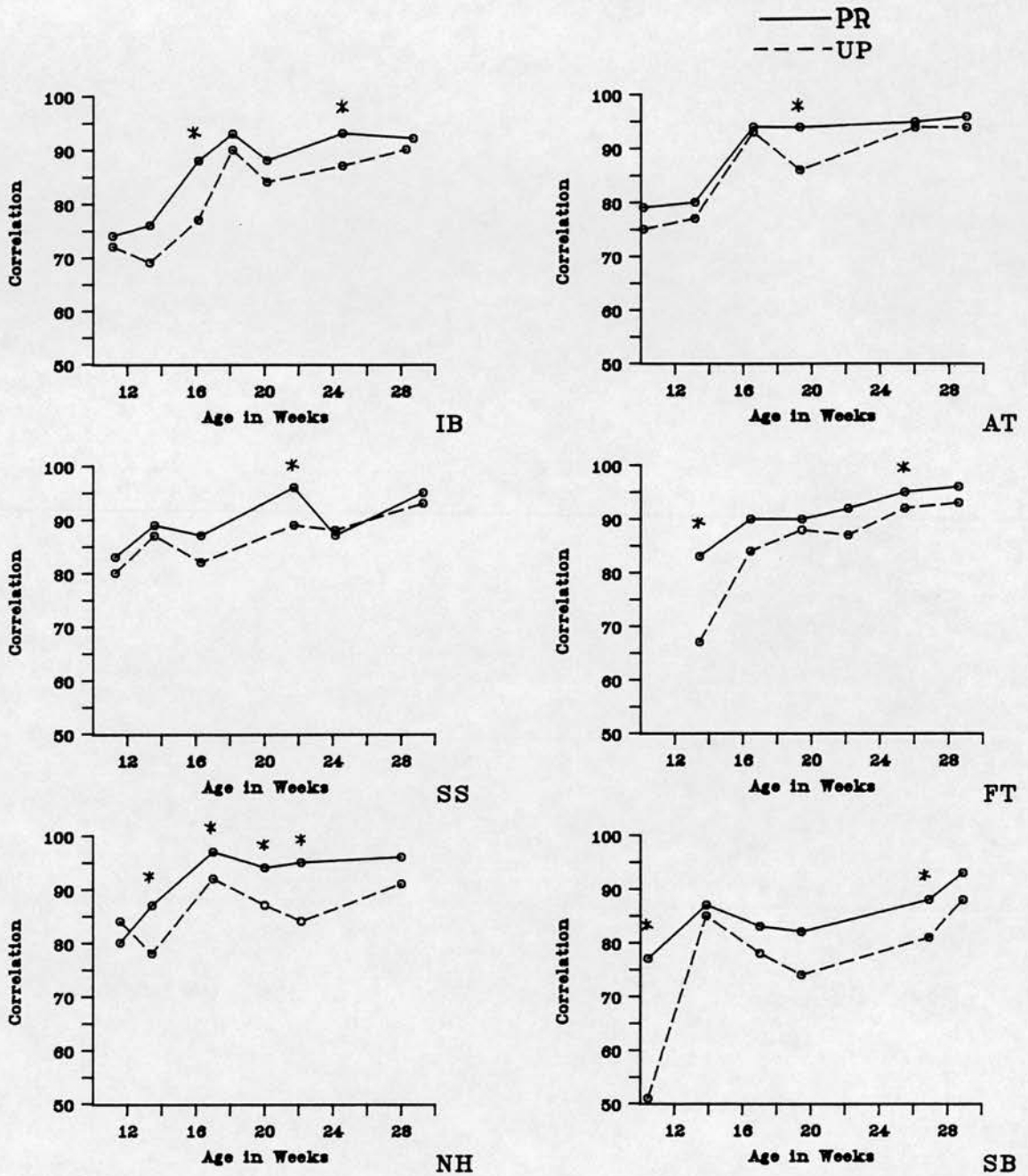


Figure 3.3 Zero-lag cross-correlation between head/shoulder and target/shoulder angles for each infant. Broken down by PR/UP. * - Significant difference.

— Predictable Movement
 - - - Unpredictable Movement

Effect of Predictable/Unpredictable Movement :

Peak Cross-Correlations

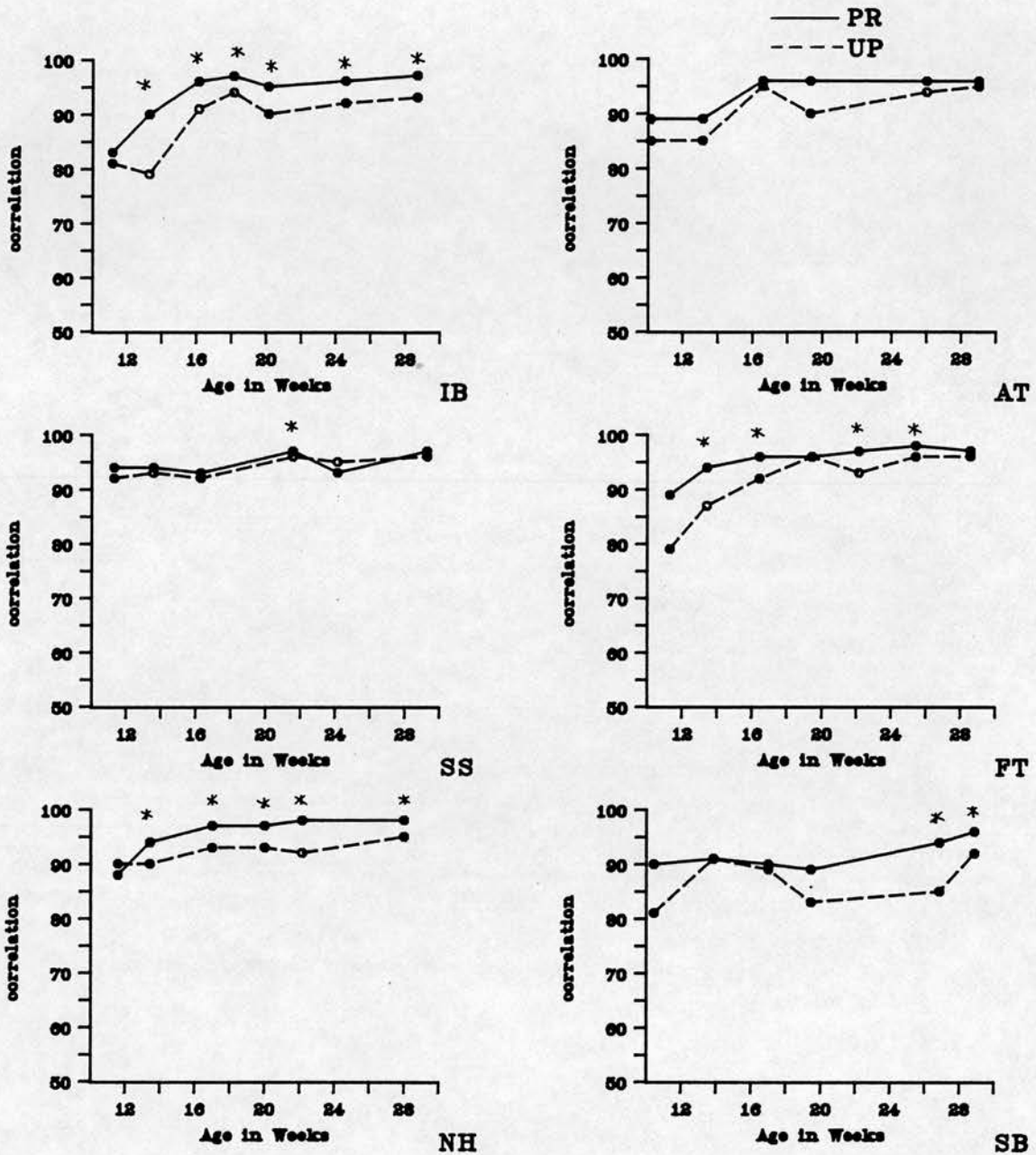


Figure 3.4 Peak correlation between head/shoulder and target/shoulder angles for each infant, broken down by PR/UP. * - significant difference.

— Predictable Movement
 - - - Unpredictable Movement

Effect of Predictable/Unpredictable Movement : GVE

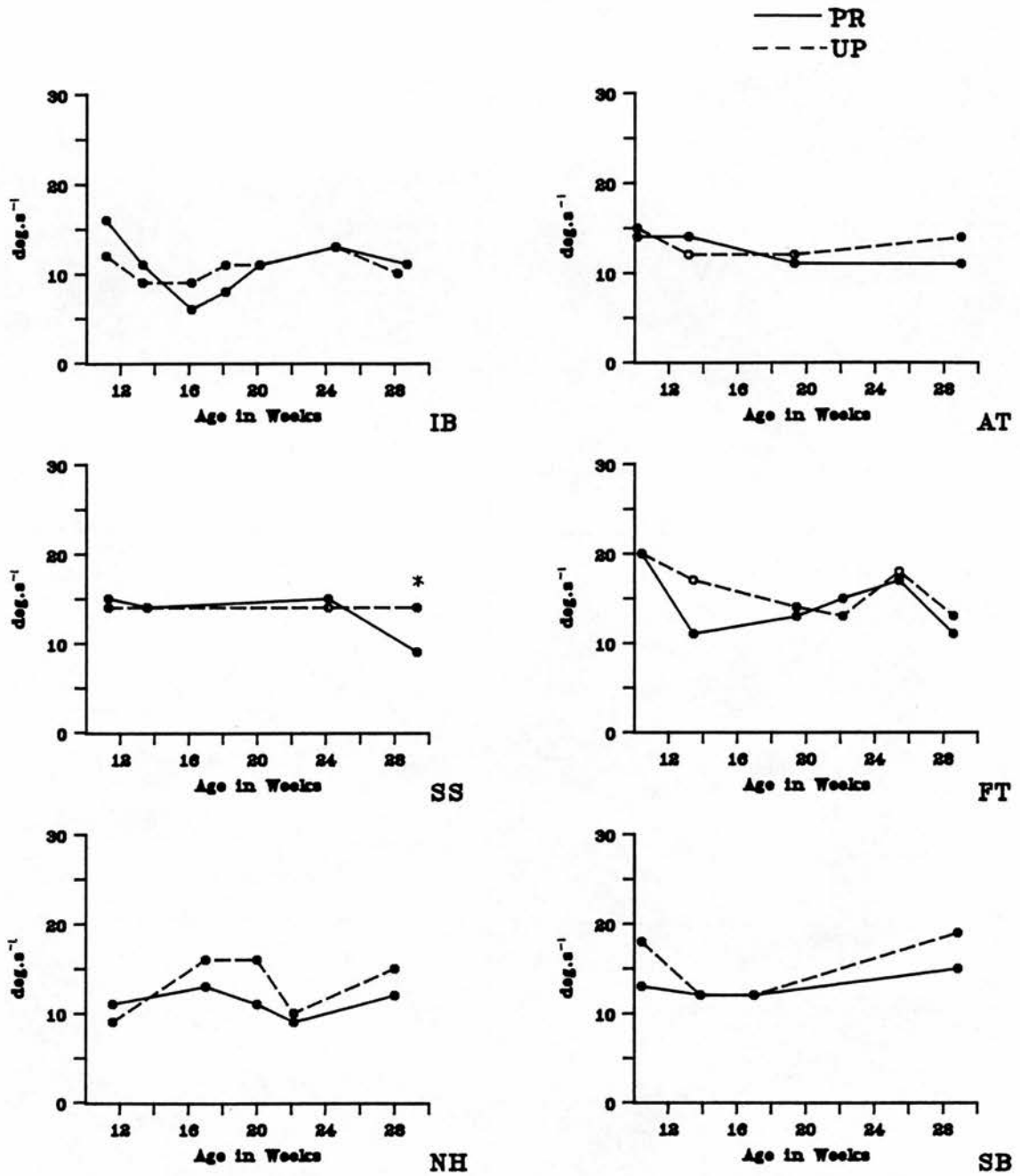


Figure 3.5 GVE for each infant broken down by PR/UP.

* - significant differences.

— Predictable Movement
 - - - Unpredictable Movement

Effect of Predictable/Unpredictable Movement :
 Proportion of Head/Target Movement

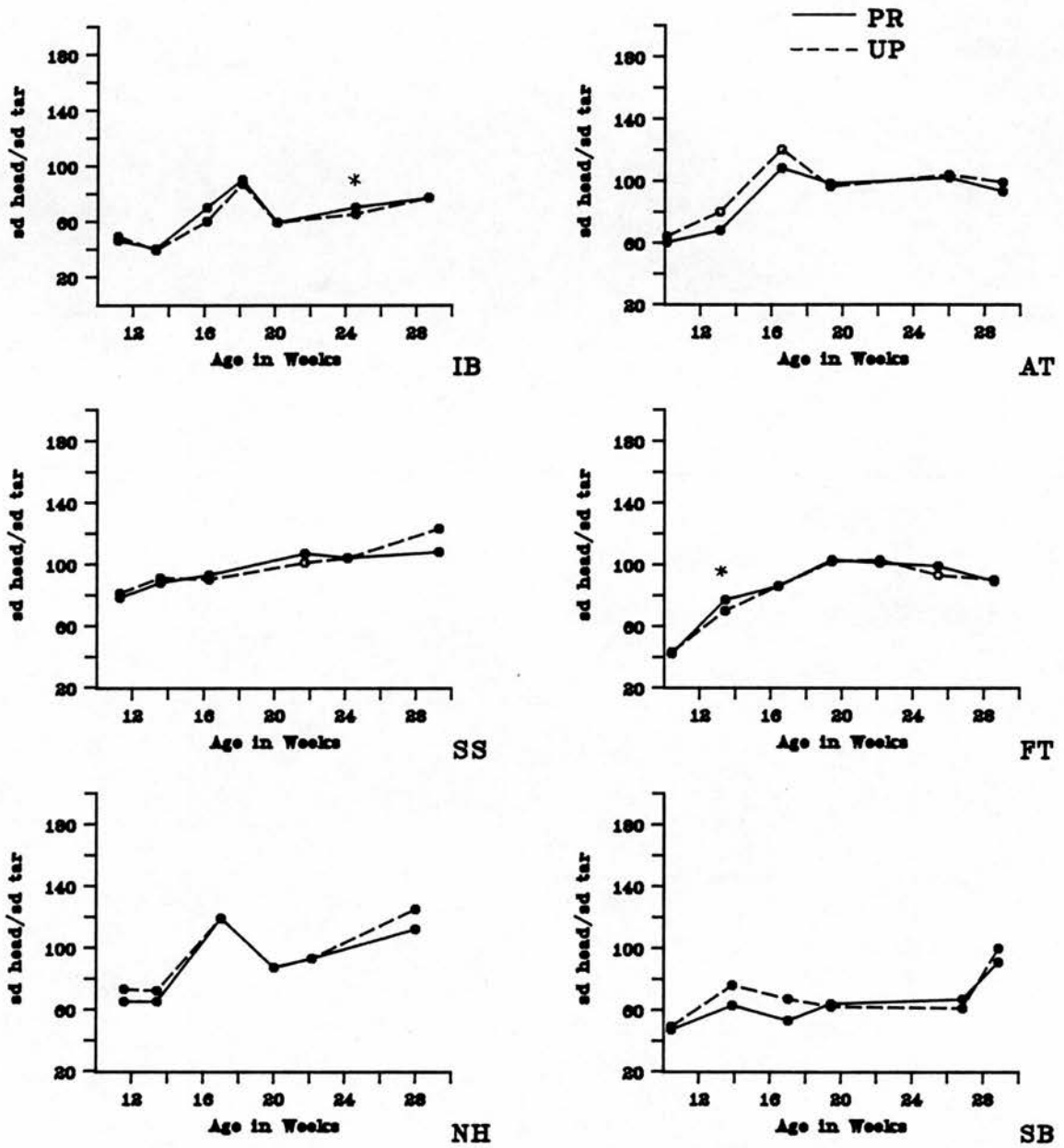


Figure 3.6 Proportion of head/target movement for each infant, broken down by PR/UP. * - significant difference.

———— Predictable Movement
 - - - - - Unpredictable Movement

3.3.2. The Effect of Target Movement versus Chair Movement

Cross-Correlation

Fig 3.7 shows that whereas predictability did not significantly reduce the amount the head lagged behind the target, chair movement did. In all but one case (IB: 1), lag times were shorter in response to chair rather than target movement and these differences were largely significant (see table 3.4 for statistical details). When sessions were combined over age, MT/MC emerged as an overall significant factor for five of the babies (NH, FT, SS, SB $p < .001$; AT $p < .01$) and in the other from sessions 4-7 (IB $p < .01$).

Although chair movement strongly affected the lag times, the cross-correlations were not so clearly affected (figs 3.8 and 3.9). Apart from SS who showed much higher zero-lag cross-correlations in the MC case for all sessions, the pattern of results was not very clear, although the MC condition was significantly higher on several sessions.

GVE

Graph 3.10 shows that GVE, where it was possible to compute, tended to be higher in the MT condition with a number of significant differences emerging.

Proportion of Head/Target Movement

Again the proportion of head/target movement was not largely or consistently affected by the different conditions. The graphs (3.11) show a bit more separation than in the PR/UN condition, but only IB responded with significantly less head use when the target was moving. From three of the babies (SS, AT, FT) many of the responses tended to be in the opposite direction.

Effect of Moving Target/Chair : Lags

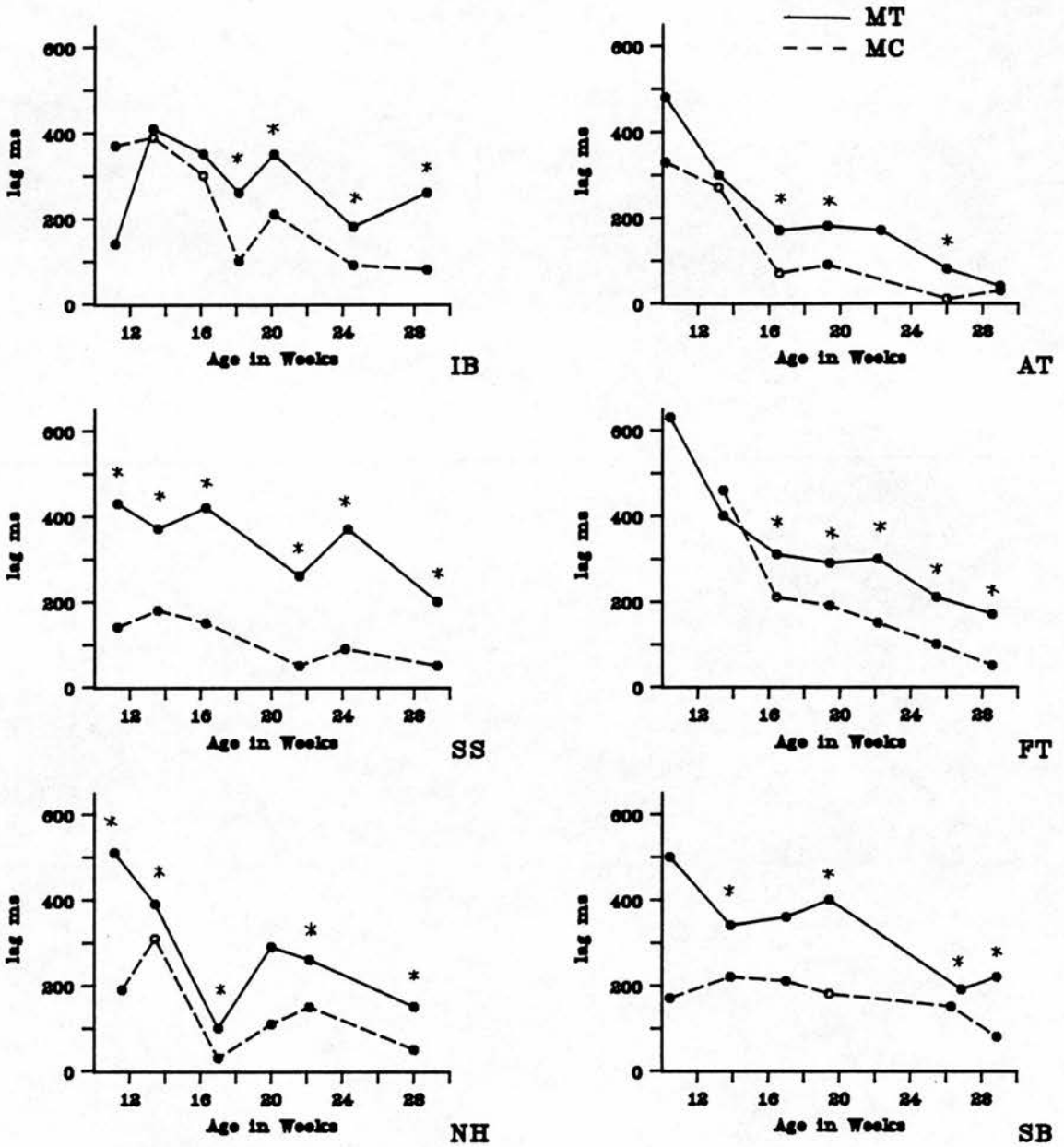


Figure 3.7 Lags between head/shoulder and target/shoulder angles for each infant. Broken down by whether chair was moving or fixed. *- significant difference.

———— Moving Target
 - - - - Moving Chair

Effect of Moving Target/Chair : Zero-Lag Cross-Correlations

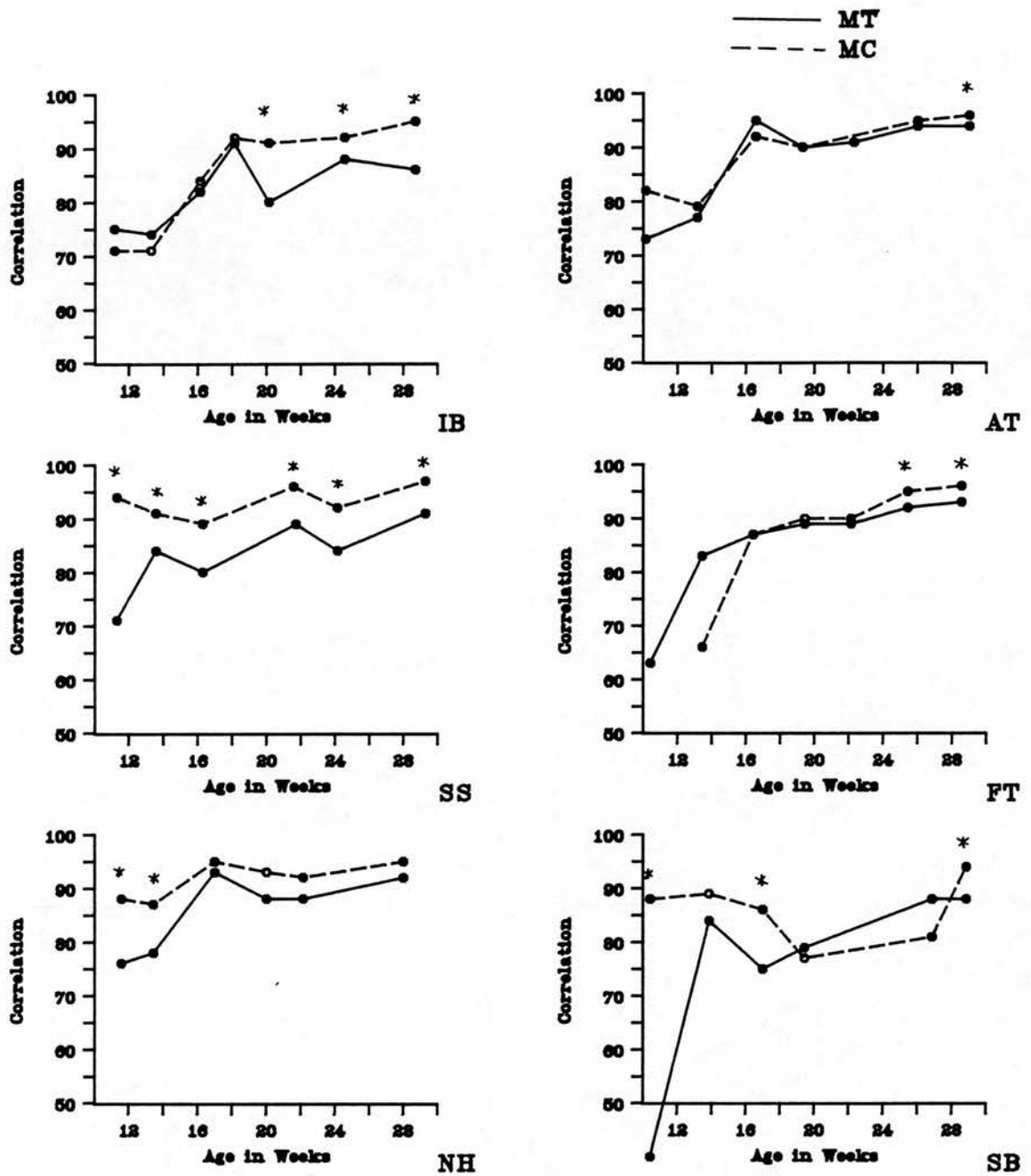


Figure 3.8 Zero-lag cross-correlation between head/shoulder and target/shoulder angles for each infant. Broken down by MT/MC. *- significant difference.

— Moving Target
 - - - Moving Chair

Effect of Moving Target/Chair : Peak Cross-Correlations

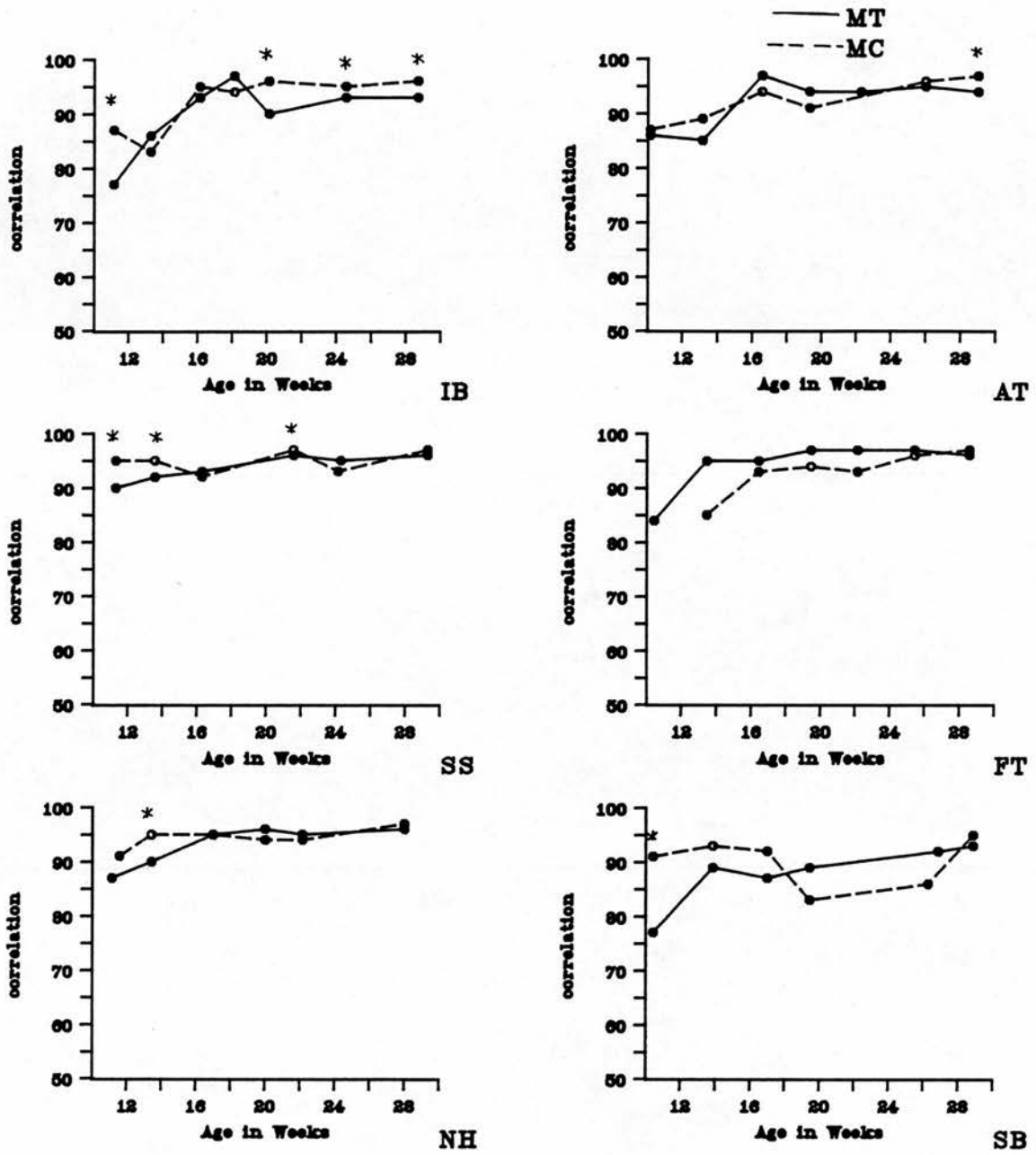


Figure 3.9 Peak correlation between head/shoulder and target/shoulder angles for each infant, broken down by MT/MC. *- significant difference.

———— Moving Target
 - - - - Moving Chair

Effect of Moving Target/Chair : Gaze Velocity Error

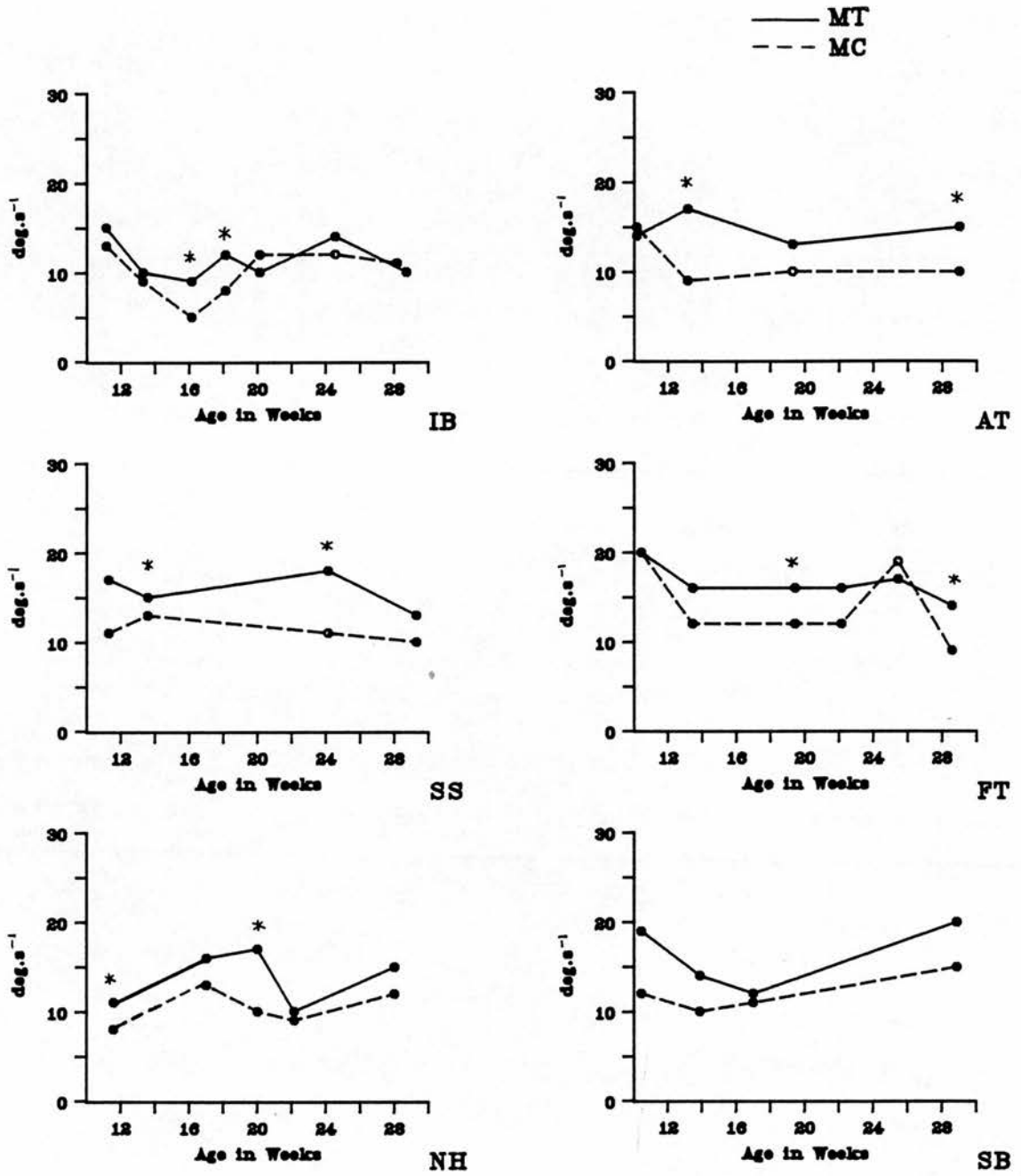


Figure 3.10 GVE for each infant broken down by MT/MC.
* - significant difference.

— Moving Target
- - - Moving Chair

Effect of Moving Target/Chair :
Proportion of Head/Target Movement

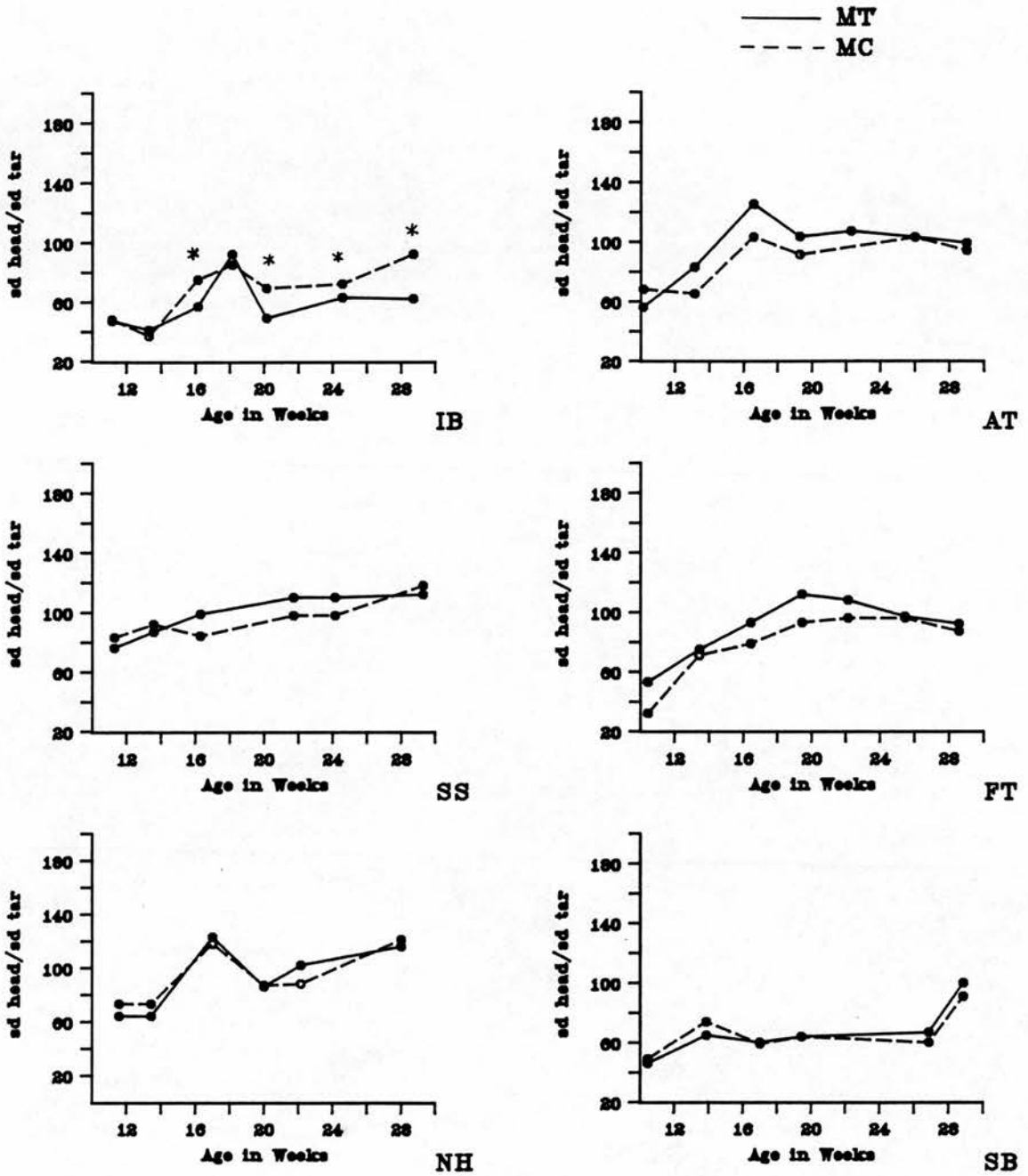


Figure 3.11 Proportion of head to target movement for each infant. Broken down by MT/MC. *- significant difference.

——— Moving Target
 - - - Moving Chair

3.4. The Effects of the Individual Experimental Conditions

The results partially support the predictions (see 3.3), but the picture seems more complicated than predicted. An interesting distinction is emerging between the different effects of the conditions, particularly on the cross-correlation measures. In the previous section the individual conditions were collapsed to some extent in order to look at the effects of predictability and chair movement separately. But what was the effect of each of the four individual conditions : MTPR, MTUP, MCPR, MCUP ? The poorest performance might have been expected in MTUP and the best in MCPR, with MTPR and MCUP in between.

To overcome the possibility of marked differences between cells in one or two sessions swamping overall mean effects (which are presented in appendix IV), the mean score for each individual condition for every session was allotted a rank from 1 (worst performance) to 4 (best performance). In the case of the lags, the shortest lag between head and target was ranked highest; if there were negative lags, then the most negative was ranked highest. The mean rank over age for each of the four conditions is presented by infant subject in table 3.5 along with the mean ranks and sds (individual scores for each of the conditions are shown in appendix V). Each mean rank was itself given a rank to facilitate comparison across subject.

The relative performances on the four different conditions for each infant subject are graphed in Figs 3.12 - 3.15 according to mean rank order across subjects from the best to the worst. With a few exceptions these orderings represent a very consistent pattern in the order of task performance by the infant subjects :

	Best		Worst	
Head-target lags	MCUP	MCPR	MTUP	MTPR
Head-target correl.	MCPR	MTPR	MCUP	MTUP
Head-target peak corr.	MCPR	MTPR	MCUP	MTUP
GVE	MCUP	MCPR	MTPR	MTUP

Head-target correlation

Subj	MTPR			MTUP			MCPR			MCUP		
	mean	sd	rk	mean	sd	rk	mean	sd	rk	mean	sd	rk
NH	2.75	.98	3	1.17	.41	1	3.67	.52	4	2.42	.80	2
SS	2.00	.00	2	1.00	.00	1	3.83	.41	4	3.17	.41	3
IB	3.00	.96	3	1.43	.73	1	3.43	.84	4	2.14	.78	2
AT	3.17	.82	4	1.33	.82	1	3.00	1.26	3	2.50	.63	2
FT	3.25	.88	4	1.67	.82	1	3.17	.98	3	1.92	1.02	2
SB	2.50	1.22	3	1.50	.55	1	3.67	.52	4	2.33	1.03	3
Over subjects												
mean (sd)	2.78 (.47)			1.35 (.24)			3.46 (.32)			2.41 (.43)		
Adult mean (sd)	2.92 (1.02)			1.75 (1.50)			3.58 (.80)			1.75 (.52)		

Head-Target lag (ms)

NH	1.42	.49	1	1.75	.76	2	3.33	.82	3	3.50	.55	4
SS	1.50	.55	1.5	1.50	.55	1.5	3.00	.00	3	4.00	.00	4
IB	1.50	.76	1	2.36	1.18	2	2.71	.95	3	3.43	.79	4
AT	1.50	.84	1	2.25	1.08	2	3.33	.82	4	2.92	1.02	3
FT	1.58	.67	1	2.00	1.10	2	3.25	.61	4	3.17	1.17	3
SB	1.50	.55	1.5	1.50	.55	1.5	3.00	.00	3	4.00	.00	4
Over subjects												
mean (sd)	1.50 (.05)			1.89 (.37)			3.10 (.25)			3.50 (.44)		
Adult mean (sd)	3.00 (1.26)			1.83 (.98)			2.83 (1.33)			2.33 (.82)		

Head-Target peak correlation

NH	3.08	1.28	3	1.42	.49	1	3.25	.42	4	2.25	1.08	2
SS	2.92	.92	3	1.42	.67	1	3.08	1.20	4	2.58	.80	2
IB	2.93	.84	3	1.57	.61	1	3.64	.63	4	1.86	.95	2
AT	3.08	1.28	4	1.83	.98	1	2.92	.97	3	2.17	.93	2
FT	3.92	.20	4	2.25	.76	2	2.50	.89	3	1.33	.52	1
SB	2.50	1.34	3	1.92	.80	1	3.58	.59	4	2.00	.89	2
Over subjects												
mean (sd)	3.07 (.47)			1.74 (.33)			3.16 (.43)			2.03 (.42)		
Adult mean (sd)	3.11 (.71)			1.75 (.76)			3.28 (.79)			1.70 (.65)		

GVE (deg.s)

NH	2.60	1.08	2	1.20	.45	1	3.00	1.00	3	3.20	.76	4
SS	4.00	.00	4	2.00	.00	1	3.38	.48	2	3.63	.48	3
IB	2.57	.98	3	1.86	.75	1	2.36	1.75	2	3.36	.75	4
AT	2.25	.50	3	1.50	1.00	1	3.50	.58	4	2.75	1.26	2
FT	2.50	.71	3.5	1.30	.45	2	2.50	.94	3.5	3.30	1.04	1
SB	2.38	.75	2	1.13	.25	1	3.13	1.18	3	3.38	.48	4
Over subjects												
mean (sd)	2.72 (.47)			1.50 (.36)			2.98 (.46)			3.27 (.29)		
Adult mean (sd)	2.58 (1.43)			2.17 (1.17)			2.33 (.82)			2.92 (1.20)		

Table 3.5 Mean and sd of the ranks for each individual conditions and their rank for each infant, and mean and sd of the ranks over all the adult subjects.

The differential effects of the two variables are reflected here in the pattern of rank ordering. In the infants, cross-correlations divide by predictability and lags and GVE by MT/MC. But it is not the case that the other conditions are undifferentiated. In the cross-correlations, as expected, there is a split by PR and UP, and within these conditions there is an advantage when the chair is moving ie MCPR > MTPR and MCUP > MTUP (with the exception of FT, fig 3.13 but fig 3.9 shows her to have a MT advantage). The lags on the other hand do not conform to this pattern; although the superiority of the MC condition is again apparent, within these conditions for four of the subjects there seems to be an advantage in the UP condition (MC : IB, SS, NH, SB; MT : IB, NH, AT, FT).

The expectation was that MTUP would always produce the poorest performance and this is the case using the zero-lag and peak cross-correlation measures, (apart from FT). But for the lags, the MTPR is the consistently poor condition, (except for SS and SB, but their two lowest conditions are very close). Again the cross-correlations confirmed expectations and were mainly highest in the MCPR condition. Only FT and AT showed lower lag times in this condition, in all the other infants the lag times were shorter for the unpredictable chair movement. The mean rank order for GVE reveals the same advantage for MCUP over MCPR, but not for MTUP over MTPR.

The mean rank order of cross-correlations for the adults is the same as that of the infants but table 3.6 illustrates that their performance was more variable than that of the infants. The best condition tended again to be MCPR. The lags were even more variable and the mean rank order is different from the infants. Interestingly, whilst MTPR produces the longest lag in the infants it is the best or second best for five of the adults. (See appendix VI for mean scores in each condition). Individual performance is most consistent in the zero-lag cross-correlations and fall into the same pattern as the infants:

	Best		Worst	
Head-target lags	MTPR	MCPR	MCUP	MTUP
Head-target correl.	MCPR	MTPR	MCUP / MTUP	
Head-target peak corr.	MCPR	MTPR	MTUP	MCUP
GVE	MCUP	MTPR	MCPR	MTUP

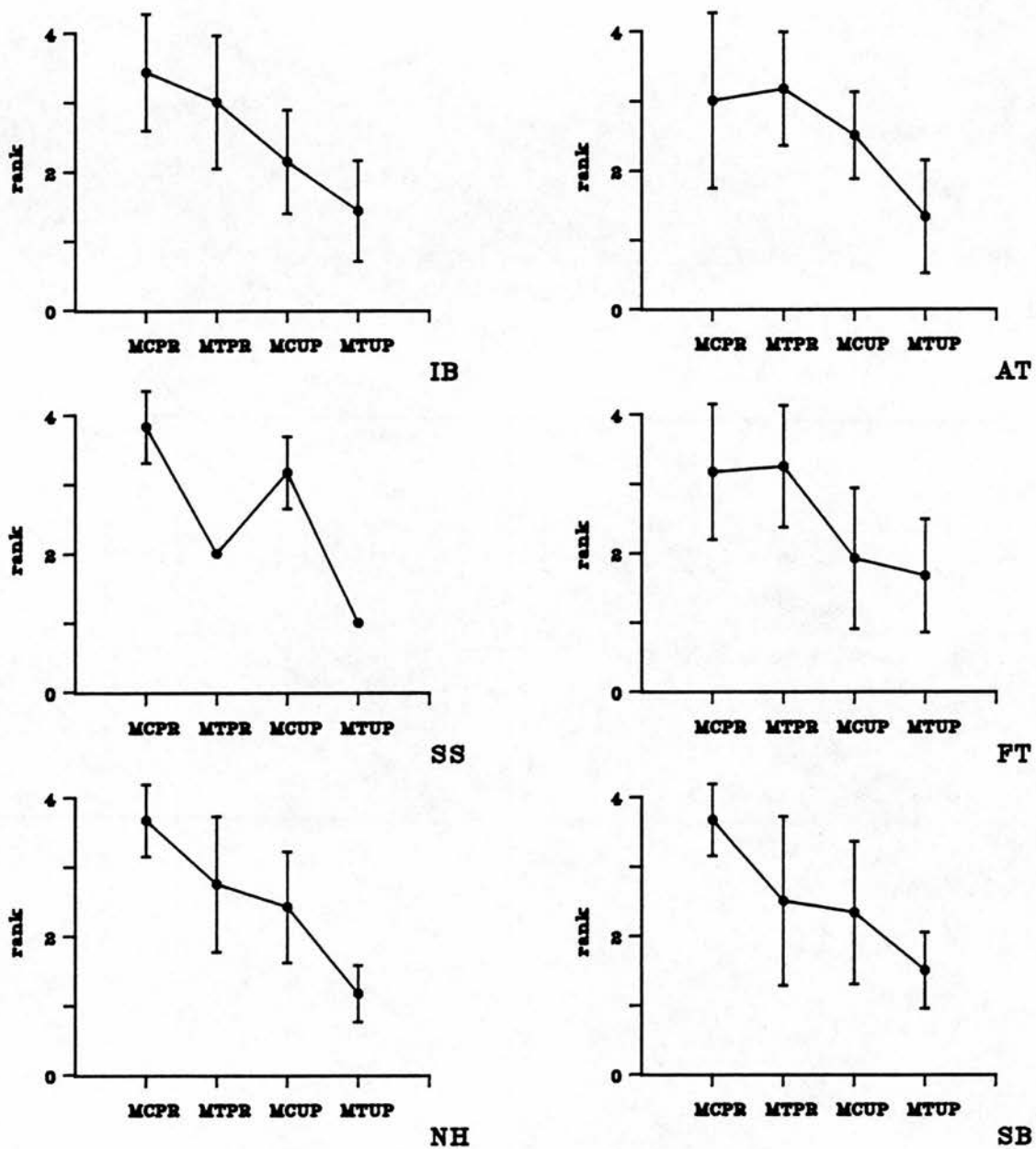


Figure 3.12 Mean ranks and sd of zero-lag cross-correlation between head/shoulder and target/shoulder angles for each individual condition.

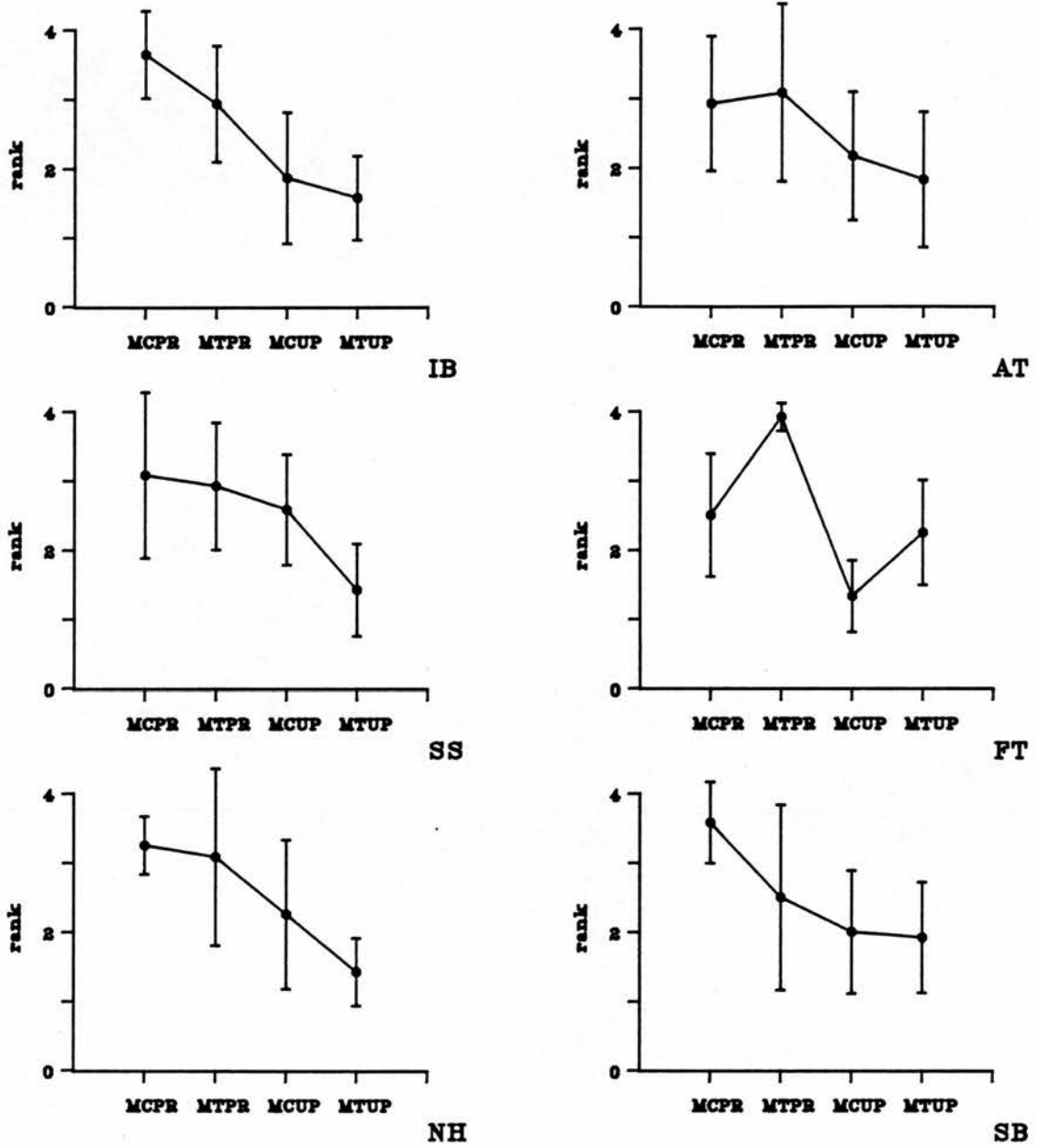


Figure 3.13 Mean ranks and sd of peak correlations between head/shoulder and target/shoulder angles for each individual condition.

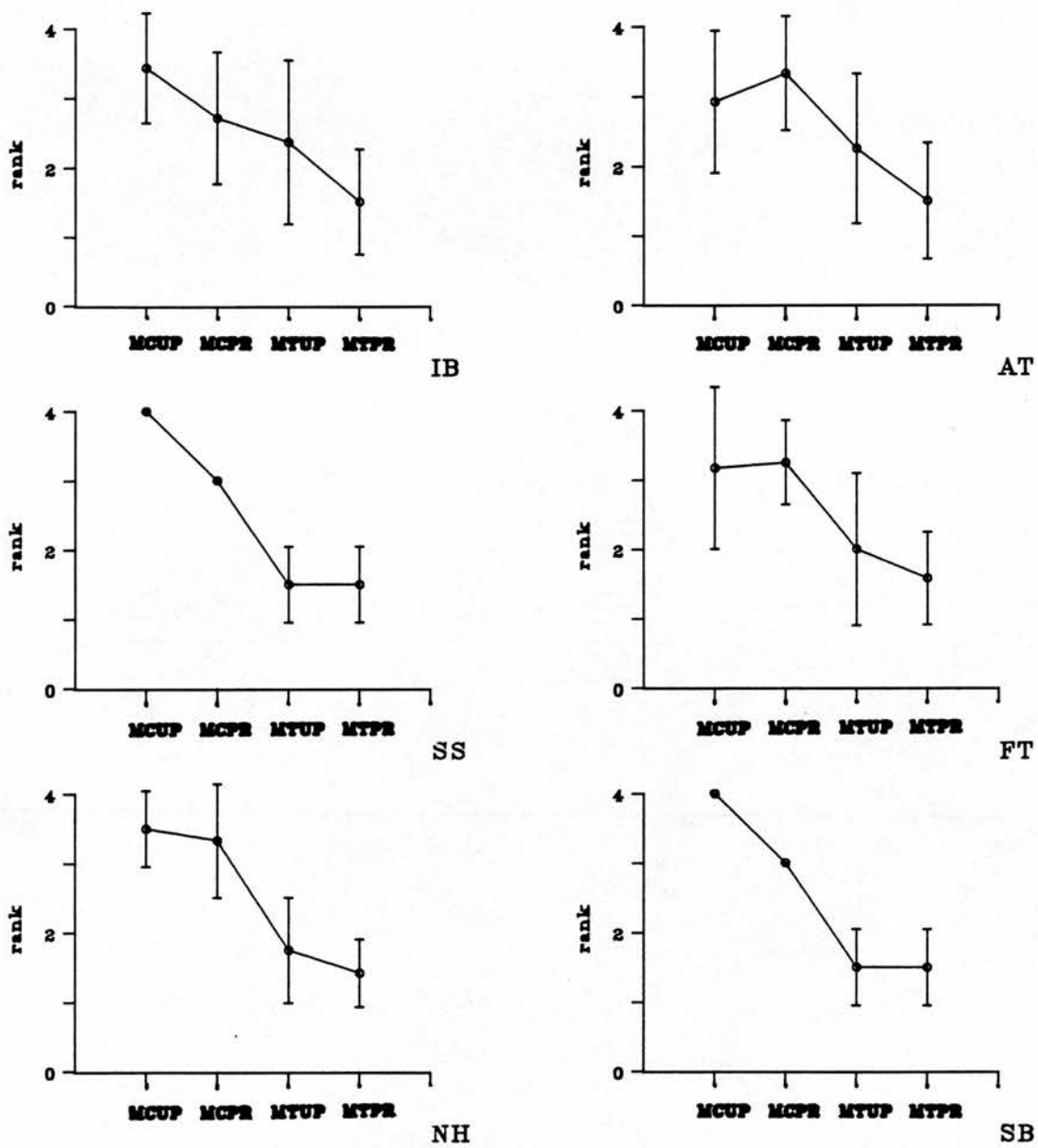
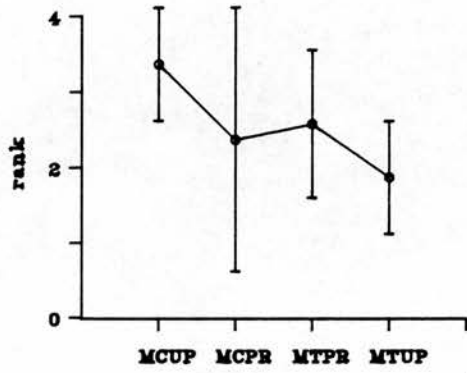
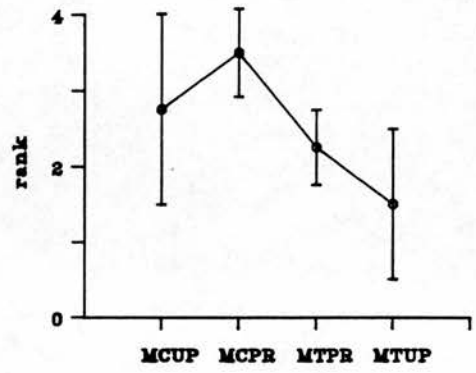


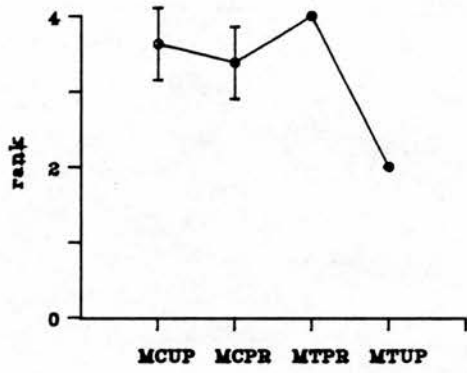
Figure 3.14 Mean ranks and sd for lags between head/shoulder and target/shoulder angles for each individual condition.



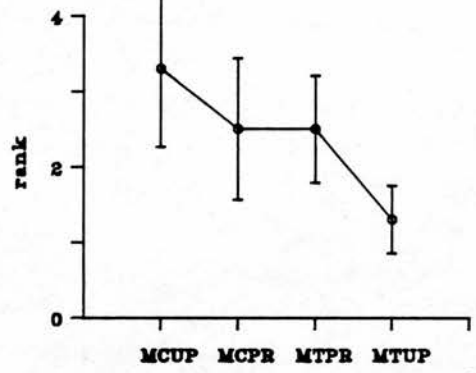
IB



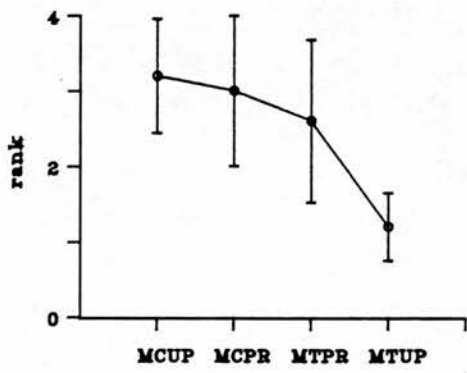
AT



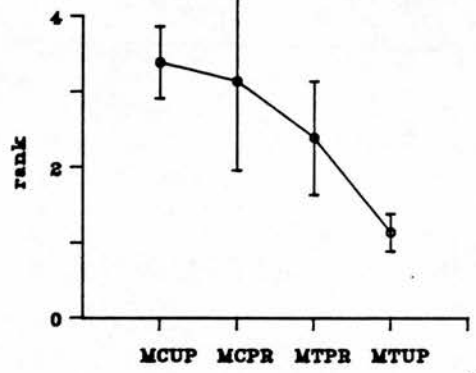
SS



FT



NH



SB

Figure 3.15 Mean ranks and sd for GVE for each individual condition.

Table 3.6 Mean ranks for each adult subject on each individual condition and mean and sd over subjects.

Head-target correlation

Sub	MTPR	MTUP	M CPR	MCUP
1	3	1	4	2
2	4	3	2	1
3	1	2.5	4	2.5
4	3	1	4	2
5	3.5	1.5	3.5	1.5
6	3	1.5	4	1.5
Mean Rank	2.92	1.75	3.58	1.75
Sd	1.02	.82	.80	.52

Head-target lag

Sub	MTPR	MTUP	M CPR	MCUP
1	1	2	4	3
2	4	3	1	2
3	4	3	2	1
4	3	1	4	2
5	4	1	2	3
6	2	1	4	3
Mean Rank	3.00	1.83	2.83	2.33
Sd	1.26	.98	1.33	.82

Head-target peak correlation

Sub	MTPR	MTUP	M CPR	MCUP
1	3.5	1.5	3.5	1.5
2	4	3	2	1
3	2	2	4	2
4	3	1	4	2
5	2.67	1	2.67	2.67
6	3.5	2	3.5	1
Mean Rank	3.11	1.75	3.28	1.70
Sd	.71	.76	.79	.65

GVE

Sub	MTPR	MTUP	M CPR	MCUP
1	2	3	1	4
2	3.5	1	2	3.5
3	1	2	3	4
4	4	2	3	1
5	1	4	2	3
6	4	1	3	2
Mean Rank	2.58	2.17	2.33	2.92
Sd	1.43	1.17	.82	1.20



3.5. Summary

In summary, adult and infant performance was most similar on cross-correlation measures. Both tended to show highest cross-correlations between target/shoulder and head/shoulder angles when the chair was moving in a predictable fashion, and lowest cross-correlations when the target was moving in an unpredictable fashion. The main difference between the two groups was found in the lags between target/shoulder and head/shoulder angles. The adults showed much individual variation in lag times and also much individual variation in the relative performance under each of the experimental conditions. Performance tended to be better when movement was predictable, but was equally successful whether the target or chair was moved. The infants, however, showed large variability in lag times, but very consistent relative lag times under the four different conditions. The lags between target/shoulder and head/shoulder angles were significantly lower when the chair, rather than the target, was moved, and there was a trend, albeit statistically insignificant, for superior performance when target or chair movement was unpredictable. Infant GVE was much higher than adult GVE under all conditions, but tended to be lower when the chair, rather than the target was moved.

CHAPTER 4
CHANGES OVER AGE

4.1. Zero-Lag Cross-Correlations

The zero-lag cross-correlations between head and target tended to rise over age (see fig 4.1 and table 4.1).

Table 4.1 Mean zero-lag cross-correlation between head/shoulder angle and target/shoulder angle for each infant at each session.

Session	1		2		3		4		5		6		7	
	s	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	mean sd	
NH		.82 .12	.83 .09	.94 .05	.91 .07	.90 .09	.94 .04							
SS		.82 .17	.88 .07	.84 .08	.92 .07	.88 .11	.94 .04							
IB		.75 .09	.72 .14	.83 .09	.92 .04	.86 .07	.90 .05	.91 .07						
AT		.77 .12	.78 .08	.93 .05	.90 .08	- -	.94 .04	.95 .03						
FT		.23 .46	.75 .15	.87 .09	.89 .08	.90 .06	.93 .03	.94 .03						
SB		.64 .35	.86 .08	.81 .11	.78 .13	.85 .11	.91 .06							

For each subject there was a significant increase between the first and last session (see table 4.2). All subjects showed an early increase in cross-correlation. The plateauing that occurs in all the graphs at the later ages may be due in part to a ceiling effect imposed by the upper limit of cross-correlation. Four of the infants (SB, IB, AT, NH) showed a significant jump followed by a significant drop. This occurred at 17,0 (wks,dys) in NH, 18,1 in IB, 16,4 in AT, and 13,6 in SB. FT began to plateau out at 16,3. SS showed two small peaks, one at 13,2 that was not statistically significant and a second significant jump at 21,4.

The standard deviation of cross-correlations for each session were low and did not show any obvious changes with age. By the end, the infant head/target cross-correlations compared favourably with adult figures. (See fig 3.1).

Table 4.2 Statistical Differences Between Sessions: zero-lag cross-correlations between head/shoulder and target/shoulder angles.

IB							AT						
1	2	3	4	5	6		1	2	3	4	5	6	
2	ns						2	ns					
3	**	**					3	**	**				
4	**	**	**				4	**	**	ns			
5	**	**	ns	ns			5						
6	**	**	**	ns	*		6	**	**	ns	*		
7	**	**	**	ns	**	ns	7	**	**	ns	*		ns

SS					PT						
1	2	3	4	5	1	2	3	4	5	6	
2	ns				2	**					
3	ns	ns			3	**	**				
4	**	**	**		4	**	**	ns			
5	ns	ns	*	ns	5	**	**	ns	ns		
6	**	**	**	ns	*	6	**	**	*	*	*
					7	**	**	**	**	**	ns

NH					SB						
1	2	3	4	5	1	2	3	4	5		
2	ns				2	ns					
3	**	**			3	ns	ns				
4	*	**	ns		4	ns	ns	ns			
5	**	**	ns	ns	5	ns	ns	ns	*		
6	**	**	ns	ns	ns	6	**	**	**	**	*

One - tailed tests : $p < .05 = *$, $p < .01 = **$, $p < .001 = ***$
 - : indicates that differences would be significant in the opposite direction to that predicted on a two - tailed test.

Changes over Age : Zero-Lag Cross-Correlations

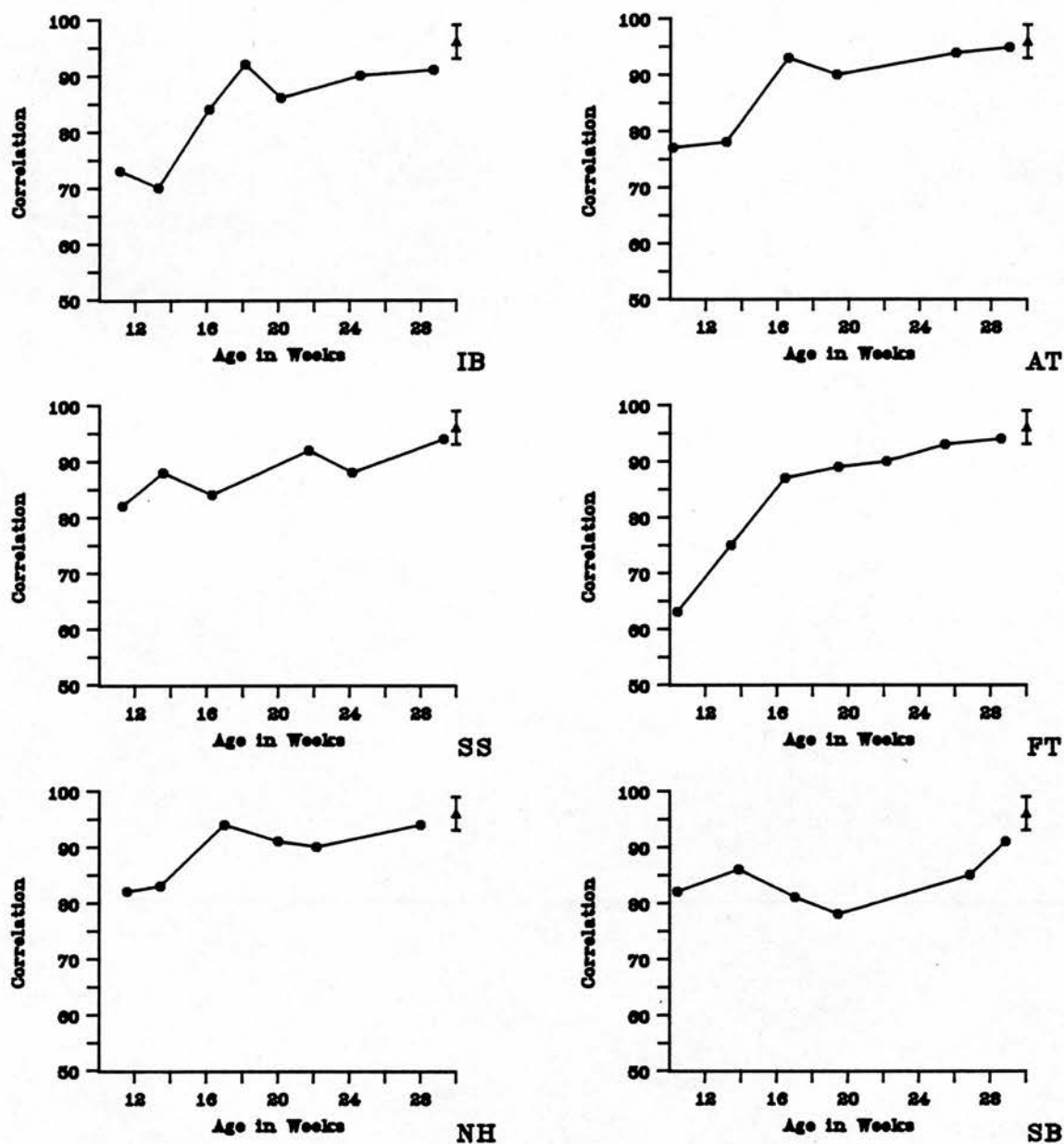


Figure 4.1 Graphs showing the changes over age in zero-lag cross correlation between head/shoulder angle and target/shoulder angle for each infant.

▲ - Adult mean and sd on same measure.

4.2. Peak Cross-Correlations

From fig 4.2 and table 4.3 it is apparent that, as expected, the peak cross-correlations were higher than the zero-lag cross-correlations.

Table 4.3 Mean peak cross-correlation between head/shoulder angle and target/shoulder angle for each infant at each session.

Session	1		2		3		4		5		6		7	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	.89	.07	.92	.05	.95	.04	.95	.05	.94	.07	.97	.02		
SS	.93	.05	.93	.05	.93	.04	.92	.03	.94	.02	.96	.09		
IB	.82	.08	.85	.11	.94	.05	.96	.04	.93	.05	.94	.05	.95	.04
AT	.87	.07	.87	.08	.96	.04	.93	.07	-	-	.95	.04	.96	.03
FT	.84	.10	.90	.07	.94	.06	.96	.04	.95	.05	.97	.02	.97	.02
SB	.86	.11	.91	.07	.89	.07	.86	.13	.89	.10	.94	.04		

Although the curves are flatter, the mean peak cross-correlation at the last session was always significantly higher than that at the first session, indicating that there was improvement over age (see table 4.4). Most of the increases occurred at the early ages. NH showed significant improvements up to 17,0, AT up to 16,4, SS up to 21,4, and FT up to 16,3 and these points are equivalent to the ages of significant rises in zero-lag cross-correlation (see table 4.2). The peak cross-correlations of IB, however, began to level off at 16,1, one session before the significant rise in his zero-lag cross-correlations, while SB showed a significant difference only between session 6 and sessions 1, 3 and 4. Again the most mature peak cross-correlations and standard deviations compared favourably with those of the adults (table 3.1).

Table 4.4 Statistical Differences Between Sessions: peak cross-correlations between head/shoulder and target/shoulder angles.

IB							AT					
	1	2	3	4	5	6	1	2	3	4	5	6
1												
2	ns						ns					
3	**	**					**	**				
4	**	**	ns				**	**	ns			
5	**	**	ns	ns								
6	**	**	ns	ns	ns		**	**	ns	ns		
7	**	**	ns	ns	ns	ns	**	**	ns	ns		ns

SS					FT						
	1	2	3	4	5	1	2	3	4	5	6
1											
2	ns					ns					
3	ns	ns				**	*				
4	**	**	**			**	**	ns			
5	*	*	**	ns		**	**	ns	ns		
6	**	**	**	ns	ns	**	**	*	ns	ns	
						**	**	ns	ns	ns	ns

NH					SB					
	1	2	3	4	5	1	2	3	4	5
1										
2	*					ns				
3	**	**				ns	ns			
4	**	*	ns			ns	ns	ns		
5	**	**	ns	ns		ns	ns	ns	ns	
6	**	**	ns	ns	ns	**	ns	*	**	ns

One - tailed tests : $p < .05 = *$, $p < .01 = **$, $p < .001 = ***$
 - : indicates that differences would be significant in the opposite direction to that predicted on a two - tailed test.

Changes over Age : Peak Cross-Correlations

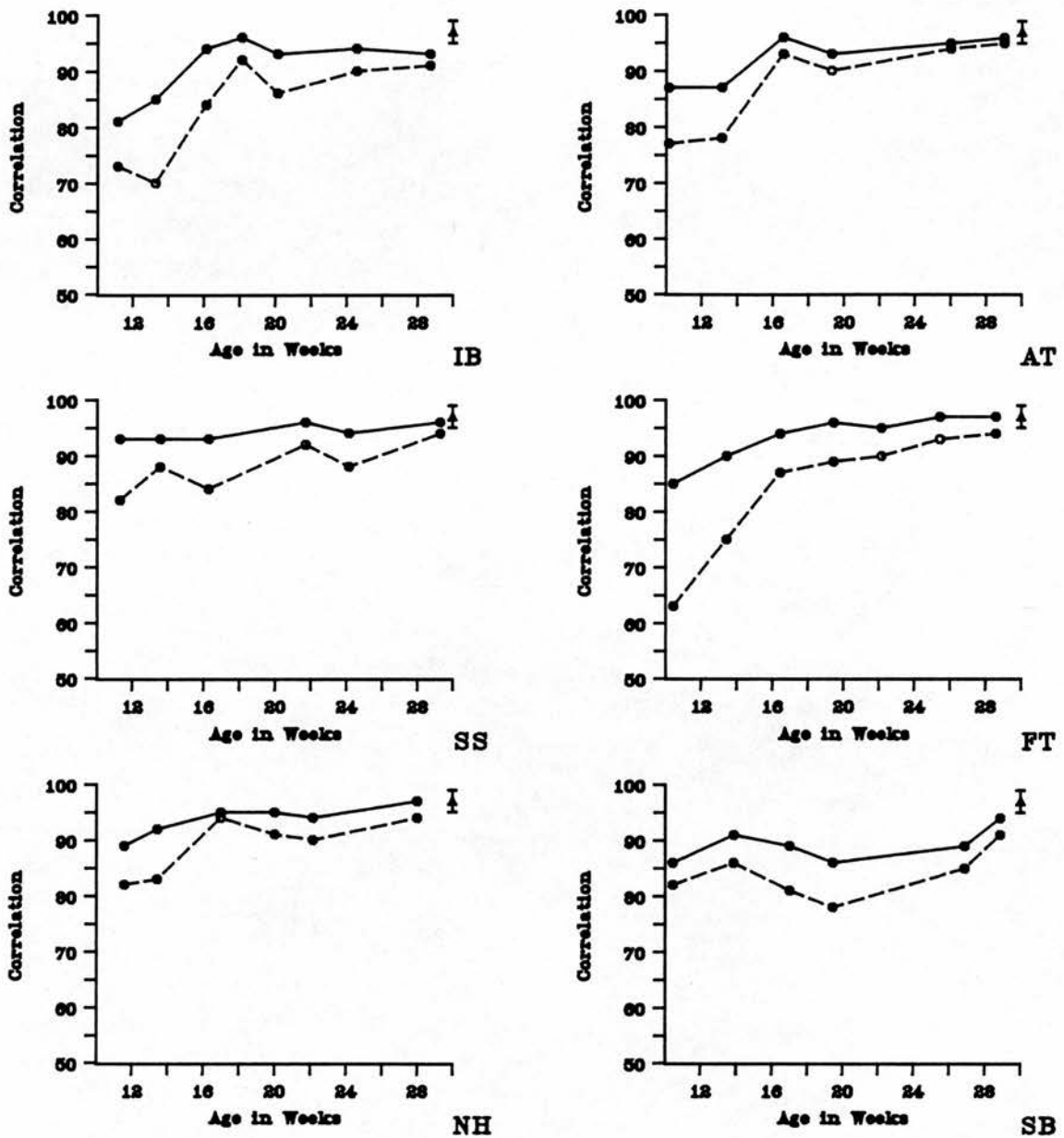


Figure 4.2 Graphs showing the changes over age in peak — and zero-lag ---- cross-correlation between head/shoulder angle and target/shoulder angle for each infant.

▲ - Adult mean and sd for peak correlation.

4.3. Lags Yielding Peak Cross-Correlations

In all cases with increasing age there was a significant decrease in the amount that the head/shoulder angle lagged the target/shoulder angle (fig 4.3, table 4.5).

Table 4.5 Mean lag (ms) between zero-lag and peak cross-correlation for each infant at each session.

Session	1		2		3		4		5		6		7	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	350	230	360	130	70	70	190	120	210	80	100	80		
SS	280	180	270	160	280	160	160	160	230	130	120	170		
IB	240	180	400	160	330	70	180	100	280	120	120	100	170	130
AT	410	230	290	130	120	90	140	70	-	-	40	60	30	40
FT	630	170	430	130	260	110	240	120	230	100	160	70	110	70
SB	280	200	280	120	270	170	290	210	170	60	150	100		

The last session lags were significantly lower than those in the first (table 4.6). The boys all showed significant surges in performance at the same stage as they did in the zero-lag cross-correlations (NH, 17 wks; SS, 21,4 wks; IB, 18,1); the performance of AT and FT began to plateau at the same stage (FT, 16,3; AT 16,4). For AT this matches the age of the jump in zero-lag cross-correlation and for FT the age when zero-lag cross-correlation began to level off. SB only began to show significant drops in lag at 26,6 weeks. Although the lags by the end of testing compared favourably with those of the adults (see table 3.1), the standard deviations remained higher and did not tend to become smaller over this age range, supporting the conclusion that the change in lag time was not due to a reduction in variability.

Table 4.6 Statistical Differences Between Sessions: lags yielding peak cross-correlation between head/shoulder and target/shoulder angles.

IB							AT					
1	2	3	4	5	6		1	2	3	4	5	6
2	ns						ns					
3	**	**					**	***				
4	*	**	**				**	***	ns			
5	**	**	ns	ns								
6	**	**	ns	ns	*		**	***	***	***		
7	*	**	*	ns	***	ns	**	***	***	***		ns

SS					PT						
1	2	3	4	5	1	2	3	4	5	6	
2	ns				**						
3	ns	ns			**	***					
4	*	**	***		**	***	ns				
5	ns	ns	*	ns	**	***	*	ns			
6	*	***	***	*	**	**	***	**	**	**	
					**	***	***	***	***	**	

NH					SB					
1	2	3	4	5	1	2	3	4	5	
2	ns				ns					
3	***	***			ns	ns				
4	ns	ns	ns		ns	ns	ns			
5	**	***	ns	ns	ns	**	**	**		
6	***	***	ns	ns	ns	ns	***	**	**	ns

One - tailed tests : $p < .05 = *$, $p < .01 = **$, $p < .001 = ***$
 - : indicates that differences would be significant in the opposite direction to that predicted on a two - tailed test.

Changes over Age : Lags

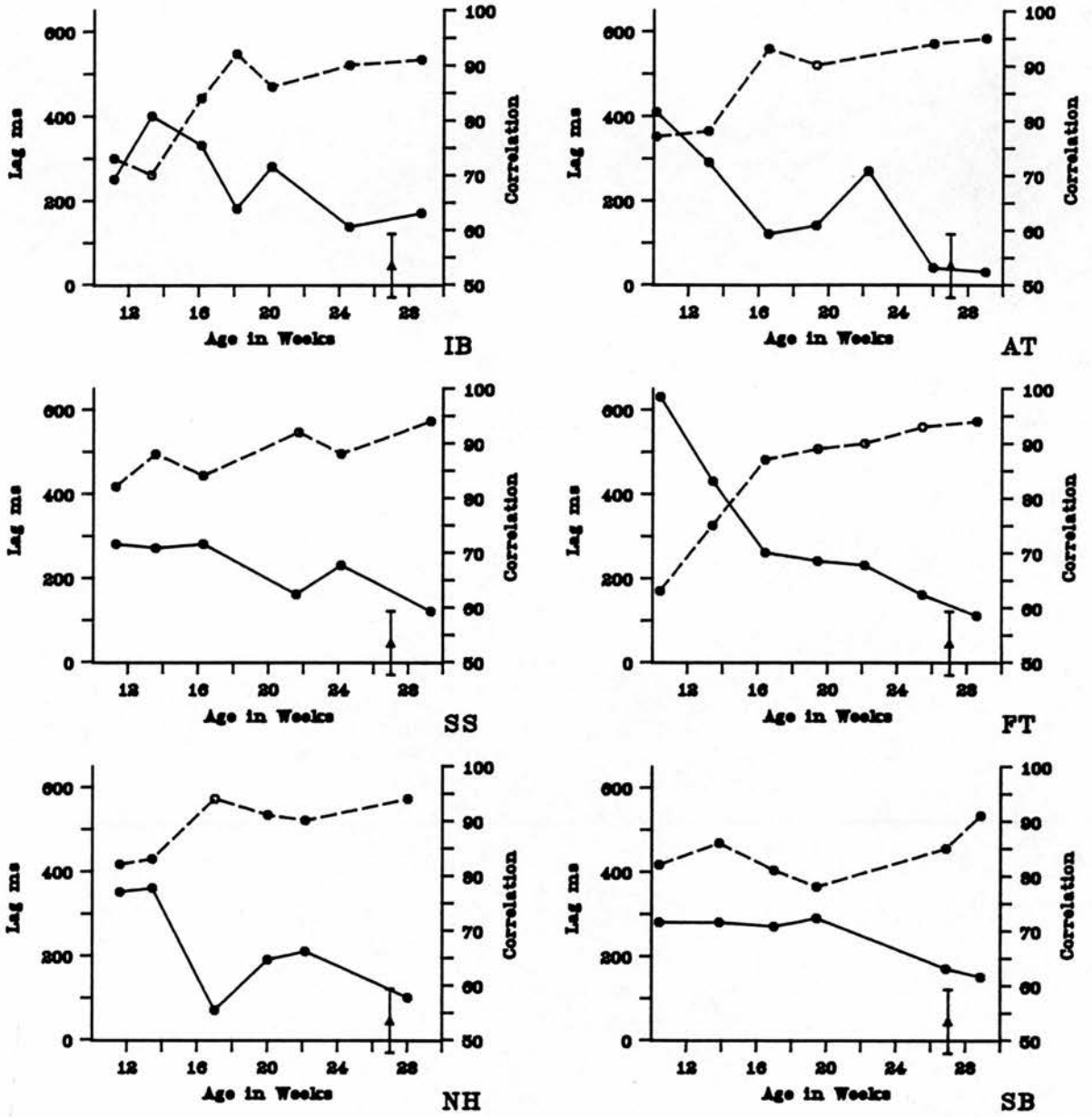


Figure 4.3 Graphs showing the changes over age in lag— and zero-lag cross-correlation--- between head/shoulder angle and target/shoulder angle for each infant. ▲ - Adult mean and sd for lag.

4.4. Proportion of Head to Target Movement

All the infants used their heads a lot more than the adults (fig 4.4, table 4.7) to maintain gaze on the target.

Table 4.7 Mean proportion of head/target movement, (sd head/sd tar), for each infant at each session.

Session	1		2		3		4		5		6		7	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	.69	.19	.68	.17	1.21	.13	.86	.22	.95	.19	1.18	.12		
SS	.80	.16	.89	.09	.91	.14	1.04	.12	1.08	.25	1.15	.22		
IB	.47	.10	.39	.19	.66	.14	.88	.12	.59	.11	.68	.13	.77	.20
AT	.62	.24	.74	.18	1.14	.22	.97	.15	-	-	1.03	.13	.96	.15
FT	.42	.17	.73	.09	.86	.16	1.02	.14	1.02	.14	.96	.10	.89	.11
SB	.48	.12	.70	.15	.60	.16	.63	.19	.64	.16	.96	.15		

The mean proportion of head movement to target movement was always high, and on several occasions went above 1. Unlike the lag data though, the standard deviations compared very favourably with those from the adults. Even though head use was high in the first session all the infants showed significantly higher use by the last session (table 4.8). The pattern of change over age was very similar to that shown by the cross-correlation analysis. Three of the subjects showed significant jumps at the same point as in the zero-lag cross-correlations and lags: NH at 17,0, AT at 16,4, IB at 18,1. SS began to plateau out at 21,4 which matches the surge in performance above. FT showed significant increases until 19,3 - one session later than the beginning of the plateau seen above (fig 4.3) - then a significant drop back in amount of head use, although in the final session the proportion was higher than in the first. For SB head use rose at first but then plateaued out between the second and fourth sessions before making a sudden upward jump at 28,6. Examples of a proportion of head use greater than unity, and occurring at the same time as the sudden drop in lag times, are shown in fig 4.5.

Table 4.8. Statistical Differences Between Sessions: proportion of head to target movement.

IB							AT					
1	2	3	4	5	6		1	2	3	4	5	6
2	ns						*					
3	**	**					**	***				
4	*	**	**				**	***	ns			
5	**	**	ns	ns			**	**	ns	*		
6	**	**	ns	ns	*		**	***	ns	ns	ns	
7	*	**	*	ns	***	*	**	***	ns	ns	ns	ns

SS					PT					
1	2	3	4	5	1	2	3	4	5	6
2	**				***					
3	*	ns			**	**				
4	**	**	***		**	**	**			
5	**	ns	**	ns	**	**	**	ns		
6	**	***	***	*	*	***	***	**	ns	ns
					**	**	ns	ns	ns	*

NH					SB					
1	2	3	4	5	1	2	3	4	5	
2	ns				**					
3	***	***			***	ns				
4	*	*	ns		**	ns	ns			
5	***	***	ns	*	**	ns	ns	**		
6	***	***	ns	***	**	**	***	**	***	***

Tables showing significance of differences between sessions.

One - tailed tests : $p < .05 = *$, $p < .01 = **$, $p < .001 = ***$

- : indicates that differences would be significant in the opposite direction to that predicted on a two - tailed test.

Changes over Age : Proportion of Head/Target Movement

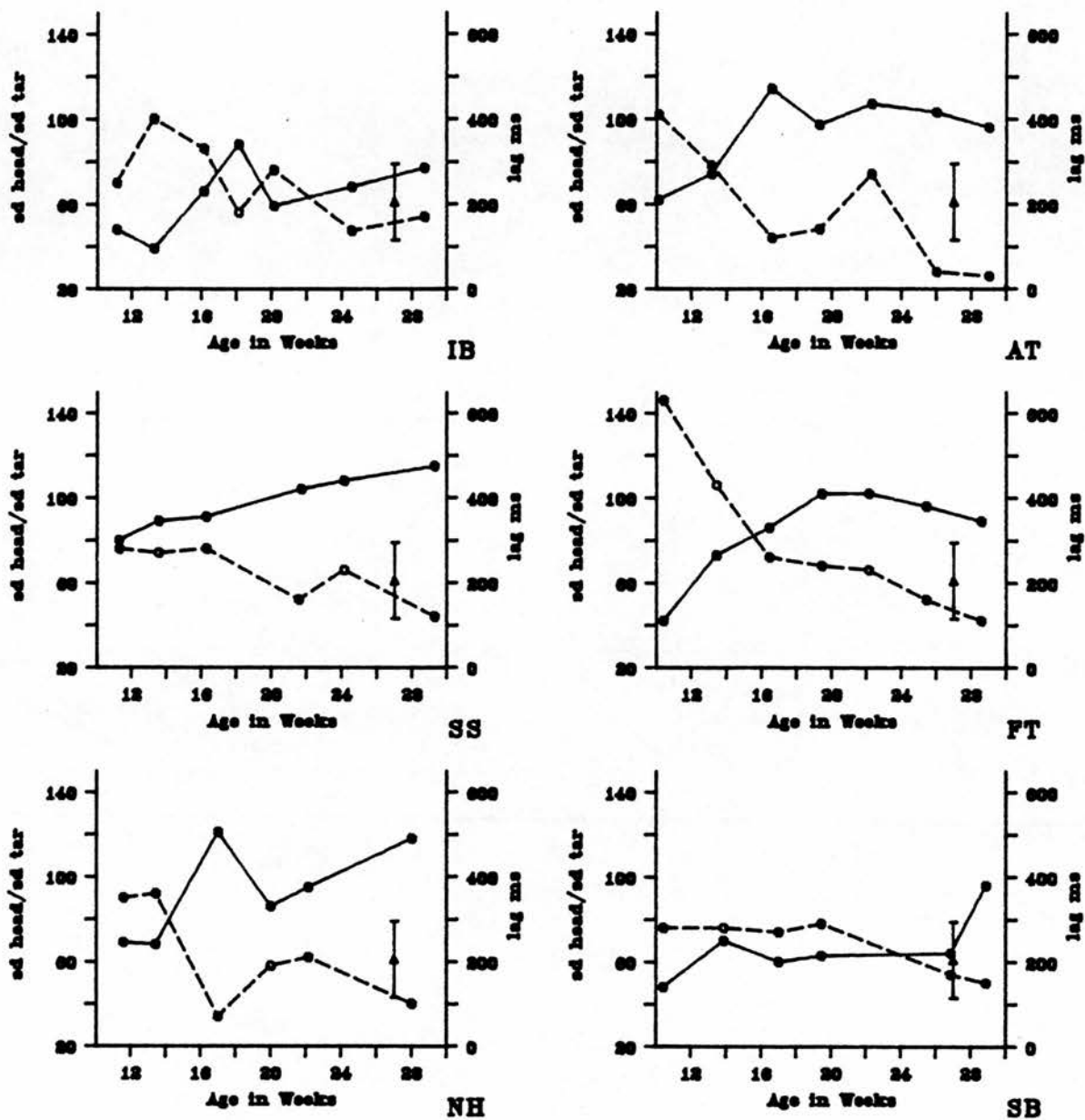


Figure 4.4 Graphs showing the changes over age in sd tar/sd head movement — and lag --- between head/shoulder angle and target/shoulder angle for each infant.

▲ - Adult mean and sd on sd head/sd tar movement.

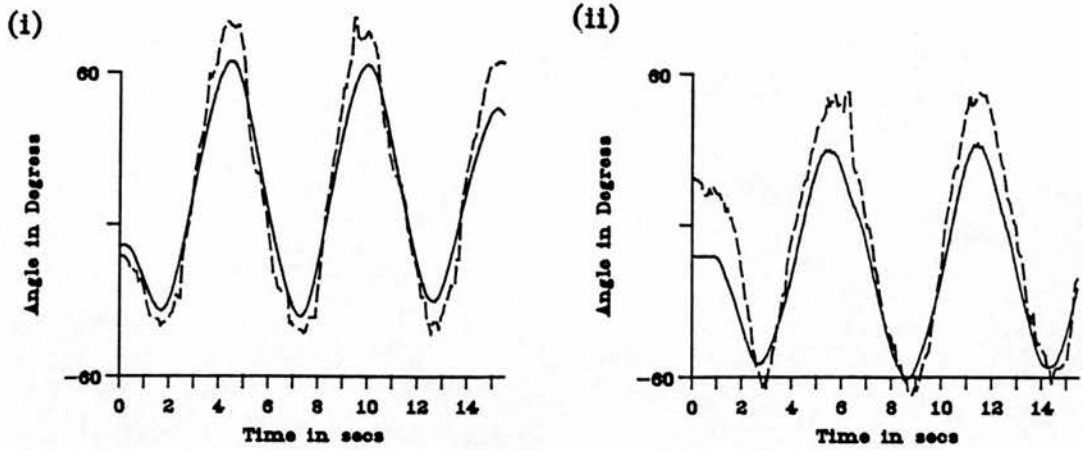


Figure 4.5. Showing examples of trials where $sd\ head/sd\ target$ was above unity. (i) MC condition, NH: session 3, age 17.0; (ii) MT condition, AT: 3, age 16.4. - - - - - Head ——— Target

4.5. Accuracy of Gaze - gaze velocity error (GVE.)

From fig 4.6 and table 4.9 it is apparent that, at least within the above limitations, the mean and standard deviations of the GVE remained reasonably constant over the tested age period but were always higher than the adult figures shown above.

Table 4.9 Mean GVE (degs.s⁻¹) for each infant at each session.

Session	1		2		3		4		5		6		7	
	s	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	10	4	-	-	14	6	14	7	9	3	14	5		
SS	14	8	14	5	-	-	-	-	15	7	12	5		
IB	14	8	10	3	7	3	10	4	11	6	13	6	10	4
AT	15	4	13	8	-	-	11	5	-	-	-	-	12	5
FT	20	9	14	10	-	-	14	5	14	5	18	3	11	4
SB	15	7	12	5	12	4	-	-	-	-	17	6		

The lack of improvement in GVE over age may have been due to exploration of the target. Although the head and eyes were tracking the target, it is reasonable to suppose that there was also some scanning of the target itself, particularly as it was spinning on its own axis. An increase in the amount of

target scanning over age would have contributed to the overall gaze velocity error and therefore masked any improvements in gearing onto the target. One way to examine this hypothesis is to look at the amount of target scanning at different ages when no tracking was occurring. For several of the sessions three five-second static target trials were recorded. The GVE for these trials was computed using the calibration figure obtained from the dynamic trials. Fig 4.7 shows the mean GVE for static trials plotted over age along with the GVE for the MC and MT conditions (see chapter 3). Table 4.10 shows the mean scores for static trials.

Except for one occasion (NH, 5), the GVE in the static condition (mean GVE 8 deg.s⁻¹, sd 24) was lower than or equal to that in the dynamic conditions (mean GVE 13 deg.s⁻¹, sd 3). There is, however, no clear evidence of a rise in the static GVE over age.

Table 4.10 Mean GVE (deg.s⁻¹) on static trials.

Session	1		2		3		4		5		6		7	
	s	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean
NH	7	0	-	-	12	6	-	-	17	6	8	1		
SS	-	-	-	-	9	1	7	1	6	1	10	5		
IB	-	-	-	-	2	2	7	5	5	3	10	3	8	5
AT	6	4	1	0	-	-	-	-	17	6	8	1	-	-
FT	6	3	10	9	8	2	-	-	9	3	11	7	-	-
SB	-	-	6	3	-	-	6	1	-	-	9	5		

Changes over Age : Gaze Velocity Error

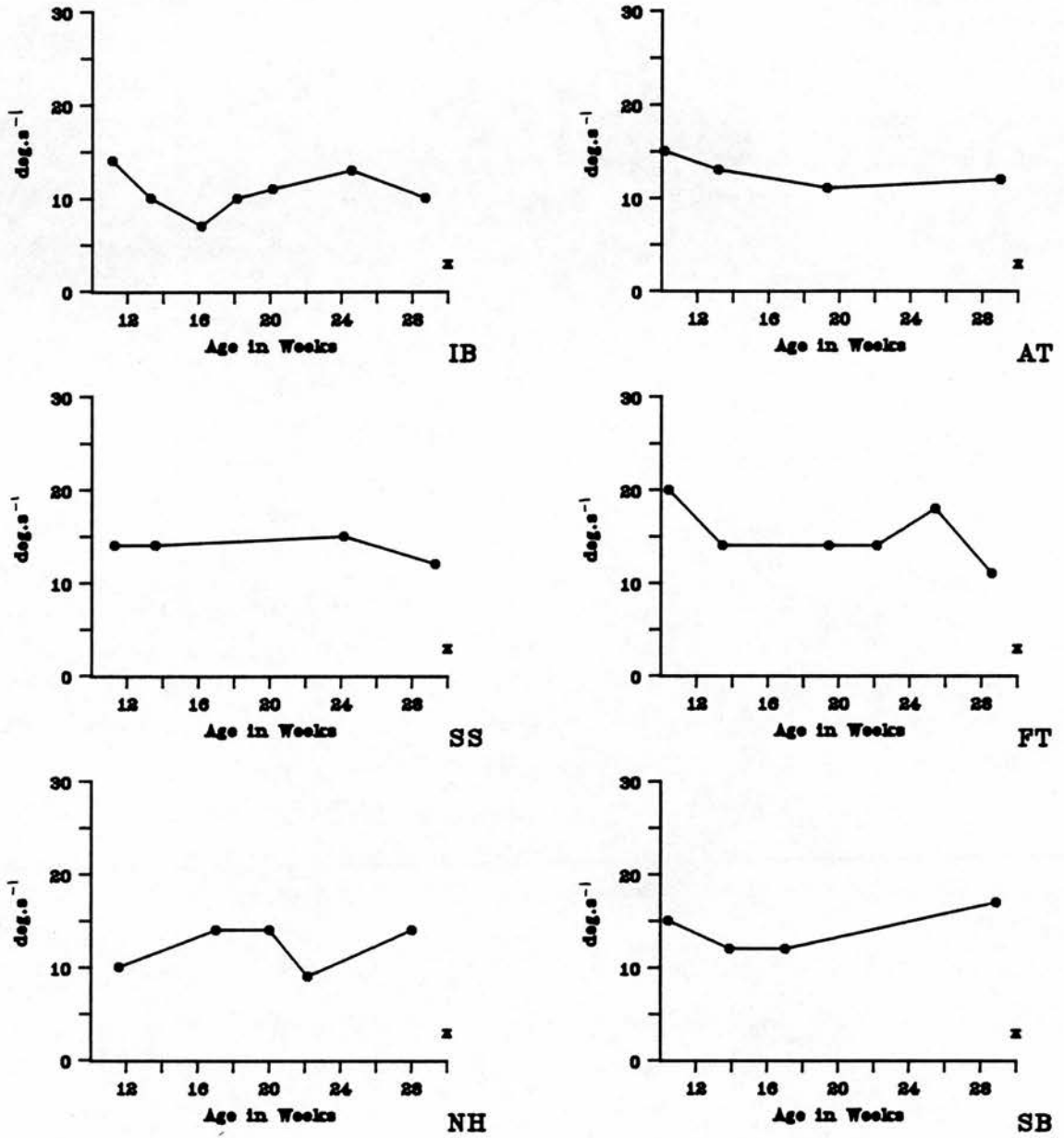


Figure 4.6 Graphs showing the changes over age in GVE for each infant.

▲ - Adult mean and sd on same measure.

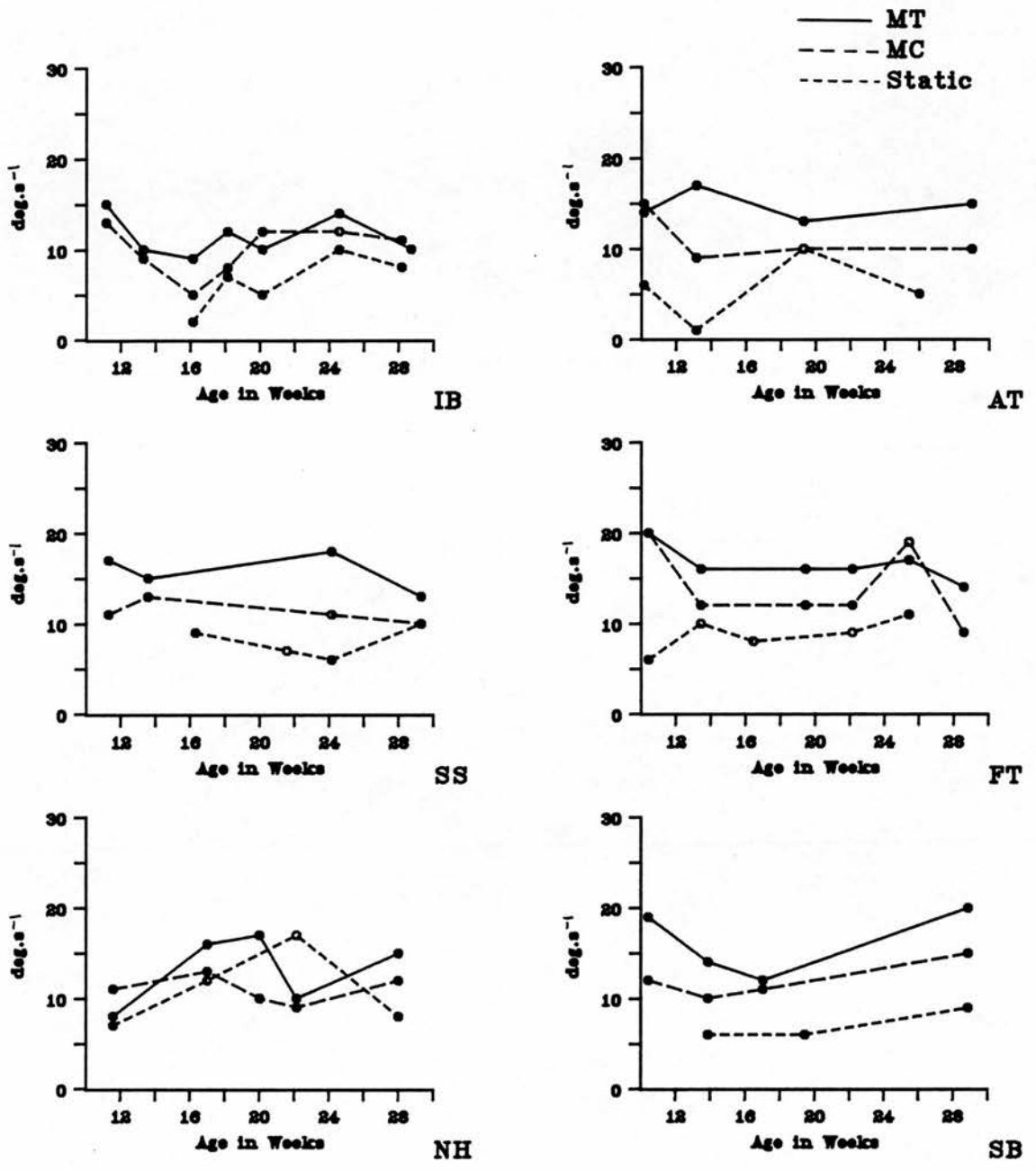


Figure 4.7 Graphs showing the changes over age in GVE when target (MT) or chair (MC) was moving and when both were static.

4.6. Summary

The above results reveal a consistent picture. With the exception of the GVE, each infant's performance significantly improved over age on all the measures. Five of the infants showed a surge in performance during the period of longitudinal study: FT and AT tended to show a marked surge in performance followed by more steady improvement, while the three boys (SS, NH, IB) showed a peak at a slightly later stage, followed by a temporary decline in performance. Figs 4.2, 4.3 and 4.4 showed the similarity amongst the changes over age in the lag times, proportion of head/target movement and peak and zero-lag cross-correlations. The GVEs on the other hand stayed fairly constant. Figs 4.8 and 4.9 illustrate these changes. They show the performance of one of the infants (FT) on all conditions at 10,3 wks and 28,4 wks respectively. Note the increase in the amount of head use and the improvement in linking onto and matching target movement.

The measure of gaze accuracy is only an estimate, but it is striking that all infants appeared to keep within a similar range of accuracy throughout the tested period, although improvements may have been occurring which were not picked up by this measure. There was no evidence for any interaction between the effects of the two variables (PR/UP, MT/MC) over age. In all testing sessions lag times were lower and GVEs higher in the MC condition while cross-correlations were higher in PR conditions. The proportion of head to target movement increased over age, as did all measures except GVE, but was not affected by the different conditions.

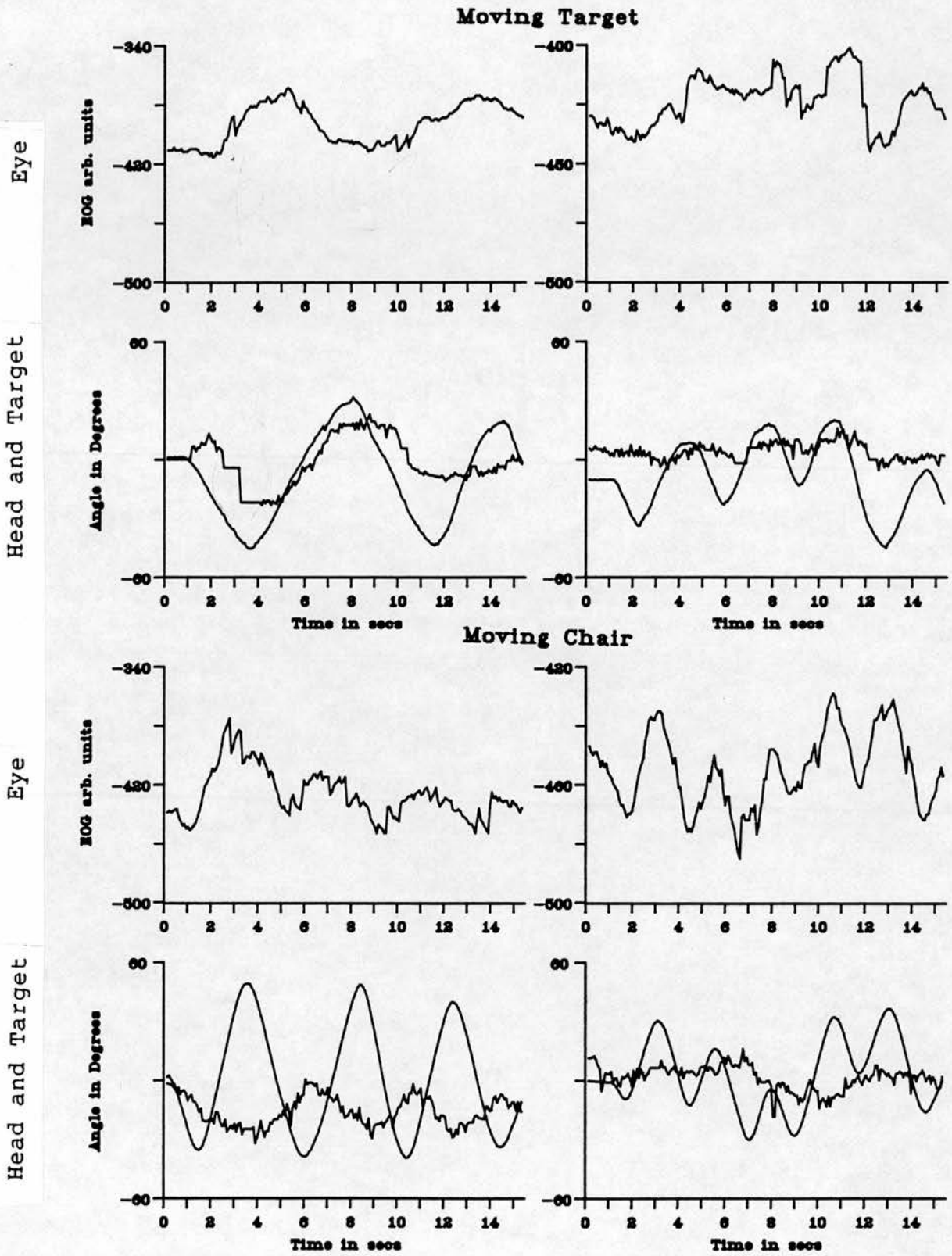
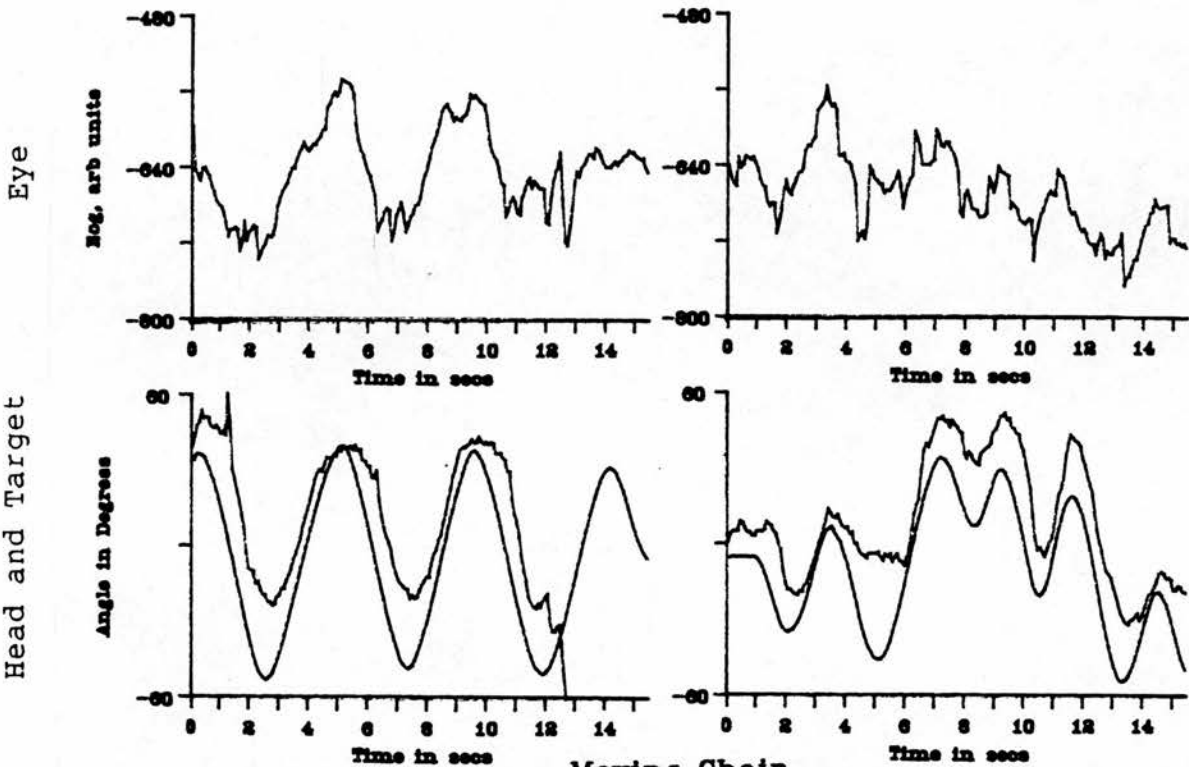


Figure 4.8 Graphs showing the performance of one infant (FT) at the first session (age 10,3 wks).

Predictable Movement (PR)

Unpredictable Movement (UP)

Moving Target



Moving Chair

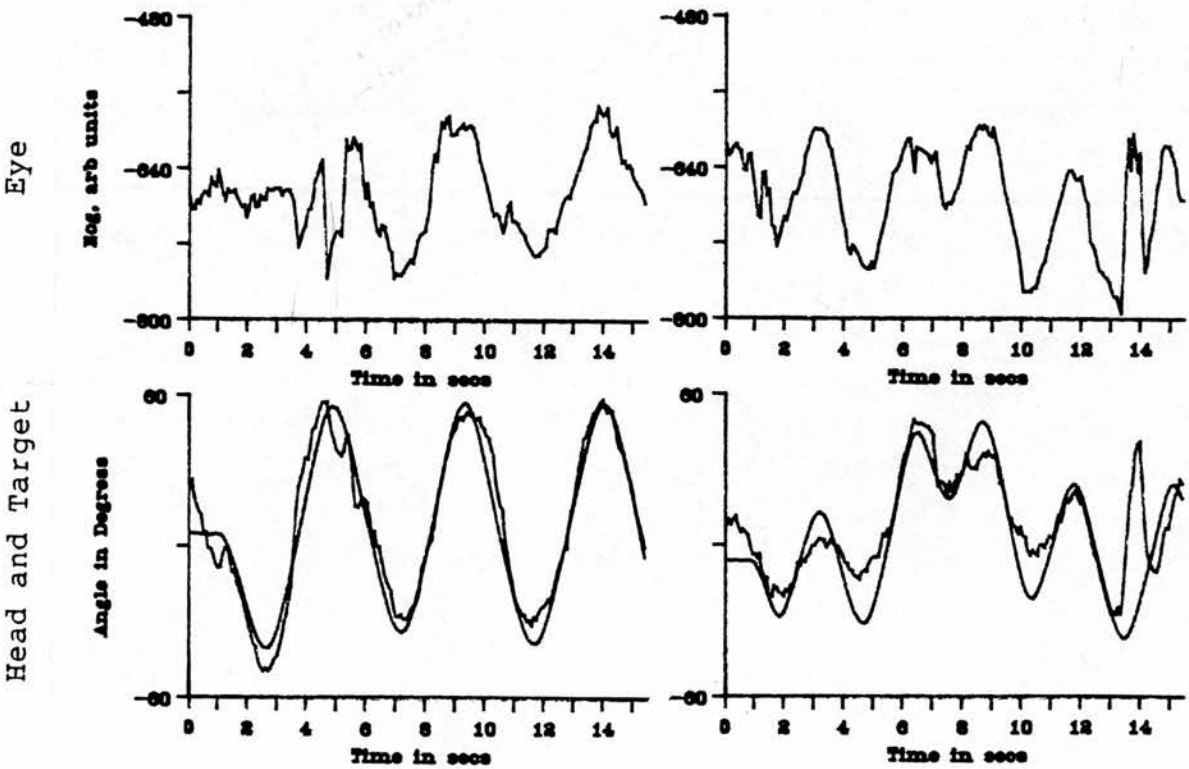


Figure 4.9 Graphs showing performance of one infant (FT) on the last session (age 28,4 wks).

5.1. Introduction

Cerebral palsy is characterized by motor dysfunction and results from non-progressive brain damage, occurring in the prenatal, perinatal or postnatal periods. There is a wide range of disability in children with cerebral palsy, but all show retardation in motor development, with weakness in either or all of the muscles of the head, trunk, shoulder or pelvic girdle (Levitt, 1982). An important feature is that the lesion affects the immature brain and therefore interferes with normal maturation of the central nervous system (Bobath, 1980).

Cerebral palsy is notoriously difficult to diagnose in very early infancy (Ellenberg et al, 1981); children are often described as growing into their handicap as the damaged cortex develops and fails to exert normal control (Brown, 1983). One study that attempted to look at early correlates of later diagnosed cerebral palsy found that along with failure to meet developmental milestones, one of the best predictors was hypertonus of neck, arm, leg or trunk extensors at four months. Another feature was a tendency to fail in a visual following task and tremulous or jittery patterns of movement at this age (Ellenberg et al, 1981).

The ability to stabilize gaze is a basic and early developing skill. The previous sections have shown that even at around eleven weeks of age infants have good control of the head in a functional visual task. Any early deficiencies of the head and eye coordination system will have wide-ranging effects. Disorders of oculomotor function are common in cases of brain damage (Zee, 1977), are frequently observed in children with cerebral palsy and minimal brain damage (Katayama and Tamas, 1987) and have been associated with impairment of learning ability (O'Malley and Griffith, 1977). Since eye/head coordination is so fundamental to effective visually-guided action and clearly vulnerable to damage, the early detection of abnormalities could be an important element in diagnosis and assessment of brain damage.

An exploratory single case study was carried out on an infant with a

suspected right-sided hemiplegia in order to assess the level of visuo-motor function. Performance on a simplified set of tests based on the paradigm used above was recorded.

C.G. was admitted to hospital at one month of age suffering from severe pneumococcal meningitis. He was described as showing right-sided fits and facial palsy with neck stiffness. He remained in hospital for nearly two months during which time he continued to have episodes of right-sided twitching; muscle tone was lower in the right leg and grasping and stretch reflexes were poor. The doll's eye response was described as sluggish, but he did show an optokinetic response. Head ultrasound taken during the hospital stay showed dilation of the IIIrd and IVth ventricles increasing over the first few days, indicating a significant communicating hydrocephalus. On discharge he was neglecting the right side of the body with reduced right-side activity.

At four and a half months the physiotherapy report describes a clear asymmetry both in gross motor function and in visual behaviour. The head was side-flexed and rotated to the left, and weight bearing was superior on the left side. There was no reaching, head lifting or rolling. Fine motor control was impaired with both thumbs flexed and adducted across the palms and fingers clenched on the right side. Visual following was asymmetrical indicating a right-sided neglect: tracking proceeded from the left but usually ceased at the midline.

5.2. Testing schedule

C.G. was brought into the lab on eleven occasions between the ages of three and nine months. During the first few sessions it was not possible to carry out formal tests since he was very passive and showed considerable lack of attention.

1. Sessions 1 and 2 - 13,2 & 14,2 wks: Head posture was very poor and the head was held to the left with the eyes also deviated to the left in the sockets. The eyes were observed to turn only very occasionally to the right. Little interest was shown in small bright objects, but there were some pre-reaching movements.
2. Sessions 3 and 4 - 15,2 & 17,2 wks: By this stage head

posture was improved although there was still very poor visual tracking and very poor reaching. When the whole body was manually rotated, with the head held fixed with respect to the shoulders, there was good counter-rotation of the eyes, but when rotation stopped the eyes would always return to the left side of the sockets which was still the preferred position. An optokinetic response could be elicited in a clockwise direction as far as the midline and then the eyes would flick back to the left. There was no OKN in response to an anticlockwise moving field, possibly because the eyes appeared to be to some extent 'fixed' pointing to the left in the sockets. After clockwise rotation of the body there was some post-rotatory nystagmus, but not after anticlockwise rotation, although eye movements occurred during rotation.

5.2.1. Preliminary summary

The indications were that there was a clear right-sided neglect associated with reduced right side function. Both visual pursuit and OKN responses stopped at the midline, and the impaired response to rotation suggested some vestibular damage.

5.3. Head and Eye Coordination

On subsequent sessions a number of head and eye recordings were made. The apparatus and procedure were similar to that described in chapter 2, but with some modifications to suit this particular child. As this subject was tested over a longer period than the normal infants and was therefore larger, he did not sit on his mother's lap, but was strapped safely into a padded Britax car seat mounted on the turntable. The target movements were regular as in the PR conditions, but not as smooth as for the normal infants as it was found to be easier to elicit attention on the target if it was hand held. Trials were shorter (9 secs) and fewer successful trials were obtained.

On some trials a large piece of patterned paper was hung from the top support so that it surrounded the chair. This was oscillated around the subject in order to look at visual stabilization of the eyes on a moving field (OKN). In addition, on some trials the chair was turned back and forth in complete darkness in order to record vestibularly-driven eye movements (VOR).

Sections of the record in which C.G. appeared to be fully engaged in the task were picked out (see chapter 2). As the head was used so very little this was not always possible.

5.3.1. Results

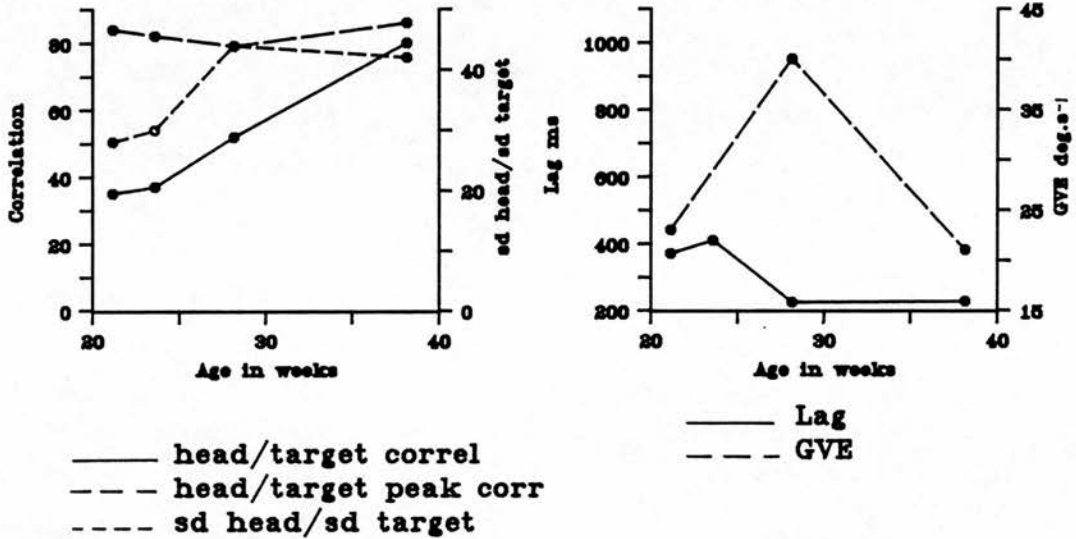


Figure 5.1 Mean results at each age for peak and zero-lag cross-correlation and lag between head/shoulder and target/shoulder angle, sd head/sd target and GVE for C.G.

Table 5.1 shows the results for each trial and overall means and sds from each session. Overall mean results for each session are plotted over age in fig. 5.1. Several differences between C.G. and the normal infants described above are very clear:

1. Head-target cross-correlations were much lower than those of normal infants of the same age, especially at 21,1 and 23,4. By this stage the normal infants were producing cross-correlations of .88 (mean zero-lag cross-correlation at sessions 4 and 5, see chapter 4).
2. Head-target lag times tended to be much higher from C.G.

3. The proportion of head to target use was very low in the first session and never reached the level shown by the normal infants (see chapter 4).

Table 5.1 C.G.: Results on each trial for peak and zero-lag cross-correlation and lag between head/shoulder and target/shoulder angles, sd head/sd target and GVE. Mean results for each session according to MT or MC and overall mean for each session.

21,1 wks						
	Head-Target correl	Head-Target lag(ms)	Head-Target peak corr	sd head /sd tar	GVE (deg.s ⁻¹)	
MT	.33	-	-	.11	40	
	-.49	-	-	.08	9	
	-.43	-	-	.09	42	
	.74	780	.87	.05	-	
Mean (sd)	.04 (.60)	780 (0)	.87 (0)	.08 (.03)	30 (19)	
MC	-.11	-	-	.85	17	
	.26	-	-	.24	21	
	.83	310	.87	.59	17	
	.78	20	.78	.24	14	
Mean (sd)	.44 (.45)	165 (205)	.83 (.06)	.48 (.30)	17 (3)	
Overall mean (sd)	.35 (.46)	370 (384)	.84 (.05)	.28 (.29)	23 (13)	
23,4 wks						
MT	-.07	-	-	.11	-	
	.41	-	-	.08	-	
	.73	1070	.97	.31	-	
Mean (sd)	.36 (.40)	1070 (0)	.97 (0)	.17 (.13)	-	
MC	-.22	-	-	.52	-	
	.77	700	.88	.44	-	
	.59	90	.60	.33	-	
Mean (sd)	.38 (.53)	395 (431)	.74 (.20)	.43 (.10)	-	
Overall mean (sd)	.37 (.42)	410 (572)	.82 (.19)	.30 (.18)	-	

/cont.

Table 5.1 (cont.)

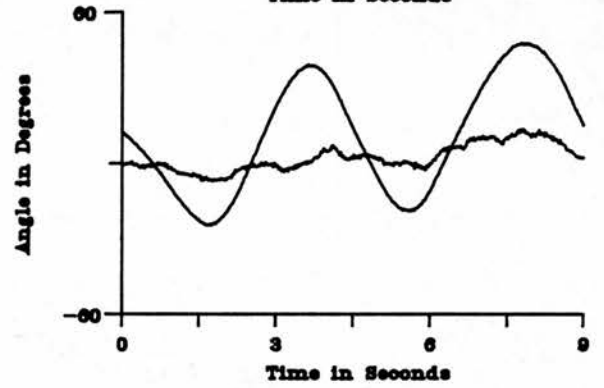
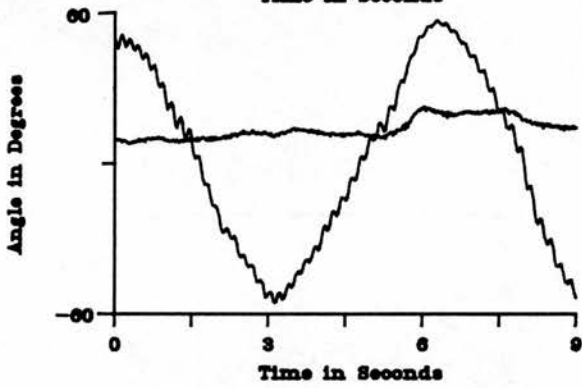
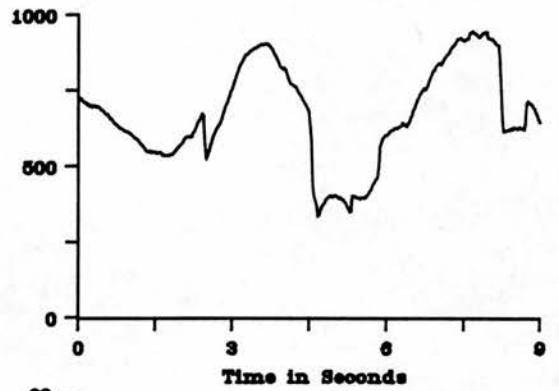
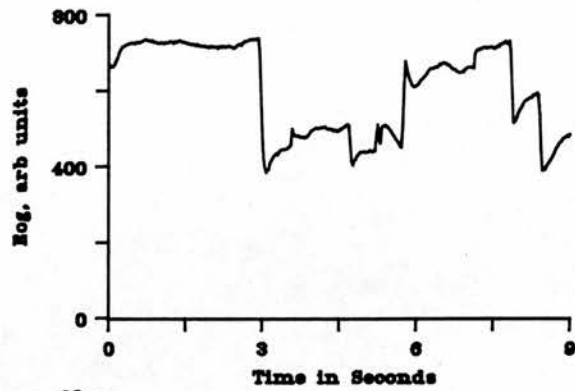
28,1 wks					
	Head-Target correl	Head-Target lag(ms)	Head-Target peak corr	sd head /sd tar	GVE (deg.s ⁻¹)
MT	.74	80	.74	.30	-
	.92	300	.97	.55	45
	.70	250	.73	.39	40
	.72	10	.74	.30	26
Mean (sd)	.77 (.10)	160 (137)	.61 (.42)	.39 (.12)	37 (10)
MC	.53	750	.77	.52	-
	.44	-	-	.51	31
	-.30	-	-	.42	50
	.40	-	-	.54	46
Mean (sd)	.27 (.38)	750 (0)	.77 (0)	.50 (.05)	42 (10)
Overall					
mean (sd)	.52 (.37)	224 (309)	.79 (.10)	.44 (.10)	40 (9)
38,1 wks					
MC	.86	200	.91	.51	13
	.87	230	.96	.36	17
	.93	120	.95	.41	35
	.52	360	.63	.38	18
Overall					
mean (sd)	.80 (.19)	227 (100)	.86 (.16)	.42 (.07)	21 (10)

The variability in each session was very high and the number of trials was low, but the graphs (fig 5.2) show that there is some general improvement over the tested period: in lag times, in zero-lag cross-correlation and especially in the proportion of head to target movement. The figures from the few trials where it was possible to accept peak cross-correlations remained fairly high over the tested period.

Moving Target

Moving Chair

(i)



(ii)

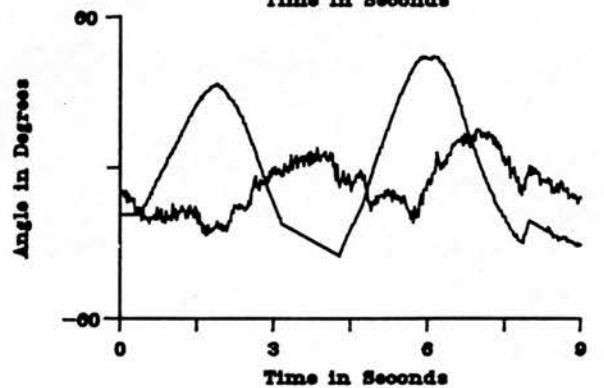
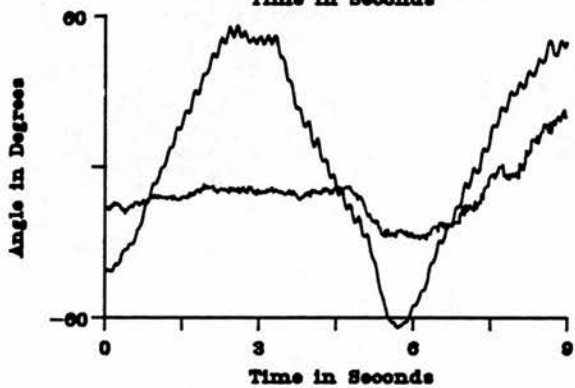
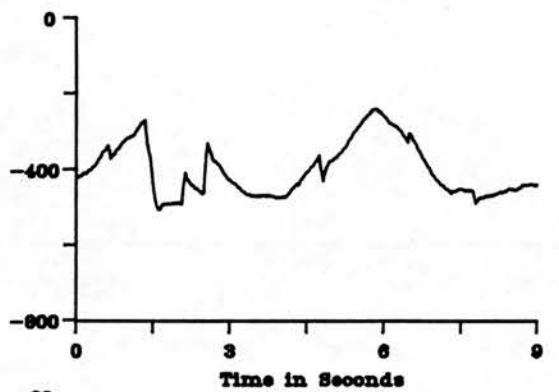
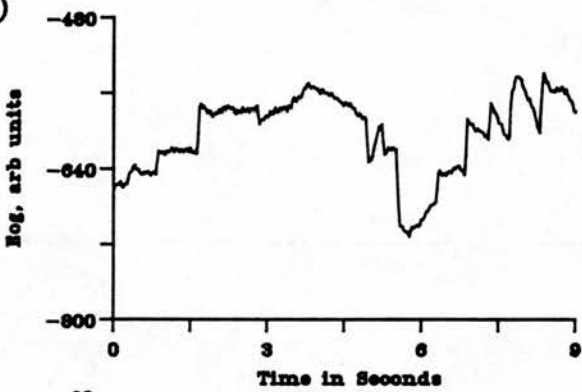


Figure 5.2 Performance of C.G at (i) 21,1 wks and (ii) 28,1 wks in moving target (MT) and moving chair (MC) conditions.

5.3.2. Effect of the Experimental Variables

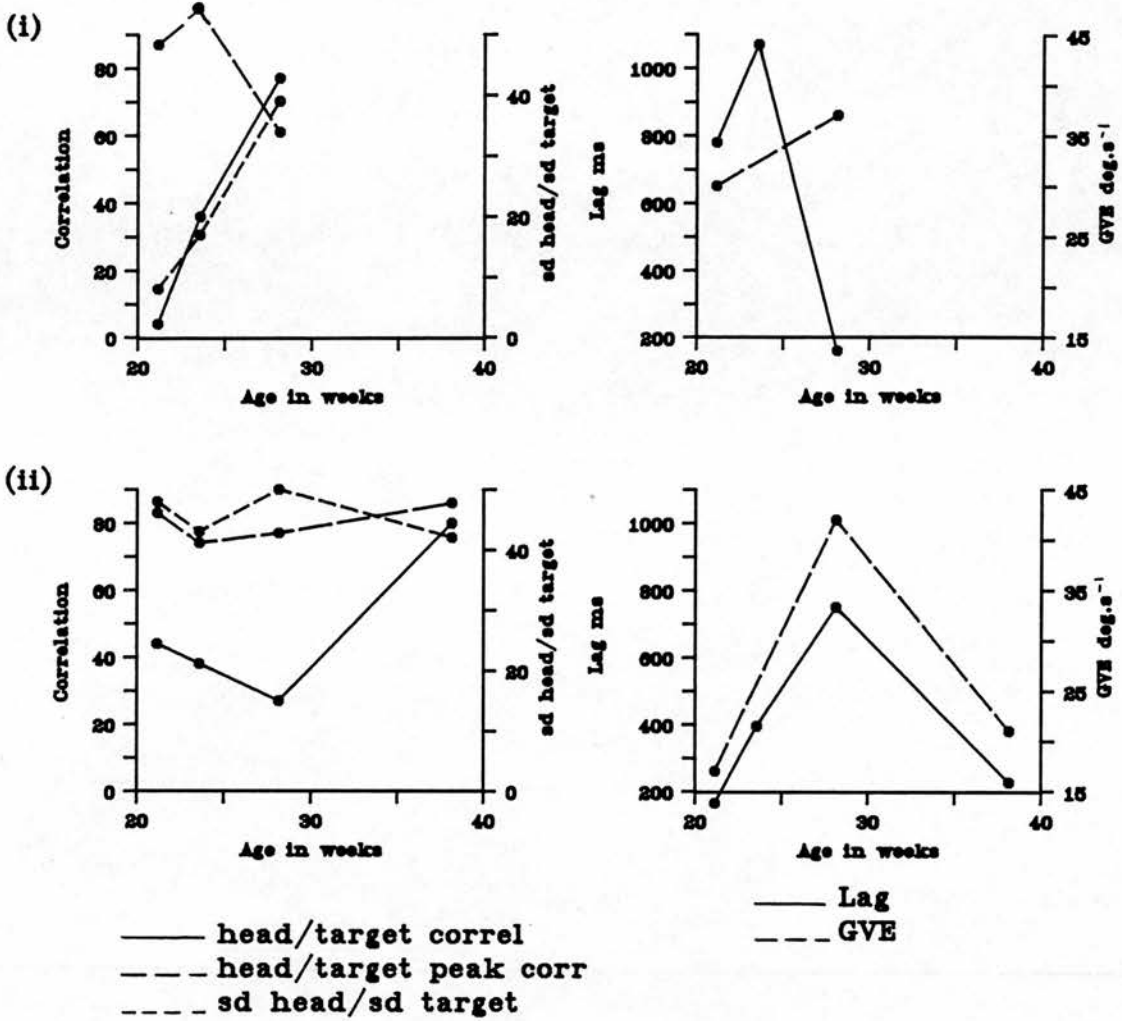


Figure 5.3 Mean results at each age for peak and zero-lag cross-correlation, and lag between head/shoulder and target/shoulder angles, sd head/sd target and GVE, broken down by (i) MT and (ii) MC.

Informal observations indicated that when the chair was turned it was possible to elicit more rotation of the eyes across the midline into the right side. At 21,1 performance was much better when the chair was moving: GVE was higher, lags lower, cross-correlations higher and in particular the head was used a lot more (figure 5.3).

Performance in the MT condition improved dramatically between 21 and 28

weeks: the proportion of head to target movement increased and the lag between head/shoulder and target/shoulder angles was reduced. The temporary drop-back in performance at 28 wks should be interpreted with caution as it represents only a small amount of data, but it could be attributed to poor control of the head as it was used more. The head movement in the MC condition at 28,1 is higher but very out of phase with the target (figure 5.1).

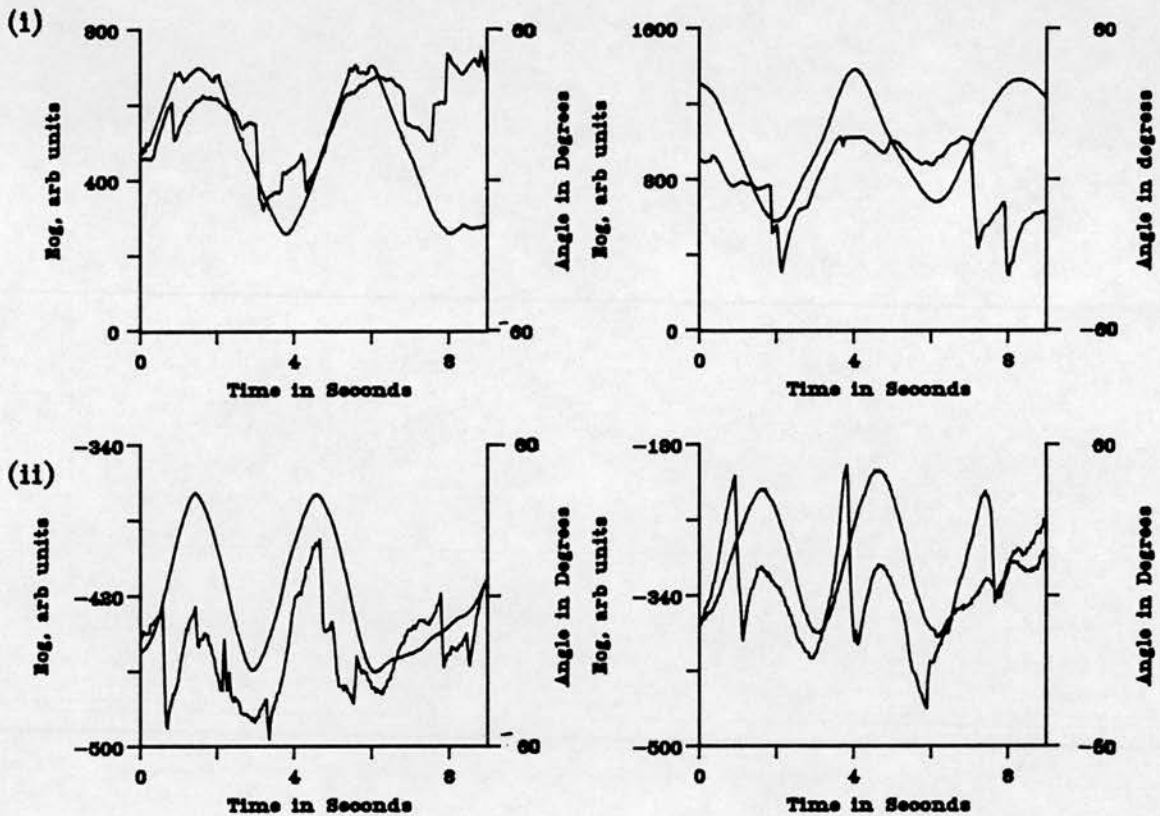


Figure 5.4 Eye movements at (i) 21,1 wks and (ii) 28,1 wks in response to an optokinetic stimulus (left-hand graphs) and to chair movement in the dark (right hand graphs).

Figure 5.4 shows that at 21,1 eye movements were more appropriate in response to the moving surround than to chair oscillation in the dark. This suggests that visual stabilization of the eyes was superior to vestibular stabilization at this stage. On the basis of this it might be expected that performance would have been better in the MT condition where only visual information was available for gaze stabilization. This seems to contradict the

finding of superior performance in the MC condition where head use was greater and GVE lower. When the chair was moving in the light as opposed to the dark, however, visual rotary flow as well as vestibular information would be available. It may have been this visual information that was used to help gaze stabilization in the MC condition.

5.4. Summary

C.G began to approach normal head/eye control at a much later stage than the normal infants described in the previous chapter. He was found to be principally deficient in head control, particularly when tracking a moving target. This delay in attaining accurate gaze stabilization was accompanied by a considerable delay in other functional activities such as weight bearing and sitting. Reaching was also considerably delayed, although by 36 weeks it was very vigorous. The finding that head use was superior in response to movement of the body suggests a basis for the design of therapy programmes for the encouragement of and practice of head and eye coordination in cases of delayed or abnormal development.

CHAPTER 6
SUMMARY AND DISCUSSION

The looking behaviour of adults and infants was examined when tracking moving objects and when maintaining gaze on a static object while their body was oscillated. It was found that the head played a major role in looking and compensating for body movement, and infants and adults showed good head control in both situations.

6.1. Visual Control of Head Movement

When the object was moving only vision could provide information about target movement; when the subject was moving other information would also be available to specify the body movement, but since the eyes translated relative to the object as the head turned, vision would again be essential for accurate fixation (see chapter 1, fig 1.1). The adults and infants were therefore using vision to stabilize gaze in all conditions.

Adult eye-movements were very smooth (see fig 3.1), but this was not always the case with the infants. The examples in fig 6.1 taken from the first and last sessions of two babies show that, especially when the target was moving, eye-movements could be fairly saccadic. In spite of this the infants were able to pick up sufficient visual information for effective head tracking. The inferior accuracy of the infants as measured by gaze velocity error could be due to their being less efficient both in the pick-up and use of the information, especially for the control of smooth eye movements.

6.2. Amount of Head Movement

The adults showed considerable individual differences in the proportion of head to target movement and in the relative effects of target and body movement upon this proportion. The gaze velocity error, however, was low for all subjects, indicating that for the adults successful performance was relatively independent of the amount of head use. The infants, however, consistently showed a higher proportion of head to target movement than the

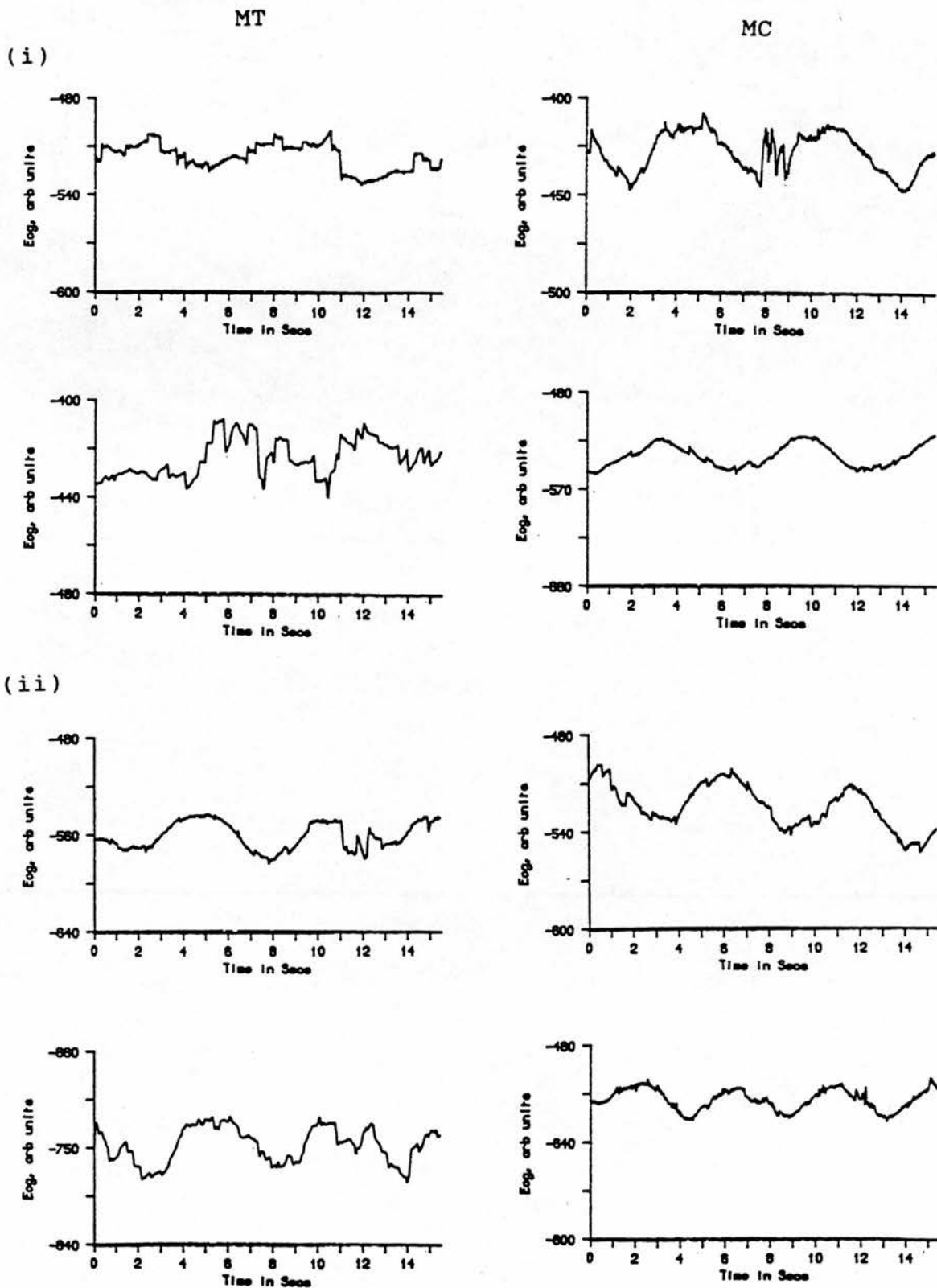


Figure 6.1 Typical eye-movements at the first session (i) and last session (ii) when the target (MT) and chair (MC) was moving. The upper graphs in each set are from SB, the lower from SS.

adults, and this proportion was not significantly affected by whether the target or chair was moved. This difference between the adult and infant head use could be for two reasons: 1) immaturity in structure and control of infant eyes and 2) the different nature of the task performed by the infants.

1) At one week of age the peripheral retina is structurally mature, but the fovea is very immature and develops over several months (Abramov et al., 1982). There is evidence based on performance for a more sensitive central region by two months, but, whereas peripheral acuity plateaus at four to five months, foveal acuity continues to develop over the first year of life (Sireteanu et al, 1984). It has been suggested that the infants' greater use of the head in tracking is due to this foveal immaturity, since their gaze-stabilization behaviour is similar to that of afoveate animals (Roucoux, et al., 1983). It has also been observed that children with a severe visual deficit follow a moving target mainly by turning their heads (Jan et al., 1986).

Even by the end of the period of longitudinal study, the infant eye movements tended to be much more saccadic than those of the adults. This suggests that control of smooth eye movements were still developing at this stage. If head control was more developed than eye control, then to perform the bulk of tracking with the head would be a good strategy. It has been noticed that very young infants occasionally make a head movement to a peripherally presented target without an accompanying eye movement (de Schonen et al., 1978).

2) In infants there is a strong compulsion to explore both visually and manually and it was apparent during testing that a prime motivation in tracking was to grab the target. The adults, however, were simply looking at the target. The fact that the amount of head use surged at around the same time that visually guided reaching normally starts developing (von Hofsten, 1980; 1986) supports the notion that the infants were attempting to keep aligned on the target in order to perform an act upon it, not simply to watch it. In adults stabilizing the head with respect to the target improves performance in basketball shooting (Ripoll et al., 1985), and reaching (Biquer et al., 1984). These are different tasks from observing a small target on which no action has to be performed. It is significant that the brain-damaged infant, who showed a very high gaze velocity error, and was considerably delayed in

many aspects of motor control, especially reaching, used his head a lot less than the normal infants, especially during the early stages of testing, when he was very passive and showed little interest in reaching. Improved performance developed along with increased head use.

6.3. The Effect of Predictable versus Unpredictable Movement

Both the adults and the infants showed higher peak and zero-lag cross-correlations between target/shoulder and head/shoulder angles when the movement was predictable; showing that both were more efficient at matching predictable movements (see chapter 2, 6.4). It could be that the difference in cross-correlations for predictable and unpredictable movement for both adults and infants was due to the unpredictable movement being more difficult to follow. The adults also showed better anticipation in the predictable conditions as shown by the significantly lower lags between head/shoulder and target/shoulder angles when the target or chair was moved in a predictable fashion. With the infants this was not the case, and if anything, lags were shorter when target or chair movement was unpredictable. This apparently shorter lag in infant response to unpredictable movement could be due in part to the movement being more interesting and so holding the attention better. The increased number of changes of direction may have attracted the children's attention and allowed more frequent reorientation to the target movement. Also at this stage, possibly due to the low frequency of movement, the infants may not have recognised the predictable pattern, or if they did perceive it may not have been able to act on that information appropriately.

6.4. The Effect of Target Movement versus Chair Movement

Adult gaze velocity error was equally low whether the target or chair was moved. Performance tended to be unaffected by this variable apart from some evidence of better anticipation of chair rather than target movement in three of the six subjects who showed significantly shorter lags when the chair was moved. Generally infant gaze velocity error was lower when the chair was moved, and all infants also showed lower lags in this condition throughout the longitudinal study. Zero-lag cross-correlations were also higher in the moving

chair condition, but as the peak cross-correlations were not similarly affected this was probably mainly due to the longer lag between head/shoulder and target/shoulder angles in this condition, rather than to a problem with matching target movement. The infants therefore showed much better anticipation when the chair rather than the target was moved. This could be due to the different information available in the two conditions and the way this information was used by the infants. When the chair was moving there was strong expropriospecific information for the change in body position. Not only was there vestibular and stretch receptor information, there was also rotary visual flow. Pick up of visual flow of the whole environment does not depend on good foveal vision (Johansson, 1977) and peripheral acuity develops dramatically in the first months of life and plateaus at about four months (Siretencanu et al., 1984). Infants have been shown to be very susceptible to peripheral visual information (Kremenitzer et al., 1979). Prelocomotor infants use visual information to control head position (Butterworth and Hicks, 1977; Jouen, 1984; Butterworth, 1986). Later when learning to walk their sensitivity to visual information in balance control is dramatically demonstrated by their response to the movement of the surroundings around them (Lee and Aronson, 1974). Infants also have very well developed vestibular responses (Eviatar et al., 1974; 1979; Eviatar and Eviatar, 1978; 1979; Herman et al., 1982). Thus in principle, infants are well equipped to pick up sufficient information for good stabilization when their bodies are moving respect to the environment.

When the target was moving, on the other hand, the infant with an immature fovea, saccadic eye movements and less smooth eye pursuit movements would be at a disadvantage when the only information was the movement of a small target against a stationary background. It has been suggested that, for infants, one of the problems in smooth visual pursuit with the eyes stems from difficulty in gating out the optokinetic response to the counter-flow of the image of the background resulting from tracking (Atkinson and Braddick, 1981; Aslin, 1981). Control of the head may be adversely affected in the same way. It is also the case that turning the head to track may stimulate a vestibular response to counter-rotate the eyes, again an inappropriate response. Although myelination of the vestibulo-cerebellar system is complete before birth (Trevorthen, 1985), the cerebellum, which is important for the integration of visual and vestibular information, expands

enormously during the first seven post-natal months (Rakic and Sidman, 1970) and continues to develop for several years (Hay, 1984). This, along with the lack of fine control associated with cortical immaturity would contribute to difficulties with the integration and use of information when the target was moving.

There must also be an effect of practice and motivation. Infants are carried about from an early age and so gain much experience of body movement. Extreme disorientation would result from failure to stabilize gaze under these circumstances, whereas the inability or choice not to follow a moving target would be less disorienting. In short, infants must learn first to stabilize the gaze with respect to the environment before they can successfully destabilize it to follow a moving target. It is interesting that the brain-damaged infant (C.G) used his head more to compensate for body movement than to follow a moving target.

6.5. Developmental Changes

As the infants were relying on their heads to a greater extent than the adults due to immaturity of morphology and control of the eyes and to the nature of the task, it was more critical for infants than adults to anticipate and match target movement with the head. The infants all showed development in head control over the tested period: the zero-lag and peak cross-correlations between target/shoulder and head/shoulder angles and the proportion of head to target movements increased showing an improvement in the ability to match the movement of the target or chair with that of the head. By the end of testing peak cross-correlations compared favourably with those of the adults.

In all infant subjects there was a dramatic drop in lag time over the tested period. The adults showed considerable individual variation in the amount of lag between head/shoulder and target/shoulder angles suggesting that the eyes were more actively used in tracking and compensating for body movement. The infants showed less individual variation in lag between head/shoulder and target/shoulder angles. The infants therefore showed dramatic improvements in anticipatory head control and especially in the period up to about 16 and 20 weeks when there was a surge in the amount of

head use and a sudden drop in the lag times. This ties in well with the period of fast muscular and visual development, when visually guided reaching also emerges, for which anticipation is vital. During this period head use was extremely vigorous, and was followed in some cases by a temporary decline possibly due to a drop in interest and motivation.

6.6. In Conclusion

The head-eye coordination system is therefore well developed at a young age. Future work would investigate the relationship between the development of anticipation in gaze stabilization and successful performance, for example in reaching. It would be interesting to look further at the interaction between the amount of head use and the task being performed. Accuracy of visually guided movements in infants may be related to the ability to accurately align the head with the target. As gaze stabilization is a fundamental part of the coordinative system, its disruption has wide-reaching effects. Greater understanding of the normal and abnormal development of head and eye coordination in relatively unconstrained experimental conditions would have important diagnostic and therapeutic consequences.

I. References

- Abramov, I., Gordon, J., Hendrickson, A., Hailine., Dobson, V. and La Bossiere, E. The retina of the human infant. *Science*, 1982, 217, 265-267.
- Aslin, R.N. Development of binocular fixation in human infants. *J. of Exper. Ch. Psych.*, 1977, 23, 133-150.
- Aslin, R.N. Development of smooth pursuit in human infants. In Fisher, D.F., Monty, R.A. and Senders, J.W. (Eds.), Eye Movements: Cognition and Visual Perception Hillsdale, NJ: Erlbaum Associates, 1981.
- Atkinson, J. Human visual development over the first six months of life: a review and a hypothesis. *Human Neurobiol.*, 1984, 3, 61-74.
- Atkinson, J. & Braddick, O. Development of optokinetic nystagmus in infants: an indicator of cortical binocularity? In Fisher, D.F., Monty, R.A. and Senders, J.W. (Eds.), Eye Movements: Cognition and Visual Perception, Hillsdale, NJ: Erlbaum Associates, 1981.
- Atkinson, J. & Braddick, O. Sensory and perceptual capacities of the neonate. In Stratton, P. (Ed.) Psychobiology of the Human Newborn. London: John Wiley & Sons Ltd, 1982.
- Banks, M.S. The development of visual accommodation during early infancy. *Child Development*, 1980, 51, 646-666.
- Bard, C. & Fleury, M. Contribution of head movement to the accuracy of directional aiming and coincidence-timing tasks. In Wade, M.G. & Whiting, H.T.A. (Eds.) Motor Development: Aspects of Coordination and Control. Dordrecht: Martinus Nijhoff, 1986.
- Barnes, G.R. Vestibular control of oculomotor and postural mechanisms. *Clin. Phys. Physiol. Meas.*, 1980, 1, 3-40.
- Barnes, G.R. Visual-vestibular interaction in the coordination of voluntary eye and head movements. In Fuchs, A.F. & Becker, W. (Eds.) Progress in Oculomotor Research. Amsterdam: North Holland Publishing Co., 1981.

- Barten, S., Birns, B. & Ronch, J. Individual differences in the visual pursuit behaviour of neonates. *Ch. Dev.*, 1971, 42, 313-319.
- Barr, C. C., Schultheis, L. W. & Robinson, D. A. Voluntary, non - visual control of the human vestibuloocular reflex. *Acta Oto-Laryngol*, 1981, 365- 375.
- Becker, W. & Fuchs, A.F. Predictive mechanisms in human smooth pursuit movement. In Roucoux, A. & Crommelinck, M. (Eds.) Physiological and Pathological Aspects of Eye Movements. The Hague: Dr W Junk Publishers, 1982.
- Beek, P.J. Perception-action coupling. In Wade, M.G. & Whiting, H.T.A. (Eds.) Motor Development: Aspects of Coordination and Control. Dordrecht: Martinus Nijhoff, 1986.
- Biguer, B. & Prablanc, C. Modulation of the vestibulo-ocular reflex in eye-head coordination as a function of target distance in man. In Fuchs, A.F. & Becker, W. (Eds.) Progress in Oculomotor Research. Amsterdam: North Holland Publishing Co., 1981.
- Biguer, B., Prablanc, C. & Jeannerod, M. The contribution of coordinated eye and head movements in hand pointing accuracy. *Exp. Brain Res.*, 1984, 55, 462-469.
- Bobath, K. The Neurophysiological Basis for the Treatment of Cerebral Palsy. Clinics in Developmental Medicine No 29. London: SIMP with Heinemann; Philadelphia, Lippincott, 1980.
- Bower, T.G.R. Development in Infancy. San Francisco: Freeman, 1974.
- Bower, T. G. R., Broughton, J. M., & Moore, M. K. Demonstration of intention in the reaching behaviour of neonate humans. *Nature*, 1970, 228, 679-681.
- Braddick, O. & Atkinson, J. Some recent findings on the development of human binocularity: a review. *Behav. Br. Res.*, 1983, 10, 141-150.
- Braddick, O. Wattam-Bell, J. Day, J. & Atkinson, J. The onset of binocular function in human infants. *Human Neurobiology*, 1983, 2, 65-69.

- Bronson, G. The hierarchical organization of the CNS: implications for learning processes and critical periods in early development. *Behav. Science*, 1965, 10, 7-25.
- Bronson, G. The postnatal growth of visual capacity. *Ch. Dev.*, 1974, 45, 873- 890.
- Brown, J.K. Hemiplegia in children. Unpublished Manuscript, 1983.
- Bullinger, A. Cognitive elaboration of sensorimotor behaviour. In G. Butterworth (Ed.), Infancy and Epistemology : An Evaluation of Piaget's theory The Harvester Press, 1981.
- Bullinger, A. Space, the organism & objects, their cognitive elaboration in the infant. In A. Hein & M. Jeannerod (Eds.), *Spatially Oriented Behaviour* New York: Springer-Verlag, 1983.
- Butterworth, G. Structure of the mind in human infancy. In L.P. Lipsett (Ed.), *Advances in Infancy Research* Vol 2, Norwood, N. J. : Ablex, 1983.
- Butterworth, G. Some problems in explaining the origins of movement control. In Wade, M.G. & Whiting, H.T.A. (Eds.) Motor Development: Aspects of Coordination and Control. Dordrecht: Martinus Nijhoff, 1986.
- Butterworth, G. & Hicks, L. Visual proprioception and postural stability in infancy. A developmental study. *Perception*, 1977, 6, 255-262.
- Casaer, P. Postural Behaviour in Newborn Infants. Clinics in Developmental Medicine no. 72, London: Spastics International medical Publications, 1979.
- Dichgans, J., Held, R., Young, L.R. & Brandt, T. Moving visual scenes influence the apparent direction of gravity. *Science*, 1972, 178, 1217- 1218.
- Ellenberg, J.H. & Nelson, K.B. Early recognition of infants at high risk for cerebral palsy: Examinations at age four months. *Dev. Med. Ch. Neurol.*, 1981, 23, 705-716.
- Eviatar, L. & Eviatar, A. Neurovestibular examination of infants and children. *Adv. Oto-Rhino-Laryng.* 1978, 23, 169-191.

- Eviatar, L. & Eviatar, A. The normal nystagmic response of infants to caloric and perrotatory stimuli. *The Laryngoscope*, 1979, 89, 1036-1044.
- Eviatar, L., Eviatar, A. & Naray, I. Maturation of neurovestibular responses in infants. *Develop. Med. Ch. Neurol.*, 1974, 16, 435-446.
- Eviatar, L., Miranda, S., Eviatar, A., Freeman, K., Borkowski, M. Development of nystagmus in response to vestibular stimulation in infants. *Ann. Neurol.*, 1979, 5, 508-514.
- Forsstrom, A. & Hofsten Von, C. Visually directed reaching of children with motor impairments. *Develop. Med. Ch. Neurol.*, 1982, 24, 653-661.
- Fuchs, A.F. Eye-head coordination. In Towe, A.L. & Luschei, E.S. (Eds.) Handbook of Behavioural Neurobiology, Vol 5, Motor Coordination. New York and London: Plenum Press, 1981.
- Gibson, J.J. The ecological approach to visual perception Boston: Houghton Mifflin, 1979.
- Goodkin, F. The development of mature patterns of head-eye coordination in the human infant. *Early Human Development*, 1980, 4, 373-386.
- Hay, L. The development of movement control. In Smith, M.S. & Wing, A.M. (Eds.) The Psychology of Human Movement. New York and London: Academic Press, 1984.
- Hein, A. Prerequisite for development of visually guided reaching in kitten. *Brain Research*, 1974, 71 (2-3), 259-263.
- Held, R. Binocular vision - behavioural and neuronal development. In Mehler, J. & Fox, R. (Eds.) Neonate Cognition. Hillsdale NJ: Erlbaum Associates, 1985.
- Held, R., Birch, E. & Gwiazda, J. Stereoacuity of human infants. *Proc. Natl. Acad. Sci. USA*, 1980, 77, 5572-5574.
- Herman, R., Maulucci, R. & Stuyck, J. Development and plasticity of visual and vestibular generated eye movements. *Experimental Brain research*, 1982, 47, 69-78.
- Hofsten, C. von, Predictive reaching for moving objects by human infants. *J. Exp. Ch. Psych.*, 1980, 30, 369-382.

- Hofsten, C. von, Eye-hand coordination in the newborn. *Developmental Psychology*, 1982, 18, 450-461.
- Hofsten, C. von, The emergence of manual skills. In Wade, M.G. & Whiting, H.T.A. (Eds.) Motor Development in Children: Aspects of Coordination and Control. Dordrecht: Martunis Nijhoff, 1986.
- Hofsten, C. von, & Lindhagen, K. Observations on the development of reaching for moving objects. *J. Exp. Ch. Psych.*, 1979, 28, 158-173.
- Illingworth, R.S. The Development of the Infant and Young Child. Edinburgh: Churchill Livingstone, 8th Ed., 1983.
- Ito, M. The Cerebellum and Neural Control. New York: Raven Press Books, 1984.
- Jan, J.E., Farrell, K., Wong, P.K., & McCormick, A.O. Eye and head movements of visually impaired children. *Dev. Med. Ch. Neurol.*, 1986, 28, 285-293.
- Johansson, G. Studies in visual perception of locomotion. *Perception*, 1977, 6, 365-376.
- Jouen, F. Visual-vestibular interactions in infancy. *Inf. Behav. & Dev.*, 1984, 7, 135-145.
- Jouen, F. La contribution des recepteurs visuels et labyrinthiques a la detection des deplacements du corps propre chez le nourrisson. To be published in *Annee Psychologique*.
- Katayama, M. & Tamas, L.B. Saccadic eye movements of children with cerebral palsy. *Dev. Med. Ch. Neurol.*, 1987, 29, 36-39.
- Kornhuber, H.H. Nystagmus and related phenomena in man: An outline of otoneurology. Kornhuber, H.H. (ed) Handbook of Sensory Physiology, Vol V1/2, 1974, 193-232.
- Kremenitzer, J.P., Vaughan, Jr. H.G., Kurtzberg, D. & Dowling, K. Smooth-pursuit eye movements in the newborn infant. *Ch. Dev.*, 1979, 50, 442-448.
- Lanman, J., Bizzi, E. & Allum, J. The coordination of eye and head movements during smooth pursuit. *Brain Res.*, 1978, 153, 39-53.
- Lee, D.N. & Aronson, E. Visual proprioceptive control of standing in human infants. *Perception & Psychophysics*, 1974, 19, 529-532.

- Lee D.N. & Lishman, R. Visual proprioceptive control of stance. *J. Human Movement Studies*, 1975, 1, 87-95.
- Levitt, S. Treatment of Cerebral Palsy and Motor Delay. Oxford: Blackwell Scientific Publications, 2nd Ed., 1982.
- Martinuik, R.G. The role of eye and head positions in slow movement execution. In Stelmach, G.E. (Ed.) Information Processing in Motor Control and Learning. New York and London: Academic Press, 1978.
- Maurer, D. Infant visual perception: Methods of study. In Cohen, L.B. & Salapatek, P. (Eds.) Infant Perception: From Sensation to Cognition, Vol 1. New York and London: Academic Press, 1975.
- Maurer, D. & Lewis, T.I. A physiological explanation of infants' early visual development. *Canadian Journal of Psychology*, 1979, 33, 232-252.
- McDonnell, P.M., Anderson, V.E.S. & Abraham, W.C. Asymmetry and orientation of arm movements in three to eight week old infants. *Inf. Behav. & Dev.*, 1983, 6, 287-298.
- McGinnis, J.M. Eye movements and optic nystagmus in early infancy. *Genetic Psych. Monographs*, 1930, 8, 321-427.
- McGraw, M.B. The Neuromuscular Maturation of the Human Infant. New York: Hafner Publishing Co. Inc, 1966.
- Melvill Jones, G. The vestibular system for eye movement control. In Monty, R.A. and Senders, J.W. (Eds.), Eye movements and psychological processes 1976, Hillsdale NJ: Laurence Erlbaum Associates.
- Melvill Jones, G. Plasticity in the adult vestibulo-ocular reflex. *Arc Phil Trans R Soc., Lond B.*, 1977, 278, 319-334.
- Miles, F.A. & Kawano, K. Visual stabilization of the eyes. *Trends in Neurosc.*, 1987, 10, 153-158.
- O'Malley, P.J. & Griffith, J.F. Perceptuo-motor dysfunction in the child with hemiplegia. *Dev. Med. Ch. Neurol.*, 1977, 19, 172-178.

- Outerbridge, J.S. & Melvill Jones, G. Reflex vestibular control of head movement in man. *Aerospace Med.*, 1971, 42, 935-940.
- Owen, B.M. & Lee, D.N. Establishing a frame of reference for action. In Wade, M.G. & Whiting, H.T.A. (Eds.) Motor Development: Aspects of Coordination and Control. Dordrecht: Martinus Nijhoff, 1986.
- Peiper, A. Cerebral Function in Infancy and Childhood. New York: Consultants Bureau, 1963.
- Pope, M.J. Visual proprioception in infant postural development. Unpublished Ph.D. thesis, University of Southampton, 1984.
- Rakic, P. & Sidman, P.N. Histogenesis of cortical layers in human cerebellum, Particularly the Lamina Dissecans. *J. Comp. Neur.*, 1970, 139, 473-500.
- Rashbass, C. Second thoughts on smooth pursuit. In Bach-y-Rita, P. & Collins, C.C. (Eds.) The Control of Eye Movements., New York and London: Academic Press, 1971.
- Regal, D. M., Ashmead, D. M. & Salapatek, P. The coordination of eye and head movements during early infancy : a selective review. *Behav. Brain Research*, 1983, 10, 125- 132.
- Ripoll, H., Bard, C. & Paillard, J. Stabilization of head and eyes on target as a factor in successful basketball shooting. *Human Movement Science*, 1985, In press.
- Robinson, D.A. The mechanics of human smooth pursuit eye movement. *J.Physiol.*, 1965, 180, 569-591.
- Robinson, D.A. The physiology of pursuit eye movements. In Monty, R.A. & Senders, J.W. (Eds.) Eye-Movements and Psychological Processes. Hillsdale, NJ: Erlbaum Associates, 1976.
- Robinson, D.A. Control of eye movements. In Handbook of Physiology, Section 1, Vol 2 , Part 2, American Physiological Soc., Bethesda, M.D. 1981.
- Robinson, R.J. Cerebral hemisphere function in the newborn. In Robinson, R.J. (Ed.) Brain and Early Behavioural Development in the Fetus and Infant. New York and London: Academic Press, 1969.
- Roucoux, A., Culee, C. & Roucoux, M. Development of fixation and pursuit eye movements in human infants. *Behav. Brain Research*, 1983, 10, 133-139.

- Salapatek, P. Pattern perception in early infancy. In L.B. Cohen & P. Salapatek (Eds.), Infant Perception: From sensation to Cognition Vol 1, New York and London: Academic Press, 1975.
- Schmid, R., Buizza, A. & Zambarbieri, D. Visual stabilization during head movement. In Ingle, D.J., Jeannerod, M. & Lee, D.N. (Eds.) Brain Mechanisms and Spatial Vision. Dordrecht: Martinus Nijhoff, 1985.
- de Schonen, S., McKenzie, B., Maury, L. & Bresson, F. Central and peripheral object distances as determinants of the effective visual field in early infancy. Perception, 1978, 7, 499-506.
- Sireteanu, R., Kellerer, R. & Boergen, K.P. The development of peripheral visual acuity in human infants. Human Neurobiol., 1984, 3, 81-85.
- Stark, L., Vossius, G. & Young, L.R. Predictive control of eye tracking movements. Ire. Trans. Hum. Fac. Elec., 1962, 3, 52-57.
- Tomlinson, R.D., Saunders, G.E. & Schwartz, D.W.F. Analysis of human vestibulo-ocular reflex during head movements. Acta Otol., 1980, 90, 184-190.
- Trevarthen, C. Early sensory - motor development. In Bruner, J.S. Research Program on intellectual development cooperative research project no: z-014 (BR 5-0232) Cambridge: Harvard University, 1968.
- Trevarthen, C. Growth of visuomotor coordination in infants. Journal of Human Movement Studies, 1975, 57, .
- Trevarthen, C. Neurological development and the growth of psychological functions. In Sants, J. (Ed.) Developmental Psychology & Society. London: The Macmillan Press Ltd, 1980.
- Trevarthen, C. Biodynamic structures, cognitive correlates of motive sets and the development of motives in infants. In W. Prinz & A. F. Sanders (Eds.), Cognition and Motor Processes Berlin: Springer-Verlag, 1984a.
- Trevarthen, C. How control of movement develops. In H. T. A. Whiting (Ed.), Human Motor Actions : Bernstein Reassessed Elsevier Science Publishers B. V. (North-Holland), 1984b.

- Trevarthen, C. Neuroembryology and the development of perceptual mechanisms. In Falkner, F. & Tanner, J.M. (Eds.) Human Growth. 2nd Ed., New York: Plenum Press, 1985.
- Tronick, E. & Clanton, C. Infant looking patterns. Vision Research, 1971, 11, 1479-1486.
- Twitchell, T.E. Normal motor development. J. Am. Physical Therapy Ass., 1965, 45, 419-423.
- White, B. L., Castle, P. & Held, R. Observations on the development of visually - directed reaching. Child Development, 1964, 349-364.
- Williams, H.G. Perceptual & Motor Development NJ, Englewood Cliffs: Prentice-Hall Inc., 1983.
- Wong, S.C.P. & Frost, B.J. Subjective motion and acceleration induced by the movement of the observer's entire field. Perception and Psychophysics, 1978, 24, 115-120.
- Young, L.R. Pursuit eye-tracking movements, In Bach-y-Rita, P. and Collins, C.C. (Eds) The Control of Eye Movements. New York and London: Academic Press, 1971.
- Young, L.R. Pursuit eye movement - what is being pursued? In Baker, R. & Berthoz, A. (Eds.) Control of Gaze by Brain Stem Neurons, Developments in Neuroscience, Vol 1. Elsevier, North-Holland Biomedical press, 1977.

II. Appendices

Appendix I: Program used to compute sd head/sd target

```
PROGRAM head ;

USES
  {$U brigid:selspot.rd.code}
  selspot_reader;

CONST
  pi=3.1415926;
  dc=300;

VAR
  vp:boolean;
  prop, master:text;
  reply:char;
  name:string;
  start, finish, frameinc:integer;
  sdz, sumz, sumzz, should, mc, sumx, sumy, sumxx, sumyy, sumxy, sdx, sdy:real;
  tdel, tdinc, nn, lagi, lags, lage, i, und, tar, dcp, dist, a, b, u, d,
  n, m, c, newx, newy, xg, yg, s, h, xh, yh, xd, yd, xc, yc, xb,
  xa, ya, xt, yt, yb, xe, ye, xf, yf, ang:real;

PROCEDURE init;
BEGIN
  sumxy:=0;
  sumx:=0;
  sumy:=0;
  sumxx:=0;
  sumyy:=0;
  n:=0;
END;

PROCEDURE accum(x,y:real);

BEGIN
  sumxy:=sumxy+(x*y);
  sumx:=sumx+x;
  sumy:=sumy+y;
  sumxx:=sumxx+(x*x);
  sumyy:=sumyy+(y*y);

END;

PROCEDURE working;

VAR
  x1,x2,y1,y2:real;

BEGIN
  sdx:=sqrt(n*sumxx-sqr(sumx))/n;
  sdy:=sqrt(n*sumyy-sqr(sumy))/n;
END;

FUNCTION angle(x1,y1,x2,y2: real): real;
  (Returns the angle to the y-axis of the line joining the
```

```

two pairs of coordinates given.)
function atan2(x,y: real): real;
{Returns arctan(x/y) using signs properly}
const
  half_pi = 1.5707963;
  pi = 3.1415926;
begin
  if y > x then
    if y > -x then
      atan2:= arctan(x/y)
    else
      atan2:= -half_pi - arctan(y/x)
  else
    if y > -x then
      atan2:= half_pi - arctan(y/x)
    else
      if x > 0.0 then
        atan2:= pi + arctan(x/y)
      else
        if y <> 0.0 then
          atan2:= -pi + arctan(x/y)
        else
          atan2:= 0.0;
  end; {atan2}
begin
  angle:= atan2(x2-x1,y2-y1)
end;

```

PROCEDURE error;

```

BEGIN
writeln('hit end of file');
END;

```

PROCEDURE extract;

```

BEGIN
REPEAT
  sr_crds('A',xa,ya);sr_crds('B',xb,yb);sr_crds('C',xc,yc);
  sr_crds('D',xd,yd);sr_crds('H',xh,yh);sr_crds('G',xg,yg);
  IF (xa<>undefined) AND (ya<>undefined) and (xb<>undefined) and
  (yb<>undefined) and (xc<>undefined) and (yc<>undefined) and
  (xd<>undefined) and (yd<>undefined) and (xh<>undefined) and(yh<>undefined)
  and
  (xg<>undefined) and (yg<>undefined) then
  BEGIN
    should:=angle(xb,yb,xa,ya)-angle(xc,yc,xd,yd);

    s:=(should/pi)*180;
    IF vp THEN tar:=(angle(xg,yg,xh,yh)/pi)*180
    ELSE tar:=-(angle(xc,yc,xd,yd)/pi)*180;
    accum(s,tar);
    n:=n+1;
  END else und:=und+1;
  if not sr_incf then error;

```

```
UNTIL sr_fcur>=finish;
end;
```

```
{program body}
BEGIN
  vp:=false;
  rewrite(prop, '%4:prop.text');
  writeln(prop, '          head   tar   h/t');
  write('master file: ');readln(name);
  reset(master,name);
  write('Is it vp? ');readln(reply);
  vp:=reply='y';
  write('what frame inc?');readln(frameinc);
  WHILE NOT eof(master) DO
    BEGIN
      readln(master,name);

      if sr_file(name) then writeln(name,' opened') else begin
        writeln('can''t find it');
        close(prop,crunch);exit(program); end;

      readln(master,start);
      if not sr_setf(start)then writeln('start frame not set');
      readln(master,finish);
      sr_seti(frameinc);
      init;extract;
      working;
      writeln(prop,name,' ',sdx:4:2,' ',sdy:4:2,' ',sdx/sdy:4:2);
    END;close(prop,crunch);
  END.
```

Appendix II: Program used for cross-correlational analysis

```

PROGRAM infant;

USES
  {$U brigid:selspot.rd.code}
  selspot_reader;

VAR
  r, master: text;
  file_name, s: string;
  input_file: file;
  sitn, cond: char;
  sumx, sumy, sumxx, sumyy, sumxy: real;
  z, tdel, tdinc, nn, lagi, lags, lage, frameinc, i, und, t: integer;
  dcp: real;
  X: array [1..4000] of real;
  Y: array [1..4000] of real;

FUNCTION angle(x1, y1, x2, y2: real): real;
  {Returns the angle to the y-axis of the line joining the
  two pairs of coordinates given.}
  function atan2(x, y: real): real;
    {Returns arctan(x/y) using signs properly}
    const
      half_pi = 1.5707963;
      pi = 3.1415926;
    begin
      if y > x then
        if y > -x then
          atan2 := arctan(x/y)
        else
          atan2 := -half_pi - arctan(y/x)
        else
          if y > -x then
            atan2 := half_pi - arctan(y/x)
          else
            if x > 0.0 then
              atan2 := pi + arctan(x/y)
            else
              if y <> 0.0 then
                atan2 := -pi + arctan(x/y)
              else
                atan2 := 0.0;
            end; {atan2}
          begin
            angle := atan2(x2-x1, y2-y1)
          end;
    end;

PROCEDURE tmsrs;

CONST
  pi=3.1415926;

  dist=440.0;

```

```

dc=300.0;

VAR
  xa,ya,xh,yh,xc,yc,
  xd,yd,xb,yb,xf,yf,
  xg,yg,xt,yt,xi,yi,a,b,c,d:real;

BEGIN
  REPEAT
    t:=t+1;
    sr_crds('A',xa,ya);sr_crds('H',xh,yh);sr_crds('C',xc,yc);
    sr_crds('D',xd,yd);sr_crds('A',xa,ya);sr_crds('B',xb,yb);
    sr_crds('G',xg,yg);sr_crds('I',xi,yi);
    CASE sitn OF

      '1':BEGIN
        {neck-twist coordinates}
        IF (xc<>undefined) AND (yc<>undefined) AND (xd<>undefined) AND
          (yd<>undefined) AND (xa<>undefined) AND (ya<>undefined) AND
          (xb<>undefined) AND (yb<>undefined) THEN
          BEGIN
            X[t]:=((angle(xb,yb,xa,ya)-angle(xc,yc,xd,yd))/pi)*180;
          END ELSE
            X[t]:=undefined          ;
          END;
      '2':BEGIN
        {eog coordinates}
        IF (xi<>undefined) THEN
          X[t]:=-(xi) ELSE X[t]:=undefined;
        END;
    END(case);
    CASE cond OF
      '1':BEGIN {target coordinates}
        IF (xh<>undefined) AND (yh<>undefined) AND
          (xg<>undefined) AND (yg<>undefined) THEN
          BEGIN

            Y[t]:=(angle(xg,yg,xh,yh)/pi)*180;
          END ELSE BEGIN Y[t]:=undefined;END;
        END;
      '2':{inverted chair coordinates}
        BEGIN
          IF (xc<>undefined) AND (yc<>undefined) AND
            (xd<>undefined) AND (yd<>undefined) THEN
            Y[t]:=-((angle(xc,yc,xd,yd)/pi)*180)
            ELSE Y[t]:=undefined END;

        END(case);
    UNTIL NOT sr_incf;
  END;

PROCEDURE init;

BEGIN
  sumx:=0;

```

```

sumy:=0;
sumxx:=0;
sumyy:=0;
sumxy:=0;
nn:=0;
END;

```

```

PROCEDURE xcorr;

```

```

VAR
lag,beg,stop,loopy,loopx:integer;
a,b,c:real;

```

```

BEGIN
writeln(r,s);

```

```

writeln(r,'lag':6,'time':6,'n':6,'corr':6);
tdinc:=frameinc*lagi;
tdel:=frameinc*lags;

```

```

lag:=lags;

```

```

REPEAT

```

```

  init;

```

```

  IF (1-lag)>1 THEN beg:=(1-lag) ELSE beg:=1;

```

```

  IF t<(t-lag) THEN stop:=t ELSE stop:=(t-lag);

```

```

  loopy:=beg+lag;

```

```

  FOR loopx:=beg TO stop DO

```

```

    BEGIN

```

```

      a:=X[loopx];b:=Y[loopy];

```

```

      IF (a<>undefined) AND (b<>undefined) THEN

```

```

        BEGIN

```

```

          sumx:=sumx+a;

```

```

          sumy:=sumy+b;

```

```

          sumxx:=sumxx+(a*a);

```

```

          sumyy:=sumyy+(b*b);

```

```

          sumxy:=sumxy+(a*b);

```

```

          nn:=nn+1;

```

```

        END ;

```

```

      loopy:=loopy+1;

```

```

    END;

```

```

  c:=(nn*sumxy-sumx*sumy)/sqrt((nn*sumxx-sumx*sumx)*(nn*sumyy-sumy*sumy))

```

```

  writeln(r,lag:6,tdel*(sr_ratd*time_unit):6:2,nn:6,c:6:3);

```

```

  lag:=lag+lagi;tdel:=tdel+tdinc;

```

```

UNTIL lag>=lage+lagi;

```

```

END;

```

```

{program body}
BEGIN
  rewrite(r,'&4:r.text');
  writeln('Warning: check leds, and dist and dcp');
  write('master file: ');readln(s);
  reset(master,s);readln(master,s);
  write('vp(1) or vor(2)? ');readln(cond);
  write('do you want to correlate nt (1) or eog (2) with target/chair');
  readln(sitn);
  write('what frame inc?');readln(frameinc);
  write('Start lag: ');readln(lags);
  write('End lag: ');readln(lage);
  write(' Increment :');readln(lagi);
  WHILE NOT eof(master) DO
    BEGIN
      und:=0;
      if sr_file(s) then writeln(s,' opened') else begin
        writeln('can''t find it');
        close(r,crunch);exit(program); end;
      t:=0;sr_seti(frameinc);
      tmsrs;
      xcorr;
      readln(master,s);
    END;close(r,crunch);
  END.

```

Appendix III

Tables showing the infant results on zero-lag and peak cross-correlation and lag between head/shoulder and target/shoulder angles, sd head/sd target and GVE for each session broken down by MC/MT and PR/UP.

Zero-Lag cross-correlations

Session	1 2 3 4 5 6 7												
	s	cond	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	
NH	MC	.88	.08	.87	.05	.95	.04	.91	.06	.92	.09	.95	.04
	MT	.76	.12	.78	.10	.93	.06	.88	.08	.88	.10	.92	.04
	PR	.80	.14	.87	.05	.97	.03	.94	.06	.95	.02	.96	.03
	UP	.84	.09	.78	.10	.92	.05	.87	.07	.84	.11	.91	.03
SS	MC	.94	.03	.91	.06	.89	.04	.96	.01	.92	.12	.97	.01
	MT	.71	.17	.84	.06	.80	.08	.89	.08	.84	.09	.91	.03
	PR	.83	.19	.89	.05	.87	.04	.96	.02	.87	.12	.95	.03
	UP	.80	.16	.87	.08	.82	.10	.89	.09	.88	.11	.93	.04
IB	MC	.71	.19	.71	.13	.84	.11	.92	.05	.91	.05	.92	.08
	MT	.75	.07	.74	.15	.82	.08	.91	.02	.80	.05	.88	.03
	PR	.74	.10	.76	.09	.88	.03	.93	.04	.88	.08	.93	.04
	UP	.72	.18	.69	.17	.77	.10	.90	.04	.84	.07	.87	.06
AT	MC	.82	.13	.79	.09	.92	.06	.90	.08	-	.95	.04	.96
	MT	.73	.11	.77	.08	.95	.03	.90	.08	.91	.05	.94	.03
	PR	.79	.10	.80	.10	.94	.07	.94	.03	-	.95	.04	.96
	UP	.75	.15	.77	.07	.93	.03	.86	.09	-	.94	.05	.94
FT	MC	-.13	.32	.66	.15	.87	.11	.90	.09	.90	.08	.95	.02
	MT	.63	.17	.83	.08	.87	.06	.89	.06	.89	.04	.92	.03
	PR	.24	.56	.83	.09	.90	.06	.90	.09	.92	.04	.95	.02
	UP	.22	.36	.67	.15	.84	.11	.88	.06	.87	.07	.92	.03
SB	MC	.88	.06	.89	.08	.86	.05	.77	.12	.81	.13	.94	.04
	MT	.40	.36	.84	.07	.75	.13	.79	.14	.88	.06	.88	.07
	PR	.77	.26	.87	.07	.83	.11	.82	.09	.88	.11	.93	.03
	UP	.51	.39	.85	.09	.78	.12	.74	.15	.81	.10	.88	.08

Peak cross-correlations

Session	1 2 3 4 5 6 7												
	s	cond	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	
NH	MC	.91	.07	.95	.02	.95	.03	.94	.06	.94	.07	.97	.02
	MT	.87	.07	.90	.06	.95	.06	.96	.02	.95	.07	.96	.02
	PR	.88	.09	.94	.03	.97	.03	.97	.01	.98	.02	.98	.01
	UP	.90	.04	.90	.06	.93	.05	.93	.06	.92	.08	.95	.02
SS	MC	.95	.02	.95	.03	.92	.04	.97	.01	.93	.12	.97	.01
	MT	.90	.05	.92	.04	.93	.03	.96	.02	.95	.06	.96	.02
	PR	.94	.05	.94	.04	.93	.03	.97	.02	.93	.12	.97	.02
	UP	.92	.05	.93	.05	.92	.03	.96	.01	.95	.06	.96	.01
IB	MC	.85	.09	.83	.12	.95	.06	.94	.05	.96	.04	.94	.08
	MT	.77	.08	.86	.09	.93	.04	.97	.02	.90	.05	.93	.04
	PR	.83	.10	.90	.05	.96	.03	.97	.03	.95	.05	.96	.03
	UP	.79	.09	.79	.13	.91	.05	.94	.05	.90	.04	.91	.07
AT	MC	.87	.09	.89	.08	.94	.05	.91	.08	-	.96	.03	.97
	MT	.86	.06	.85	.07	.97	.02	.94	.06	.94	.04	.95	.05
	PR	.89	.07	.89	.09	.96	.05	.96	.03	-	.96	.02	.96
	UP	.85	.07	.85	.06	.95	.02	.90	.08	-	.94	.05	.95
FT	MC	-	.85	.06	.93	.08	.94	.04	.93	.06	.96	.02	.97
	MT	.84	.10	.95	.03	.95	.02	.97	.02	.97	.02	.97	.02
	PR	-	.94	.04	.96	.03	.96	.04	.97	.03	.98	.01	.97
	UP	-	.87	.06	.92	.08	.96	.03	.93	.06	.96	.02	.96
SB	MC	.91	.04	.93	.07	.92	.05	.83	.14	.86	.13	.95	.03
	MT	.77	.15	.89	.07	.87	.09	.89	.11	.92	.05	.93	.05
	PR	.90	.05	.91	.07	.90	.08	.89	.10	.94	.06	.96	.02
	UP	.81	.15	.91	.07	.89	.07	.83	.15	.85	.11	.92	.04

sd Head/ sd Target

Lags (ms)

Session	sd Head/ sd Target							Lags (ms)							
	1	2	3	4	5	6	7	1	2	3	4	5	6	7	
s	cond	mean	sd	mean	sd	mean	sd	s	cond	mean	sd	mean	sd	mean	sd
NH	MC	.73	.11	.73	.21	1.18	.15	.87	.20	.88	.19	1.21	.10		
	MT	.64	.24	.64	.12	1.23	.11	.86	.24	1.02	.17	1.16	.14		
	PR	.65	.19	.65	.09	1.11	.15	.87	.22	.93	.16	1.12	.10		
	UP	.73	.18	.72	.23	1.23	.11	.86	.23	.98	.23	1.25	.11		
SS	MC	.83	.07	.92	.09	.84	.09	.98	.06	.98	.14	1.18	.20		
	MT	.76	.22	.87	.07	.99	.14	1.10	.14	1.10	.26	1.12	.25		
	PR	.78	.12	.88	.10	.93	.16	1.07	.14	1.04	.18	1.08	.13		
	UP	.81	.20	.91	.07	.90	.12	1.01	.08	1.04	.25	1.23	.27		
IB	MC	.50	.08	.37	.15	.75	.09	.85	.09	.69	.04	.72	.13	.92	.08
	MT	.44	.12	.41	.23	.57	.13	.92	.15	.49	.06	.63	.12	.62	.15
	PR	.48	.09	.40	.15	.70	.12	.90	.11	.59	.12	.70	.10	.77	.21
	UP	.46	.12	.39	.23	.60	.15	.87	.14	.59	.11	.65	.16	.77	.19
AT	MC	.68	.27	.65	.16	1.03	.26	.91	.11	-	-	1.03	.10	.94	.18
	MT	.56	.19	.83	.17	1.25	.14	1.03	.18	1.07	.15	1.03	.16	.99	.12
	PR	.60	.24	.68	.14	1.08	.24	.98	.15	-	-	1.02	.12	.93	.13
	UP	.64	.24	.80	.21	1.20	.19	.96	.16	-	-	1.04	.15	.99	.17
FT	MC	.32	.08	.71	.09	.79	.16	.93	.11	.96	.12	.96	.06	.87	.12
	MT	.53	.17	.75	.08	.93	.13	1.12	.19	1.08	.13	.97	.14	.92	.11
	PR	.42	.20	.77	.08	.86	.13	1.03	.14	1.01	.09	.99	.10	.89	.15
	UP	.43	.14	.70	.08	.86	.19	1.02	.22	1.03	.17	.93	.10	.90	.07
SB	MC	.49	.10	.72	.12	.59	.11	.64	.24	.60	.19	.91	.14		
	MT	.46	.15	.69	.17	.60	.20	.62	.12	.67	.12	1.00	.16		
	PR	.47	.09	.65	.17	.53	.16	.64	.17	.67	.12	.91	.17		
	UP	.49	.15	.75	.11	.67	.14	.62	.21	.61	.19	1.00	.12		
	NH	MC	190	110	310	60	30	40	110	50	150	60	50	50	50
	MT	510	220	390	170	100	80	290	100	260	100	260	60	150	70
	PR	400	220	400	140	40	60	190	150	210	60	90	80	80	80
	UP	310	240	290	100	90	80	200	90	200	111	111	80		
	SS	MC	140	70	180	100	150	80	50	370	30	50	40		
	MT	430	130	370	150	420	80	260	110	90	130	200	50		
	PR	280	170	320	170	310	120	140	80	270	210	130	90		
	UP	290	210	220	110	260	190	180	160	190	130	120	100		
	IB	MC	370	150	390	160	300	60	100	70	210	50	60	80	40
	MT	140	120	410	190	350	70	260	60	350	140	180	90	260	130
	PR	320	190	480	140	330	50	200	110	320	130	120	90	190	160
	UP	170	120	310	120	310	80	160	90	230	110	130	120	150	90
	AT	MC	330	220	270	160	70	80	90	50	-	10	40	30	30
	MT	480	220	300	90	170	70	180	50	170	70	80	60	40	50
	PR	480	220	310	120	150	90	140	50	-	-	50	80	30	40
	UP	340	230	260	140	90	80	140	80	-	-	40	40	40	50
	FT	MC	-	-	460	180	210	80	190	110	150	80	100	30	50
	MT	630	170	400	60	310	110	290	110	300	60	120	40	170	40
	PR	-	-	420	120	260	130	250	130	270	110	160	60	110	80
	UP	-	-	440	150	250	90	220	110	190	90	160	70	120	60
	SB	MC	150	110	220	80	210	40	180	170	150	50	80	70	
	MT	500	140	340	110	330	220	400	190	190	50	220	80		
	PR	300	200	270	120	240	160	340	220	190	50	170	110		
	UP	250	170	290	120	300	180	240	200	160	60	140	90		

GVE (deg.s⁻¹)

Session	1		2		3		4		5		6		7	
	s	cond	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	MC	8	5	-	13	7	10	3	9	3	12	4		
	MT	13	5	-	16	6	17	8	10	3	15	6		
	PR	11	4	-	13	7	11	5	9	3	12	2		
	UP	9	3	-	16	5	16	7	10	3	15	6		
SS	MC	11	4	13	6	-	-	-	11	3	10	5		
	MT	17	11	15	4	-	-	-	18	9	13	5		
	PR	15	7	14	5	-	-	-	15	8	9	3		
	UP	14	9	14	5	-	-	-	14	6	14	5		
IB	MC	13	11	9	3	5	2	8	1	12	7	12	6	11
	MT	15	4	10	2	9	3	12	4	10	4	14	7	10
	PR	16	9	11	3	6	2	8	2	11	7	13	6	11
	UP	12	5	9	2	9	4	11	5	11	5	13	7	10
AT	MC	15	4	9	7	-	-	10	4	-	-	-	-	10
	MT	14	5	17	7	-	-	13	5	-	-	-	-	15
	PR	14	5	14	8	-	-	11	5	-	-	-	-	11
	UP	15	3	12	8	-	-	12	4	-	-	-	-	14
FT	MC	20	12	12	6	-	-	12	4	12	3	19	3	9
	MT	20	5	16	12	-	-	16	6	16	7	17	2	14
	PR	20	12	11	4	-	-	13	5	15	7	17	4	11
	UP	20	6	17	12	-	-	14	6	13	3	18	2	13
SB	MC	12	2	10	4	11	3	-	-	-	-	-	-	15
	MT	19	8	14	5	12	4	-	-	-	-	-	-	20
	PR	13	3	12	5	12	3	-	-	-	-	-	-	15
	UP	18	9	12	5	12	4	-	-	-	-	-	-	19

Appendix IV

Table showing the mean and sd derived from the mean scores from each cell for each session for zero-lag and peak cross-correlation and lag between head/shoulder and target/shoulder angles and GVE.

Head-target zero-lag cross-correlation

Sub	MTPR		MTUP		MCPR		MCUP	
	mean	sd	mean	sd	mean	sd	mean	sd
NH	.894	.11	.814	.11	.935	.06	.897	.07
SS	.860	.11	.799	.11	.929	.08	.933	.04
IB	.845	.07	.801	.11	.885	.12	.828	.15
AT	.890	.10	.852	.12	.904	.09	.879	.10
FT	.920	.04	.856	.07	.902	.09	.846	.16
SB	.842	.09	.786	.14	.885	.07	.792	.20

Head-target lag (ms)

Sub	MTPR		MTUP		MCPR		MCUP	
	mean	sd	mean	sd	mean	sd	mean	sd
NH	300	204	286	189	143	136	131	89
SS	537	340	477	345	348	413	356	440
IB	343	169	229	118	235	167	186	120
AT	243	215	171	138	138	154	124	179
FT	288	126	274	80	192	141	188	175
SB	310	183	318	157	191	155	134	79

Head-target peak correlation

Sub	MTPR		MTUP		MCPR		MCUP	
	mean	sd	mean	sd	mean	sd	mean	sd
NH	.949	.06	.905	.07	.958	.05	.928	.05
SS	.943	.04	.929	.05	.948	.07	.949	.03
IB	.916	.08	.880	.08	.953	.05	.889	.10
AT	.933	.07	.905	.07	.938	.06	.911	.08
FT	.976	.01	.950	.03	.960	.03	.934	.06
SB	.901	.18	.881	.11	.933	.06	.865	.11

GVE

Sub	MTPR		MTUP		MCPR		MCUP	
	mean	sd	mean	sd	mean	sd	mean	sd
NH	12	2	16	5	10	2	10	3
SS	16	4	16	1	11	2	12	2
IB	10	3	12	2	12	3	8	2
AT	14	1	16	2	11	3	11	4
FT	14	3	19	3	15	5	14	4
SB	14	2	18	6	12	2	12	2

Appendix V

Tables showing the infant results on zero-lag and peak cross-correlation and lag between head/shoulder and target/shoulder angles, sd head/sd target and GVE for each session broken down by individual conditions: MTPR, MTUP, MCPR, MCUP.

Zero-Lag cross-correlations

Session	1		2		3		4		5		6		7	
	s	cond	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	MTPR	.73	.16	.85	.06	.97	.02	.92	.07	.94	.01	.95	.02	
	MTUP	.78	.07	.72	.09	.90	.07	.84	.06	.81	.11	.90	.02	
	MCPR	.86	.10	.90	.04	.96	.04	.96	.02	.95	.03	.96	.03	
	MCUP	.90	.06	.85	.06	.93	.03	.89	.07	.88	.11	.93	.04	
SS	MTPR	.74	.22	.86	.02	.85	.03	.94	.02	.85	.05	.92	.02	
	MTUP	.67	.12	.83	.08	.74	.08	.83	.09	.82	.13	.90	.04	
	MCPR	.95	.02	.93	.04	.88	.05	.97	.01	.89	.17	.97	.02	
	MCUP	.93	.03	.90	.07	.90	.04	.95	.01	.95	.03	.96	.01	
IB	MTPR	.75	.09	.79	.05	.87	.03	.93	.01	.81	.03	.90	.03	.86
	MTUP	.74	.05	.67	.21	.77	.08	.89	.02	.80	.07	.85	.02	.86
	MCPR	.73	.11	.71	.12	.90	.02	.93	.06	.95	.02	.97	.01	.98
	MCUP	.70	.27	.71	.15	.77	.14	.91	.05	.88	.04	.88	.09	.93
AT	MTPR	.75	.07	.78	.10	.95	.03	.95	.01	.93	.04	.95	.03	.95
	MTUP	.71	.15	.76	.07	.94	.03	.85	.09	.89	.05	.92	.06	.92
	MCPR	.84	.12	.82	.10	.92	.09	.93	.03	-	-	.94	.05	.97
	MCUP	.79	.15	.77	.08	.93	.03	.86	.10	-	-	.95	.03	.95
FT	MTPR	.72	.12	.89	.02	.91	.06	.93	.03	.91	.04	.94	.02	.94
	MTUP	.51	.13	.77	.07	.85	.05	.84	.06	.88	.03	.90	.03	.91
	MCPR	-.25	.30	.76	.10	.90	.06	.87	.12	.93	.04	.96	.02	.97
	MCUP	-.4	.32	.57	.14	.84	.15	.92	.04	.87	.09	.94	.02	.96
SB	MTPR	.61	.08	.83	.07	.75	.13	.84	.07	.90	.06	.91	.02	
	MTUP	.24	.31	.84	.08	.75	.15	.75	.19	.86	.05	.84	.08	
	MCPR	.91	.05	.91	.04	.89	.04	.80	.12	.87	.14	.95	.04	
	MCUP	.85	.07	.86	.11	.83	.04	.73	.13	.75	.11	.93	.04	

Peak cross-correlations

Session	1		2		3		4		5		6		7	
	s	cond	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
NH	MTPR	.86	.10	.92	.03	.97	.02	.98	.01	.98	.01	.98	.01	
	MTUP	.88	.03	.87	.08	.93	.07	.95	.02	.91	.09	.94	.02	
	MCPR	.90	.08	.96	.02	.96	.04	.97	.02	.97	.02	.98	.01	
	MCUP	.92	.05	.93	.02	.94	.03	.91	.07	.91	.09	.96	.02	
SS	MTPR	.91	.06	.92	.03	.94	.03	.96	.02	.97	.03	.97	.01	
	MTUP	.90	.05	.91	.05	.93	.03	.95	.01	.93	.08	.95	.01	
	MCPR	.96	.02	.96	.03	.93	.06	.98	.00	.90	.17	.97	.01	
	MCUP	.95	.03	.94	.03	.92	.04	.96	.01	.96	.03	.97	.01	
IB	MTPR	.78	.11	.91	.05	.95	.04	.98	.01	.91	.05	.93	.03	.95
	MTUP	.77	.05	.80	.10	.91	.04	.96	.02	.88	.04	.92	.04	.91
	MCPR	.88	.05	.88	.04	.98	.01	.96	.04	.99	.01	.98	.01	.98
	MCUP	.81	.12	.78	.16	.91	.08	.92	.06	.93	.03	.90	.10	.95
AT	MTPR	.90	.03	.83	.10	.98	.01	.97	.01	.95	.96	.02	.01	.95
	MTUP	.83	.07	.86	.03	.96	.02	.92	.07	.94	.93	.06	.03	.93
	MCPR	.87	.10	.94	.03	.94	.07	.94	.03	-	.96	.02	.02	.97
	MCUP	.88	.08	.84	.09	.94	.03	.88	.10	-	.95	.03	.02	.97
FT	MTPR	.89	.05	.96	.02	.98	.01	.98	.01	.98	.01	.98	.01	.97
	MTUP	.79	.12	.93	.02	.94	.02	.96	.03	.96	.02	.96	.03	.95
	MCPR	-	-	.90	.04	.95	.03	.94	.06	.96	.03	.97	.02	.97
	MCUP	-	-	.80	.02	.90	.11	.95	.03	.90	.07	.95	.01	.96
SB	MTPR	.87	.04	.86	.08	.84	.10	.91	.09	.94	.06	.96	.03	
	MTUP	.63	.11	.92	.05	.89	.09	.88	.14	.90	.05	.90	.04	
	MCPR	.92	.04	.95	.03	.95	.03	.88	.11	.94	.07	.96	.02	
	MCUP	.90	.02	.90	.09	.88	.05	.78	.15	.79	.13	.93	.04	

Lags (ms)

GVE (deg.s⁻¹)

Session	Lags (ms)							GVE (deg.s ⁻¹)																					
	1	2	3	4	5	6	7	1	2	3	4	5	6	7															
	s	cond	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd													
NH	MTPR	550	180	470	170	70	50	300	130	260	30	150	70	14	5	-	-	12	5	14	6	8	3	12	4				
	MTUP	470	250	300	140	140	90	290	60	270	90	150	80	11	4	-	-	20	4	20	8	11	3	17	7				
	MCPR	240	130	330	80	10	50	80	70	160	50	20	20	8	2	-	-	14	9	8	2	10	3	11	1				
	MCUP	140	50	280	40	40	30	120	30	130	70	70	60	7	1	-	-	12	4	12	3	8	2	13	6				
SS	MTPR	400	110	440	160	410	40	200	60	450	140	200	50	19	10	16	4	-	-	-	-	18	10	11	2				
	MTUP	450	160	290	100	420	110	330	110	300	80	190	70	16	12	15	3	-	-	-	-	17	7	16	5				
	MCPR	160	90	200	70	200	70	70	60	90	30	50	40	11	1	12	5	-	-	-	-	12	3	8	3				
	MCUP	120	60	170	130	100	50	30	40	80	20	40	30	11	5	14	7	-	-	-	-	11	2	13	5				
IB	MTPR	190	150	540	120	350	80	290	50	410	120	160	60	320	120	15	4	11	2	7	1	8	3	9	4	14	6	8	1
	MTUP	90	70	250	130	350	70	230	50	280	130	210	110	200	110	15	4	9	2	12	2	15	3	10	5	14	9	11	2
	MCPR	420	180	420	150	320	20	110	50	230	40	70	90	50	40	17	13	11	4	6	2	9	2	12	9	13	7	13	5
	MCUP	270	100	370	80	270	80	90	70	180	50	50	70	100	20	8	4	8	2	4	1	7	1	11	5	11	5	8	3
AT	MTPR	640	90	340	90	190	80	170	60	180	80	100	80	30	50	14	7	15	8	-	-	12	5	-	-	-	-	13	6
	MTUP	330	210	260	90	150	60	190	50	160	60	60	40	40	60	14	3	18	7	-	-	13	6	-	-	-	-	17	1
	MCPR	320	180	280	150	110	90	110	30	-	0	60	20	20	14	5	12	9	-	-	9	5	-	-	-	-	8	1	
	MCUP	350	290	270	170	40	50	80	70	-	-	10	20	40	40	15	3	6	2	-	-	11	2	-	-	-	-	11	6
FT	MTPR	700	220	420	60	340	170	250	150	340	70	200	40	180	60	18	4	10	3	-	-	15	5	14	2	16	2	12	2
	MTUP	560	40	380	60	290	40	320	50	270	40	210	50	170	30	23	4	22	16	-	-	18	6	18	9	17	2	16	3
	MCPR	-	-	410	180	200	50	250	120	190	90	110	30	40	40	23	17	11	6	-	-	12	4	12	3	19	4	10	2
	MCUP	-	-	500	190	220	110	120	60	110	20	100	40	70	30	18	6	13	6	-	-	11	5	12	4	19	2	8	2
SB	MTPR	530	60	320	130	240	260	390	260	210	50	230	80	14	3	13	5	11	2	-	-	-	-	-	-	16	1		
	MTUP	460	250	360	110	333	220	400	120	180	60	200	80	23	9	14	6	12	5	-	-	-	-	-	-	23	6		
	MCPR	160	130	220	100	230	30	290	170	160	50	100	100	13	3	10	5	12	4	-	-	-	-	-	-	14	8		
	MCUP	150	90	210	70	210	50	80	110	140	60	70	40	11	2	11	4	11	3	-	-	-	-	-	-	15	2		

Appendix VI

Table showing the mean and sd on zero-lag and peak cross-correlation and lag between head/shoulder and target/shoulder angles, sd head/sd target and GVE for each individual condition.

Sub	n	Head-target correl.		Head-target lag(ms)		Head-target peak corr.		sd head /sd tar		GVE (deg.s ⁻¹)		
		mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	
1	MTPR	5	.95	.02	170	50	.98	.02	.37	.09	3.44	.77
	MTUP	5	.92	.03	140	50	.95	.02	.29	.10	3.32	.67
	MCPR	5	.98	.01	60	20	.98	.01	.43	.03	3.56	.17
	MCUP	5	.94	.03	70	70	.95	.02	.45	.05	3.31	.42
2	MTPR	5	.99	.00	- 39	31	.99	.00	.75	.06	2.40	.35
	MTUP	5	.95	.02	1	21	.95	.02	.90	.06	2.90	.46
	MCPR	5	.90	.03	267	50	.94	.03	.35	.04	2.76	.72
	MCUP	5	.79	.09	262	99	.82	.09	.22	.06	2.40	.57
3	MTPR	5	.96	.01	-139	87	.97	.02	.84	.06	3.64	.50
	MTUP	5	.97	.01	-121	55	.97	.01	.82	.08	3.39	.82
	MCPR	5	.99	.01	- 10	33	.99	.01	.74	.05	2.00	.37
	MCUP	5	.97	.02	15	62	.97	.02	.73	.11	1.78	.43
4	MTPR	5	.97	.00	89	20	.98	.01	.45	.07	2.89	1.38
	MTUP	5	.88	.01	128	23	.91	.06	.35	.09	3.19	1.20
	MCPR	5	.99	.01	22	18	.99	.01	.60	.06	3.00	.51
	MCUP	5	.94	.04	116	38	.95	.04	.55	.07	3.21	1.47
5	MTPR	5	.99	.01	- 48	31	.99	.00	.57	.06	3.38	.84
	MTUP	5	.98	.01	7	7	.98	.01	.59	.06	2.80	.53
	MCPR	5	.99	.01	- 14	20	.99	.01	.59	.03	3.27	.58
	MCUP	5	.98	.01	- 32	20	.99	.01	.55	.08	3.02	.82
6	MTPR	5	.99	.01	40	20	1.00	.00	.86	.03	2.07	.21
	MTUP	5	.98	.00	81	15	.99	.00	.86	.05	3.11	.36
	MCPR	5	1.00	.00	- 5	22	1.00	.00	.90	.04	2.28	.62
	MCUP	5	.98	.02	20	14	.98	.02	.86	.04	2.37	.93