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Measuring dysfunction of basic movement control in cerebral palsy

F.R. (Ruud) van der Weel [a,*], Audrey L.H. van der Meer [a], David N. Lee [b]

[a] Department of Psychology, University of Trondheim, N-7055 Dragvoll, Norway

[b] Perception in Action Laboratories, Department of Psychology, University of Edinburgh, 7 George Square, Edinburgh, EH8 9JZ, UK

Abstract

Devising effective therapy for movement disorder in the cerebral palsied child requires in-depth measures of the child's motor functioning. Current assessment mainly uses measures of surface behaviour, but these measures cannot reveal the underlying causes of movement disorder which therapy needs to address. This paper reviewed five different experiments from our laboratory which measured in detail the functioning and development of *basic* movement control mechanisms. In particular these experiments investigated the degree in which cerebral palsied children are capable of picking up and use prospective perceptual information for movement control. The research revealed several perceptuo-motor difficulties in these children which could be used towards developing better, more detailed assessment, diagnosis, and therapy procedures.

PsycINFO classification: 2225

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1. Introduction

1.1. General theoretical framework

This paper gives an overview of the work on movement disorders we have carried out in the Perception in Action Laboratories at Edinburgh University

* Corresponding author. Tel.: 47 7359-0614.

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over the past few years. In addition, the paper puts the experiments into a theoretical framework, namely that of an ecological approach to perception and action, in order to give the experiments an extra dimension.

One core idea of the ecological approach is that perception and action are tightly coupled and that perception involves active exploration: As perceptual information that is relevant for action is extended in space and time, activity is essential for the pickup of the information. The aim of the ecological approach is to quantify how prospective perceptual information for movement control changes (or remains constant) over time as a function both of the actions of the observer and structures and changes in the environment.

Instead of presupposing an unstructured, meaningless, flat two-dimensional retinal image as a starting point for visual perception (indirect perception), the ecological approach takes a structured, meaningful, and infinitely rich ambient optic array as its point of departure. The concept of optic array (or optic flow) can be defined as the changing pattern of light reflected to a moving eye (Gibson, 1961). It is of fundamental importance in understanding direct perception because it stands outside particular perceptual systems: It is the input available to each and every one of them. The job of the perceptual system is to pick up the information in the flow field.

The concept of optic array has been refined over the past decades and mathematical descriptions of it have been developed. For instance, *optic tau* (Lee, 1976) specifies the time it would take a surface element to reach the nearest position to the point of observation under constant velocity. The more generally defined *tau function* is a central feature in a general theory of control of velocity of approach.

1.2. Theory of control of velocity of approach

Most actions require perceptually controlling the velocity of approach of an effector to a destination. Everyday examples are directing the hand to an object to be grasped, the foot to an appropriate stepping place when walking and gaze to a point of interest. When approaching a destination, the ratio of distance $(-x)$ away at any time to speed of approach $(\dot{x})$ provides a first order estimate of time-to-contact of the effector with the destination. (If speed of approach stays constant then the ratio provides an accurate estimate; if speed decreases/increases the ratio under/overestimates time-to-contact.) The ratio $x/\dot{x}$ is called the *tau function* of x. In symbols:

$$\tau(x) = x/\dot{x}$$

$\tau(x)$ is directly specified, e.g., in the optic input to the eye (Lee, 1976). Behavioural experiments have indicated that $\tau(x)$ is used during approach (a) to time preparatory interceptive actions with respect to moving objects by humans, not only when approach speed is constant but also when there is acceleration (see e.g., Bootsma and Van Wieringen, 1990; Lee et al., 1983); (b) to time locomotor actions preparatory to contacting surfaces, by flies, gannets, and humans, again under accelerative as well as constant speed approaches (see e.g., Wagner, 1982; Lee and Reddish, 1981; Sidaway et al., 1989; Warren et al., 1986).

Thus $\tau(x)$ appears to be an informative variable for timing actions during approach. It also provides information for controlling speed of approach.

1.2.1. Controlling speed to stop at a destination

The rate of change of $\tau(x)$ with respect to time, i.e., $\dot{\tau}(x)$, is a dimensionless quantity that provides information for controlling braking (Lee, 1976). Control of braking to avoid colliding with a surface might appear to require computing appropriate deceleration on the basis of information about current distance from the surface and velocity of approach. However, this is not necessary. To avoid collision it is sufficient to register the value of $\dot{\tau}(x)$, adjust braking so that $\dot{\tau}(x) \leq 0.5$ and then keep braking constant. This procedure would generally result in stopping short of the surface.

A general procedure to *stop at* a surface is to adjust braking so that $\dot{\tau}(x)$ stays *constant* at a value k within the range 0 to 0.5. Following this procedure requires steadily slackening off the brakes as the surface is approached (except for $k = 0.5$ when deceleration is constant). Analysis of braking behaviour of test drivers indicated that they followed the stop-at procedure with $k = 0.425$ (Lee, 1976).

1.2.2. Controlled collision

If $\dot{\tau}(x)$ is kept constant at a value k between 0.5 and 1.0 then braking has to get progressively *harder* as the object is approached. In fact, stopping at an object in this way theoretically requires reaching infinite braking force. A realistic procedure – the *controlled collision procedure* – is to keep $\dot{\tau}(x)$ constant at a value between 0.5 and 1.0 until maximum braking power is reached, and then maintain this braking force. This would result in an animal colliding with the object, but in a controlled way. Film analysis of a hummingbird aerial docking on a feeder tube indicated it followed the controlled-collision procedure; as it braked it held $\dot{\tau}(x)$ constant at a mean value of 0.71 and its bill passed into the feeder rather than stopping at the opening (Lee et al., 1991). Similar results have been found for bats flying down a tunnel, slowing down to pass through a narrow aperture in the end to get a food reward (Lee et al., 1992a), and for pigeons landing on a perch (Lee et al., 1993).

An experiment with human subjects has shown (Kim et al., 1989) that a person can judge from a computer simulation of approach to a surface with $\dot{\tau}(x)$ held constant at different values (but with no information about distance, velocity and deceleration of approach) whether the approach would result in a 'soft collision' ($\dot{\tau}(x) \leq 0.5$) or a 'hard collision' $\dot{\tau}(x) > 0.5$). It has also been shown that somersaulters on a trampoline control their landing by regulating body extension so that angular-tau converges linearly to zero at landing, at a rate between 0.5 and 1.0. In other words, angular $\dot{\tau}$ is kept constant between 0.5 and 1.0 at a value equal to the ratio of angular-tau/time-to-landing (Lee et al., 1992b).

1.3. The therapeutic problem

Cerebral palsy, a chronic neurological condition that results in abnormal development of movement and postural control in children, can severely affect quality of life and ability to receive normal education. Incidence of cerebral palsy is about 2 per 1000 but could rise as more pre-term infants survive with improved intensive care techniques (Paneth et al., 1981). Devising effective therapy is therefore an important problem.

Cerebral palsy is not a homogeneous condition (Brown et al., 1991). Therefore, effective therapy requires assessing each individual child's problems in order to decide appropriate therapy and adjust it to the child's progress. Since underlying problems (e.g., poor (prospective) eye movement control or disorders in proprioception) can hinder performance of everyday skills such as reaching (Lee et al., 1990; Van der Meer et al., 1994), simple assessment of overt behaviour is in many cases not adequate; it can only describe the symptoms of movement disorder. To determine the underlying causes – and so pin-point where therapy needs to be directed – it is necessary to measure basic perceptuo-motor functions that subserve the disordered everyday skills. Such a scientific approach could yield dividends not only for the treatment of cerebral palsy but also for the treatment of related problems such as adult stroke.

1.4. Measuring basic perceptuo-motor function in cerebral palsy

There has been little research on basic perceptuo-motor functions in cerebral palsy. In summarizing the work up to 1990 on postural, locomotor and manual disabilities of spastic hemiplegic children, Sugden and Keogh (1990) concluded that a principal underlying problem seemed to be poor temporal ordering of muscle contractions. This could account for the observed jerkiness and inaccuracy of movement. Perceptual dysfunction could be a contributing cause of disordered timing of muscle activity.

In Edinburgh we have been measuring basic perceptuo-motor functions in hemiplegic children (Lee et al., 1990; Van der Weel et al., 1991; Wann, 1991; Van der Meer et al., 1995b). In the present paper we will review some of these studies. In particular we focus on the studies that address the question as to what extent children with cerebral palsy are capable of (1) picking up predictive perceptual information and (2) using that information adequately for the prospective control of movement.

The first two studies that will be reviewed deal with two fundamental perceptuo-motor functions that are necessary for the adequate *pick up* of prospective movement control information. The first study investigates the ability to stabilize vision on the environment and on moving objects by means of coupled head/eye movements. The second study assesses the ability of cerebral palsied children to link felt position sense to visual position sense – an ability that is essential for the development and maintenance of coordinated movement.

The remaining studies that will be reviewed deal with the question as to whether cerebral palsied children are capable of *using* prospective movement control information adequately. The theoretical model of control of speed of approach which was outlined above has been used as one of our methods for measuring normal perceptuo-motor control (Lee et al., 1991; Lee et al., 1992a; Lee et al., 1993). How such detailed descriptions of the use of prospective perceptual information for movement control can also be used in studying handicapped movement behaviour is shown in the last three studies described in this paper.

2. Control of head and eye movements

2.1. Introduction

Humans generally stabilize gaze when walking, running, turning and so on by rotating both head and eyes. The precision of control is evident in the ease with which one can read from a noticeboard while twisting the trunk to and fro. As the body rotates to the left, the head turns to the right relative to the shoulders and the eyes to the right relative to the head, so that fixation is maintained.

Coordination in this task is far from being a passive process. It requires precise control of the direction of gaze through coordinated eye, head and body movements, as well as control of accommodation of the lens and convergence of the eyes.

In a study of the development of gaze stabilization in infants, Daniel and Lee (1990) found that head movement is *precisely controlled.* We here summarize those developmental results and compare them with data collected on cerebral palsied children (Lee et al., 1988).

2.2. Method

Four groups of subjects were run in separate experiments. Normal children ($n = 5$; 3–4.5 years old), cerebral palsied children ($n = 5$; 3–7 years old) and adult subjects ($n = 6$) sat on a normal chair; infants ($n = 6$; 29 weeks old) sat in car seat (see Fig. 1). In one condition the subject looked at a stationary object

Fig. 1. An infant taking part in the experiments. Note the headband, to which are attached two Selspot lights to record head orientation, and the EOG electrodes to record eye orientation.

about 50 cm away, while the chair was gently rotated from side to side. In the other condition the same object was moved from side to side while the chair was kept still. The rotation of the head and eyes were recorded with Selspot and electro-occulography (EOG) on a computer along with the movements of the object and chair. How well the head and eyes were geared onto the target was calculated from the records.

2.3. Results

2.3.1. Head / target gearing

This was measured by the cross-correlation between the direction of pointing of the head and the direction of the target (calculated over a 15 s period). Fig. 2(a) shows the average results for infants, children and adults. Between 11 and 29 weeks of age, the infants improved to near adult level in gearing the head to the target. Interestingly, most of the improvements took place by 20 weeks, which is the age when visually guided reaching and catching normally starts developing (Von Hofsten, 1980; Van der Meer et al., 1994). In fact, by 20 weeks the infants were reaching towards the object as if to grab it.

The cerebral palsied children and normal nursery children showed weaker head/target coupling than the infants. For the normal children, this could have been due to an indisposition to move their heads, since eye movements were largely sufficient to look at the video target. They, in fact, moved their heads least of all the subjects. The cerebral palsied children, on the other hand, turned their heads much more, and so their weak performance is likely due to their inability to gear their head movement to the target movement.

2.3.2. Eye / target gearing

This was measured by how well the speed of turning of the eye matched the speed of the target, as indexed by the gaze velocity error [1] (the root-mean-square relative velocity between eye and target). The infants' eye/target gearing did not improve with age and it was significantly weaker than the adults (see Fig. 2(b)). The normal children's eye/target gearing was similar to the infants. The cerebral palsied children, however, showed very weak eye/target gearing compared with all other subjects, even the 11-week-old infants. This weakness could have a common origin with their apparent weakness in gearing the head to

[1] Cross-correlation was not used in this case because of drift in EOG base level.

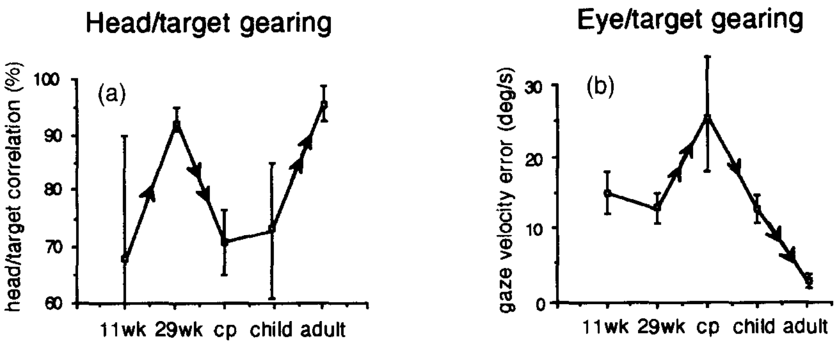


Fig. 2. Means and standard deviations of the measure of (a) head/target gearing (head/target correlation) and (b) eye/target gearing (gaze velocity error). Good performance is indicated by high correlation and low error. The subject groups were: 11 wk and 29 wk – six normal infants at these ages; CP – five cerebral palsied children with hemiparesis aged 2 yr 2 mths to 7 yr 8 mths. Children – five normal children aged 3 yr 2 mths to 4 yr 6 mths; adults – six normal adults aged 24 to 40 yrs. Single and double arrows on the graph lines indicate significant differences on t-test at $p < 0.05$ and $p < 0.01$ respectively.

the target. On the other hand, it could be that their poor eye/target gearing (which presumably was similar in infancy) handicapped the development of head/target gearing in stabilizing gaze, since that requires good visual information.

2.4. Discussion

A basic requirement for perceptuo-motor development is stabilizing vision on the environment by coupling head and eye movements, in order to optimize the pickup of information for controlling actions (Lee et al., 1989a). This function was found to be impaired in the young hemiparetic cerebral palsied children. In stabilizing gaze, the hemiparetic children's eye/target gearing and head/target gearing was weak compared with that of normal 11-week-old infants. Since it was also found that head-eye coordination in stabilizing gaze normally develops rapidly between about 11 and 16 weeks and shows quite a consistent pattern, it is likely that measures of head-eye coordination would provide valuable information about basic perceptuo-motor development in young infants with known or suspected brain damage.

Owen and Lee (1986), for instance, reported a case where, as a result of pneumococcal meningitis soon after birth, a young male infant was diagnosed as having suspected right-sided hemiplegia and right-sided neglect. It became apparent that at 21 weeks he was not controlling his head either to compensate for body movement or when tracking an object of interest. By 28 weeks, head control was improving but the head/target correlations were lower than those of the normal 14 weeks old and the head/target lag was longer. Eye movements were also jerkier than normal. The weakness of head/eye control carried through to an inability to keep the trunk erect when the child was at the normal age for sitting. Thus, studies of this kind could help in pin-pointing particular problems in the development of control, and aid early diagnosis of such problems.

3. Coupling visual and non-visual information

3.1. Introduction

In everyday life we constantly use vision to guide our actions. However, we do not, and indeed cannot, keep an eye on all the movements of all the body parts that make up an action. Therefore, it is essential to feel accurately the position of the body parts through the receptors in the joints and muscles. This information must be linked precisely to visual information about the relationship of the body to the outside world (Van der Meer et al., 1995a). The linking of information is crucial to the development and maintenance of motor competence.

3.2. Method

Lee et al. (1990) assessed this ability in hemiparetic cerebral palsied ($n = 4$) and normal children ($n = 12$), by asking them to localize objects and their own limbs with respect to the body. In particular, they measured the precision of localizing with a hidden hand (a) a visible object (seen target), (b) the other hand when it could be seen (felt and seen target), and (c) the other hand, when it could not be seen (felt target). In random order, the child positioned the slider 16 times with each hand under each of the three experimental conditions. The apparatus is illustrated in Fig. 3.

3.3. Results

The normal children actively localized the targets very accurately, with no significant difference between the hands. Whether the target was both seen and felt or only seen the error in positioning was merely 1.6–1.8 cm. When the

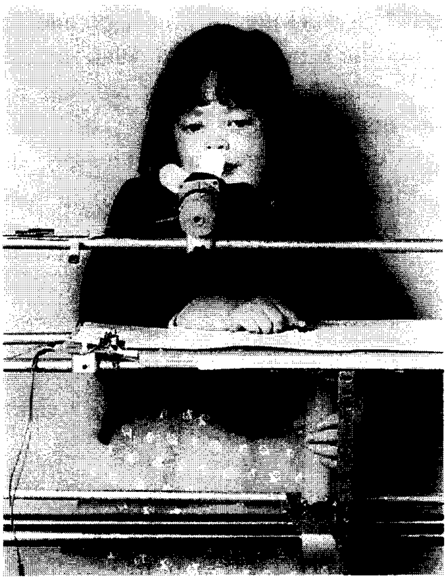


Fig. 3. Apparatus to measure ability to localize objects and one's own limbs. The child is wearing a cloak so that it cannot see its left hand and arm. With that hand the child is moving a slider along a track, attempting to line it up beneath the target button on which the right finger rests. In this case, it is a seen and felt target. With eyes closed, it would be a felt target. With eyes open and finger not on button, it would be a seen target. The three types of target were used in the experiment. The target was opposite either the child's left or right shoulder, and the child used the left or the right hand. Errors in positioning were read off the scale on the viewer's side of the apparatus. The toy in front of the child was rotated on 50% of trials on a random basis to keep up the child's interest.

target was only felt, the error was significantly higher. In short, the children were better at localizing what they could see than what they could feel. Von Hofsten and Rosblad (1988) obtained similar results with children from 4 to 12 years of age.

Fig. 4 shows for each hemiparetic child the errors in (1) visual localization of targets, (2) felt localization of the affected limb, and (3) active localization with the affected limb, as a percentage of the mean errors of the normal children. It is clear that the four hemiparetic children performed less well than the normals. Their handicap was investigated in terms of the following questions:

1. How good was visual localization of targets? This was measured by the error in localizing the seen target with the hand that was the more accurate. For the hemiparetic children this was the unaffected hand; for the normal children it was (marginally) the left hand. Two of the hemiparetic children showed significantly higher error in visual localization. This high error is probably

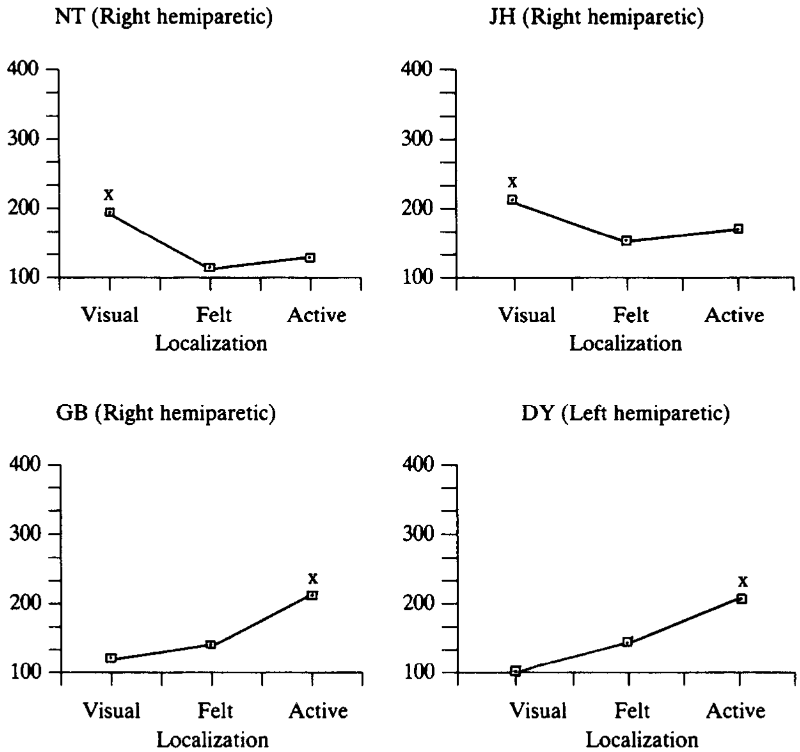


Fig. 4. Different error patterns of four hemiparetic cerebral palsied children in: visual localization of targets (pointing with the unseen unaffected hand); felt localization of the affected limb (pointing to it with the unaffected hand with eyes covered); active localization with the affected limb (pointing with it, unseen, to a seen or felt target, whichever allowed the better performance). RMS errors are plotted as percentage of the mean RMS error produced by 12 normal nursery school children. Asterisks indicate errors which are significantly ($p < 0.05$, normal test) higher than those of the nursery school children.

due to a disturbed sense of the orientation of the eyes in the head and/or of the head on the shoulders. This would affect visual localization of objects with respect to the trunk.

2. How good was the felt localization of the affected limb? For the hemiparetic children, this was measured by the error in localizing the affected hand, when it could not be seen, with the unaffected hand. For the purposes of comparison, the normal children's left hand was considered the affected one, since they were all right hand dominant; in fact, there was virtually no difference between the hands in performance on the experiment. Fig. 4 shows that none of the hemiparetic children showed a significantly higher error in felt localization of the affected hand.

3. How good was the affected limb at actively localizing targets? This was measured by the error in localizing with the affected hand (left for the normals, as above) the target, seen or felt, on which the subject performed better. Two of the cerebral palsied group showed significantly high error in active localization. This cannot be attributed to a deficiency in the felt stationary position of that limb when it had reached its endpoint, since, as just discussed, the error in the felt stationary localization of the limb was not significantly higher than normal (Fig. 4). Thus, the error would seem to be due to poor felt position of the arm when it is moving, or to an inability to put the information into action, or to both.

3.4. Discussion

Lee et al. (1989b) assessed the ability of hemiparetic cerebral palsied children to link felt position sense with visual position sense – an ability that is essential for the development and maintenance of coordinated movement. Two different forms of disorder were revealed. In two hemiparetic children the felt position of the head/eyes was affected, which impaired visual localization of objects. In two others, active localization with the hemiparetic arm was affected. Wann (1991) found similar visual/proprioceptive linking problems in cerebral palsied children.

4. Effect of task on movement control

4.1. Introduction

Detailed clinical neurological measurement of perceptuo-motor dysfunction in cerebral palsy (and other disorders) is made mainly using abstract tasks (Bleck, 1987; Brown et al., 1987; Reddihough et al., 1987). Isolated movements such as abduction and adduction of the leg, flexion and extension of the wrist, or pronation and supination of the forearm are used for assessing limb movement. Such tests measure range, speed and acceleration of movement, and muscle tone and power. But what if movement in such abstract tasks is not a good reflection of the child's ability to move in normal concrete tasks, as rehabilitation professionals commonly believe? If in fact a child does show a measurable difference in quality of movement depending on how concrete the task is, then understanding why this happens should give insight into the child's disability and enable therapy to be improved.

Fig. 5. Cerebral palsied child taking part in experiment.

To test whether children with cerebral palsy perform better on a concrete 'bang-the-drum' task than on an abstract 'move-as-far-as-you-can' task requiring the same movement, Van der Weel et al. (1991) carried out an experiment involving pronation and supination of the forearm, a movement these children tend to find difficult.

4.2. Method

Nine cerebral palsied children and 12 nursery school children were tested on a specially designed rotation apparatus (see Fig. 5). Each child performed the task under three rotation conditions: (1) passive rotation condition: The child was asked to hold the handle tightly while the experimenter rotated the drumstick back and forth in the elbow joint until passive resistance was felt (this

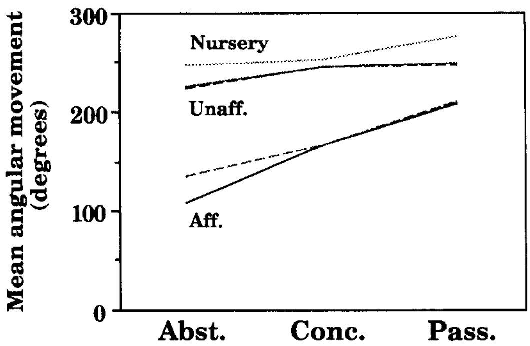


Fig. 6. Means of pronation movements (dashed lines) and supination movements (solid lines) in abstract, concrete and passive rotation conditions for nine hemiparetic CP children for each hand (affected and unaffected). Mean data for 12 nursery-school children are combined (dotted line), since no significant differences between pronation and supination or non-dominant and dominant hand were found.

measured the maximum amount of pronation and supination possible in the elbow joint); (2) abstract rotation condition: The child was then asked to try to do it on his/her own and was urged to turn the handle back and forth as far as possible; (3) concrete rotation condition: As a game, the child was encouraged to 'bang the drums' alternately with the drumstick. The experimenters on either side of the apparatus lowered the drums progressively during the 20 s Selspot recording time to facilitate optimum performance.

4.3. Results

4.3.1. Movement range

The mean results of both groups of children's average pronation and supination amplitudes in each condition are illustrated in Fig. 6. Movement range for the cerebral palsied children was significantly larger for the concrete (drum) task than for the abstract task, but the nursery children showed no such difference. The concrete task increased particularly the movement range for the cerebral palsied children's affected hand, both for supination and pronation. In supinating, all but one cerebral palsied child increased the range of movement by more than 20% when performing the concrete task. In pronating, the same increase was found for seven of the nine cerebral palsied children. The difference in range of movement was sometimes pronounced. For instance, four of the cerebral palsied children achieved a maximum supination of the forearm of $< 67°$ in the abstract task, $> 93°$ in the concrete task, i.e., an increase in range of 41% or more.

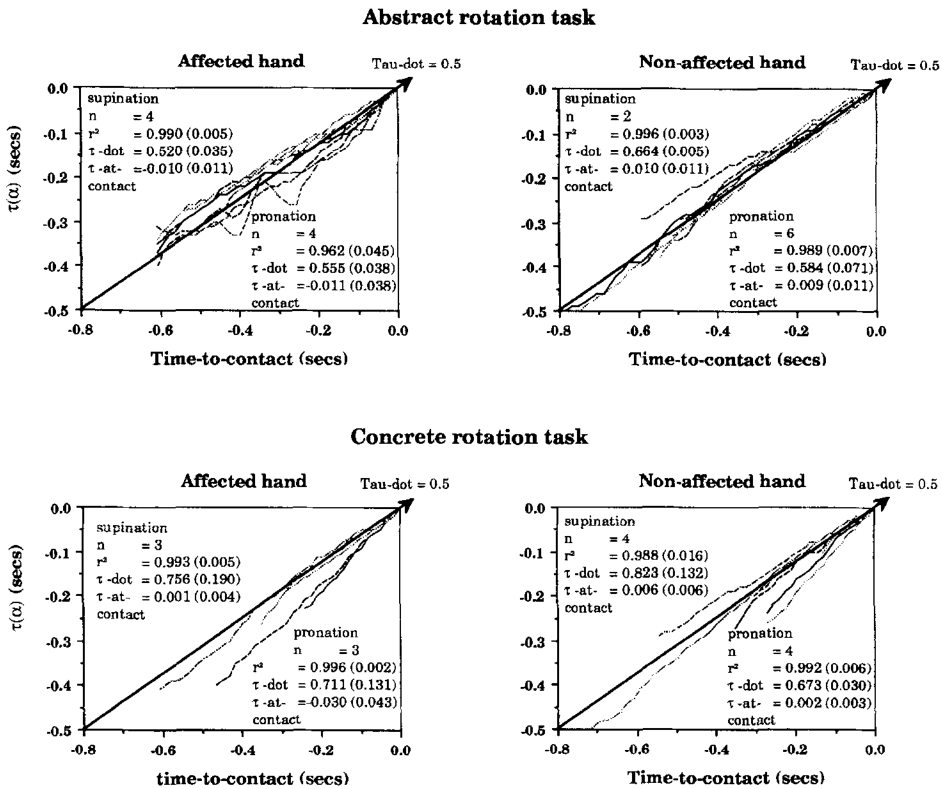


Fig. 7. Showing that the child, with both hands, kept angular tau-dot closely constant during deceleration to contact with extreme pro/supination position. Solid lines: plots for supination movements; dotted lines: plots for pronation movements. Means (standard deviations) of linear regression coefficients of $\tau(\alpha)$ against time are given in each panel. r^2 values approaching unity indicate linearity – i.e., that the rate of change of $\tau(\alpha)$ was kept constant during deceleration, as predicted. Regression slopes were always higher in the concrete rotation task than in the abstract rotation task, indicating different types of perceptuo-motor control.

4.3.2. Control of movement

The pronation and supination movements of a typical cerebral palsied child from the same subject group were also analyzed in terms of the theory of control of velocity of approach (Van der Weel, 1992). This was done in order to establish whether, between the abstract and the concrete rotation task, not only was *range* of movement different but also *control* of movement was different. Fig. 7 shows that the child, in both the abstract and the concrete rotation tasks, kept angular $\dot{\tau}$ closely constant during the deceleration phase of the movements towards contact with the extreme pro/supination position (angular $\dot{\tau} = \dot{\tau}(\alpha) =$ rate of change of $\tau(\alpha)$, where $\tau(\alpha) = \alpha/\dot{\alpha}$, and α is defined as angular position of drumstick relative to extreme position. For further explanation see above: theory of control of velocity of approach). $\dot{\tau}(\alpha)$ was kept constant at a value between 0.5 and 1.0 which means the child used a *controlled collision* procedure. The value of $\dot{\tau}(\alpha)$ was significantly higher in the concrete 'bang-the-drum' than in the abstract rotation task, indicating more forceful controlled collision.

4.4. Discussion

The cerebral palsied children achieved a significantly larger range of movement in the concrete 'bang-the-drum' task than in the abstract 'move-as-far-as-you-can' task, and, although the form of the pronation and supination movements in the abstract and concrete rotation tasks looked indistinguishable by eye, the underlying control procedures proved significantly different between these tasks. Namely, the rate at which the relationship between angular-tau and time was kept constant during the rotation movements was significantly higher in the concrete rotation task indicating that the children in this condition were 'colliding' at a higher rate with the extreme pro/supination positions. How can these results be explained and what are the implications?

Movement is not an independent process, but is generally an integral part of an act. Therefore a person's range or quality of movement will depend not only on peripheral factors, such as limits of muscular activity, but also on their ability to perform the act on which the movement is being measured. That ability, in turn, will depend on how much practice they have had performing the act, their interest in performing the act and the quality of information available for controlling the movement.

The factor discriminating concrete and abstract tasks is the degree to which the act required is directed to controlling physical interaction with the environment, as opposed to producing movement for its own sake. Concrete tasks generally have greater informational support from the environment. In the concrete 'bang-the-drum' task, the movement was controlled by visual, auditory and tactile information about the child's relation to the drum, and the attainment of the goal was readily perceptible by the child. In contrast, progression toward the goal in the abstract 'move-as-far-as-you-can' task could not be controlled by information about movement relative to the environment, but had to depend on propriospecific information corresponding to sense of muscular effort or feel for limb configuration. Therefore a likely reason why the cerebral palsied children performed less well in the abstract task is that the propriospecific information available to them was inadequate for the act. Consequently they could not demonstrate fully their potential for making the movement. This concurs with Lee et al. (1990) who found proprioceptive deficiencies in hemiparetic children.

These findings have practical implications for measuring perceptuo-motor dysfunction in cerebral palsy. Most methods for measuring limb movement use only abstract tasks or passive movements. These results show that a measure of movement in a concrete task can better reflect a child's ability to move than the equivalent measure in an abstract task. Therefore concrete tasks also need to be used in assessments in order to obtain a full picture of the child's ability. The difference between measures on abstract and concrete tasks should also help in making more detailed diagnoses regarding, for example, proprioceptive or other perceptual deficiencies. Thus, it should be possible to accommodate the child with therapy better tailored to his or her deficit.

5. Perceptuo-motor control in premature at risk infants

5.1. Introduction

Catching a moving object requires the pick-up of predictive information and rather advanced timing skills. Von Hofsten (1979, Von Hofsten (1980, Von Hofsten (1983) has shown that as soon as infants start reaching for stationary objects around 4 months of age they can also catch moving objects quite well. To catch accurately a fast moving toy requires prospective control of eye, head and hand movement. Head and eye movements in tracking should anticipate the moving toy and the hand should be aimed at the place where the toy will be caught rather than where it is seen when the reach is initiated. This means that infants have to be able to predict an object's future location.

Recently, we investigated the development of prospective control of the head-eye-hand coordination system in six healthy, full-term infants while reaching for a temporarily occluded moving toy (Van der Meer et al., 1994). We then compared the results with those of ten infants who were classified neurologically at risk of brain damage because of prematurity and low birthweight (Van der Meer et al., 1995b).

5.2. Method

Fig. 8 shows a photograph of a 11-month-old baby taking part in the experiments. The infant was strapped safely into a car seat facing the middle of a horizontal track. Within reaching distance, small attractive toys were placed on

Fig. 8. A 40-week-old infant taking part in the experiment.

a rod that moved at four different speeds on the track to and fro in front of the infant. In order to catch the moving toy, the infant had to reach through the gap between two transparent perspex screens which were placed between the infant and the track. Two 7.5 cm wide occluders, obscuring the last part of the toy's approach, were attached to the screens on each side of the reaching gap. There was one occluder for when the toy was moving from the infant's left and one for when it was moving in the opposite direction. The motion of the toy and the infant's arm movements were monitored by a Selspot system. Infra-red LEDs were fastened onto soft bands around the baby's wrist and on the toy, and were viewed by an overhead camera. Each session was also videotaped, and the times the infant's gaze arrived at the point where the toy would reappear from behind the occluder were taken from the video record.

5.3. Results

We found that all the healthy, full-term infants in the catching study showed prospective control of both gaze and hand. In all but the youngest (20 weeks old) infants, gaze shifted to the catching place on average 0.6 s before the toy had disappeared behind the screen. By the time the infants were 10 months old, the hand also started to move before the toy had disappeared. In the premature group, all but one of the infants showed prospective control of both gaze and hand in their final testing session at one year corrected age. However, anticipation of the toy's disappearance with gaze was considerably delayed in all

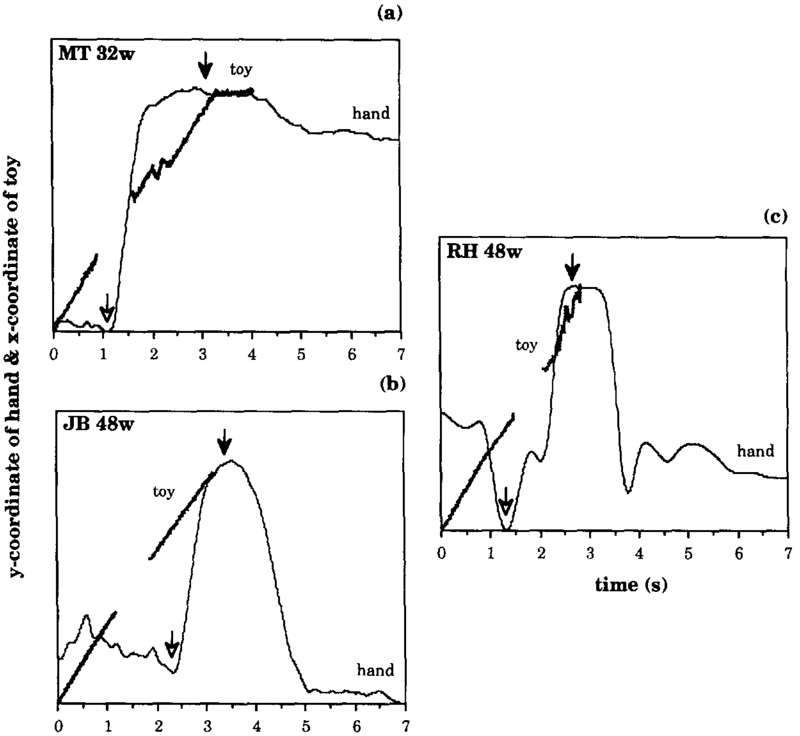


Fig. 9. Typical records of hand movement in relation to motion of toy of three premature infants. (a) Typical y-coordinate record of hand movement (thin line) relative to x-coordinate record of toy motion (thick line) in MT at 32 weeks of age with toy travelling at 10.5 cm/s. The interruption in the toy record represents the period of time that the toy was behind the occluder. Note that the hand started moving forward (open arrow) about 0.45 s before the toy reappeared from behind the occluder. Anticipating the reappearance of the toy with the hand is normal for a 32-week-old. The closed arrow indicates when the toy was caught. (b) Typical y-coordinate record of hand movement relative to x-coordinate record of toy motion (11.5 cm/s) in JB at 48 weeks of age, not showing anticipation of toy's reappearance. Note that the hand started moving forward in reaction to toy's reappearance. JB was one of the infants from the premature group who was diagnosed as suffering from mild Cerebral Palsy at 18 months corrected age. (c) Typical y-coordinate record of anticipation in hand movement relative to x-coordinate record of toy motion in RH at 48 weeks of age, with the toy travelling at 11.5 cm/s. Note that the hand started moving forward about 0.2 s before the toy had disappeared behind the occluder. Anticipating the toy's disappearance is normal behaviour for a 48-week-old.

premature infants. Also, only three out of ten premature infants anticipated the toy's disappearance with their start of hand movement by the age of one year (see Fig. 9).

The information used by the infants for prospectively controlling the *timing* of shift of gaze and movement of hand appeared to change with age. The normal infants up to 8 months seemed to use a Distance Strategy that involved shifting gaze and starting to move the hand when the distance of the toy to the reappearance point reached certain values. This meant that as the speed of the toy increased, the available time to arrive with the gaze at the reappearance point and start the hand moving was reduced. Thus, the Distance Strategy is not efficient since it entails moving the hand increasingly faster the faster the toy, until the hand can move no faster. From the age of 10 months, the normal infants changed strategy to a Time Strategy that entailed shifting their gaze and starting to reach when the toy was certain *times* rather than distances away from the reappearance point. They thus kept the time to gaze arriving and hand starting about constant, so that as the speed of the toy increased, the distance of the toy from the reappearance point increased. In this way, the infant always made available the same average time to catch successfully whether the toy was moving slowly or quickly.

In the at risk group, only one infant switched strategies at the same age as the normal infants. However, by the age of one year another seven infants showed evidence that they were using the Time Strategy, gearing their actions to when the toy was certain times away from the reappearance point. However, two infants from the at risk group still seemed to use the less efficient Distance Strategy when shifting their gaze and starting to move their hand at their final reaching session at the age of one year. These infants also showed the least anticipation of the toy's reappearance with their hand. The same two children were unique in the at risk group in having neurologically abnormal scores on standard tests. At 18 and 21 months they were diagnosed as having mild and moderate Cerebral Palsy. The diagnoses were made by a paediatric consultant at the local hospital and were revealed to us only after the data analysis of the catching studies was complete. Thus poor development of prospective skill on the catching task is very likely to serve as an indicator of brain damage.

5.4. Discussion

Greater understanding of both normal and abnormal development of use of perceptual information in prospectively guiding action might therefore have important diagnostic and therapeutic consequences. The mastering of reaching and grasping normally develops very early and it provides a foundation for more specific perceptuo-motor skills that rely on these abilities. Catching, for example, requires the pick-up of predictive information and quite advanced timing skills. Thus if there is a problem with basic timing of action, then more complex timing skills might also be affected later on in life.

6. Timing interceptive actions

6.1. Introduction

Similar interceptive timing actions were also analyzed to determine what kind of perceptual information cerebral palsied ($n = 6$) and nursery school children ($n = 6$) used to initiate their hands to strike an approaching ball (Van der Weel et al., 1995).

6.2. Method

The children sat on a chair close to a table with a track directly in front of them (see Fig. 10). A ball could be rolled down the track at three different speeds. This resulted in the ball accelerating towards the subjects, reaching a final velocity of 0.24 m/s at velocity 1, 0.36 m/s at velocity 2, and 0.44 m/s at velocity 3. The task for the children was to intercept the approaching ball and knock it off the track as it passed. In each case, if the ball was struck properly it knocked over a pile of empty cans placed at the side. Infrared light emitting diodes were fixed to the children's wrists and bats, making four LEDs in all.

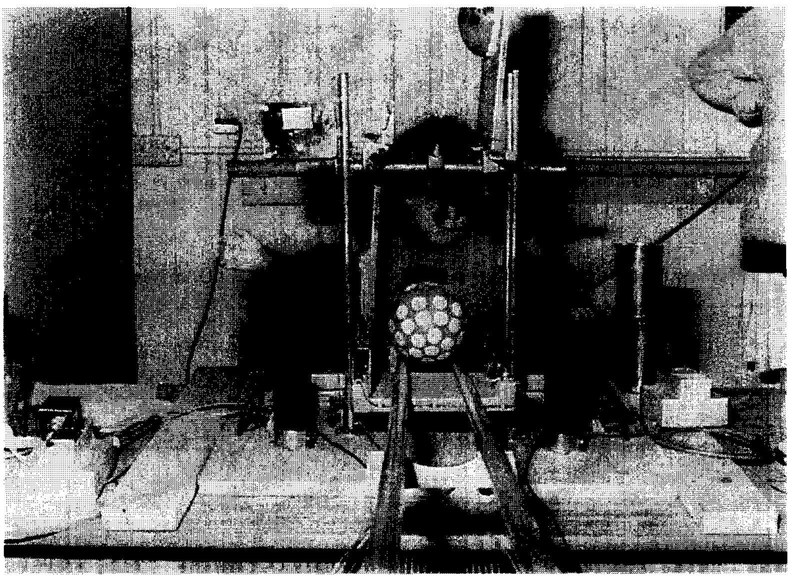
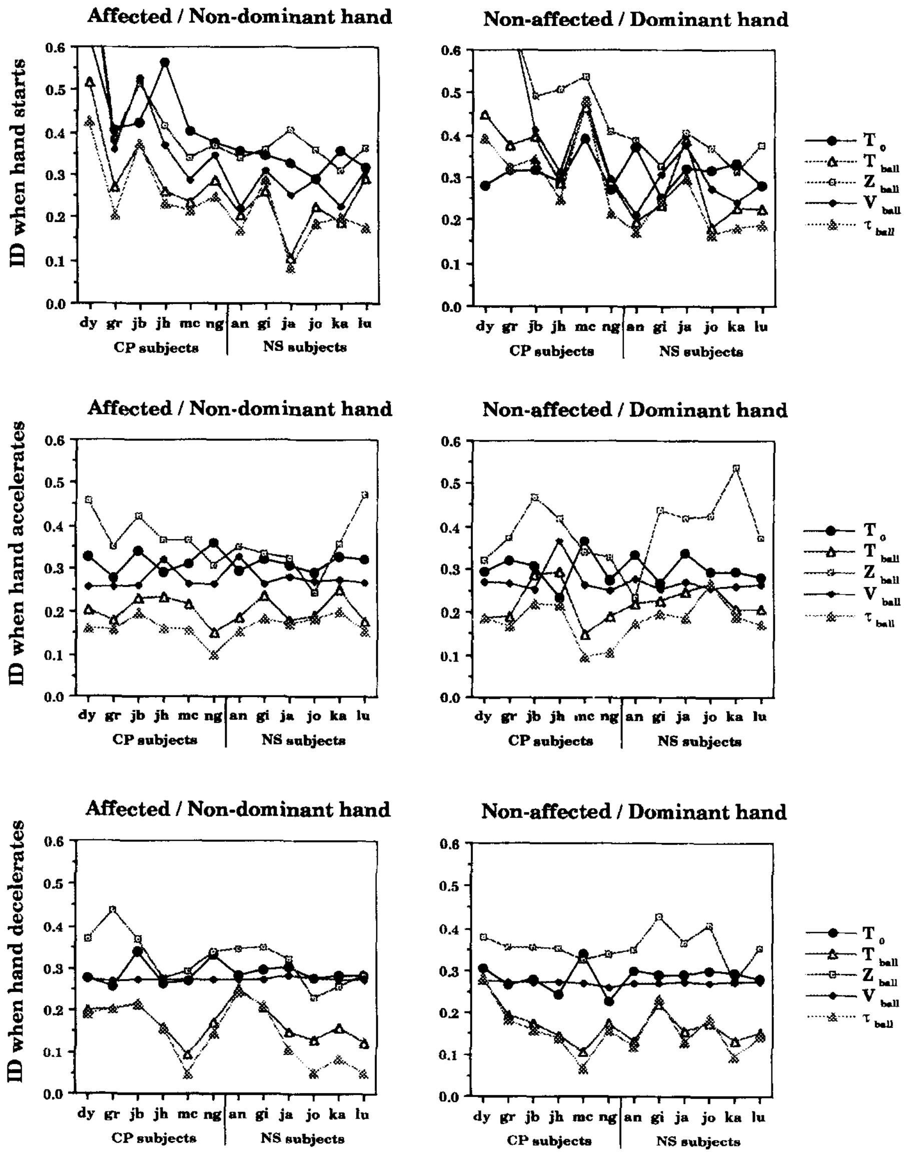


Fig. 10. Nursery school child taking part in the experiment.

These were viewed from above by a Selspot camera. We also carried out a separate video analysis in order to record the movement of the approaching ball. In order to determine what underlying control procedures were being used and



possibly might be defective in the cerebral palsied children we sought answers to two questions:

Question 1. What perceptual variable governed when the children initiated different phases of their hand movement when reaching to strike the bat?

We considered five possible perceptual variables that might govern when the children (a) started to move their hand (HS), (b) started to accelerate it (HA) and (c) started to decelerate it (HD). The five possibilities considered were: Initiation point (1) occurs a certain time (T_0) after the ball is released; (2) it occurs a certain time (T_{ball}) before the ball is due to arrive at the bat; (3) it occurs when the ball is a certain distance (Z_{ball}) from the bat; (4) it occurs when the ball reaches a certain velocity (V_{ball}); (5) it occurs when the tau function of the distance between ball and bat ($= \tau_{ball} = Z_{ball}/V_{ball}$) reaches a certain value.

To determine which of these variables most likely governed the start of hand movement, the start of hand acceleration and the start of hand deceleration, we sought the variable that showed the least variability at those initiation points. Since the putative governing variables are measured in different units (cm, sec, cm/sec^{-1}), the standard deviation cannot be used to compare variability. What is required is a dimensionless quantity. We chose the index of dispersion = standard deviation/mean, and computed the standard deviation and mean of each variable across the three different ball speeds for each subject and each hand separately. The individual values for T_0 and T_{ball} at HS, HA, and HD were taken from the Selspot records directly. The values for Z_{ball}, V_{ball}, and τ_{ball} at these three initiation points were obtained from the video calibration data. The results are presented in Fig. 11.

6.3. Results Q1

In general, the index of dispersion of τ_{ball} was smaller than that of T_0, T_{ball}, Z_{ball} and V_{ball} at each initiation point and for all children. Thus τ_{ball} was

Fig. 11. In each graph, the indices of dispersion of the five initiation variables are plotted for the two groups and for each child separately. Between graphs, the affected/non-dominant hand is compared with the non-affected/dominant hand at each of the three initiation points HS, HA and HD. The closed triangles, representing τ_{ball}, appear always at the bottom of the graphs, showing that the indices of dispersion of τ_{ball} were smaller than those of T_0, T_{ball}, Z_{ball} and V_{ball} for the cerebral palsied children's affected hand and non-affected hand and for the nursery children's non-dominant and dominant hand. This indicates that, although the ball was travelling under constant accelerative approaches, the τ_{ball} variable was, in fact, the governing variable for initiating the striking actions.

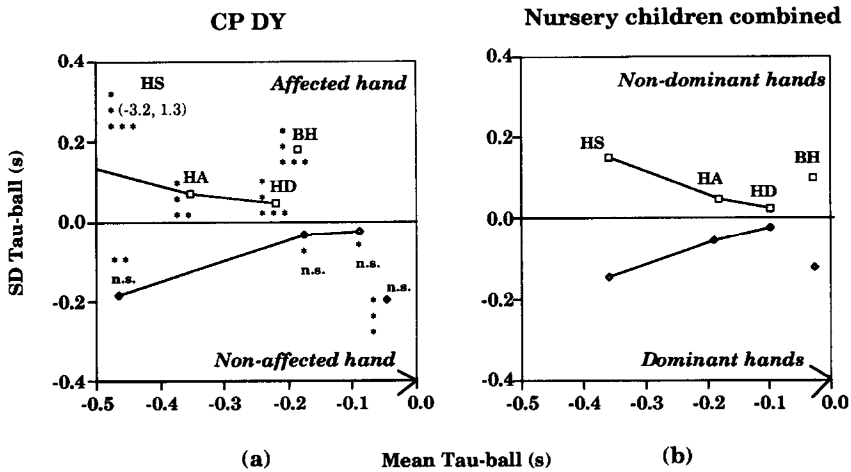


Fig. 12. Typical graphs of (a) cerebral palsied child and (b) combined nursery school children. Standard deviations of τ_{ball} plotted against mean values at (reading from left to right) the three initiation points HS, HA, HD and at the moment the bat was hit (BH) for the affected/non-dominant hand(s) and non-affected/dominant hand(s). Note that standard deviations of the non-affected hand and dominant hands are plotted with negative values. This was done for display purposes only. Significance levels ($^{***} = p < 0.0001$; $^{**} = p < 0.005$; $^{*} = p < 0.01$) indicate differences between CP child and combined nursery school children. Asterisks in horizontal orientation indicate significant differences in mean τ_{ball} and asterisks in vertical orientation indicate significant differences in standard deviation τ_{ball}.

indicated to be the most likely governing variable for initiating different phases of the bat striking actions.

Having established that both the CP children and the nursery children most likely used the τ_{ball} variable as the governing variable when initiating the striking actions, we then investigated whether there were any differences in the use of τ_{ball} between the groups of children and hands used (see Fig. 12).

These results showed that for the cerebral palsied children the striking action was initiated (HS) much earlier with the affected hand than with the non-affected hand. That is to say, the affected hand started the striking action always at a larger τ_{ball} value than the non-affected hand did. Between the nursery children's non-dominant and dominant hand there was no such difference. The CP children's variability in τ_{ball} at initiation point HS was also higher than the nursery children's both for the CP children's affected and non-affected hand.

At initiation points HA and HD the affected hand of the CP children was still significantly earlier than the nursery children's non-dominant hand except for the two least affected CP children. The standard deviations at these initiation points showed a similar division, namely they were significantly higher for the affected hand of the four most affected CP children.

Overall timing performance of the two experimental groups at initiation point BH (Bat Hit = timing error) was slightly early. No significant differences were found between the CP group and the nursery group as a whole. However, separate tests on the individual CP children showed that the four most affected CP children had significantly higher timing errors with their affected hand and non-affected hand compared to the non-dominant hand and dominant hand of the nursery children. Further, all CP children were less consistent in their terminal timing performance. Namely, they had significantly higher standard deviations at initiation point BH.

6.4. Discussion Q1

Statistical analyzes on initiation points HS, HA, and HD revealed that for both the affected and non-affected hand in the CP group and for both the dominant hand and non-dominant hand in the nursery group, the variability of τ_{ball} at HS was larger than at HA, which was in turn larger than at HD. This decrease in variability indicates a zeroing-in of successive initiation actions towards arrival of the ball at the striking place. In other words, the act of reaching out and striking the bat was under continuous prospective visual guidance, the hand being geared to the value of τ_{ball}; if the striking action had been pre-programmed, variability should have increased towards the end of the action because of the variability in movement time.

These results were confirmed by the fact that a high correlation existed between the children's movement time and initiation variable τ_{ball}. Namely, the high positive correlation between these variables indicated that the striking actions were being modulated to fit the available time-slot. This means that if the children's preparatory striking actions were initiated at a numerically higher (or smaller) than average value of τ_{ball} then they made the subsequent movement up to the moment the bat was struck longer (or shorter). The correlation coefficients for the nursery children were significantly higher than those for the CP children, suggesting a tighter coupling between movement time and τ_{ball} in this group. Also this correlation dropped for the CP children at initiation point HD, indicating less precise regulation of duration of deceleration.

Question 2. How did the children regulate deceleration of the hand in order to reach the bat at the same time as the ball?

Such perceptuo-motor control might seem to require complex neural computation based on registering the arm's and the ball's position, velocity and

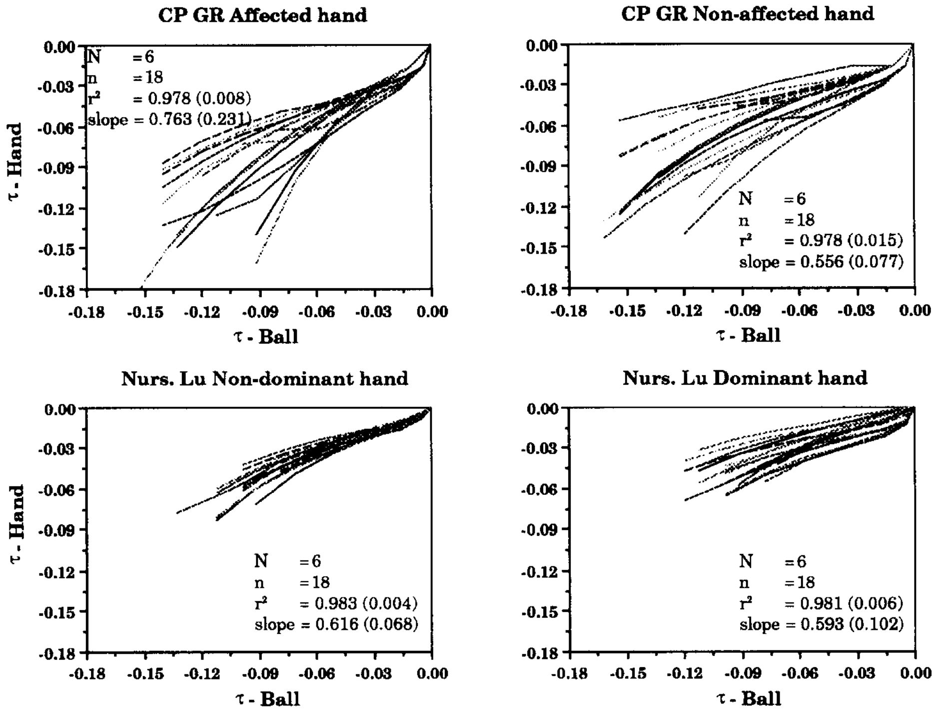


Fig. 13. Typical graphs of a cerebral palsied child's affected and non-affected hand (top two graphs) and a nursery school child's non-dominant and dominant hand (bottom two graphs). Means and standard deviations of linear regression coefficients for *all subjects* tested are given in each panel for each hand. The cerebral palsied children and the nursery school children with each hand maintained a close linear relation between τ_{hand} and τ_{ball} when the hand was decelerating to hand-bat contact. (r^2 values approaching unity indicate linearity.)

acceleration. However, extending the constant $\dot{\tau}$ theory of control of approach leads us to the hypothesis that deceleration is controlled by attempting to keep τ of the hand relative to the bat (τ_{hand}) proportional to τ of the ball relative to the bat (τ_{ball}). If this were achieved it would ensure that τ_{hand} and τ_{ball} reached zero simultaneously; i.e., that the hand reached the bat at the same time as the ball.

6.5. Results Q2

Fig. 13 shows plots of τ_{hand} against τ_{ball} during deceleration of the hand towards the bat, together with the summary linear regression coefficients. In one important respect the cerebral palsied children and the nursery children behaved similarly. They all maintained a close linear relation between τ_{hand} and τ_{ball}.

(The r^2 values for the plots were all very close to 1.0, the value corresponding to perfect linearity). In this regard it does not appear that the CP children were particularly handicapped with their affected hand.

However, some CP children seemed clearly affected on another aspect of the hit. This becomes clear if we concentrate on where the regression plots intercept the τ_{ball} axis. If τ_{hand} had been kept proportional to τ_{ball} then not only should the plots be linear but also the intercept should be at $\tau_{\text{hand}} = 0$. For the nursery children the intercept was consistently close to zero, which corresponds to the ball and hand reaching the bat at the same time. However, for the most affected CP children the intercepts were significantly less than zero, corresponding to the hand being late, and were quite variable. This fits with the data in Fig. 12 which also shows timing errors on the early side.

6.6. Discussion Q2

The significant non-zero intercepts together with the high r^2 values indicate that the CP children were, like the nursery children, trying to keep τ_{hand} proportional to τ_{ball}, but on each trial there was an appreciable error on the perceptual side of their estimate of τ_{ball} and/or τ_{hand}, that error remaining constant during the trial. The CP children did not appear to err so much on the movement side because their r^2 values were as high as the nursery children's.

7. Summary and general discussion

Current assessment of movement disorder in the cerebral palsied child mainly uses measures of surface behaviour, but these measures cannot reveal the underlying causes which therapy needs to address. Devising effective therapy requires in-depth measures of the child's perceptuo-motor functioning. The work reported in this paper aimed to develop such in-depth measures of basic movement control mechanisms in cerebral palsy.

Daniel and Lee (1990) and Lee et al. (1989a) were concerned with two basic perceptuo-motor functions which are necessary for the control of many actions. The first was locking the eyes on an aspect of the environment when that or the person was moving. This basic skill is necessary for the accurate visual control of movement. The second was linking visual information about the position of an object to proprioceptive information obtained through receptors in the muscles and joints about the position and movement of a limb. Such linking of information is necessary for gearing actions to the environment. Both these functions were found to be impaired in young hemiplegic children who, however, showed different forms of disorder. In some children, the sensed position of the head/eyes was disturbed, which impaired visual localization of objects. In others, active localization with the affected arm was disturbed. Wann (1991) found similar visual/proprioceptive linking problems in cerebral palsied children. These findings further suggest that perceptual dysfunction is implicated. A similar conclusion was reached in the study by Van der Weel et al. (1991) where it was found that increasing the richness of visual information for controlling movement increased something so basic as range of limb movement in children with cerebral palsy.

Special attention has also been directed to the timing aspect of movement control. Van der Meer et al. (1995b) showed that two out of ten infants at risk from brain damage used less efficient strategies for catching moving objects. At 18 and 21 months these children were diagnosed as having mild and moderate Cerebral Palsy. Thus, poor development of prospective skill on the catching task could likely serve as an indicator of brain damage.

Measures of normal and abnormal development of use of perceptual information in prospectively guiding action also has important diagnostic potential for older children. The theory of control of speed of approach to a goal (Lee et al., 1991; Lee et al., 1992a; Lee et al., 1993) was used to pin-point perceptual difficulties in the cerebral palsied child (Van der Weel, 1992; Van der Weel et al., 1995).

These studies investigated what perceptual information was used by CP children and nursery children when performing an interceptive timing task. The results showed that both the CP children and the nursery children, using either hand, used τ_{ball} ($= Z_{\text{ball}}/V_{\text{ball}}$) as the governing variable for initiating their hand movement. The whole act of striking the ball was under continual visual guidance, that was kept geared to τ_{ball} until the moment the bat was hit. The results further showed that the CP children initiated the striking much earlier (i.e., at a significant larger value of τ_{ball}) with their affected hand than the non-affected hand. This strategy was probably taken to 'create' extra time in order to allow for the fact that the affected hand was more difficult (i.e., slower) to move. Overall terminal timing performance (timing error) was slightly early. Especially the four most affected CP children had significantly higher timing errors with both hands. All CP children were also less consistent in their terminal timing performance.

However, not only their terminal timing performance was less accurate and also more variable, but various other aspects of their timing performance was so too. This became evident from analyzing deceleration of the hand in order to reach the bat at the same time as the ball. This was probably due to an error in perception rather than in movement execution. The CP children did not appear to err so much on the movement side, because the linearity of τ_{hand} against τ_{ball} was as high as the nursery children's. Rather they appeared to err in their perception of the value of τ_{hand} or τ_{ball}, the approximately constant error during a reach being quite variable between reaches. This, of course, fits in with their larger timing error in hitting the bat.

Detailed assessment of perceptuo-motor disorders, such as described in this paper, in which perceptual variables and motor variables are assessed in close relation to each other, is essential. This is because it is the perceptual information that gears the movement of the effector to the destination. Thus kinematic variables of movement must have their counterpart in variables of the perceptual flow during the movement. This means that deficiencies in picking up perceptual flow variables will impose constraints on the control of kinematic variables.

This could have important implications for devising rehabilitation programs for children suffering from CP. In particular, therapies for overcoming motor disorder should not only concentrate on promoting *movement patterns* as such, which may or may not transfer to *perceptuo-motor* activities of daily life, but should also concentrate on these activities directly. To facilitate perceptuo-motor learning and rehabilitation, all sources of perceptual information relevant to the performance of the task should be present during the acquisition process (Van der Weel, 1992).

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