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Planning to reach for a rotating rod: Developmental aspects

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Abstract

Hand adjustments of 6- and 10-month-old infants and adults were studied as they reached to grasp a rotating rod. It was found that the subjects in all three age groups adjusted the hand prospectively to the rotating rod during the approach of it. They also adjusted the reaches to the rotating rod in such a way that almost all of the grasps were overhand ones as predicted by the endpoint comfort hypothesis. Finally, it was found that the rotation of the hand was made up of movement units as translational movements are, and that the approach units were relatively independent of the rotational ones.

Efficient actions must anticipate what is going to happen next and use that information for control. This entails foreseeing the ongoing stream of events in the world as well as the unfolding of one's own movements. For instance, when catching a fast moving object the reach must be directed toward an upcoming position of the object where the hand can intercept it. Earlier research has found that infants catch fast moving objects successfully by reaching toward a future position (von Hofsten & Lindhagen, 1979; von Hofsten, 1980, 1983; Robin, Berthier, Clifton, 1996; Wentworth, Benson, & Haith, 2000). However, the dynamic properties that must be anticipated when reaching for an object are not just those related to position. When grasping an object, the hand must also move into a favorable posture before the encounter of the object in order to enable the fingers to close around it in optimal opposition space. If the object is turning, the hand must turn in an anticipatory way to a future orientation to secure a successful grasp. Are infants able to take such changes into consideration when planning a reach? This is the theme of the present article.

Thus, when grasping a rod, the hand should optimally aline itself with the longitudinal axis of the rod ahead of time. Earlier studies show that infants make such adjustments when reaching for a static rod (von Hofsten & Fazel-Zandy, 1984; Lockman, Ashmead & bushnell, 1984; Morrongiello & Rocca, 1989; Wentworth, Benson, & Haith, 2000; McCarty, Clifton, Ashmead, Lee, & Goubet, 2001). Some of these studies found indications that crude pre-adjustments were made shortly after the onset of functional reaching at 5 months of age (von Hofsten & Fazel-Zandy, 1984; Lockman, Ashmead & Bushnell, 1984; Morrongiello & Rocca, 1989). All studies found that over the months succeeding reaching onset, increasingly appropriate preadjustments of hand orientation were made in anticipation of the encounter of the stationary rod.

How are these adjustments of hand orientation planned? McCarty et al. (2001) removed the sight of the object towards the end of the reach or during the entire reach. Infants pre-adjusted the orientation of the hand to the orientation of the object to a similar extent under these different conditions. This suggests that the adjustment of hand orientation in infant reaching is pre-set at the beginning of the action.

The above studies used an object with fixed orientation. How are changes to object orientation handled when they occur during the reach? Morrongiello & Rocca, (1989) found that when the orientation of the rod was switched from vertical to horizontal or vice versa sometimes during the reach, the original reach was interrupted and a new one was launched. Perturbations are by definition unexpected and cannot therefore be anticipated. It is possible that adjustments of hand orientation are made during the reach if the changes are continuous and predictable. Wentworth, Benson & Haith (2000) studied the adjustments of hand orientation made by 5.5-, 8.5-, and 11.5-month-old infants when reaching for a rod rotating at 1 Hz. They found some indications of adjustments of hand orientation during the approach of the rod, although the orientation of the hand and the orientation of the rod at the encounter were only crudely related. The average angle difference between the hand and the object was about 60°. This might have been due to the very fast spinning or rotating velocity. As an infant reach takes over a second to complete a reach, the future orientation of the rod has to be foreseen up to a full rotation ahead of time. In the experiment to be presented, the rotation velocities are much lower than the ones used by Wentworth et al. (2000), but sufficiently high to necessitate a predictive strategy when reaching for it. The rod shaped object rotated perpendicularly to its longitudinal axis either with 18 or with 36°/s. We asked how precisely infants and adults are able to adjust the hand orientation to these changes when reaching for the rotating rod.

The second question had to do with the relationships between hand adjustments to object rotation and the structuring of the approach to the rod. Reaching movements of both infants and adults are typically divided into sub-movements (MU), each with an acceleration phase and a deceleration phase (von Hofsten, 1991). Von Hofsten (1991) showed that alternations to the direction of the reach were implemented at the transitions between the MUs indicating that these were points where the prospective control of the reach was updated. To what extent are the MUs of the approach movement coupled to the MUs of hand rotation? In a series of studies, Palignan et al. (1990, 1991a, 1991b) selectively perturbed the position and size of the object to be reached for at the beginning of the reach. They found that while initiating an altering of the arm movement in response to a sudden position change of the object was rapid, the initiation of an altering of grip aperture in response to sudden change in object size occurred much later. While the adjustment to object position was accomplished by altering the movement trajectory, the correction of grip aperture in response to a size change was more awkward. The grip aperture first peaked to the size corresponding to the small dowel and then re-increased. These differences suggest some degree of independence of the mechanisms generating finger movements during grip formation from these generating the transport of the hand.

A third set of questions was related to the relationship between overhand and underhand grips and object orientation. When a rod rotates around an axis perpendicular to its longitudinal axis (Rosenbaum et al., 1990) there are certain preferred orientation intervals for grasping it. One questions is whether subjects can choose to begin their approach for the object when the object is in certain orientations in order to be able to grasp it comfortably. If they begin to approach the object at an unfavourable time, to what degree are subjects able to anticipate the uncomfortable underhand grasp and correct the reach by switching to an overhand grasp.

Method

Subjects: Two groups of infants participated in the study. Group 1 had a mean age of 26 weeks (± 1 week) and included 6 boys and 3 girls. Group 2 had a mean age of 44 weeks (± 1 week) and included 3 boys and 7 girls. All infants were born within a week of their expected birth. In addition to these infants, a group of 10 adults participated. They were all healthy. The parents of the participants were recruited by mail. If they wrote back declaring an interest in participating in the study, they were contacted by phone. At arrival at the lab they signed written consent form before the study began. The study was approved by the Regional Ethic Committee according to the 1964 Declaration of Helsinki.

Apparatus: The stimulus was a rod, 20 cm long and 1 cm in diameter. Several versions of it were used in the experiment. They were covered with different kinds of interesting cloth and when the subject got fed up with one rod a different one replaced it. The center of the rod was attached via a magnetic coupling to the perpendicular shaft of and electric motor with adjustable speed and direction. If enough force was applied to the rod it could be ripped off its attachment.

The motion of the rod and the movements of the subject's hands were registered by a movement analyzing system using passive markers (Qualisys, Proreflex). Small reflective markers were attached to the wrist and the base of the thumb and the little finger. Two additional markers were attached to the end-points of the stimulus rod. Five Proreflex cameras were positioned in such a way that at least two of them would register the markers at each point in time. Sampling was made at 240 Hz. A pre-trigger system was used to record the reaching events. The experimenter started the pre-trigger at the moment of grasping. It was set to sample measurements from 3 s before until 4 s after it was pressed. A video camera monitored the subjects during the entire experiment.

Procedure: The rod was placed in front of the subject at arms length. Only the rod itself and a small section of the axis of the motor were visible to the subject. The motor itself was positioned behind a black curtain. At the different trials, the rod was either stationary or rotated around its shortest axis in the fronto-parallel plane. When it was stationary, its orientation was either horizontal or vertical. When moving its rotational velocity was either18 or 36 °/s and the motion direction was either clockwise or anti-clockwise. Thus, there were altogether 6 conditions in the experiment. Each condition was presented twice making altogether 12 trials. The order between trials was randomized.

Two experimenters conducted the experiment. One of them handled the position of the infant chair and entertained the infant between trials. The other one handled the rotation of the rod and the collection of data by the Qualisys system. At the start of the experiment, the infant was placed in an infant chair in front of the rod but out of reach. When the rod was set to the appropriate condition and the equipment was ready to measure the movements of the child and the rod, the chair with the subject was quickly moved forward to within reaching distance. If the infant was distracted at the beginning of a trial, the experimenter tried to make the infant attend to the rod by pointing to it. If the infant became unhappy during the experiment, it was immediately interrupted, the chair turned around, and the parent(s) recruited to sooth the infant. When the infant became happy again, the experiment was continued. Such interruptions were rather uncommon. Most infants eagerly reached for the rod at all trials. For some infants the experimenter actually had to hold the arms of the infant when the chair was moved forward. Otherwise the infants tended to reach forward far too early with their arms already stretched out as the chair as the chair came within reaching distance.

Data analysis: All data were collected on line and saved within the Qualisys software. Before any analyses were made, each individual reach was compared to the video recording of the same action. If not enough markers were visible during the reach, the subject was judged to engage in something else than reaching for the object, or became disinterested in the task, the trial was excluded from the data treatment. There were 68 such cases.

A total of 280 reaches were analyzed. To begin with, certain qualitative data were extracted from the video records. It was noted whether the reach was conducted with the right or the left hand and whether the grasp was performed from above or below. All the quantitative analyses were performed within the Matlab programming environment. The first step of the analysis was to filter the data with a 16Hz lowpass median filter. The hand movements were then analyzed in terms of translation in 3-D space and rotation in the fronto-parallel plane (the plane of rotation of the rod). The translational and rotational movements of each individual reach were divided up into movement units (MU), each consisting of one acceleration and one deceleration phase. When, after the hand had decelerated and started to accelerate again, a new MU was defined when the velocity had increased more than 20 mm/s for the translational units and 15°/s for the rotational units.

Secondly, he angular difference at encounter between the orientation of the hand and the rod was analyzed. Finally, a correlation analysis was performed between the approach velocity and the rotational velocity at each point in time for individual reaches was performed.

Results

Almost all subjects grasped the rod from above. The 6-month-old infants did so in 87% of the trials, the 10-month-olds did so in 96% of the trials, and the adults in 92% of the trials. The 6-month-olds performed altogether 79 reaches in the different conditions: 25 for the stationary rod, 23 for the slower rotating rod (18°/s), and 31 for the faster rotating rod (36°/s). Thirty reaches were performed with the right and 49 with the left hand. The 10-month-olds performed 95 reaches: 31 for the stationary rod, 35 for the slower rotating rod, and 29 for the faster rotating one. Fifty-one were performed with the right hand and 44 with the left hand. Finally, the adults performed 106 reaches: 33

for the stationary rod, 37 for the slower rotating rod and 36 for the faster one. Ten of the reaches were performed with the left hand, 96 with the right hand. The average duration of the reaches performed by the 6-month-olds was 0.83s, those performed by the 10-month-olds was 0.79 s, and those performed by the adults 0.53 s.

Analysis of hand rotation relative to rod

It was found that all groups of subjects turned the reaching toward a better alignment with the rotating rod at the end of the reach. This effect was only marginal for the 6-month-olds ($F(1,8)=5.274$, $p=0.051$, $\eta^2=0.397$) but clearly significant for the 10-month-olds ($F(1,9)=15.75$, $p=0.003$, $\eta^2=0.64$), and for the adults ($F(1,9)=65.33$, $p<0.0001$, $\eta^2=0.88$). There was no effect of the rotational velocity of the rod, however, on the decrease in the angle between the hand and the rod at touch ($F=1.19$). These effects are illustrated in Figure 1.

-------------------- Insert Figure 1 about here -----------------

An analysis was carried out on the angular adjustments when reaching for vertical and horizontal stationary rods. There was a slight tendency for the markers to be occluded in the vertical rod condition and therefore slightly fewer reaches could be analyzed than in the moving rod condition. Thus, two of the 6-month-olds and two of the 10-month-olds and one of the adults did not provide reaching data for the vertical rod. In addition, one of the 10-month-olds did not provide reaching data for the horizontal rod. It was found that the hand was adjusted to the horizontal rod ($F(1,25)= 24.1$, $p<0.001$, $\eta^2=0.49$), but the effect was not significantly different for the different age groups. There was also significant adjustments to the vertical rod ($F(2,21)=26.51$, $p<0.001$, $\eta^2=0.56$) and this effect was dependent on the age of the subjects ($F(2,21)=8.147$, $p=0.002$, $\eta^2=0.44$). These effects are illustrated in Figure 2. The 6–month-old infants started off reaching with the hand about halfway between horizontal and vertical hand orientation but with it significantly more horizontal when reaching for the horizontal than the vertical rod ($F(1,6) = 7.073$, $p = 0.03$, $\eta^2= 0.54$). This is in accordance with the results of von Hofsten & Fazel-Zandy (1984). The older infants and the adult started off with the hand more horizontal irrespective of the condition.

-------------------- Insert Figure 2 about here -----------------

Analysis of MUs.

Figure 3 shows two examples of the structuring of reaches in terms of MUs. Note that the rotational MUs are more distinctly separated in time than the translational MUs.

-------------Insert Figure 3 about here--------------

There were more rotation MUs than approach MUs ($F(1,26)=13.6$, $p<0.01$, $\eta^2 = 0.34$). There was also an effect of age on both for the number of approach MUs ($F(2,26)=11.82$, $p<0.001$, $\eta^2 = 0.48$) and rotation MUs ($F(2,26) = 8.41$, $p<0.01$, $\eta^2 = 0.39$). These effects are illustrated in Figure 4. There was no effect of velocity of rod rotation for either the number of approach MUs or the number of rotation MUs.

-----------------Insert Figure 4 about here----------------

It has earlier been found that the position of the largest MU reflects the maturity of the reaching system (von Hofsten, 1991). Ideally the largest MU, the approach unit, should be the first one and the subsequent ones should have the function of preparing for the final grasping action. An effect of age on position of the largest unit was found for both the approach analysis ($F(2,26)=8.40$, $p<0.002$, $\eta^2=0.39$) and the rotation analysis ($F(2,26)=7.598$, $p=0.003$, $\eta^2= 0.37$). The largest approach unit was generally positioned more to the beginning of the reach than the largest rotation-of-the-hand unit ($F(1,26)=8.315$, $p<0.01$, $\eta_2=0.242$). If the first unit is given the value of 1, the second the value of 2, etc., then the average position of the largest approach MU was 1.54, 1.33, and 1.06 for the 6-month-olds, the 10-month-olds, and the adults respectively. The corresponding values for the rotation-of-the-hand analysis were 1.72, 1.40, and 1.28.

The maximum approach velocity was affected by age ($F(2,26)=32.40$, $p<0.001$, $\eta^2 = 0.71$) but not by the rotation velocity of the rod ($F<1.0$). The opposite was valid for the maximum rotation velocity of the hand. There was a significant effect of rod rotation velocity on the maximum rotational velocity of the hand ($F(2,52)= 4.836$, $p<0.02$, $\eta^2 = 0.157$), but there was no effect of age ($F(2,26)=1.997$, $p=0.156$, $\eta^2 = 0.133$). The maximum rotation velocity of the hand was 72 °/s when reaching for the stationary rod, 80°/s when reaching for the rod rotating at 18°/s, and 92°/s when reaching for the rod rotating at 36°/s.

Correlation analysis

Correlating the approach velocity with the rotational velocity shows that they are only moderately related. On the average this correlation was found to be 0.236 for the 6-month-olds, 0.302 for the 10-month-olds, and 0.044 for the adults. The correlations for the infant groups were significantly different from zero, but not the correlations for the adults. Figure 5 shows an example of a reach where the velocity profile of the approach was significantly correlated with the velocity profile of the hand rotation ($r = 0.39$).

Discussion

Prospective control of reaching for a rotating rod

The results show that infants as well as adults when approaching the rotating rod turn the reaching hand predictively toward a future orientation of the rod in order to grasp it in an optimal way. While the hand-rod angular difference was similar for all age groups (close to 45°), the average angular difference at touch decreased with age from 31° for the 6-month-olds, to 26° for the 10-month-olds, and 16° for the adults. An even more remarkable result was that the average angular difference at touch was the same irrespective of the rotation velocity of the rod. This suggests that the rotation adjustments of the hand were faster and more extensive when the rod rotated faster. The obtained relationship between the turning velocity of the hand and the rotation velocity of the rod is another indication that the rotation of the rod was taken into account when reaching for it.

There is an apparent contradiction in the literature concerning infants' ability to update hand alignment during the approach of a rod. Morrongiello and Rocca (1989) found that infants were unable to adjust the orientation of the hand when the dowel reached for suddenly turned 90° and xx. The studies by von Hofsten (1980, 1983) on reaching for a moving object, however, show that when the object moves in a predictable fashion young infants are very capable of adjusting to its dynamic properties. The results obtained in the present study suggest that infants can also adjust to the dynamic changes in object orientation when they are smooth and predictable.

At a superficial level the results are rather different from Wentworth et al. (2000). They found that the angle between the hand and the dowel at touch was, on the average, about 60°. In their study, however, the rod rotated at approximately 1 Hz. As an average infant reach takes almost one second to complete, it implies that in order to foresee the object orientation at touch, the subjects must have foreseen a full rotation of the rod. The angle between the hand and the rod at touch can maximally be 90°, that is, the orientation of the hand is perpendicular to the orientation of the rod. If the angle difference is randomly determined, a 45° difference is expected. In other words, the average hand-rod orientation difference in Wentworth et al. (op.cit) was slightly more toward a perpendicular orientation than an alignment. In the present study, a 45° degree hand-rod orientation difference was actually obtained at the start of the reach for infants, as well as, the adults in the present study. This implies that the hand did not adjust for the rod turning before the onset of the approach for it but rather during it.

Another indication that the subjects made prospective adjustments to the rotation of the rod is the fact that in almost all cases the rod was encountered with an overhand grasp. This was the same for the infants as well as the adults. From earlier studies, it is well known that grasping an object in this way is more comfortable than using an underhand grasp (Rosenbaum, 1990). In the present study, it happened in a few cases that the child began approaching the rod too late to be able to catch it with an overhand grasp, and consequently interrupted the reach, withdrew the hand somewhat, and finally approached again with an overhand grasp. This is illustrated in Figure 6. Figure 6 shows that this reach is adjusted on line in order to provide better end point comfort.

<u>The structure of the reach</u>

In several ways the results indicate that moving the hand towards the rotating rod and adjusting its rotation to the rotation of the rod are independent actions. First, the analysis of the maximum approach velocity of the hand showed that it was not affected by the rotation velocity of the rod while the rotation velocity of the hand was dependent on the rotation velocity of the rod. Secondly, the low correlations between the rotation and approach velocity of the hand support the conclusion that these two actions are relatively independent. Both the translation and the rotation of the hand are divided into units with a beginning and an end (MU). The MUs with reference to the approach have earlier been described and analyzed in infants as well as in adults. The present study suggests that the same kinds of units are present when adjusting the orientation of the reaching hand to the orientation of the object. von Hofsten (1991) showed that alternations to the direction of the reach were implemented at the transitions between the MUs indicating that these were points where the prospective control of the reach was updated. This suggests that as the prospective control of each phase in the prehension action goes further into the future, the number of updating points decrease. The low correlation between the velocity of the approach and the turning of the hand indicate that these two components of the reach do not function as a synergy. However, in the infants tested, the approach and the turning are not independent either. Figure 5 shows an example of a reach where the translation and rotation of the hand are related. The present study indicate that there are more rotation MUs than translational ones, but also that their number decreased in a similar way with age. The present results support the conclusions made by Palignan et al. (1990, 1991a, 1991b) and Stelmach, Castello, & Jeannerod (1994) that the control of the approach of the hand in a prehension action was relatively independent of the control of hand adjustments before grasping the object.

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Figure captions

Figure 1. The hand-rod angle differences at the beginning and end of the reaches for the rotating rod. The different age groups are depicted separately. The unfilled symbols represent the lower rotation velocity (18°/s) and the filled symbols the higher rotation velocity (36°/s).

Figure 2. The hand angle for the different age groups at the beginning and end of reaches for vertically and horizontally oriented rods (0° is horizontal and 90° is vertical). The unfilled symbols represent the reaches for the horizontal rod and the filled symbols, the reaches for the vertical rod.

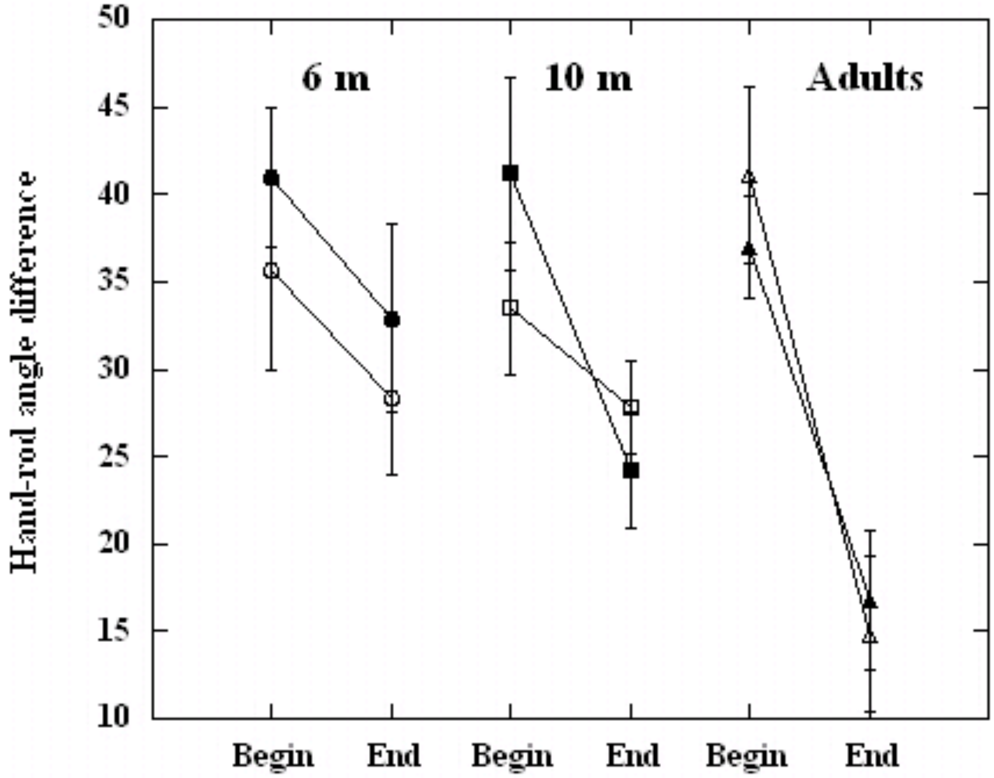
Figure 3. a) The velocity profile of hand rotation (°/s) for a reach to the moving rod. Three angular velocity movement units can be seen. b) A velocity profile for the approach movement to the rod. Four translation MUs can be seen. It can also be seen that the movement had already started when the measurements began.

Figure 4. A section of a reach with the translation velocity profile superimposed on the rotational velocity profile (dashed line). The correlation between the two velocity profiles is 0.39.

Figure 5. The average number of MUs for the approach movement and the hand rotation for the different age groups.

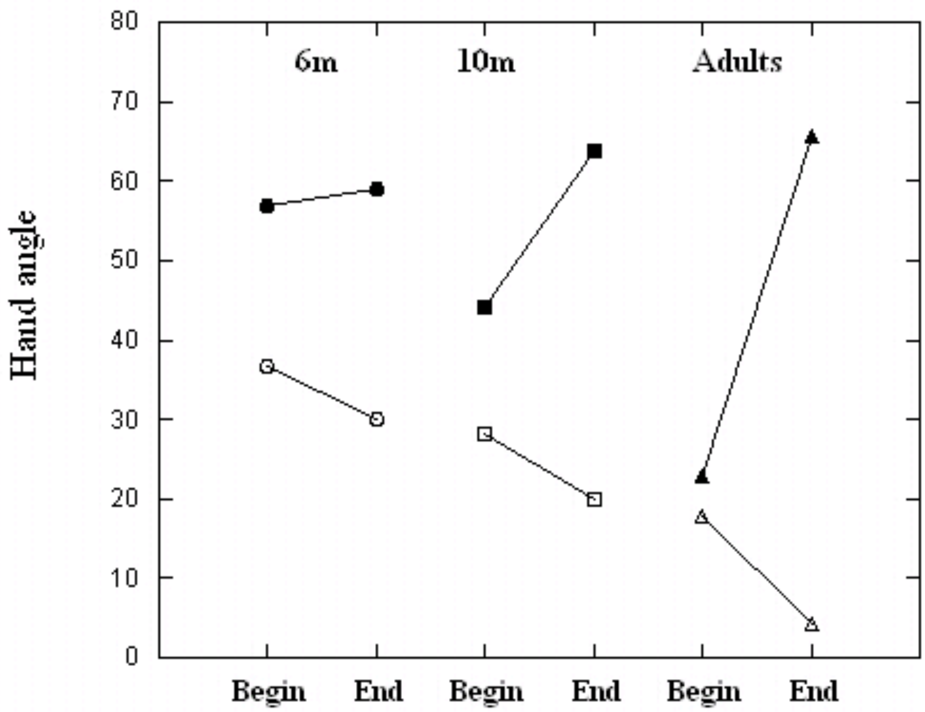
Figure 6. A 9-month-old subject correcting a reach that was launched too late for accomplishing a comfortable end state. a) the beginning of the reach b) 1.0 s later, correction starts c) 1.4 s later, hand is withdrawn. d) 1.8 s later, a new approach begins. e) 2s later, the new approach is on its way. f) 2.4s later, the grasp is accomplished.

Figure 1.



6 m
10 m
Adults
Hand-rod angle difference
50
45
40
35
30
25
20
15
10
Begin
End
Begin
End
Begin
End

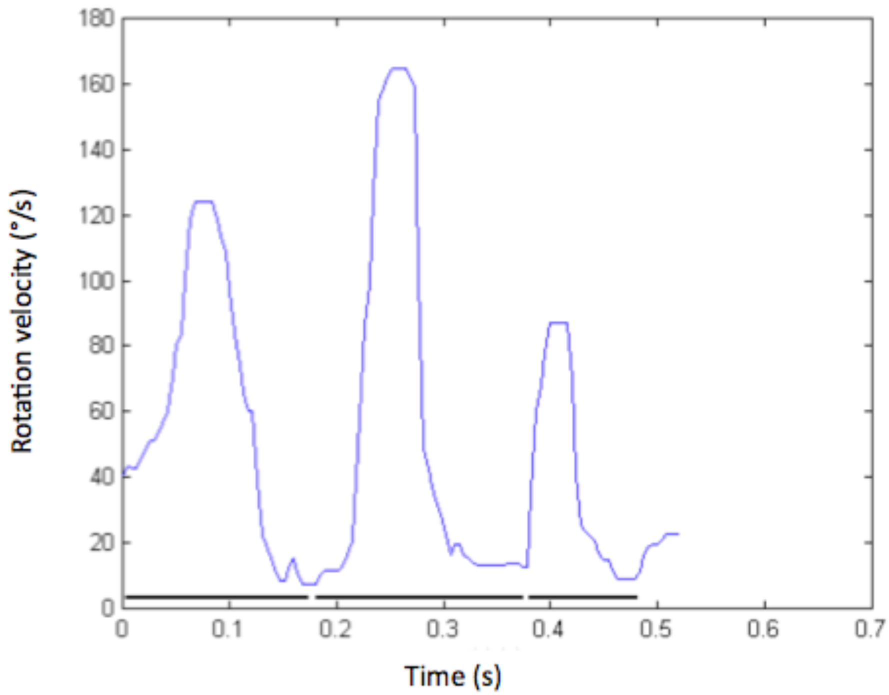
Figure 2



Hand angle
80
70
60
50
40
30
20
10
0
6m
10m
Adults
Begin
End
Begin
End
Begin
End

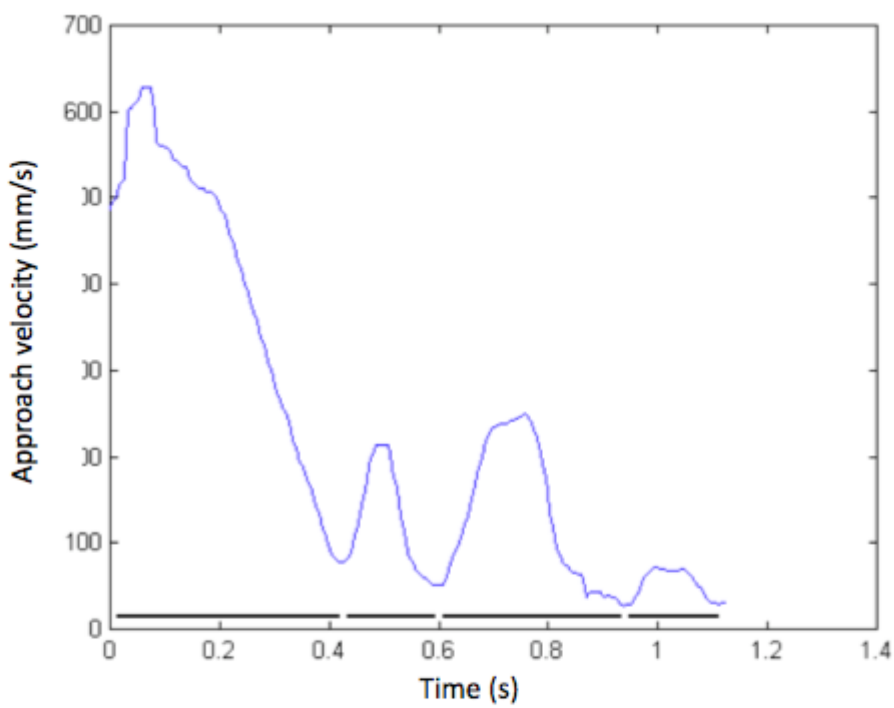
Figure 3

a)



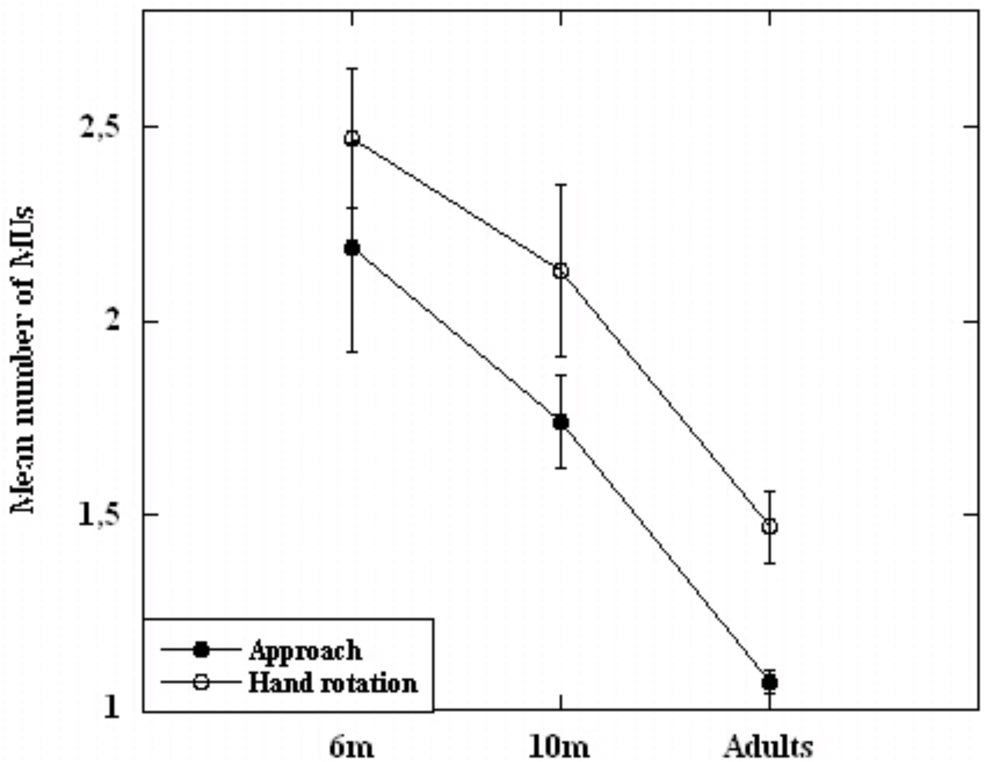
180
160
140
120
100
80
60
40
20
0
Rotation velocity (°/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time (s)

b)



700
600
100
0
Approach velocity (mm/s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Time (s)

Figure 4



Mean number of MUs
2,5
2
1,5
1
6m
10m
Adults
Approach
Hand rotation

Figure 5

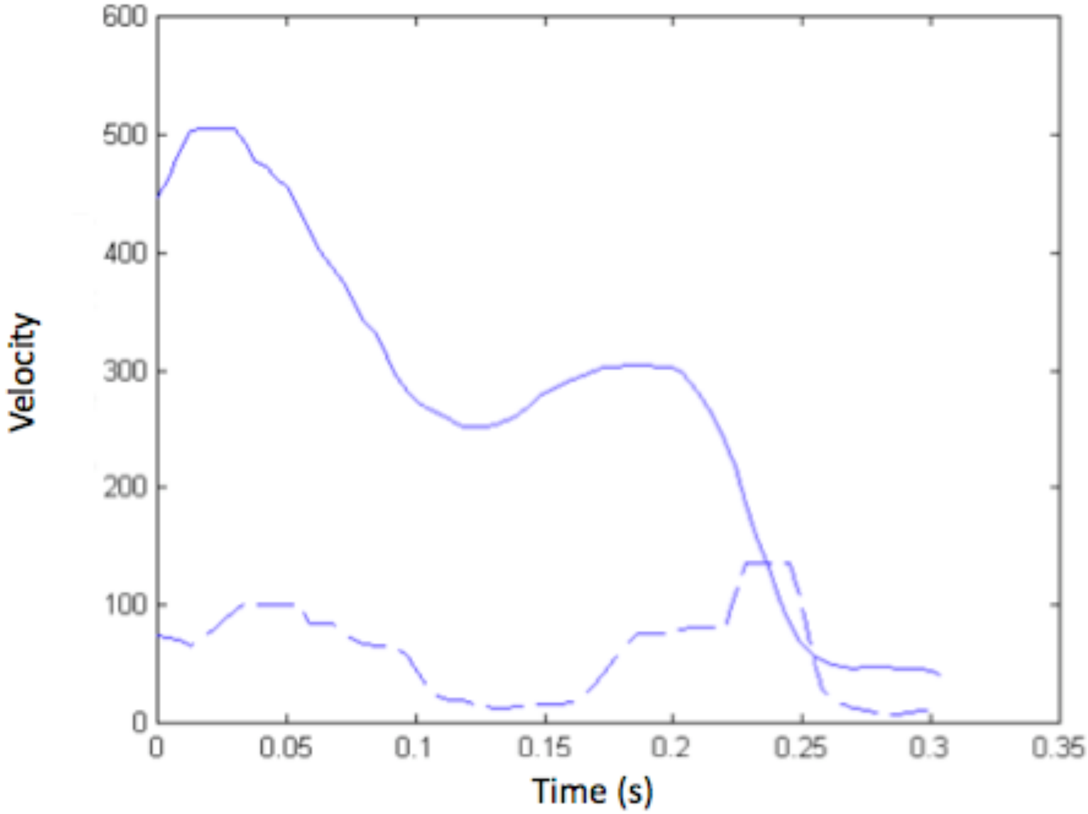

600
500
400
300
200
100
0
Velocity
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Time (s)

Figure 6