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Development of Reaching During the First Year: Role of Movement Speed

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When infants first learn to reach at about 4 months, their hand paths are jerky and tortuous, but their reaches become smoother and straighter over the first year. Here the authors consider the role of the underlying limb dynamics, which scale with movement speed, on the development of trajectory control. The authors observed 4 infants weekly and then biweekly from reach onset to 1 year. Improvements in trajectories were not linear, but showed plateaus and regressions in straightness and smoothness. When infants' nonreaching movements were fast, their reaches were also fast, and faster reaches were also less straight. This is consistent with an equilibrium trajectory form of control, where development involves the increasing ability to stabilize the trajectory against self-generated movement perturbations.

Recently, there has been increasing interest in the development of infant reaching as a means of understanding the more general issue of how the brain controls the upper limbs. Hundreds of studies have addressed this question using adult participants, and we know a great deal about arm trajectory formation when the participants are well practiced and the tasks are simple and repeated from trial to trial (see Georgopoulos, 1986; Jeannerod, 1988, for reviews). Only a few studies, however, have asked how humans actually learn to control their limbs during infancy. Whereas adults are highly accomplished in integrating the cognitive, visual, proprioceptive, and biomechanical demands of reaching and grasping, this is not true of infants. Thus, the gradual emergence of reaching skill offers an opportunity (a) to identify the multiple problems infants face in getting their hands to objects and (b) to examine the ways in which they solve them. Such studies are not easy to accomplish, however, as infants will not perform the typical discrete and constrained laboratory tasks on demand, and their abilities and motivation may change rapidly.

Infant Reach Trajectory Development

From the pioneering research of Halverson (1931, 1933), Hofsten (1979, 1991), and others, we know the broad outlines of the developmental changes in infant hand trajectories as they learn to reach. Infants first reach consistently at about 3 to 4 months of age. In the first months, their reaches are inaccurate and show poor control of the hand trajectory, with characteristic jerky and zig-zag movements. Such movements are identified kinematically as multiple segments of acceleration and deceleration or "movement units" (Hofsten, 1979). With age, infants' reaches become straighter and more directly aimed toward the target and show fewer movement units. In addition, as the number of movement units decreases, the first movement unit occupies a larger proportion of the reach, so that one acceleration and deceleration brings the hand close to the target, followed perhaps by a small correction (Halverson, 1931; Hofsten, 1979, 1991). Moreover, within the movement unit, investigators have found a relation between the speed of the movement and its curvature, with speed valleys associated with curvature peaks (Fetters & Todd, 1987; Mathew & Cook, 1990). (The developmental implications of the speed–curvature correlations within the movement units are unclear, however, inasmuch as this relation is also characteristic of adult hand trajectories and even of spontaneous arm movements in newborns; Hofsten & Rönnqvist, 1993.)

The major question generated by these studies is how to interpret the acceleration–deceleration movement units that give early reaching its ataxic character. In particular, the debate has centered on whether infants make corrections to their hand paths only at the boundaries of the movement units or whether they are continuously monitoring and correcting errors within the movement unit as well (Berthier, 1994; Fetters & Todd, 1987; Hofsten, 1980; Mathew & Cook, 1990). The larger issue is whether trajectory control

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in general is primarily ballistic, that is, whether only the target location is explicitly planned and represented or whether the nervous system uses primarily feedback or closed-loop control.

A core assumption of the existing studies of infant reaching is that the trajectory—the starts and stops and the curved hand path—reflects planning on the part of the infant, that is, deliberate strategies to get the hand to the presented object. On the surface, this is a reasonable assumption. There is abundant evidence in the adult literature that reaching is planned at the level of the trajectory of the hand in space. Adult reaches show very nearly straight paths to the target and a characteristic smooth, single movement unit of acceleration and deceleration (Jeannerod, 1988). These hand kinematics are preserved over a range of speeds, imposed mechanical perturbations, and positions in the work space, despite variability at the levels of coordination of the joints involved and patterns of muscle coordination (Berkinblit, Feldman, & Fukson, 1986; Flash, 1987; Hogan, Bizzi, Mussa-Ivaldi, & Flash, 1987; Karst & Hasan, 1990; Saltzman & Kelso, 1987). Adults do seem to have a deliberate plan to get their hands to the target in as straight and smooth a path as possible, and they protect this goal whenever they can.

By the time adults demonstrate this trajectory invariance in the laboratory, however, they have had 20 or more years of practice, involving perhaps millions of reaches. What this practice may have done is to stabilize the overall plan of the movement (the abstract trajectory) against the perturbations arising from other levels contributing to the execution of the movement. These include control of joint coordination and timing, setting appropriate levels of limb stiffness and muscle activation, and accommodation to passive, elastic, and gravitational forces (Latash & Gutman, 1993; Schöner, 1994). Thus, adults are good reachers because they can maintain a smooth hand path when reaching at different speeds, with varying visual information, in different postural contexts, and under taxing task demands.

It is not clear, however, that infants just learning to reach isolate and control their hand trajectory in a similar manner. Thus, one reason why early reaching may be poorly aimed and tortuous is that, given their overall goal of getting their hand to the offered toy, young infants cannot stabilize the reach very well in the face of perturbations from the other components of the system (Schöner, 1994). The infants' problem may not be just one of executing a trajectory, that is, providing the right patterns of muscle activity, but also of stabilizing the trajectory from other influences. In this article, we provide evidence that one reason why reaching in young infants is unskilled is because the trajectories are still tightly coupled to the energetic and biomechanical constraints of the movement execution. Infants' own ongoing movement tendencies act as perturbations to their immediate higher level goal of grabbing the toy.

Reaching From a Dynamic Systems Perspective

Our study differs from previous studies of infant reach trajectory development in several important ways. First, we designed and executed this study from the perspective that infant movements and their changes may be viewed as self-organizing dynamic systems (Thelen, 1986; Thelen, Kelso, & Fogel, 1987; Thelen & Ulrich, 1991). From a dynamic perspective, movements are always a product not only of the central nervous system but also of the biomechanical and energetic properties of the body, the environmental support, and the specific (and sometimes changing) demands of the particular task. The relations among these components are not simply hierarchical (the brain commands, the body responds) but are widely distributed, heterarchical, self-organizing, and nonlinear. In previous work on infant lower limb movements, Thelen and colleagues have shown that these distributed factors—the spring-like qualities of the legs (Thelen, Kelso, & Fogel, 1987), their intrinsic coordination dynamics (Thelen & Ulrich, 1991; Thelen, Ulrich, & Niles, 1987), and passive and inertial forces (Schneider, Zernicke, Ulrich, Jensen, & Thelen, 1990)—were critical determinants of early leg movement patterns and their emergent control. Despite the demonstrated importance of these physical, energetic, and dynamic components for lower limb patterns, conventional studies of infant upper limb function have considered trajectory control only as an issue of abstract planning. In the present study, we raise the issue of the multiple contributions to reaching development by looking at the role of movement speed, a kinematic variable that both reflects and influences the dynamics of the multiple levels.

Second, our study is also unique in situating the development of reaching within the context of nonreaching movements. Previous work has looked at infant reaches only in isolation. But a dynamic approach emphasizes that new skills must arise from the interplay of new task demands with the already existing movement dynamics (e.g., Corbetta & Thelen, 1996; Thelen, 1994). Thus, a central question is not just how infants control the reach itself but how they modulate their particular patterns and coordination preferences to produce new skills—that is, how reaching emerges from other movements and how reaching continues to be embedded in nonreaching movement dynamics.

Finally, this research contributes several methodological innovations to the study of infant arm control: (a) in following infants with a dense longitudinal design over the entire first year of reaching, (b) by applying rigorous criteria for the start of a reach, and (c) by considering individual infants as the unit of analysis.

Role of Movement Speed in Learning to Reach

This particular analysis of the year-long changes in reach development follows an earlier report of this longitudinal data set. In that article, Thelen et al. (1993) used a dynamic systems perspective to describe in detail one developmental shift, the transition to reaching, and to address how infants fashioned their first reaches from their ongoing spontaneous movements. What they discovered was that reaching posed a different dynamic and biomechanical problem for each infant. At the time of reach onset, each of the 4 infants studied had preferred and characteristic spontaneous movement speeds. These motor sets provided individual and different challenges. In order to fashion a goal-directed reach from ongoing movements, 2 of the infants had to discover how to damp down their fast, highly energetic, often oscillating movements in order to get their hands near the desired toy. Their movements generated high passive torques that required counterbalancing by muscle contraction. The other 2 infants faced another problem. Their movements were slow and not very energetic; therefore, they had to learn to provide sufficient muscle contraction to lift and extend their arms. They generated small passive forces and used their muscles primarily to counteract gravity. These individual intrinsic energetic dynamics were associated with striking differences in the ages of onset of first reaches, hand trajectories, patterns of interjoint coordination, and distribution of forces generating the reach.

The discovery that preferred speeds of spontaneous movements were critical in first acquiring reaching control led us to ask whether and how this parameter affected the later changes in reaching, the topic of the current article. The speed of movements—reflecting the amount of energy delivered to the limbs—is a critical parameter in many aspects of motor control. Faster movements are generally less accurate, probably because there is less time to make fine adjustments (Fitts, 1954). Reach trajectories may require different strategies of control and different patterns of muscle activation depending on whether they are performed slowly or rapidly (Flanders & Herrmann, 1992; Gottlieb, Corcos, & Agarwal, 1989). Similarly, very fast movements produce much greater motion-related passive forces than slow ones and thus pose different problems for neural control (Latash & Gottlieb, 1991; Schneider, Zernicke, Schmidt, & Hart, 1989). Interlimb coordination in cyclic movements is also affected by speed, as certain patterns of coordination become unstable as speed increases (Kelso, Scholz, & Schöner, 1986).

We had ample evidence that at the time of first reaches, the dynamic and biomechanical consequences of infants' characteristic movement speeds critically influenced their emergent trajectory control. Here we ask about the developmental course of infant reach trajectories, not just at the earliest performance of the movements, but over the whole first year, when we would expect dramatic improvements in control. We show that movement speed continues to be an important parameter in several ways. First, characteristic speed preferences are echoed in both reaching and nonreaching movements. Second, speed appears to be related to trajectory control, and finally, infants are increasingly able to stabilize their reaches against the disruptions of fast movements. Note that in this article we do not deal with biomechanical variables directly. We deal only with changes in the hand path trajectory as a function of speed, where speed is a metric of the energy delivered to the limbs.

In addition to being the first study to situate reaching development within a wider context of intrinsic movement dynamics, this research also demonstrates important nonlinearities, individual differences, and covariances among kinematic measures that have not previously been reported. We show that improvements in reaching cannot be understood by looking only at the reach itself, but that reaching emerges in an ongoing dynamic and biomechanical context.

Method

Participants

Participants were 4 normal, full-term infants, 1 girl (Hannah) and 3 boys (Gabriel, Nathan, and Justin), with no known sensory or motor impairments. Families were recruited before the infants were born through local prenatal classes or after the birth through published birth announcements. The infants were from White, middle-class families. All of the families visited the laboratory before consenting to participate. Parents were paid $15 for each observation session.

Procedure

We observed each infant every week from 3 until 30 weeks of age and once every 2 weeks thereafter until 52 weeks of age. The infants participated in two sessions each week of observation. First, we videotaped a quasi-naturalistic play session with parents for later behavioral coding. This article, however, uses only data from the second weekly visit, during which we collected position–time and electromyographic data of infants, supported in an infant seat, reaching for objects. Our intention was to document the transition to goal-directed reaching and the subsequent improvements in this skill, using a situation that would allow comparisons over the full age span. Participants never missed a session except for one infant, Nathan, who was ill when he was 25 weeks old. Because Nathan cried at his Week 50 session, he also had an additional session at Week 51.

We recorded position–time data with a four-camera WATSMART optical–electronic movement analysis system. The WATSMART system tracks small, individually pulsed infrared light-emitting diodes (IREDs) attached to the infants. Infants were seated in the center of a calibrated volume of 53.5 × 65.5 × 53.5 cm (width, height, depth), with two cameras positioned on the right and two cameras on the left. These cameras collected two-dimensional (2-D) data from each IRED within a calibrated volume. Three dimensional (3-D) coordinates were calculated using the direct linear transformation technique. The x axis was along the infant's lateral plane (forward–backward), the y axis along the frontal plane (left–right), and the z axis was vertical (up–down). Average measurement error for the calibrated volume was <1 mm. Coordinates were sampled at 150 Hz. All of the trials were videotaped from a lateral and either a frontal or an overhead view. Both views were simultaneously recorded using a split-screen generator, with an added frame counter. Position–time and video data were all synchronized.

When infants arrived at the laboratory, we removed their shirts and taped IREDs to the skin overlying the rotational centers of the shoulder, elbow, and wrist joints of both arms. A fourth IRED on each arm was placed on the distal end of the third metacarpal to track the position of the hand (see Thelen et al., 1993). We secured the infants by means of a broad torso strap in a specially constructed infant seat that allowed free arm movement. The seat had removable lateral head rests to support the heads of young infants with poor head control. The seat was reclined at 30° from vertical for most trials, although some trials at the end of each session were collected with the seat at vertical.

We collected data in a series of 14-s trials. We kept some flexibility in the order of the trials to hold the infants' interest and to accommodate their changing motivation with age. The study design included three conditions: baseline, social, and toy trials. We collected one baseline trial at the beginning of each session and a second at the end of the session if the infant maintained interest. In baseline, parents were in view of the infants, although not actively engaging them, and no toys were presented. Usually baseline was followed by two or more social trials. We asked parents to interact with the infants in an arousing and playful manner, but to offer no toys. Toy trials involved presenting small (from 4.5 to 5.5 cm wide), attractive, graspable toys to the infants at midline, shoulder height, and just at the distance of their extended arms. The toys were presented several seconds after the data collection began in order to capture both reaching movements and movements before and after the reach. Toys were offered in one of three ways: (a) using an apparatus with the toy attached to a dowel and moved by the experimenter from behind the infant through a lateral arc to midline, (b) by the parent, who lifted the toy to the appropriate position, or (c) by the experimenter, who presented the toy in a similar manner. We decided the order of trials during the experiment to optimize reaching. For example, if the infant ignored the toy and socialized with the parent, we used the apparatus to offer the object. We attempted to collect 3–4 trials in each toy condition (about 12 reach trials).

Data Analysis and Dependent Variables

Motion analysis of infants' spontaneous and unskilled arm movements presents formidable problems. For 3-D trajectories, optical recording equipment requires visibility of joint IREDs by two cameras. Long trials are needed to capture psychologically interesting behavior because infants do not always behave on demand. This generates massive data sets. In addition, young infants hold and move their arms in a seemingly endless variety of positions that obscure IREDs from camera view or move them out of the calibrated area. For example, IRED visibility may be obscured when infants extended their arms below and behind the chair, flexed their arms close to their bodies, or put their hands in their mouths.

Thus, in order to capture both the dynamics of spontaneous movements and the properties of the reach itself, we designed a procedure to select segments for various levels of analysis, based first, on the behavior of the infants (i.e., whether they were moving) and second, on the quality of the data. This led to a disproportionate number of analyzed nonreaching movements for infants who were very active and whose IREDs were visible, compared with those infants who were either more quiet or whose arm postures resulted in nonvisible IREDs. However, these differences were not apparent in goal-directed movements.

The segmentation process began with video coding of each trial by two coders working together. Right and left hands were coded in separate passes. First, coders determined trials and portions of trials that we deemed behaviorally interesting. Behaviorally interesting segments included (a) spontaneous movements performed either in conjunction with a reach or not in conjunction with a reach (i.e., rhythmical movements of one or both arms) and (b) object or goal-oriented movements (i.e., reaches, hand-to-mouth movements). Excluded, for example, were times when the infant was not moving at all, clutching the clothing, sucking on the fingers with the hands close to the face, or making very small hand movements. Thus, segments could be the entire 14 s of the trial or a portion of it.

With behaviorally interesting segments identified, the next step was an estimation of the visibility of each of the eight IREDs. Data were considered usable when the markers were visible through 70% of the behaviorally interesting segment and when gaps of missing data frames were smaller than one third of a second.

The next steps in data processing depended on the level of analysis desired. Here we report only the kinematics of the hand (the endpoint), using hand or wrist IREDs. The selection of the wrist or hand IRED was based on marker visibility alone (the least stringent criterion).

When position–time data are derived to produce velocities and accelerations, noise is greatly magnified. Thus, we spent considerable effort developing procedures to smooth our data in a manner that would produce interpretable data, yet preserve data integrity and allow us to compare within and between infants. The procedure we report produced a fully automatic, repeatable, and objective technique.

We interpolated and filtered coordinate data for each marker for the full 14-s trial, but only segments selected by the above segmentation process were used for data analysis. Interpolation for x, y, z coordinate values with obscured data was conducted using a linear spline (straight line) function to avoid introducing frequency components not in the original data set. We determined the cutoff frequency for filtering from a spectral analysis. We constructed a spectral density profile for each IRED and each coordinate, resulting in an integral for each of the 24 curves (8 IREDs × 3 coordinates). The cutoff frequency used was 97% of the integral's value. This cutoff frequency was determined from pilot analyses to produce smooth torques but not lose information in the lower derivatives. Then, we smoothed each coordinate individually for each IRED, using its specific cutoff frequency. The smoothing function was a fourth-order Butterworth filter.

The final step was a rigorous identification of the reach segment itself. A reach was defined as an arm extension toward the toy that ended with a contact of the hand with the toy. But it is not simple to infer when the infants actually started to reach. The infants were not restrained and were free to initiate reaching anytime after they saw the toy, starting from any position or from another movement. Unlike adults, infants sometimes did not directly aim their hands toward the objects, but began reaches with small, backward movements or vertical lifts. These initial arm movements are properly part of the reach. To both capture the reach in its entirety and to consistently identify reaching initiation with minimal assumptions about the infants' intentions, we developed an interactive technique based on both movement direction and change in movement speed (see Corbetta & Thelen, 1995).

In brief, this involved using a computer program that prompted the user to choose reach initiation and hand–toy contact by comparing the continuous 3-D hand kinematics (distance from hand to toy and speed displayed on the computer screen) with the corresponding videotaped behavior. Reach identification began by examining the video. A reach was identified when the following criteria were met: (a) The object was located in the infant's reachable space. (b) The infant was looking at the object or had noticed it before reaching. (c) The arm movement resulted in one or two hands contacting the target. (Note that we did not require that infants actually grab the toy.)

Then the user searched for the video frames of hand–toy contact and reach start. The user always identified the frame of contact first, which could be unambiguously defined by the first contact of the hand with the target. If the view of the hand was occluded by the toy, the video frame of hand–toy contact was coded as the frame of first toy displacement. Then, the user searched for the approximate frame of reach initiation by moving the video backward from the frame of contact until the estimated point of reach start. This search was facilitated by comparing the video with the displayed kinematics for continuous movements ending in toy contact. The user entered both the approximate reach start and the hand–toy contact video frames into the program. (Interrater reliability was high for initiation and contact frames. See Corbetta & Thelen, 1995, for details.) The program then more rigorously identified the frame of reach initiation by searching the kinematic data for the velocity minima that matched most closely the selected video frame. When reaches were bimanual, each arm was coded in separate passes. In this article, however, we report only data from the hand contacting the object first.

Table 1 reports the total number of reaches and total amount of kinematic data (reaching and nonreaching movements) analyzed after data selection.[1] Table 1 also displays the average percentage of time spent reaching of the total time spent moving for each infant at every session. Typically reaches accounted for about 10%–20% of the trials (Corbetta & Thelen, 1996).

Movement variables for reach segments. (a) Speed at reach initiation was the 3-D resultant speed of the hand averaged over a 333-ms (50-frame) window, that is, 25 frames before and 25 frames after the identified point of reach initiation. It reflects the activity of the hand at the initiation of the reach. (b) Average speed was calculated as the mean 3-D resultant speed of the hand from the entire reach segment. (c) Speed peak was the maximum resultant 3-D speed within the reach segment. (d) Number of movement units, a measure of hand-path smoothness, was determined by an algorithm that identified above-threshold increasing and decreasing hand speeds. A movement unit was defined as a speed maximum between two minima, where the difference between the maximum speed and both minima exceeded 1 cm/s. (e) The straightness index was the ratio between the virtual path, a straight line from the 3-D coordinates of reach initiation to toy contact, and the actual hand path length. The obtained 0 to 1 interval ratio was then standardized using the following *Z*-transform equation: $z(x) = 2ln((1 + x)/(1 - x))$. Increasing values indicate straighter paths. Note here that although the movement units and straightness may be related (a path with many movement units is usually not straight), they are not identical. A path composed of several small, low-speed movement units could be straighter than one composed of an equal number of large, fast, movement units. (f) Speed at contact was the instantaneous hand speed at the frame of toy contact.

Movement variables of nonreaching movements. (a) The average speed of all the movements recorded in the 14-s trial, or portion thereof with usable data. The reach itself was not included in this measure. (b) The average speed of the movement segments prior to reach initiation. This measure also does not include reaching data.

We also calculated reach duration and path length, but there were no consistent developmental trends, and we do not report these results. This is not surprising because reach duration and path length depend in part on the starting position of the hand at reach initiation, which was completely uncontrolled.

Developmental periods. As we looked at the data on reaching speed and hand path control, we noticed that amid the considerable variability both between and within infants, changes were not linear but were clustered into apparent epochs. These were an *early* period, in which all path and speed variables were unstable and there was considerable fluctuation in means and standard deviations from week to week; a *stable* period in the second half of the year, in which variability was considerably reduced and means did not change in any systematic or unsystematic way from week to week; and an *active* period occurring before the transition to stability, in which infants appeared to move noticeably faster for a period of several weeks. For Justin and Nathan, the early period was the active period. For those infants, we labeled the subsequent epoch of moderate stability and speed as the *middle* period. Four judges independently determined transition to stability on the basis of hand speed and path characteristics. There was good agreement. For Hannah, Justin, and Nathan, three of the four judges agreed on the exact weeks of transition between epochs and the fourth judge chose an adjacent week in both cases. For Gabriel, the judges chose 3 adjacent weeks for the transition to stability and the intermediate week was chosen. The other periods were defined by the authors on the basis of the criteria above.

Results

As in previous articles, we report results of individual infants. We describe each infant's developmental trajectory in terms of consecutive periods, on the basis of the speed characteristics of the reaches and their relative stability. The developmental periods are not meant to instantiate any overall structural stage assumptions, but are instead convenient means of describing related and cohesive states of the collective variables.

Gabriel

The top six panels of Figure 1 illustrate the changes in several parameters of Gabriel's reaches during his entire first year.

Early period. As detailed in Thelen et al. (1993), Gabriel reached first at 15 weeks. Before reach onset, his spontaneous movements were very fast and energetic, and he fashioned his first reaches from his ongoing large and cyclic flapping arm actions. Within 2 weeks after reach onset, Gabriel had learned to slow down his reaches a little and to produce less force.

In the early period, from 15 to 23 weeks, Gabriel's reaches were initiated from a background of moderate ongoing activity, measured by the speed at the initiation of the reach (see Table 2). His reaching speeds during this period were somewhat tempered from the fast movements of the onset week (29.57 cm/s at Week 15; see also, Thelen et al., 1993), but the average and peak speeds were still quite fast. During the first 4 weeks after reach onset, Gabriel's movement paths were variable in straightness and smoothness. Finally, Gabriel did not regulate the speed of his hand well as it contacted the toy; especially at first, he sometimes batted the toy with a high velocity and at other times approached more slowly.

Although his early period was marked by high speeds and variable trajectory control, Gabriel's reaching quality became relatively consistent during the last 5 weeks of this

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[1] The number of reaches used varied for some analyses on the basis of the following criteria: (a) Analyses using the before-reach data contained only trials that had at least 333 ms of data before the start of the reach. (b) Analyses using the initiation speed contained only data for which the reach segment was at least 333 ms long (i.e., at least as long as the window for the initiation speed calculation). The exact number of reaches used per analysis are noted in Tables 2 through 13.

Table 1
Total Number of Reaches and Kinematic Data Processed for Each Infant From Week of Reach Onset Until End of First Year and Average Percentage of Time Spent Reaching of Total Time Spent Moving

Participant (reaching)	No. of weeks	No. of reaches	Amount of kinematics (in s)	Average % of reaching per session *M*	Average % of reaching per session *SD*
Gabriel (Weeks 15–52)	27	186	1,900.12	13.82	3.85
Nathan (Weeks 12–52)	30	194	1,705.44	17.40	6.15
Hannah (Weeks 20–52)	22	158	1,513.70	19.41	8.42
Justin (Weeks 20–52)	22	138	1,334.52	20.90	5.89

period (Weeks 19–23). Judging from this consistency, it would appear that he discovered a stable solution to the problem of controlling his arm movements. Nevertheless, this consistency was short-lived, as evidenced by decrements in his reach quality during the next period, the active period.

Active period. Despite 9 weeks of reaching experience and 5 weeks of relative consistency in his reach parameters, Gabriel showed a marked decrement in reach quality during his active period (Weeks 23–32). During this period, he was moving especially rapidly at reach initiation, and his average and peak reach speeds were correspondingly fast. These fast reaches were jerky and tortuous, with indirect trajectories consisting of several movement units. Also, there was little improvement in his control of contact speed.

Stable period. Gabriel had a somewhat gradual transition at around Week 32 to a stable period (Weeks 32–52) marked by an increasingly consistent kinematic profile. This profile consisted of the following: (a) slow to moderate initiation speeds and reaching speeds, (b) consistently straight reaching paths, (c) a stable number of movement units, and (d) relatively low contact speeds.

Reach–nonreach speed relation. The two bottom panels of Figure 1 depict the speed of all of Gabriel's nonreaching movements (14 s) and of the movements prior to reach initiation (before). First, note that Gabriel's active period of reach disruption corresponded closely to an increase in his overall movement speed, not just that of the reach. During the active period, the mean speed across the entire 14 s increased from 8.09 cm/s to 18.46 cm/s, and the mean speed before the reach increased from 10.04 cm/s to 27.33 cm/s (see Table 2). These speeds returned to a lower level during the stable period, with the speed before the reach decreasing to 8.56 cm/s. Thus, Gabriel seemed better able to begin his reaches from a quiet position as the year progressed.

Table 3 reports the correlations between speeds of ongoing movements (entire 14 s and before), reach initiation, and the reach itself (average/peak) for the three developmental periods (early/active/stable). Of the 12 correlations, 11 were significant and positive, demonstrating that when Gabriel was moving fast outside of the reach segment (14 s/initiation), his reach was also fast. In sum, these data suggest that Gabriel's reach speed was influenced by his general movement energy, which shifted gradually across the first year.

Reach speed and trajectory control. Table 4 shows the correlations between the reach peak speed and two measures of control, path straightness and smoothness. During the early period, only reach peak speed was related to straightness; faster reaches were less straight. During the active period, in contrast, reaching speed affected both measures of trajectory control; as reach speed increased, so did the jerkiness of the hand path (decreased straightness, increased movement units). During the final, stable period, Gabriel's reach straightness was still disrupted by fast reaching movements.

Nathan

Early period. Nathan first reached at 12 weeks, the earliest age of the 4 infants. Like Gabriel, he was a very active infant prior to reach onset and needed to control his fast-moving arms to approach the toy. As shown in Figure 2 (top panels), he did slow his movements in the month after the onset week (see also, Thelen et al., 1993). Despite these speed changes, his reaches were not straight (see Table 5) and contained several movement units.

Active–middle period. Nathan's speed reduction was temporary, however. From Weeks 16–21, his active period, Nathan had high initiation speeds, very high average and peak speeds during the reach, and high speeds at contact. These speeds were associated with relatively poor and variable trajectory control; his reaches were indirect with several movement units.

Unlike Gabriel, Nathan's active period was followed by a middle period (Weeks 21–30) of tempered speed and marginal trajectory control. His initial, average, peak, and contact speeds decreased slightly. Nevertheless, Nathan's reaches were relatively indirect, and the smoothness of his hand path was moderate and variable.

Stable period. From Weeks 32–52, Nathan settled in on a much improved and consistent kinematic profile. Like Gabriel, Nathan's reaches started with low initiation speeds, with stable reach and contact speeds. In addition, his reaches were straight and smooth throughout the 22-week stable period.

Reach–nonreach speed relation. The relationship between Nathan's reaching and nonreaching speeds was quite similar to the relationship found for Gabriel; the speeds of the nonreaching segments (14 s/before) were strongly re-

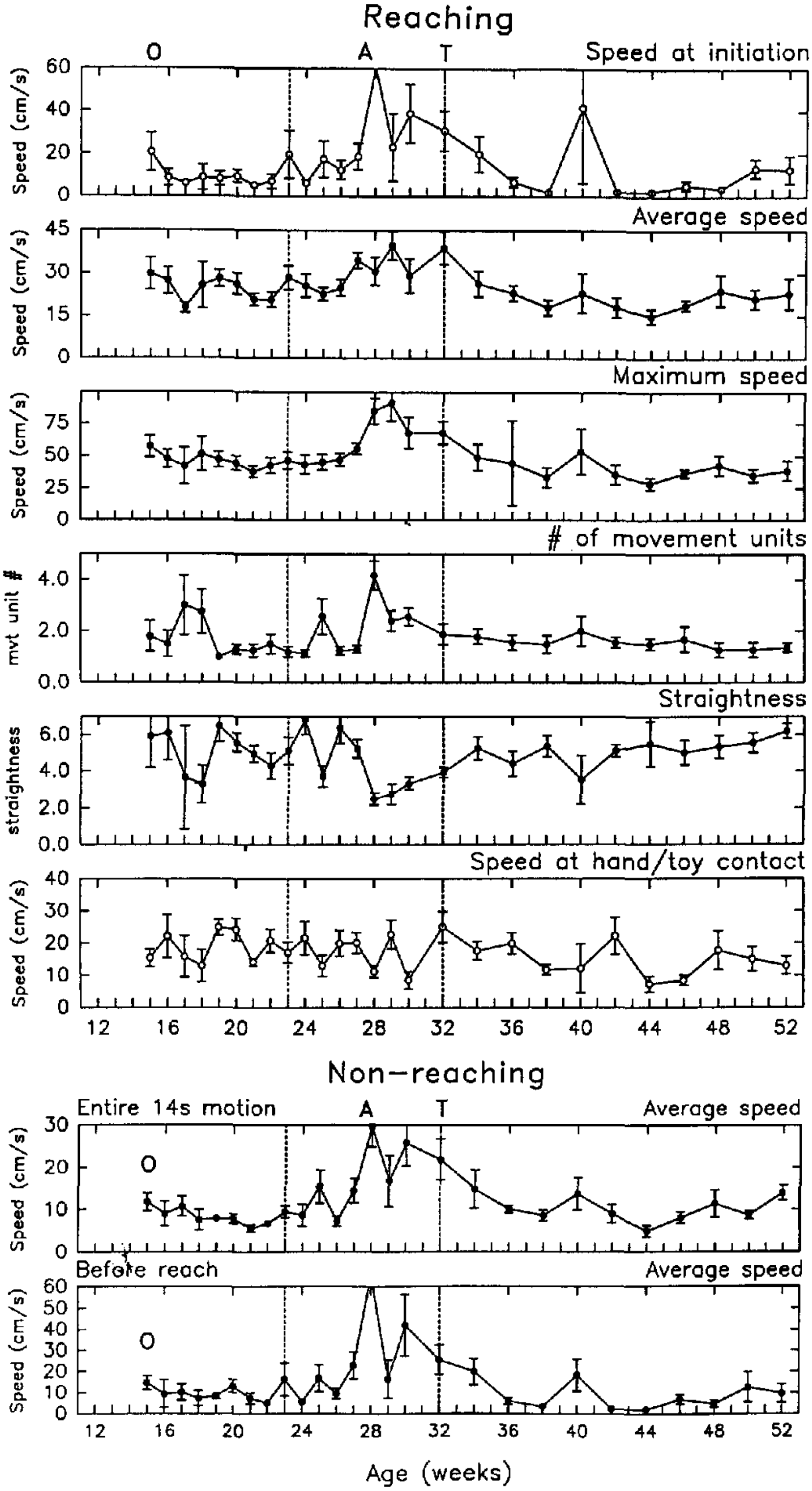

Figure 1. Dependent variables of Gabriel's reaching and nonreaching movements from Week 15 to Week 52. Six top panels: means and standard errors of the speed at reach initiation (calculated over 333-ms window), speed of the reach, maximum reach speed peak, path straightness, number of movement units, and speed at hand–toy contact. Two bottom panels: means and standard errors of the average speed of all nonreaching movements and average speed of the segment of motion prior to reach initiation. O = onset of reaching behavior; A = active period; T = transition week from less to more stable reaching patterns.

Table 2
Means and Standard Deviations of Gabriel's Reaching and Nonreaching Dependent Variables as a Function of Developmental Period

	Early period (N = 50)		Active period (N = 66)		Stable period (N = 70)	
Dependent variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reaching						
Speed at initiation	9.79	11.87[a]	28.73	31.91	9.72	18.22
Averaged speed	24.77	9.29	30.65	13.69	21.26	10.29
Peak speed	45.50	16.34	63.28	29.20	39.66	19.33
Straightness	5.11	2.37	4.27	2.12	5.20	1.82
No. of movement units	1.56	1.07	2.26	1.56	1.54	0.88
Speed at toy contact	18.95	8.83	17.05	11.21	14.65	10.31
Nonreaching						
Entire 14-s speed	8.09	3.56	18.46	14.22	10.31	7.30
Speed before reach	10.04	8.39[b]	27.33	28.10[b]	8.56	10.89[b]

Note. N = No. of trials per developmental period.
[a] N = 49. [b] Ns = 47 (early), 60 (active), and 60 (stable).

lated to the reaching speeds (average or peak). The bottom panels of Figure 2 and Table 5 indicate that, in contrast to the early, middle, and stable periods, Nathan's active period was one of general motor activation with high speeds both during the entire trial and before the reach.

Table 6 shows that for Nathan, as for Gabriel, the speeds of nonreaching movements carried over to reaching movements. The 10 significant and positive correlations indicate that the reach speed was strongly related to both the 14-s nonreach speed and the initiation speed. In addition, the speed at the initiation of the reach was strongly related to the nonreaching speed prior to initiation.

Reach speed and trajectory control. Once again, as for Gabriel, there was a moderate influence of the peak speed of the reach on the path straightness during the early and active–middle periods, with faster movements leading to more tortuous hand paths (see Table 7). This influence was not evident in the stable last period of the year.

Hannah

Early period. Hannah had very different movement characteristics than did Gabriel and Nathan. She was a motorically less active baby right from the start. She reached first at Week 20 and consistently at Week 21. During her early period (Weeks 20–29) shown in Figure 3, Hannah's reaches started with arms either at rest or moving very slowly (see Table 8), and her reaching and contact speeds were moderately slow. Hannah's reaches were also indirect, with a variable and relatively high number of movement units. Like Gabriel, Hannah showed a brief period of relative consistency from Weeks 26–29. Nevertheless, this consistency ended abruptly at the start of the active period.

Active period. Hannah's active period (Weeks 29–36) was highlighted by fast initiation speeds, indirect trajectories, and a variable and high number of movement units. Reaches during this period were primarily initiated from ongoing, fast arm movements (flaps). At Week 32, she had relatively high reach speeds, whereas during Week 34 her trajectory control was particularly poor (see Figure 3).

Stable period. Hannah's shift to a stable kinematic profile was quite dramatic at Week 36. From Weeks 36–52, Hannah's reaching speeds were once again moderately slow. More exemplary was her improvement in trajectory control; reaches were very stable with straight paths and smooth trajectories.

Reach–nonreach speed relation. As with Gabriel and Nathan, Hannah's active period was reflected in her nonreaching movements. Prior to the active period, her nonreaching speeds were quite slow (6.1 and 5.68 cm/s for the entire period and before the reach). These speeds jumped to 10.88 and 17.49 cm/s, respectively, during the active period. It is interesting that Hannah's 14-s speed remained relatively high during the stable period (although this speed was still slow compared with Gabriel's), but her before speed dropped to 5.34 cm/s. Thus, Hannah differentially decreased her nonreaching speeds, choosing to remain quiet prior to the reach, thereby eliminating any carryover speed effects as the reach began. Table 9 shows that, like the two boys we described, Hannah's reach speeds, both at initiation and during the reach, were strongly related to her nonreach

Table 3
Gabriel's Speed Correlations

Correlated variables	Early period (N = 50)	Active period (N = 66)	Stable period (N = 70)
14-s speed/reach speed	.271*	.320*	.616**
Before speed/init. speed	.627[a]**	.902[a]**	.763[b]**
Init. speed/reach speed	.482[b]**	.389**	.596**
Init. speed/peak speed	.199[b]	.614**	.635**

Note. N = No. of trials per developmental period; init. = initiation.
[a] Ns = 46 (early), 60 (active), 60 (stable). [b] N = 49 (early).
* $p < .05$. ** $p < .002$.

Table 4
Gabriel's Correlations Between Reach Speed and Trajectory Variables

Correlated variables	Early period ($N = 50$)	Active period ($N = 66$)	Stable period ($N = 70$)
Peak speed/movement units	.136	.409**	.127
Peak speed/straightness	−.225	−.431**	−.370**

Note. N = No. of trials per developmental period.
** $p < .002$.

speeds. In her case, 10 of the 12 correlations investigated were significant.

Reach speed and trajectory control. During the early and active periods, Hannah's path straightness correlated negatively with the reaching peak speed (see Table 10). These results paralleled those for Gabriel and Nathan. In addition, the number of movement units during the early period was positively related to peak speed. The final period of the year, the stable period, revealed no significant relationship between speed and trajectory control.

Justin

Early–active period. Justin, like Hannah, reached first at Week 20 and consistently from Week 22. Like Hannah, he was a motorically quiet infant. Throughout the year, Justin initiated his reaches primarily from slow movements (see Table 11). As shown in Figure 4, in the month or so after reach onset (Weeks 20–25), his reaching speeds and contact speed were moderately fast (for him), especially during Weeks 23 and 24. During this early–active period, hand trajectories consisted of a variable and high number of movement units.

Middle period. From Weeks 25–30, Justin's reach speeds and contact speed decreased somewhat. Nevertheless, his reaches became slightly less straight with a still variable number of movement units.

Stable period. Justin's control improved after Week 30, showing a stable kinematic profile. During this stable period (Weeks 32–52), Justin's reach speeds and contact speeds were quite similar to previous months (see Table 11), whereas his trajectory control improved; he had relatively straight and consistently smooth trajectories. The exception was during Week 50, when Justin became more active with faster and less direct reaches (see Figure 4).

Reach–nonreach speed relation. Justin's early–active period was somewhat reflected in his nonreaching speeds; his 14-s mean decreased from 6.43 cm/s (early–active period) to 5.82 cm/s (middle period). This trend was not consistent, however, because the before mean increased slightly during the middle period (see Table 11). In fact, during Justin's stable period, he actually showed an increase in both nonreaching speeds. Nevertheless, as with the reaching speeds, much of this increase can be accounted for by the exuberant Weeks 50 and 52. The correlations in Table 12 reflect that, despite the somewhat altered nonreach speed trends, the reach and nonreach speeds were still highly related. Consistent with the other 3 infants, 10 of the 12 correlations examined were significant.

Reach speed and trajectory control. Like Gabriel, Nathan, and Hannah, Justin's path straightness was affected by his reaching peak speed (see Table 13). This effect was significant throughout the year, showing, again, that faster reaches were less straight.

Statistical Test of Nonlinear Changes in Reach Variables

In order to support our judgment that the developmental periods captured real changes in reach variables, we performed an analysis of variance on the averaged data per period from all 4 infants, using participants as a random factor and periods as a within factor. Table 14 gives the F values and their significance levels for each dependent variable. For the reaching variables, the periods were significantly different in speed at initiation, peak speed, straightness, and number of movement units. There were no statistically significant differences in the nonreaching variables.

Summary of Results

In summary, the 4 infants we studied showed several common changes in their reaching skill across the first year. All of the infants had active periods during which reaching speed affected trajectory control, and they all showed a stable period marked by a steady kinematic profile. These profiles illustrated more consistent control, with all of the infants settling in on similar parameters for straightness and smoothness. In addition, active periods were reflected in the nonreaching speeds, and both reach and nonreach speeds were highly related. Finally, data from all 4 infants showed that as reach speeds increased, path straightness decreased primarily during the periods prior to stability.

These results also showed several individual differences. Specifically, there were differences in the timing of reach onset, the timing of the active periods, and the timing of the transitions to the stable periods. Infants also differed in the developmental organization of consistent and inconsistent reach weeks. Gabriel and Hannah both had early periods ending in several weeks of reach consistency followed by active periods and stable periods. By contrast, Nathan and Justin were active relatively early after reach onset. Their active periods were followed by middle periods of tempered speeds but still relatively poor trajectory control and, finally, stable periods.

Discussion

Good reaching means keeping the hand moving in a direct and smooth manner toward the desired target. By these criteria, new reachers are notoriously poor, but they improve considerably after several months of practice, as several previous studies have documented (e.g., Halverson,

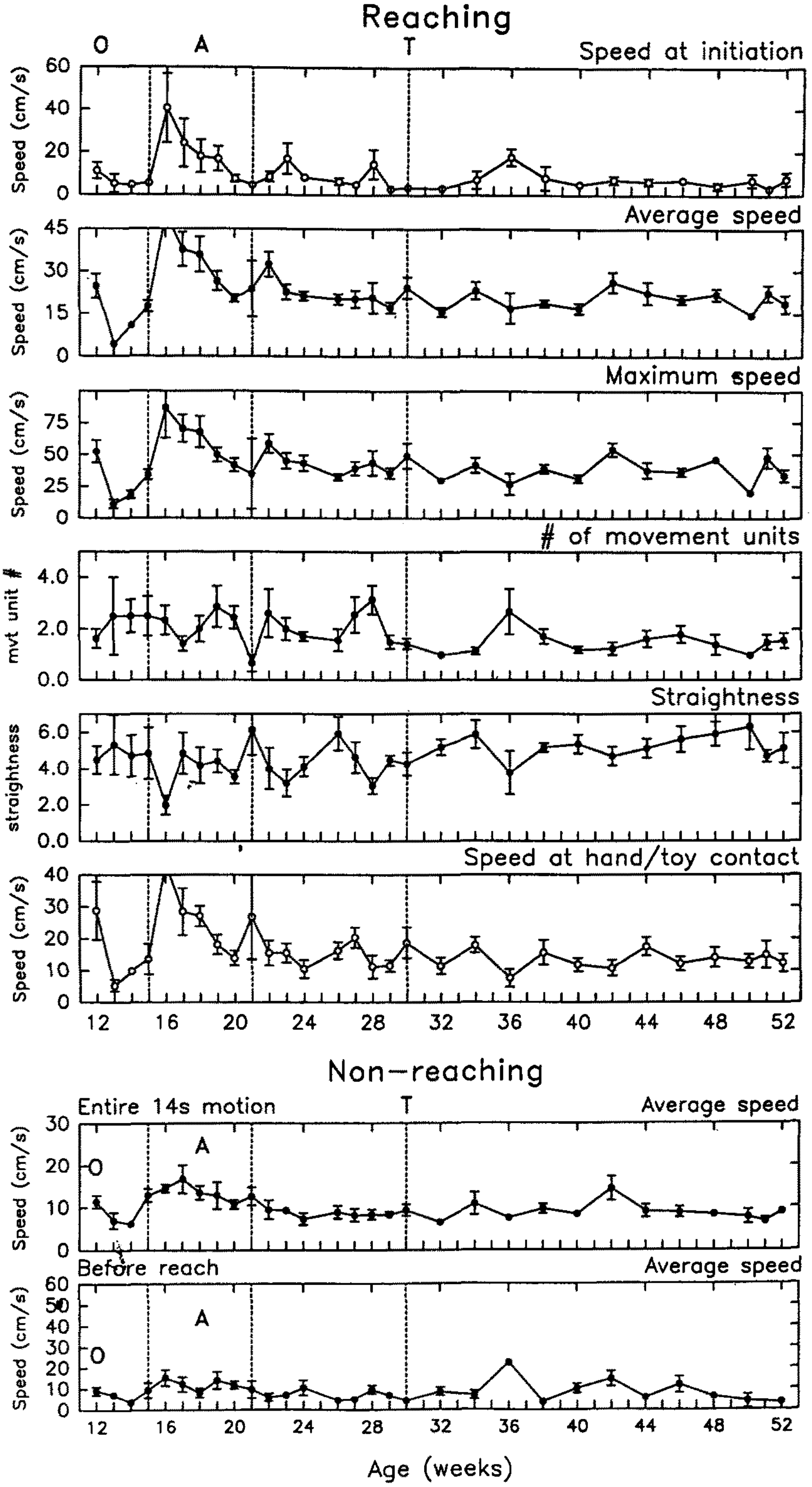

Figure 2. Dependent variables of Nathan's reaching and nonreaching movements from Week 12 to Week 52. Six top panels: means and standard errors of the speed at reach initiation (calculated over 333-ms window), speed of the reach, maximum reach speed peak, hand path straightness, number of movement units, and speed at hand–toy contact. Two bottom panels: means and standard errors of the average speed of all nonreaching movements and average speed of the segment of motion prior to reach initiation. O = onset of reaching behavior; A = active period; T = transition week from less to more stable reaching patterns.

Table 5
Means and Standard Deviations of Nathan's Reaching and Nonreaching Dependent Variables as a Function of Developmental Period

Dependent variable	Early period (N = 20)		Active period (N = 39)		Middle period (N = 59)		Stable period (N = 76)	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Reaching								
Speed at initiation	7.56	7.45	19.14	23.94[a]	7.85	10.05	6.59	7.10
Averaged speed	17.74	10.58	32.22	19.43	21.73	9.05	19.87	7.04
Peak speed	36.01	22.52	59.64	33.73	42.30	18.22	36.94	13.31
Straightness	4.71	2.46	3.98	2.22	4.24	1.97	5.30	1.64
No. of movement units	2.15	1.42	2.13	1.47	2.03	1.38	1.46	0.77
Speed at toy contact	18.03	19.21	25.49	16.43	14.89	8.94	13.48	7.31
Nonreaching								
Entire 14-s speed	10.33	4.21	13.29	5.60	8.49	3.41	8.82	3.77
Speed before reach	8.40	6.49[b]	12.16	7.88[b]	6.95	4.97[b]	8.25	6.68[b]

Note. N = No. of trials per developmental period.
[a] $N = 38$. [b] Ns = 17 (early), 35 (active), 49 (middle), 66 (stable).

1931; Hofsten, 1991). Implicit in this previous work is that over time, infants gain better control of their limbs. However, these studies are unclear as to what "control" really means and by what mechanisms practice may lead to improved control. In this article, we too have described changes in the hand trajectory as infants learn to reach, but we begin to probe more deeply into the nature of evolving arm control. In particular, we suggested that one metric of control was the ability to maintain a good reach trajectory in the face of perturbations from other levels of the motor system—in this case, from the ongoing characteristic movement speed and from the biomechanical effects of speed on movement.

Nonlinearity of Trajectory Development

This study is the first to report dense kinematic data over the entire first year of learning to reach. Our research design was critical to understanding the collective and individual changes that occurred across the first year. Cross-sectional or less dense longitudinal data would not have yielded such a consistent view of changing trajectory control. Although we expected that infants would become better reachers, we were surprised by the noticeable nonlinearities within the developmental course of general improvement. Each infant had several months in which reach trajectories were unstable and poorly controlled; for Gabriel and Hannah, the presence of active periods seemed to indicate an even greater loss of stability after a few weeks of seemingly more mature performance. Equally dramatically, each infant shifted to improved trajectory and speed control at around 30–36 weeks, with little further improvement by the end of the first year.

At this time we can only speculate as to the system parameters that engendered these developmental shifts in trajectory control. We suggest and discuss below that infants become increasingly able to stabilize movement trajectories against perturbations generated by their own movement dynamics, but the processes underlying these developmental changes is unknown. The 4 infants required from 10 (Justin) to 18 (Nathan) weeks of reaching practice to discover the more stable configuration, so it is unlikely that weeks of practice alone were the determining factor. On the other hand, what constitutes necessary and sufficient practice of a skill for any individual is itself unknown.

Equally plausible is that reaching improvement emerges from other related changes in the neuromotor system. For instance, infants become stable independent sitters at about 6 to 8 months of age and begin to creep and crawl soon

Table 6
Nathan's Speed Correlations

Correlated variables	Early/active period (N = 59)	Middle period (N = 59)	Stable period (N = 76)
14-s speed/reach speed	.531**	.214	.413**
Before speed/init. speed	.579**	.491[a]**	.345[a]**
Init. speed/reach speed	.689[b]**	.288*	.265*
Init. speed/peak speed	.591[b]**	.257*	.105

Note. N = No. of trials per developmental period; init. = initiation.
[a] Ns = 51 (early/active), 49 (middle), 66 (stable). [b] $N = 58$.
$^*p < .05$. $^{**}p < .002$.

Table 7
Nathan's Correlations Between Reach Speed and Trajectory Variables

Correlated variables	Early/active period (N = 59)	Middle period (N = 59)	Stable period (N = 76)
Peak speed/movement units	−.042	.072	−.052
Peak speed/straightness	−.299*	−.374**	−.038

Note. N = No. of trials per developmental period.
$^*p < .05$. $^{**}p < .002$.

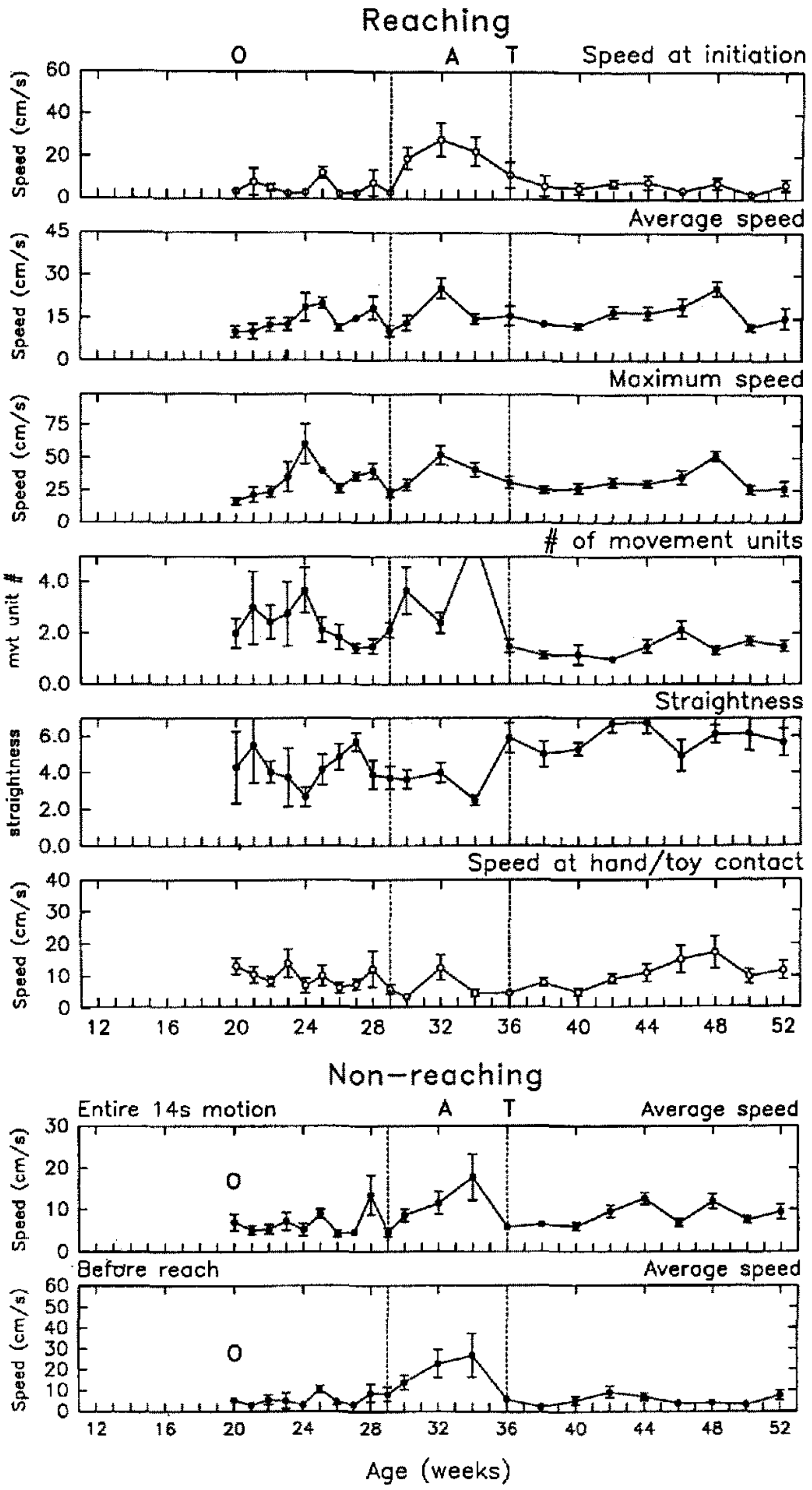

Figure 3. Dependent variables of Hannah's reaching and nonreaching movements from Week 20 to Week 52. Six top panels: means and standard errors of the speed at reach initiation (calculated over 333-ms window), speed of the reach, maximum reach speed peak, hand path straightness, number of movement units, and speed at hand–toy contact. Two bottom panels: means and standard errors of the average speed of all nonreaching movements, and average speed of the segment of motion prior to reach initiation. O = onset of reaching behavior; A = active period; T = transition week from less to more stable reaching patterns.

Table 8

Means and Standard Deviations of Hannah's Reaching and Nonreaching Dependent Variables as a Function of Developmental Period

Dependent variable	Early period ($N = 62$) *M*	Early period ($N = 62$) *SD*	Active period ($N = 35$) *M*	Active period ($N = 35$) *SD*	Stable period ($N = 61$) *M*	Stable period ($N = 61$) *SD*
Reaching						
Speed at initiation	4.92	6.10	20.63	20.08	6.15	7.51
Averaged speed	14.34	6.79	17.74	9.96	16.85	7.54
Peak speed	33.23	18.53	39.03	18.50	32.44	13.50
Straightness	4.35	2.20	4.00	2.00	5.90	1.93
No. of movement units	2.19	1.53	3.29	2.33	1.44	0.72
Speed at toy contact	8.75	6.44	6.67	7.79	11.20	9.15
Nonreaching						
Entire 14-s speed	6.10	4.07	10.88	9.77	9.08	4.29
Speed before reach	5.68	4.95[a]	17.49	19.51[a]	5.34	4.44[a]

Note. N = No. of trials per developmental period.

[a] *N*s = 50 (early), 32 (active), 50 (stable).

thereafter. One possibility is that stable sitting posture allows infants to better control their reaches. Rochat (1992), for example, found that the ability to sit alone modifies patterns of interlimb coordination in infants' reaching; self-sitters reach more with one hand, whereas nonsitters reach more with two arms simultaneously. Kamm (1994), in contrast, found no effect of postural instability on the quality of hand trajectories. Another possibility is that experience supporting weight on the arms in prone and moving them in alternation transfers to improved trajectory control. For instance, Goldfield (1993) showed a correspondence between unilateral reaching and onset of alternate-pattern crawling, but it is not clear whether crawling led to differentiated reaching or vice versa, or whether both milestones were the result of other system changes.

Reaching in the Context of Preferred Movement Speed

What is clear is that understanding the processes leading to the changes in infant reach trajectory cannot come from looking only at the reach variables themselves and in isolation. One of the assumptions of a dynamic systems approach is that developmental milestones, or transitions to new forms such as reaching, are individually discovered as infants explore movement solutions in the face of desired goals, such as getting an attractive toy. Thus, reaching as a new pattern is not imposed on the system but evolves as a product of infants' current movement preferences and abilities, the histories of those preferred patterns, and from the everyday activities that allow them to discover new patterns. To understand the origins of change, therefore, we must first understand what infants bring into new task situations.

In this study, we showed that characteristic movement speed was an important constraint on infants' discovery of stable reach patterns. Infants had individually characteristic speed preferences. Within these preferences, they also showed developmental variability, with each infant having an epoch of faster or more variable movements preceded and followed by periods of greater stability.

Although we do not yet understand why these infants moved faster at certain times and then became more quiet, we did see a strong influence of their preferences on all aspects of their movements. There were strong correlations between speeds of nonreaching movements and the initial, average, and peak speeds of the reach itself. With age, infants became increasingly able, however, to isolate the reach speed from the speed of their ongoing movements. Notice that by the second half of the year, all of the infants

Table 9

Hannah's Speed Correlations

Correlated variables	Early period ($N = 62$)	Active period ($N = 35$)	Stable period ($N = 61$)
14-s speed/reach speed	.282*	.382*	.281*
Before speed/init. speed	.479[a]**	.744[a]**	.819[a]**
Init. speed/reach speed	.429**	.696**	.293*
Init. speed/peak speed	.199	.749**	.171

Note. N = No. of trials per developmental period; init. = initiation.

[a] *N*s = 50 (early), 32 (active), 50 (stable).

* $p < .05$. ** $p < .002$.

Table 10

Hannah's Correlations Between Reach Speed and Trajectory Variables

Correlated variables	Early period ($N = 62$)	Active period ($N = 35$)	Stable period ($N = 61$)
Peak speed/movement units	.389**	.096	−.113
Peak speed/straightness	−.334*	−.325*	.041

Note. N = No. of trials per developmental period.

* $p < .05$. ** $p < .002$.

Table 11
Means and Standard Deviations of Justin's Reaching and Nonreaching Dependent Variables as a Function of Developmental Period

Dependent variable	Early/active period (N = 32) *M*	*SD*	Middle period (N = 32) *M*	*SD*	Stable period (N = 74) *M*	*SD*
			Reaching			
Speed at initiation	5.36	9.83	3.15	3.77	6.48	10.37^{a}
Averaged speed	15.48	9.70	13.56	5.41	16.12	11.02
Peak speed	34.74	23.39	27.21	11.36	30.15	18.79
Straightness	4.61	1.88	4.33	1.55	4.96	2.30
No. of movement units	2.53	2.29	1.84	1.32	1.88	1.02
Speed at toy contact	13.51	10.86	9.53	5.75	10.49	13.42
			Nonreaching			
Entire 14 s speed	6.43	3.96	5.82	3.03	9.92	6.76
Speed before reach	4.16	4.27^{b}	4.24	5.21^{b}	9.39	12.40^{b}

Note. N = No. of trials per developmental period.
[a] N = 73. [b] Ns = 26 (early/active), 31 (middle), 67 (stable).

had quieter arm movements in the few seconds of the trial before they reached, while they were presumably anticipating the presentation of the toy, than in the remainder of the 14-s period. The ability to prepare for the reach task with quiet anticipation may have resulted from increased control over spontaneous arm movements or from increased knowledge about the task situation, or both. In either case, modifying ongoing activity in anticipation of an action is one component of gaining adaptive skill.

Why the Active Period?

The epoch of faster reaching and nonreaching movements and the associated apparent loss of trajectory control seen in each infant is especially intriguing, as are other seeming regressions in development. One attractive explanation for this puzzling observation is that, after gaining what we have called "ball park" control of the arms (Thelen et al., 1993), infants enter into a period of heightened exploration through increasing both the absolute speed of their movements and the range of speeds. Before the active period, infants may not have been able to control speed parameterization sufficiently well to "play around" with it. This is reminiscent of Bernstein's (1967) first phase in skill acquisition in which unskilled movers freeze out degrees of freedom; for these infants, control may have been better within a restricted speed range. However, to acquire adaptive control, infants need to parameterize movements flexibly. Thus, the active period may have enhanced exploration in the speed parameter space, allowing the infants to discover a more globally stable and appropriate speed metric both for reaching movements and for movements prior to reaching.

Role of Movement Speed in Trajectory Control

In addition to the influence of general preferred movement speed on reach speed, we found relationships between speed and other measures of trajectory control, namely movement units and straightness. Most notably, there was a significant correlation between reach peak speed and how directly the hand traversed the path to the toy. For all of the infants, faster movements were less straight, and for 2 of the infants, Nathan and Justin, this relation did not hold for the last portion of the year, the period of stable trajectories. The effect of speed on movement units was less clear, and only reached significance for Hannah in the early period and for Gabriel during his active period. One possibility is that early on, several reaches had many movement units, regardless of whether they were fast or slow, and that as reaching improved there was insufficient variability in the number of movement units to detect speed effects. But how to explain the effect of speed on reach straightness?

Movement speed changes the nature of the arm control problem. When people reach to a target very quickly, they do not have much time to make fine visual or proprioceptive corrections to their hand trajectories, and accuracy declines (Fitts, 1954). Do we have here a baby version of Fitts's law, that is, a speed–accuracy tradeoff? Although we cannot answer this question directly with these data because we did not manipulate target size, there are several reasons to believe that the speed effect is not a result of visual corrections alone. First, the accuracy demands for grabbing the toy were not great, even for new reachers. Scaled to arm and hand size, the task was similar to an adult reaching for a beer can at arm's length. There were no external demands on the baby to "reach as fast as you can," and although some reaches were clearly faster than others, we do not know what "fast" really means for an infant. Our impression was that early on, infants sometimes missed the toy no matter how fast or slowly they reached, and later on, they were very good at it and grasped it in every reach trial. Also, Clifton, Muir, Ashmead, and Clarkson (1993) reported that for target toys scaled similarly to the ones used here, infants were as good reaching in the dark without sight of the hand

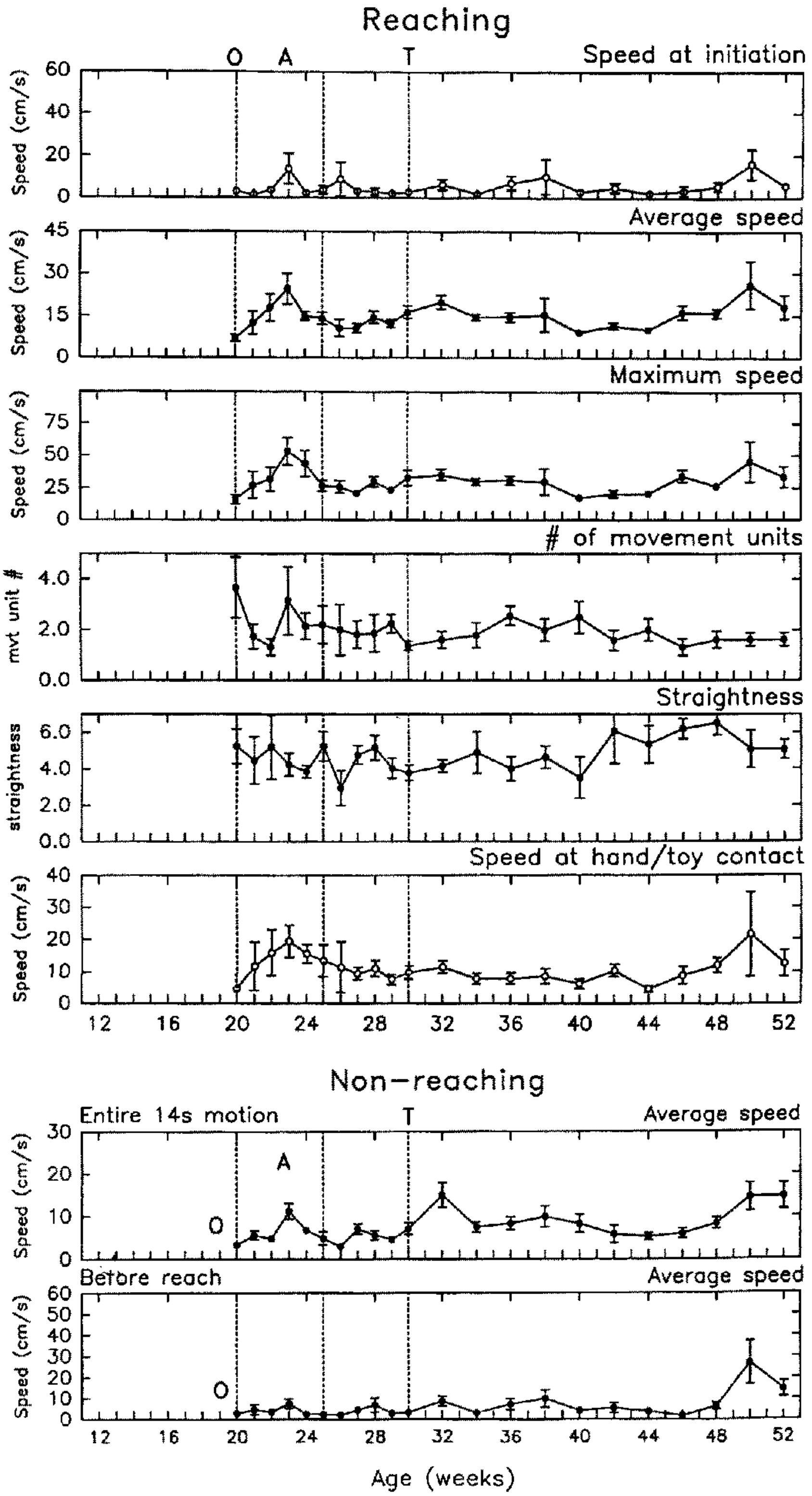

Figure 4. Dependent variables of Justin's reaching and nonreaching movements from Week 20 to Week 52. Six top panels: means and standard errors of the speed at reach initiation (calculated over 333-ms window), speed of the reach, maximum reach speed peak, hand path straightness, number of movement units, and speed at hand–toy contact. Two bottom panels: means and standard errors of the average speed of all nonreaching movements and average speed of the segment of motion prior to reach initiation. O = onset of reaching behavior; A = active period; T = transition week from less to more stable reaching patterns.

Table 12
Justin's Speed Correlations

Correlated variables	Early/active period ($N = 32$)	Middle period ($N = 32$)	Stable period ($N = 74$)
14-s speed/reach speed	.565**	.640**	.733**
Before speed/init. speed	.751[a]**	.261[a]	.732[a]**
Init. speed/reach speed	.319*	.431*	.719[b]**
Init. speed/peak speed	.253	.342*	.657[b]**

Note. N = No. of trials per developmental period; init. = initiation.
[a] Ns = 26 (early/active), 31 (middle), 66 (stable). [b] $N = 73$.
*$p < .05$. **$p < .002$.

or of the object as with full visual information. Finally, one might argue that in fast reaches, we would expect fewer, not more corrections (Latash & Gutman, 1993). In the infants, however, in each case in which speed influenced trajectories, faster movements had more movement units and less straight pathways.

Equilibrium Trajectory Hypothesis and Emergent Control

We suggest here that our data are consistent with the assumptions of a particular model of multijoint upper limb control, the so-called equilibrium trajectory hypothesis (Flash & Hogan, 1985; Hogan, 1984). As we discussed earlier, reach trajectories appear to be planned in hand space, but to execute a straight and smooth path at the hand, infants must generate more complex joint torques and muscle activation patterns to take into account nonlinear passive and elastic properties of the motor system. Does the central nervous system actually compute the second-order nonlinear dynamic equations of motion needed to solve the problem of keeping the hand path on target? Are babies bad reachers because they lack computational skills?

The equilibrium trajectory hypothesis, like several other models of arm control, was derived to circumvent the need for explicit dynamic calculations and, instead, relies on the mechanical properties of muscles, especially their spring-like qualities. In brief, individuals need only set a gradually shifting series of equilibrium points (final positions) of the hand and the required stiffness of their arm springs and the trajectory naturally falls out, just as the trajectory of a spring is not calculated but is a result of the physical properties of the spring (Flash, 1990). Computer simulations have successfully modeled the measured characteristics of real hand trajectories, including the slight curvatures as well as the deviations due to differences in locations in the work space (Flash, 1987). Most relevant to our study here is the source of hand path deviations from the ideal straight path, as described by Flash (1990):

Table 13
Justin's Correlations Between Reach Speed and Trajectory Variables

Correlated variables	Early/active period ($N = 32$)	Middle period ($N = 32$)	Stable period ($N = 74$)
Peak speed/movement units	.263	.124	−.032
Peak speed/straightness	−.297*	−.388*	−.155

Note. N = No. of trials per developmental period.
*$p < .05$.

Table 14
F Values and Significance for Within-Factor Analyses of Variance Performed on Reaching and Nonreaching Dependent Variables

Dependent variable	$F(2, 6) =$	Significance of F
Reaching		
Speed at initiation	8.34	.019
Averaged speed	3.59	.095
Peak speed	8.89	.016
Straightness	7.40	.024
No. of movement units	7.86	.021
Speed at toy contact	0.78	.500
Nonreaching		
Entire 14-s speed	2.81	.138
Speed before reach	2.76	.142

> On the basis of the success of this model in accounting for the fine details of movement curvature, we may argue that the characteristic deviations from ideally straight paths observed in actual data may reflect the combined effects of arm inertia, centrifugal and interaction torques, and the local characteristics of the arm stiffness and viscosity fields. (p. 292)

Whether or not infants are specifically using a version of an equilibrium trajectory control, biomechanical factors such as arm inertia and centrifugal and interaction torques, all of which increase considerably with increased movement speed, may be responsible for the noticeable deviations from straightness characteristic of early reaching. Indeed, what we suggest here is that infants may be particularly vulnerable to these movement-generated disruptions because they have not stabilized their abstract trajectory level—the generation of the equilibrium trajectory—against force-related perturbations exacerbated by fast movements. Good control means, therefore, learning to maintain a smooth, straight reach under various speed and load conditions and from many locations in the reaching space.

We still have not addressed the issue of the movement units themselves. Two possibilities exist, and they are not mutually exclusive. First, as conventionally believed, movement units may be deliberate corrections to the trajectory at the abstract level. Thus, the jerky nature of early reaching may indeed result from infants' inability to generate a good virtual trajectory. But we have also raised the possibility that these units may also be deviations from the trajectory caused by movement-related perturbations, much like a sailboat is blown off course by gusts of a stiff wind. Thus, it is possible that infants must learn several levels of control, that is, first, the plan level and later, the stabilization of the trajectory against movement-related perturbations. We are currently exploring this possibility by looking at the movement kinetics and associated muscle patterns.

This analysis, like our earlier report (Thelen et al., 1993), shows that arm dynamics play an important role in infant reaching development. We have demonstrated that reaching does not appear and improve as an isolated action but as one that is intimately related to other general movement characteristics. We have shown that trajectory straightness and smoothness may develop somewhat independently, and thus we raise the possibility that learning to reach involves multiple levels of control.

References

Berkinblit, M. B., Feldman, A. G., & Fukson, O. I. (1986). Adaptability of innate motor patterns and motor control mechanisms. *Behavioral and Brain Sciences, 9,* 585–638.

Bernstein, N. (1967). *The coordination and regulation of movement.* London: Pergamon Press.

Berthier, N. (1994). Infant reaching strategies: Theoretical considerations. *Infant Behavior and Development, 17,* 521.

Clifton, R. K., Muir, D. W., Ashmead, D. H., & Clarkson, M. G. (1993). Is visually guided reaching in early infancy a myth? *Child Development, 64,* 1099–1110.

Corbetta, D., & Thelen, E. (1995). A method for identifying the initiation of reaching movement in natural prehension. *Journal of Motor Behavior, 27,* 285–293.

Corbetta, D., & Thelen, E. (1996). The developmental origins of bimanual coordination: A dynamic perspective. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 502–522.

Fetters, L., & Todd, J. (1987). Quantitative assessment of infant reaching movements. *Journal of Motor Behavior, 19,* 147–166.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movements. *Journal of Experimental Psychology, 47,* 381–391.

Flanders, M., & Herrmann, U. (1992). Two components of muscle activation: Scaling with the speed of arm movement. *Journal of Neurophysiology, 67,* 931–943.

Flash, T. (1987). The control of hand equilibrium trajectories in multi-joint arm movements. *Biological Cybernetics, 57,* 257–274.

Flash, T. (1990). The organization of human arm trajectory control. In J. M. Winters & S. L-Y. Woo (Eds.), *Multiple muscle systems: Biomechanics and movement organization* (pp. 282–301). New York: Springer-Verlag.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience, 7,* 1688–1703.

Georgopoulos, A. P. (1986). On reaching. *Annual Review of Neuroscience, 9,* 147–170.

Goldfield, E. C. (1993). Dynamic systems in development: Action systems. In L. B. Smith & E. Thelen (Eds.), *A dynamic systems approach to development: Applications* (pp. 51–70). Cambridge, MA: MIT Press.

Gottlieb, G. L., Corcos, D. M., & Agarwal, G. C. (1989). Strategies for the control of voluntary movements with one mechanical degree of freedom. *Behavioral and Brain Sciences, 12,* 189–250.

Halverson, H. M. (1931). An experimental study of prehension in infants by means of systematic cinema records. *Genetic Psychology Monographs, 10,* 107–286.

Halverson, H. M. (1933). The acquisition of skill in infancy. *Journal of Genetic Psychology, 43,* 3–48.

Hofsten, C. von. (1979). Development of visually directed reaching: The approach phase. *Journal of Human Movement Studies, 5,* 160–178.

Hofsten, C. von. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Psychology, 30,* 369–382.

Hofsten, C. von. (1991). Structuring of early reaching movements: A longitudinal study. *Journal of Motor Behavior, 23,* 280–292.

Hofsten, C. von, & Rönnqvist, L. (1993). The structuring of neonatal arm movements. *Child Development, 64,* 1046–1057.

Hogan, N. (1984). An organizing principle for a class of voluntary movements. *Journal of Neuroscience, 4,* 2745–2754.

Hogan, N., Bizzi, E., Mussa-Ivaldi, F. A., & Flash, T. (1987). Controlling multijoint motor behavior. In K. B. Pandolf (Ed.), *Exercise and sport science reviews* (Vol. 15, pp. 153–190). New York: MacMillan.

Jeannerod, M. (1988). *The neural and behavioural organization of goal-directed movements.* Oxford, England: Clarendon Press.

Kamm, K. (1994). *The influence of postural development on the development of skilled reaching.* Unpublished doctoral dissertation, Indiana University.

Karst, G. M., & Hasan, Z. (1990). Direction-dependent strategy for control of multi-joint arm movements. In J. M. Winters & S. L-Y Woo (Eds.), *Multiple muscle systems: Biomechanics and movement organization* (pp. 268–281). New York: Springer-Verlag.

Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Non-equilibrium phase transitions in coordinated biological motion: Critical fluctuations. *Physics Letters A, 118,* 279–284.

Latash, M. L., & Gottlieb, G. L. (1991). Reconstruction of joint compliant characteristics during fast and slow movements. *Neuroscience, 43,* 697–712.

Latash, M. L., & Gutman, S. R. (1993). Variability of fast single-joint movements and the equilibrium–point hypothesis. In K. M. Newell & D. M. Corcos (Eds.), *Variability and motor control* (pp. 157–182). Champaign, IL: Human Kinetics.

Mathew, A., & Cook, M. (1990). The control of reaching movements by young infants. *Child Development, 61,* 1238–1258.

Rochat, P. (1992). Self-sitting and reaching in 5- to 8-month-old infants: The impact of posture and its development on early eye–hand coordination. *Journal of Motor Behavior, 24,* 210–220.

Saltzman, E. L., & Kelso, J. A. S. (1987). Skilled actions: A task dynamic approach. *Psychological Review, 94,* 84–106.

Schneider, K., Zernicke, R. A., Schmidt, R. A., & Hart, T. J. (1989). Modulation of limb dynamics during the learning of rapid arm movements. *Journal of Biomechanics, 22,* 805–817.

Schneider, K., Zernicke, R. F., Ulrich, B. D., Jensen, J. L., & Thelen, E. (1990). Understanding movement control in infants through the analysis of limb intersegmental dynamics. *Journal of Motor Behavior, 22,* 493–520.

Schöner, G. (1994, July). *Recent developments and problems in human movement science and their conceptual implications.* Paper presented at the 3rd European Workshop on Ecological Psychology, Bochum, Federal Republic of Germany.

Thelen, E. (1986). Development of coordinated movement: Implications for early human development. In M. G. Wade & H. T. A. Whiting (Eds.), *Motor skills acquisition* (pp. 107–124). Dordrecht, The Netherlands: Martinus Nijhoff.

Thelen, E. (1994). Three-month-old infants can learn task-specific patterns of interlimb coordination. *Psychological Science, 5,* 280–285.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Matching intention and intrinsic dynamics. *Child Development, 64,* 1058–1098.

Thelen, E., Kelso, J. A. S., & Fogel, A. (1987). Self-organizing systems and infant motor development. *Developmental Review, 7,* 39–65.

Thelen, E., & Ulrich, B. D. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development, 56* (1, Serial No. 223).

Thelen, E., Ulrich, B., & Niles, D. (1987). Bilateral coordination in human infants: Stepping on a split-belt treadmill. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 405–410.

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