Using the Head to Stabilize Action: Reaching by Young Children

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Abstract— **Even seemingly simple reaching task requires complex integration or remapping of reference frames with respect to eye, head and hand. Head-centered reference frame and head movement may play important roles in natural tasks and in the development of reaching. To understand the underlying control mechanism that support smooth reaching in particular and the seamless coordination of head and hand movements more generally, a semi-naturalistic experiment is designed for 1 ½ to 5 years old children, in which children are free to reach or not reach for the ball coming out from the slots on the puppet show. The fine-grained head and hand motion data were recorded. The analysis results show that (1) All the children participants stabilize their heads right before the reach; (2) During the reach, the head and hands move synergistically in the same direction. (3) Large and variable head movements co-occur with more variable and jerky reaches. The coupling of the head and hands may suggest a dynamical integration of multiple reference frames.**

Keywords- Head stabilization, Head hand coordination, Child reaching, Reference frame

I. INTRODUCTION

How do we use our body to reach a moving visual target? How to build a robot control system that can generate smooth and coordinated movements from different body parts? The seeming ease and ordinariness of reaching behavior in humans belies its underlying complexity. One source of this complexity is the coordination of sensory and motor systems, each with their own reference frames (e.g.,[1, 2]). For example, reaching to an object typically involves turning the eye or head to the object and then moving the hand in the direction of eye-gaze [3]. But the spatial coordinates of the object with respect to the eye, the head, and the hand are all different and require integration [4] or remapping into a common reference frame [5]. Laboratory studies of adult reaching often fix head position and most contemporary theories of reaching assume that the common reference frame is eye-centered.

While relatively little is known how heads, hands, bodies and eyes move together in more natural tasks, a number of adult studies suggest that head direction and head movements may play a strong role in stabilizing eye-gaze direction in natural action contexts (e.g., [6, 7, 8, 9]). Head (and body) centered frames of reference may play a particularly important role in natural tasks in which there is continual movements, many shifts of attention, and many targets that are not pre-specified as such and that emerge in a sequence of ongoing behaviors. Consistent with this idea is considerable research with adults that shows optimal reaching occurs when hand and eye movements to the target that are combined [3,10, 11].

Head movements may be a particularly critical factor in the development of reaching. Infants' first reaches (at about five months) require tight control of trunk and head to successfully grasp a single presented target [12]. By the end of the first year, infants reach more flexibly and fluidly, but head and hands still appear strongly coupled [13]. There is little research on the development of reaching beyond this period. There are several hints of potentially significant developmental changes in the coordination of reference frames, particularly in a possibly dominant head-centered frame. First, in natural tasks, active toddlers move their heads a great deal causing highly dynamic visual experience [14]. Second, the head appears to be stabilized when toddlers are holding and visually viewing an object [14]. Third, even children as old as 4 and 5 year old appear to have difficulty isolating eye movements from head movements [15].

Understanding how children coordinate head and hand – and how they may use the head to specify and organize reaches is important both for understanding the multiple reference frames for actions and for building artificial devices that reach fluidly in complex and natural tasks. What human adults do via an eye-centered reference frame may be more easily accomplished via a head (and body) reference frame. Thus, head-oriented reaching can be a more feasible engineering solution if we can discover the underlying mechanism of how humans coordinate the head and hand movements and if such mechanism can be easily implemented in an artificial system (e.g. controlling a moving head appears to be easier than more precise controls and subtle gaze directions). Accordingly, the purpose of the present study was to examine the coordination of head and hand movements in the spontaneous reaching behavior of developing children.

To these ends, we developed an engaging and semi-naturalistic task, illustrated in Figure 1a and 1b. The child sits in front of a puppet theatre. Brightly painted and textured balls emerge from behind the screen and wiggle in playful fashion toward the infant. Throughout this continuous procedure, the infant is free to reach or not reach, to reach when the object is far or to wait until it is close. This task was specifically created to be like natural tasks, engaging with multiple reaching targets and events in different spatial locations and with the dynamics of these events determined in part by the participant's own interests and activities. We used a motion tracking system to record the positions and orientations of both the head and two hands when the child performed the reaching task.

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II. METHOD

A. *Participants*

Twenty-nine young toddlers (15 female, 14 male) ranging in age from 17-months to 61-months participated in this study. For analyses, the children were partitioned into three age groups: Group 1 -- 17.03 to 24.90 months of age (M = 22.11 months of age, SD = 2.68, n = 8, 4 female, 4 male), Group 2 -- 28.60 to 38.0 months of age (M = 32.49 months of age, SD = 2.41, n = 13, 7 female, 6 male), and Group 3 -- 50.13 to 61.10 months of age (M = 55.80 months of age, SD = 3.81, n = 8, 4 female, 4 male). Another 19 children were recruited but did not contribute data due to either refusal to wear the equipment, experimenter error, or equipment failure.

B. *Experimental setup*

Participants were seated in front of the puppet-show shown in Figure 1. On the puppet-show there were three open slots in front of the child. One slot was located at the center and the other two were at the left and the right respectively. During the experiment, a moving ball would appear from one of those three slots. A video camera was located under the puppet theatre and an overhead video camera mounted was also used to record the child's activity from a bird's eye view. The motion trackers (Polhemus LIBERTY 240/8) were attached to sports head band that was placed on the child's head, and two wrist bands with one sensor on each hand (Fig. 1c).

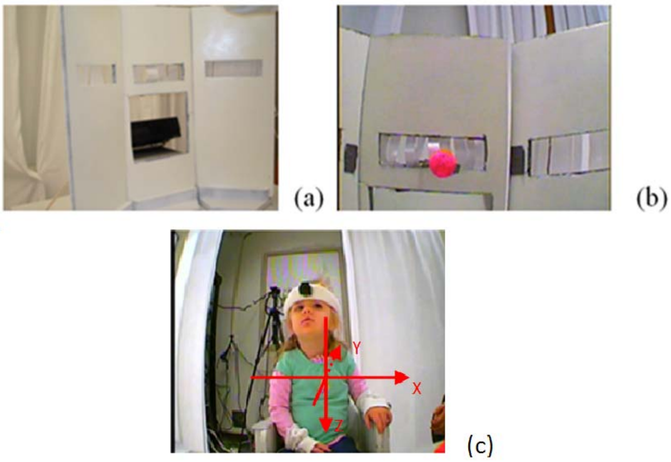


Figure 1. (a). The puppet-show apparatus. (b). Example of the colorful toy ball that the participants interacted with. (c) Participant with the motion sensors on the hands and head. The red coordinates shows the direction of location data (x,y,z) from motion sensors.

C. *Procedure*

Once the child was seated in front of the puppet-show apparatus and all head and hand sensors were attached, the session began. The session consisted of several trials and the trials lasted as long as the child is engaged in. For each trial, the experimenter stood behind the puppet-show apparatus and pushed a colorful ball on a wooden dowel through one of three small slots in the puppet-show apparatus so that the participants could reach for it. After reaching for the ball, the child might play or hold the ball for a while. Once the child drew his or her hand back from the ball, the experimenter drew the ball back behind the puppet theatre though the slot. In case that the child did not try to reach, the trial was invalid and the experimenter also drew the ball back. Immediately after the current trial with a brief break, the experimenter started a new trial wherein the slot used in the new trial might be same or different with the slot used in last trial.

D. *Data Analysis*

Head and hand motion sensor data were collected at the frequency of 240 Hz. Each sensor produced a six dimensional vector at any sample over time corresponding to three dimensional location information (x, y, z) and the orientation information along the three physical axes (h-head, p-pitch, r-roll). (The directions of x, y and z are: X axis is from the right side to the left side of the child; Y axis is from the front to the back the child; Z axis is perpendicular to the ground). Those motion tracking data were down-sampled to 60 Hz and then were low-pass filtered with a three-point zero-phase Butterworth filter with a cut-off frequency of 10 Hz. We chose this frequency and filter based on the work in [16] which collected and analyzed human body motion data in a similar scenario. The reaching events (onset and contact) were manually coded from the video from the overhead camera. Then this trial information was synchronized with position sensors. In manual coding of reaching trials, the onset was defined as the moment with a first move of the hand towards the ball. The end of reaching was coded as the moment once the hand touches the ball. The total number of reaching trials from 29 subjects is 349, which is used in the following data analysis.

III. RESULTS

A. *Reach Distance*

All of the results reported are based on a comparison between three age groups (labeled as G1, G2 and G3 in all of the figures). Figure 2 show the histogram of the displacement of the reaching hand from onset to contact (in inches). Our semi-naturalistic experiment didn't constrain when children should start reaching and they could start at any moment after the ball appeared. Due to this naturalistic setup, children's reaches varied considerably in their distances for all groups. However, in general Group 2 (2 ½ year olds) were more likely to reach when the ball was nearer than were the younger and the older children.

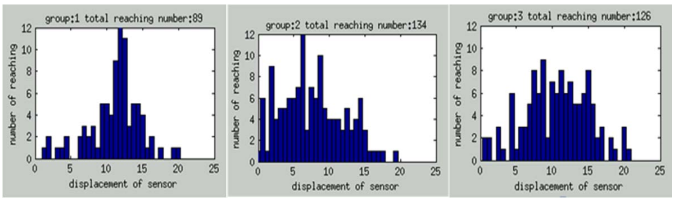


Figure 2. Histograms of reach distance (in inches). Left: Group 1; Center: Group 2; Right: Group 3

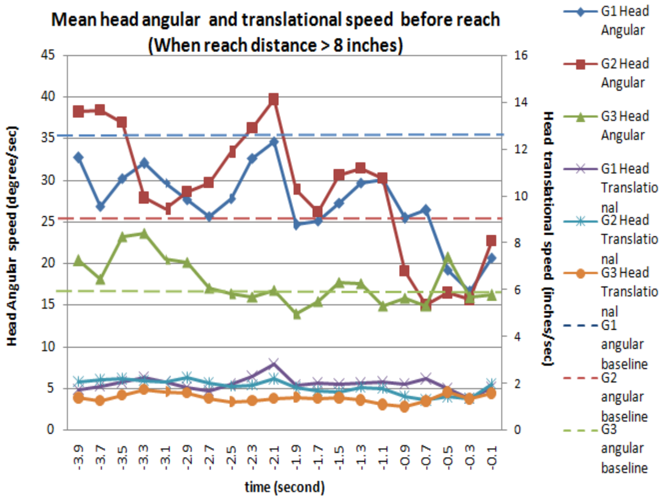
Because of this variability, we categorized reaching actions near (a distance less than 8 inches) reaching and far (a distance greater than 8 inches) reaching. We chose 8 inches so for each category the three groups have approximately equal mean of reach distance and similar variance. Also after categorizing, we can approximately equally divide reaching instances into two categories to ensure enough data in each category. We also got very similar results when we tried to categorize trials using different thresholds like 9 or 10 inches. The following results focus on discovering the patterns in those two reaching kinds.

B. Head speed before reaching

We first examined the early stage of reaching – what happened before reaching, the dynamics of the head movements as a precursor of hand reaching. As shown in Figure 3, for children at all ages, a decrease in the speed of head movements signals the start of a reach. However, this stabilization of the head varies in near versus farther reaches and also varies as a function of age. Figure 3 (upper, the left vertical axis) shows the mean angular head speed in the 4 seconds just preceding the start of a far reach for the three age groups. Overall, the youngest children’s heads are moving faster than the oldest group (4 and 5 year olds). However, the speed of angular head movements decreases for all groups in the preceding second before the start of the reach. Nevertheless, group 2 (2 ½ year olds) stabilize their head earlier than do the youngest children (1 ½ year olds).

Figure 3 (bottom, the left vertical axis) shows the mean head angular speed for near reaches. These near reaches emerge out of very stable periods of little movement for older children but out of periods of very rapid head movements for the youngest children.

Recall that the children were free to reach (or not reach) whenever they want and thus they chose when to reach -- whether to start when the ball was far or wait until it got closer. In cases of near reaches, the two older groups of children appear to watch the ball, holding the head reasonably steady, and then reach for the ball when it is close. The youngest children, in marked contrast, appear to be moving their head constantly and perhaps not centering the head on the ball until the immediately prior to the reach.



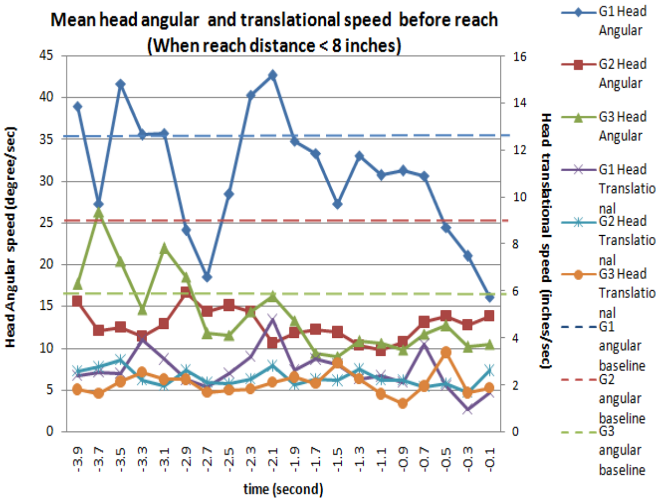


Figure 3. The mean head angular and translational speed just prior to the reach for far (top) and near (bottom) reaches. Time 0 indicates reach onset. The baselines of children’s head angular speed are the mean speeds of head rotation during the experiment sessions except the time intervals from 4 seconds before reaches to the offsets of the reaches.

Another way to think about this pattern is that youngest children’s angular head movements look the same for short and long reaches –considerable movement until just prior to the reach. The oldest children’s angular head movements also look the same for short and long reaches – minimal movement with the head centered on the ball – long before the reach. The middle group of children perform more like the oldest children on near reaches but more like the youngest children on far reaches.

Figure 3 (right vertical axis) shows the head translational speed prior to far (top) and near (bottom) reaches. Again, the youngest children show more movement than oldest group prior to both far and near reaches. The head translational speed of mid-age children is in between the youngest group and oldest group.

C. Head speed during reaching

Next, we examined head dynamics during reaching. Figure 4 shows angular and translational head speeds during the reach. For all the three groups of children, far reaches are accompanied by more rapid head movements over the course of the reach. The youngest group of children, on average, rotate their heads most at the half of the reaching process, whereas their near reaches are characterized by a burst of movement at the beginning and the end. The older children show both less and smoother patterns of head movements than younger children for both near and far reaches. The oldest group of children also rotate their heads less and less at the second half of reaches.

The comparison of Fig. 4 and 3 also shows that, except for the near reaches of groups 2 and 3, the head angular speed of children during reach is faster than the stationary head state before the reach.

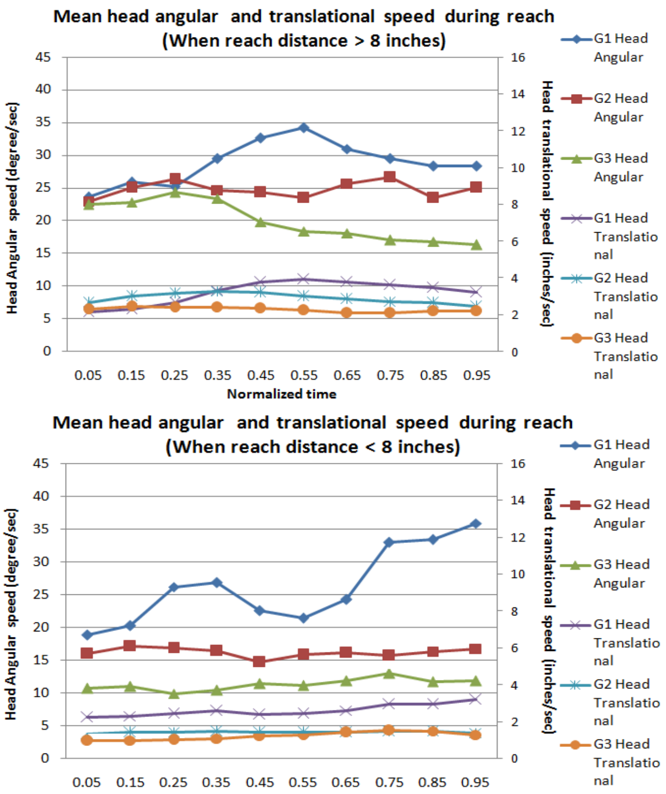


Figure 4. The mean head angular and translational speed during the reach for far (top) and near (bottom) reaches. All the reach time are normalized to 1.

D. *Hand Movement*

The next analysis is based on hand movements. In far reaches, the youngest group of children moves their hand faster than the older groups (figure 5, top). The mid-age group's mean hand speed profile has an earlier peak than the other two groups in the normalized time scale. That may suggest that the mid-age group spent more proportion of reaching time on final hand adjustment (when hand speed slowed down at the end of reach). As shown in Figure 5 (bottom), for near reaches, the velocity profiles of the hand movements themselves appear similar for all three age groups at the first half of reach whereas the youngest group of children have a burst of hand movement at the end. Also just before the contact of far reaches, the youngest group of children do not decrease their hand speed as low as the older groups do. This suggests youngest children have a more ballistic reach.

To measure the smoothness of the children's reaches, we used the norm of the jerk because minimum jerk model [17] has been used to successfully fit the hand kinematic data of adult's reaches under various experiment settings. The jerkier the movement is, the less smooth the movement is. The norm of jerk of movement is calculated by formula (1).

$$\text{Norm of jerk} = \sqrt{\left(\frac{d^3x}{\mathrm{dt}^3}\right)^2 + \left(\frac{d^3y}{\mathrm{dt}^3}\right)^2 + \left(\frac{d^3z}{\mathrm{dt}^3}\right)^2} \qquad (1)$$

where x, y, z are the positions of the hand.

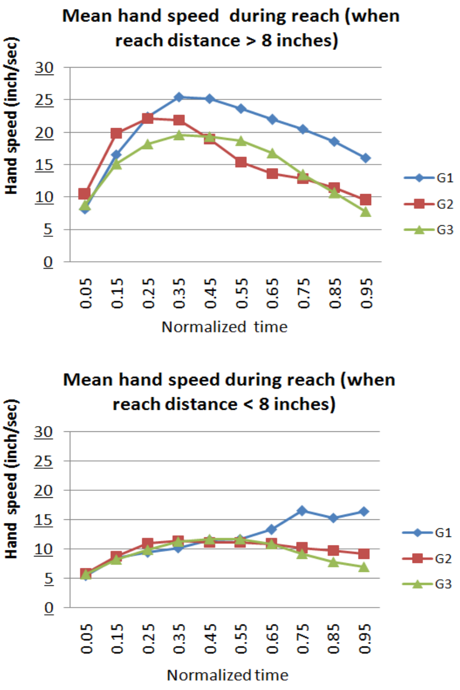


Figure 5. The mean hand speed during the reach for far (top) and near (bottom) reaches

As shown in Figure 6, the smoothness of the hands movements increase with age, even though the mean hand speed profile of three groups look similarly smooth for far reaches of three group (figure 6, top).

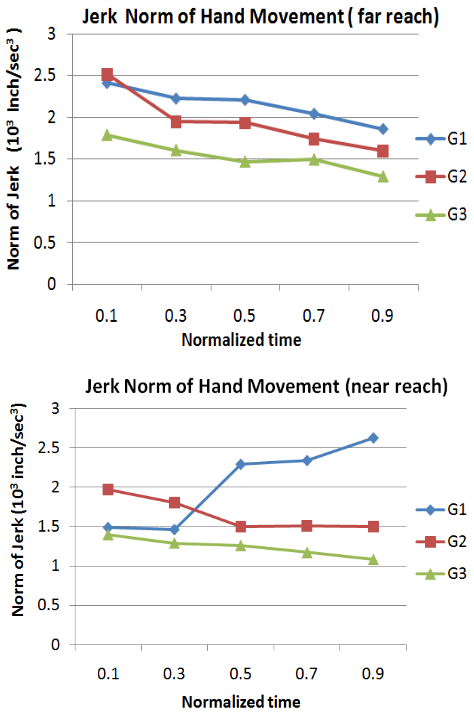


Figure 6. The mean of the norm of jerk of reach (reaching time is normalized to 1) during reaches for far (top) and near (bottom) reaches.

E. The directions of head and reaching hand movements

One of critical questions in the present study is to understand the coordination of head and hand movements. The top right of figure 7 shows a typical example that the angle (on horizontal plane) between the directions of head and hand movements becomes smaller during reach. Before and after reach the angle (on horizontal plane) between head and hand movements oscillate quickly. However, during reach the head and hand are more likely to move to similar directions. Figure 7 (left bottom) shows that in general all the three groups of children's head and hand movement follow this pattern when reaching for far object. The angles between head and hand movement of oldest group of children are larger than two younger groups. That indicates the older children's head and hand movements are more disassociated. When reaching for near object, the youngest group's head and hand move directions becomes more different in the half of reach (figure 7, bottom right). However, except for this, all the three groups also are more and more likely to move their heads and hands to similar directions.

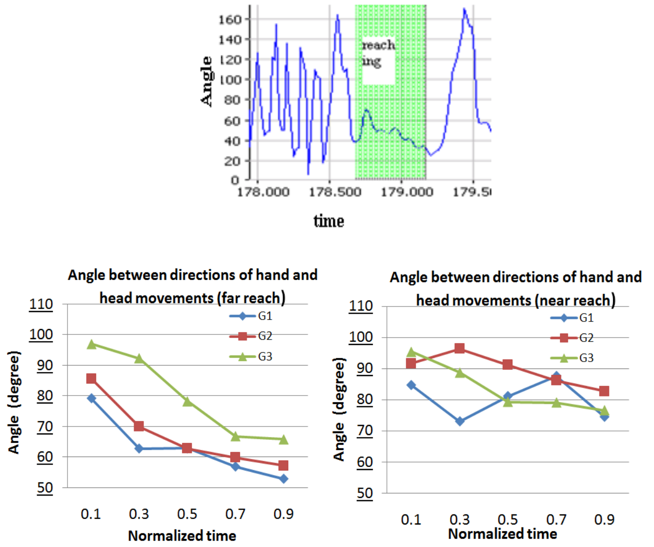


Figure 7. A typical example of angle on X-Y (horizontal) plane (in degree) between head and hand move directions (top); the mean angle on horizontal plane for far reach (bottom left) and near reach (bottom right). Note that the time in top figure is the acutally time in a long time series and the green bar marks the duration of reach; the time in the bottom two figures is normalized time in which 0 is the onset and 1 is the offset of a reach.

Figure 8 shows further analysis on movement directions. At first, the velocity of head/hand movements in 3-D space were decomposed into three 1-D vectors on X, Y and Z axes respectively (the coordinates are shown at figure 1-c). Then the decomposed 1-D head and hand velocity in same axis and be compared to see whether they in same direction or in opposite directions or nearly zero. Therefore, the proportion of head and hand moving to same direction in term of X axis, $P_{x,same}$, can be calculated by formula 2. $P_{y,same}$ and $P_{z,same}$ can be calculated similarly.

$$P_{x,same} = T_{x,same} \ / \ (T_{x,same} + T_{x,opposite} + T_{x,still}) \qquad (2)$$

In formula 2, $T_{x,same}$ is the duration of time when hand and head are moving to same direction in terms of X; $T_{x,opposite}$ is the duration of time when hand and head are moving to opposite direction in terms of X; $T_{x,still}$ is the duration of time when neither the hand nor head is moving in terms of X. Here "moving" means the head translational speed is larger than 0.2 inch/second or the hand translational speed is larger than 0.6 inch/second. These two thresholds were selected to exclude the influences of tiny head/hand movements or noises of the motions sensors. Other thresholds were also tried and the results were also similar to figure 8.

These graphs do not use normalized time in order to show the change of head-hand coordination from 0.3 second before reach onset to 1.1 second after reach onset. 1.1 second was selected here because most reaches in this experiment are less than 1.1 second. Each point in any sub-graphs of figure 8 is calculated in terms of a 0.2-second-long time window.

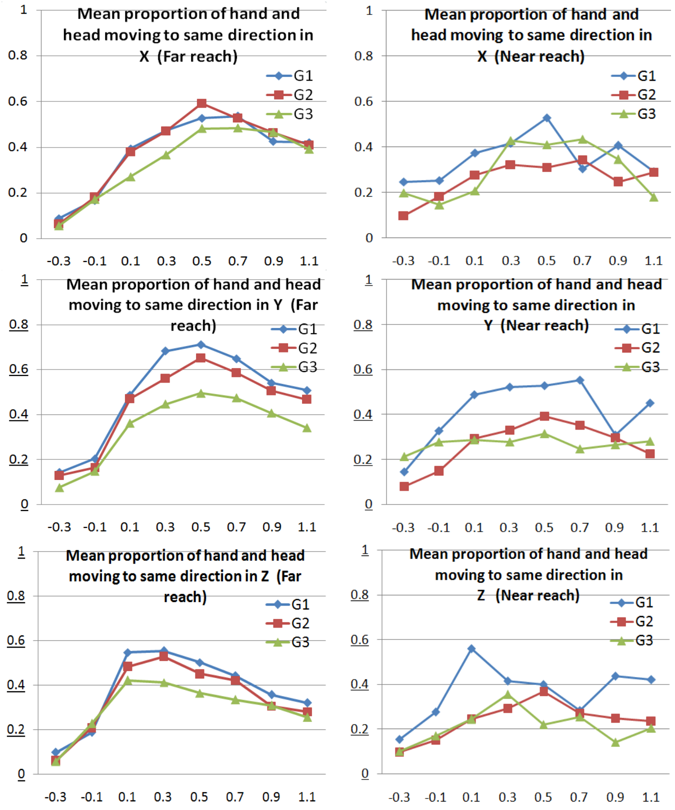


Figure 8. The mean ratio of hand and head moving to same direction in X (top row), Y (mid-row) and Z axis (bottom-row) for far reaches (left column) and near reaches (right column). All the horizontal axes of these graphs are NON-normalized time. Time 0 indicates reach onset.

Figure 8 shows that all the three groups of children's head and hand movements are more likely to move to similar directions at the same time during reach, which indicates a high degree of head-hand coordination. This is true for both far reaches and near reaches, especially for far reaches.

IV. DISCUSSION

These results suggest a strong tie between head and hands in early reaching. Three specific results support the view of head-centered reaching early in development and in naturalistic contexts. These are (1) All the children stabilize their head right before they reach. Indeed, a sharp decrease in head movement is a strong predictor of an intention to reach. (2) During the reach heads and hands move synergistically in the similar direction. Analyses currently underway and not reported here suggest that they also move at tightly coupled speeds. (3) Large and variable head movements co-occur with more variable and jerky reaches, and this is particularly so for the youngest children. These facts suggest that understanding early reaching will require understanding coordination of heads and hands.

The developmental results suggest marked changes in the coordination of heads and hands between 1½ and 2½ years-old children (group 1 versus group 2). Overall there is much about the youngest children's reaches that do not seem planned or well-controlled. Both near and far reaches emerge seem to emerge out of patterns of large head movements, to be ballistic and not slowing prior to contact, and to be preceded by only a very brief period of head stabilization. The 2 ½ year olds, show stable head movements and smooth reaches especially for the near reaches. One hypothesis that needs to be tested is that near reaches emerge from longer tracking of stabilization of the head and eye on the ball prior to the reach. That is, the quality of the reach by these young children could depend on the stability of centering the head on the ball. The fact that even the youngest children stabilize the head prior to reach suggests a head-centered frame of reference for the reach. This is also consistent with the synergistic directions of head and hand movements during the reach. Indeed, one developmental question of interest is whether the jerky pattern of hand movements for the youngest children is in some way related to the unstabilized head movements.

The coupling of head and hand in these early reaches and their possible importance of this coupling in the development of fluid and mature reaching behavior may prove deeply important to understanding reference frames and transformations among them as well for the creation of coordinated reaching in robots. Here is the conjecture: Although contemporary theories are in principle concerned with the transformation from one reference frame to another and with the ultimately common frame in which coordinated movement is planned, the system may more fundamentally be (and emerge from) the dynamic integration of multiple frames –where head direction modulates reach direction and where reach direction modulates head direction [4,11]. Similarly, head direction is coupled to eye-direction. Thus, the common frame reference may not be head or hand or eye but in between and reflecting the current and desired states of systems. Recent neuroscience evidence provides support for this idea [4]. Given the rich dataset we collected in this study, we can conduct deeper data analysis to further evaluate this theoretical idea at the sensorimotor level by investigating how the body implements smooth reaching actions in real time and how the underlying control mechanism coordinates different body parts.

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