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The Transition to Reaching: Mapping Intention and Intrinsic Dynamics

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THELEN, ESTHER; CORBETTA, DANIELA; KAMM, KATHI; SPENCER, JOHN P.; SCHNEIDER, KLAUS; and ZERNICKE, RONALD F. *The Transition to Reaching: Mapping Intention and Intrinsic Dynamics.* CHILD DEVELOPMENT, 1993, **64**, 1058–1098. The onset of directed reaching demarks the emergence of a qualitatively new skill. In this study we asked how intentional reaching arises from infants' ongoing, intrinsic movement dynamics, and how first reaches become successively adapted to the task. We observed 4 infants weekly in a standard reaching task and identified the week of first arm-extended reach, and the 2 weeks before and after onset. The infants first reached at ages ranging from 12 to 22 weeks, and they used different strategies to get the toy. 2 infants, whose spontaneous movements were large and vigorous, damped down their fast, forceful movements. The 2 quieter infants generated faster and more energetic movements to lift their arms. The infants modulated reaches in task-appropriate ways in the weeks following onset. Reaching emerges when infants can intentionally adjust the force and compliance of the arm, often using muscle coactivation. These results suggest that the infant central nervous system does not contain programs that detail hand trajectory, joint coordination, and muscle activation patterns. Rather, these patterns are the consequences of the natural dynamics of the system and the active exploration of the match between those dynamics and the task.

The ability to reach for an object is an important motor milestone, which normal infants in Western cultures acquire between 3 and 5 months of age. Like other milestones, such as lifting the head, turning over, sitting alone, crawling, and walking, reaching marks the emergence of a qualitatively new skill. Although every motor milestone appears as a discontinuous phase with a definable onset, such new forms of behavior must arise from component abilities that are themselves continuous over time. A central question for understanding perceptual-motor development, and development in general, is how infants acquire a discrete new pattern of behavior such as reaching from precursors that themselves do not contain the pattern.

Because the ability to reach and grasp has major psychological ramifications for developing infants, the question of the origins of this skill has engaged theorists and researchers for many years. The fundamental issue is how infants move the hand through space to contact a target that is perceived by vision. The developmental task, therefore, has traditionally been viewed as con-

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[*Child Development*, 1993, **64**, 1058–1098. © 1993 by the Society for Research in Child Development, Inc. All rights reserved. 0009-3920/93/6404-0011$01.00]

structing a match between the seen object and the felt hand. Most notably, Piaget (1952) concluded from his exquisitely detailed observations that grasping objects requires seeing both the object and the hand so that the schemata of vision and of proprioception and touch can be mutually assimilated, and later, fully coordinated. In Piaget's view, therefore, an essential stage in learning to reach is visual inspection of the hand in the vicinity of the desired object. Bruner and Koslowski (1972; Bruner, 1973) offered a different kind of constructionist explanation. They suggested that infants must build a sequence of visually guided hand and arm movements, not so much from disparate perception and action systems, but from awkward, undifferentiated, and poorly coordinated components. A third group of theorists reject the constructionist position, claiming that vision and prehension are united from the start. The evidence for this view is that newborn infants will extend their arms toward visual targets or in the direction of their head and gaze (Bower, Broughton, & Moore, 1970; Hofsten, 1982; Trevarthen, 1974, 1984). In the third view, development is seen more as a process of revealing and fine-tuning abilities that are already in place.

While the central role of vision in accurate reaching and grasping cannot be disputed, there is in reality little evidence that early reaching is primarily guided by visual matching and correction of the hand and the arm to the target. Rather, it looks as though the very first attempts to reach, while elicited by a seen object, do not require a seen hand or arm. Piaget (1952), for instance, saw mutual regard of hand and object only *after* the infant had brought the hand in the vicinity of the target. White, Castle, and Held (1964) cited a prolonged period of hand regard as evidence for a hand-object match, but this excessive hand watching was likely the result of the impoverished conditions of their institutionalized subjects. And while newborns may extend their arms in the presence of a visually interesting sight, their movements are not visually guided to the object. Hofsten (1982) concluded that the newborn synergy appeared to function as an attentional response rather than one used for manipulation. Indeed, as the frequency and quality of arm movements change dramatically during the first 4 months (Hofsten, 1984), there is no observable continuity between newborn arm extensions and later reaching. The most compelling support for minimum use of vision for guiding first reaches, however, comes from a study by Clifton, Muir, Ashmead, and Clarkson (1993, in this issue). These investigators found that at the time of their very first reaches, infants were equally proficient when reaching in the light or the dark to a glowing or sounding target. Once infants had located the toy in space by vision or by audition, proprioceptive information was sufficient to get the hand close to the target.

We are convinced by this evidence that it is time to recast the issue of the origins of reaching away from a primacy of visual-motor mapping. Indeed, it appears that the first task in learning to reach is to get the hand somewhere in the vicinity of the desired object, and that this is primarily a problem of *control of the arms* through haptic and proprioceptive information. Later, infants rely increasingly on vision to refine the trajectory and adjust the hand to the target (Bushnell, 1985).

Where, then, does reaching come from? What is clear is that goal-directed reaching emerges from an ongoing background of other movements of the arms. Some movements are undirected, appearing erratic, uncoordinated, and sometimes forceful. Young infants also perform smoother, aimed motions of the hands toward the face and the mouth (Butterworth & Hopkins, 1988). Neither of these types of movements are morphologically identical to directed, arm-extended reaches, yet reaches must have their origins in the neural, muscular, and energetic properties of the arms which are manifest in these other nonreaching actions. In other words, the first problem for an infant who desires an object within reach may not be to construct a map between the hand and the eye, or to recall or call forth a dormant prefigured pattern, but to adapt his or her current ongoing spontaneous and intentional movements to the specific, new task of reaching and grasping. We will emphasize throughout this paper that reaching development is thus a process of *individual problem solving*, where the problem to be solved depends on the individual's own developmental history and current sensorimotor status.

From a dynamic systems perspective, the onset of reaching, like the emergence of other new forms, can be viewed as a confluence of heterogeneous components, assembled into a cooperative unit for a specific purpose or task (Thelen, 1989; Thelen & Ulrich, 1991). When behavior is skilled—rapid, smooth, reliable, and accurate—the coupling among the component elements is stable. When movements are unskilled, however, subsystems are more loosely assembled, more variable, and more easily disrupted. In dynamic terms, we expect to see such loosely coupled components at the time of the emergence of a new qualitative form, the *phase shift*, such as the transition from no-reaching to reaching. Indeed, this transition provides us with the window to view how the system assembles itself to accomplish a particular intentional goal—get the toy. Thus, to understand the developmental process of an infant "discovering" a reach from among many and varied nonreaching movements, we must characterize the component abilities and track their contributions over the transition itself. Note that the component abilities may themselves have varied and asynchronous developmental courses. Some may be in place before reaching skill appears, while others may act as "rate limiters," whose contribution shifts the system into the new behavioral form.

What are the components infants must assemble to successfully extend their arms to reach and grasp? First, they must see and want the toy. We assume here that, by 3 or 4 months, infants' visual systems are sufficiently developed to provide a good, if not perfect, sense of an object's location in "reachable" space. By this age, infants have also had considerable experience with objects placed in their hands, and with hands and objects in the mouth, so we additionally assume that motivation to grab the toy is not lacking. What infants lack, we believe, is the ability to control their arms in order to contact the object with any precision or regularity. Thus, we propose that it is this aspect of control—of modulating the ongoing movements—that is the "rate limiter" for reaching.

Controlling the arms, however, is no mean feat. Infants must first solve what is known in motor behavior as the "degrees of freedom" problem (Bernstein, 1967). This means they must recruit a heterogeneous assembly of individual parts—neurons, muscle fibers, bones, joints, metabolic processes—with nearly unlimited combinatorial possibilities, into a device (the hand) which goes quickly and efficiently to the toy (Bingham, 1988; Saltzman & Kelso, 1987). However, at a number of levels, some of the degrees of freedom have already been constrained by the infants' existing anatomical and dynamic properties, and by the characteristics of the physical environment. Neural networks are already in place in the brain and spinal cord, as are afferent fibers detecting changes in the skin, muscles, and joints. Muscles themselves are intrinsically elastic, and neural mechanisms to detect and respond to muscle stretch appear to be functional early in life (Schneider, Zernicke, Ulrich, Jensen, & Thelen, 1990). At another level, limbs have elastic and mechanical properties and can act as springs or pendulums, with natural resonant frequencies (Kugler & Turvey, 1987). Infants have anatomical and physiological limits on the metabolic processes that produce energy to move the limbs. These characteristics, the infants' *intrinsic dynamics,* act as both constraints on the reaching problem and the physical and informational raw materials from which each infant must assemble an action to fit the specified goal—get the hand to the toy.[1]

Second, once infants transduce their intentions into a reach movement, they must correctly scale the action to match the demands of the task. If they deliver too little energy to the muscles, infants cannot lift their arms against gravity and extend them away from their bodies, and their movements are slow and inefficient. Conversely, if the muscle contractions are too strong, movements may overshoot the target and be too rapid to allow for corrections as the hand nears the toy. In addition, because arms are mechanically linked segments, vigorous movements create inertial forces that are transmitted from one segment to another. A strong muscle contraction at the shoulder, for example, if not counteracted at the forearm and hand, will produce uncontrolled reactions at those segments (Hollerbach & Flash, 1982).

To solve the degrees of freedom and scaling problems, infants could, in theory, work at several different levels of neuromotor organization. If reaching is prefigured at

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[1] We use the term *intrinsic dynamics* here to denote the collective behavior of the system in the absence of any specific task requirements or task matching (see Zanone & Kelso, 1991). The intrinsic dynamics are not just within the infant, but take into account the nonspecific effects of the environment such as gravity. We do not mean *innate* or genetic by the term intrinsic.

the level of patterns of muscle group activation, early reaches would show muscle synergies specific to reaching and common among and between infants. If, however, the primitive patterning is expressed at the level of joint or segmental coordination, we would expect invariances of phasing of the joints of the arm, similar to that found in early spontaneous movements of the legs, for example (Thelen & Fisher, 1983). A third possibility is that control is exerted at the level of the end point of the segmented arm, the hand, and that joints and muscles are recruited in whatever pattern gets the hand to the object. These solutions address primarily the problem of controlling degrees of freedom. A final possibility is that infants first work on the scaling problem, and that degrees-of-freedom solutions emerge in the context of refinements in force scaling.

It is important to note here that the issue of what the brain controls to produce a reach trajectory is far from solved in adult motor neuroscience, and indeed is an area of intense research and modeling effort. The question has not been addressed developmentally. Thus, by unpacking at what level—end points, joints, muscle, forces—infants *begin* to exert voluntary control, we hope to contribute to the issue of what is directly modulated by the CNS and what patterns emerge as a consequence of modulation at other levels. Detailed examination of *individual infants* at the transition to reaching is critical. Competing adult models predict that the brain controls the arm by controlling the joint movements, hand path, global stiffness, or individual muscle groups. One level should emerge as the developmental invariant: What do infants have in common at the reach transition, and what parameters vary with individuals' intrinsic dynamics and efforts to solve the problem of moving the hand to the desired object?

This study, therefore, has several purposes. First, we seek to describe, for individual infants, the nature of their intrinsic dynamics just before their first reaches. What are the characteristics of their spontaneous movements that form the ongoing sensorimotor context from which reaches emerge? Second, we describe how infants solve the degrees-of-freedom and scaling problems at the appearance of their very first reaches. How do they assemble the constituent components to map intention onto their intrinsic dynamics? And third, how do infants adapt or change this mapping in the weeks following the first reaches? Here we ask about the possible modulation of the discovered solutions. We then use these data to address the larger issues of motor neuroscience: What is directly controlled in the formation of a reach trajectory?

To do this, we report on a portion of a longitudinal study of four infants observed from 3 weeks until 1 year. We designed this study to follow a dynamic systems strategy (Thelen & Ulrich, 1991) by (1) mapping in considerable detail the developmental trajectories of reaching in individual infants and their constituent component variables, (2) identifying phase shifts, where new behavioral states emerge, and (3) using the instabilities associated with transitions to uncover processes of change and potential control parameters. We report here on the phase shift, the week of infants' first reaches, and the 2 weeks preceding and following this motor landmark. Within each observation, we sought to capture both spontaneous movements and the transition from spontaneous to task-directed movements when the toy was presented. Our measures allowed for concurrent assessment of the three-dimensional time-space trajectories of the hands and joints of both arms (kinematics), the forces underlying the movements of the arm segments (kinetics), and the patterns of muscle activation producing these movements. We report these results as narratives describing how each of the four infants learned to reach, accompanied by figures that show their movement kinematics and underlying kinetic and neurological mechanisms. This approach is essential because the developmental story lies in the infants' individual solutions and pathways of change. The multiple levels of explanation are also needed because movement cannot be understood by any level taken alone.

We discovered dramatic differences in how four infants first reached for toys. These differences make it impossible for reaching patterns to be iconically represented beforehand and strongly support our proposal that control per se limits reach emergence, although we do not directly test this proposal. We further suggest that reaching trajectories and patterns of coordination are by-products of infants modulating the energetic and stiffness properties of the arms as they fit their ongoing movement dynamics to the task. This supports a class of reach trajectory models based on control of the hand "equilibrium point" through modulation of limb stiffness.

Method

Subjects

Subjects were four normal, full-term infants, one girl (Hannah) and three 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 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 videorecorded a quasi-naturalistic play session with parents for later behavioral coding. This report, however, uses only data from the second weekly visit, where we collected position-time and electromyographic (EMG) data of infants reaching for objects while supported in an infant seat. 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.

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. Two cameras each collected two-dimensional data from each IRED within a calibrated volume. Three-dimensional coordinates were calculated using the Direct Linear Transformation technique. Infants were seated in the center of a calibrated volume of 53.5 × 65.5 × 53.5 cm (w,h,d), with two cameras positioned on the right and two cameras on the left. 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.

We used a Grass Model 7D polygraph to collect five channels of EMG signals, sampling at 750 Hz. Pediatric silver/silver chloride surface electrodes were taped to the infants. The EMG signals were synchronized with position-time data through WATSCOPE A/D data acquisition hardware and software. All trials were videotaped from a lateral and either frontal or overhead view. Both views were simultaneously recorded using a split-screen generator, with an added frame counter. Thus, position-time, EMG, 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 and the 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 (Fig. 1). In very young infants, the elbow IRED was often obscured from the camera because infants kept their arms flexed close to their bodies. In these cases, we substituted an additional hand IRED for the elbow IRED, hoping to increase our visibility of the hand. We placed EMG electrodes on one side only, which we determined by noting the infant's more active arm when we presented a toy in midline. (Sometimes, however, infants surprised us by using the non-monitored arm more during the actual test trials.) The EMGs were recorded from the muscle bellies of the biceps (an elbow flexor), triceps (an elbow extensor), upper trapezius (shoulder elevation and retraction), anterior deltoid (shoulder flexion and elevation), and erector spinae (trunk extension) at the approximate level of L3.

After we placed the total of eight IREDs and five EMG electrodes on the infant, the parent held the infant while we checked electrode resistances and made any final equipment adjustments. Then we secured the infant 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 head 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-sec trials. We kept some flexibility in the order of the trials to keep 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, but not actively engaging them, and

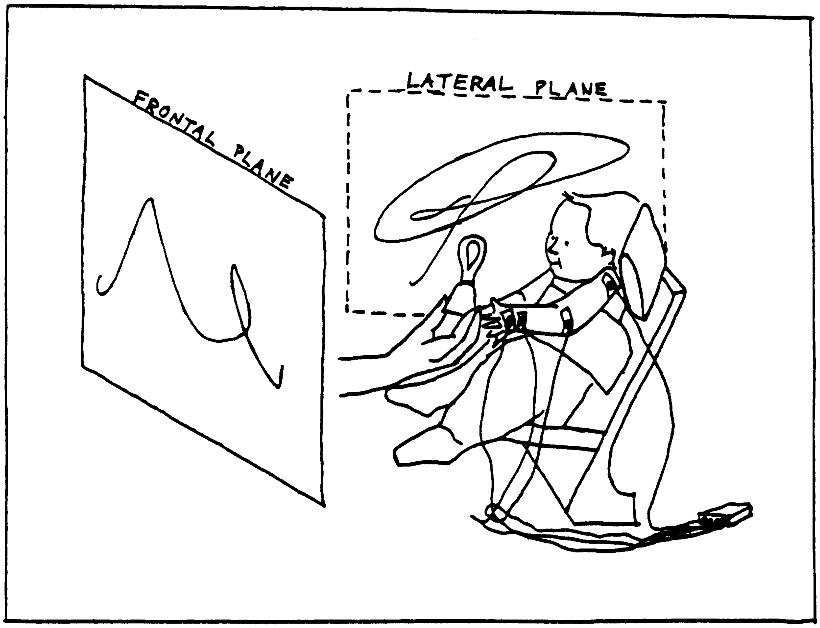

FIG. 1.—Experimental setting. IREDs were placed on the joints of the shoulder, elbow, wrist, and hand of both arms. Hand trajectories are projected on two two-dimensional planes viewed from the side (lateral plane) and the front (frontal plane).

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, attractive, graspable toys to the infants at midline, shoulder height, and just at the distance of their extended arms. Toys were offered either 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, by the parent, who lifted the toy to the appropriate position, or 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 three to four trials in each toy condition. At the conclusion of the session, we measured the IRED distances with a cloth tape. Note that in this report we use only data from the toy trials.

The analysis of joint forces using inverse dynamics required detailed anthropometric measurements of the arms to calculate the segmental masses, centers of mass, and centers of gravity. A trained experimenter measured the infants after the seminaturalistic observation, which was always within 3–4 days of the experimental session. Details of anthropometric models and measurements are reported in Schneider et al. (1990) and Schneider and Zernicke (1992).

Data Analysis

Motion analysis on infants' spontaneous and unskilled arm movements presents formidable problems. For three-dimensional trajectories, optical recording equipment requires visibility of joint IREDs by two cameras. Kinematic, and especially kinetic, analyses demand very high quality coordinate data from all joint markers. In addition, inverse dynamics calculations are appropriate only when the limb in question is freely moving and not affected by external forces. 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, which obscures IREDs from camera view or moves them out of the calibrated area. For example, arms may be extended below and behind the chair or flexed close to the infants' bodies, and sometimes the infants put their hands in their mouths.

Thus, in order to capture both the dynamics of spontaneous movements and the actual transition to reaching, in addition to 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 whether their arms were free) and second, on the quality of the data. This led to a disproportionate number of analyzed spontaneous movements for infants who were very active and whose IREDs were visible compared to 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 only (1) *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 (2) *object/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 sec of the trial or a portion of it. Video coders also noted portions of the trial for each hand when the hand was not in free motion (i.e., touching or grasping something or part of the body, or in contact with the chair).

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 the sampling frequency (50 frames).

The next steps in data processing then depended on the level of analysis desired. For the *kinematics of the hand* (the end point), only hand or wrist IREDs were used. The selection of the wrist or hand IRED was based on marker visibility alone (the least stringent criterion), and resulted in the longest segments. For *joint angles*, all markers of the same arm had to be visible within the same segment, and distances between each pair of consecutive IREDs, calculated from WATSMART data, had to deviate less than 30% from IRED distances measured on the infants.[2] For *kinetics* (inverse dynamics), we used only segments selected for joint angles that also had free arm movement. (The calculations of forces moving the joints required that the arm not be perturbed by external forces.) Thus, hand kinematics, joint angles, and kinetics were calculated on correspondingly smaller segments of the trials. The total number of toy presentation trials analyzed and the percent of total trial time analyzed for the four infants are reported in Appendix A.

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 to 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-sec 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 used 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 analysis to produce smooth torques and not lose information in the lower derivatives. Then we smoothed each coordinate individually for each IRED, using its specific cutoff frequency. The

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[2] The 30% deviation is in the calculated length of the segment and compresses the relative noise of the (X,Y,Z) coordinates into a single number, that is, the ± 15% deviation from the measured segment length. We arrived at this criterion from extensive pilot analysis where 30% emerged as a reasonable cutoff between analyzable good trials and those with missing points, excessive noise, or baseline shifts.

smoothing function was a fourth-order Butterworth filter.

This study reports, for the first time, forces moving infant arm segments during spontaneous and directed movements. Joint torques (torques are forces rotating the arm segments) were calculated using techniques of inverse dynamics. Inverse dynamics uses Newtonian equations of motion (basically $F = ma$) to calculate torques from observed motions and estimates of masses of segments involved. (The equations of motion and the model used to estimate segmental parameters can be found in Schneider et al., 1990 and Schneider & Zernicke, 1992.) Important for this study is that inverse dynamics techniques allowed us to partition torques acting on the joints into the following: NET torque (total rotational force), which is comprised of three components: (1) gravitational torque (GRA), or force of gravity acting on the center of mass of the segment, (2) motion-dependent torques (MDT), forces acting on one segment that have been mechanically transmitted from the motions of the other segments of the limb (think of how shaking the elbow makes the wrist shake too), and (3) muscle torques (MUS), forces that arise from muscle contractions (as well as passive tissue deformation). Muscle torque is the only force that can be actively controlled by the nervous system; GRA and MDT are passive forces. All reported torques were normalized to segment mass.

To determine ranges of displacement, speed, and forces, maximum and minimum values of corresponding time series ("peaks") were determined using the following cutoff values: for joint angles, .75°/sec; for speed, .1 cm/sec or °/sec, for torques, .000005 Nm/N.[3] Finally, we treated the EMG signal by band pass filtering at 75–300 Hz with a 100-frame window, demeaning to 0 mV, rectifying using a 0 mV threshold, and smoothing with an even-weighted moving average window of 8 msec.

To prepare individual narratives, the first three authors each reviewed the entire 5 weeks of processed files of one or two infants (ET, Gabriel; DC, Nathan; KK, Justin and Hannah), and reviewed their notes with the research team in conjunction with averaged and compiled data. The team also chose exemplars.

Results

We defined the *onset* of reaching as the first week in which infants consistently contacted the toy by flexing the shoulder (lifting the upper arm) up and away from the body and extending the elbow while looking at the toy. (Some infants would grasp the toy before the onset week if the toy was brought to their hands.) The four infants reached this motor milestone at very different ages, and by very different routes. At age of onset, however, infants performed equally: all frequently over- or undershot the object and sometimes failed to grasp it. To capture this variability in developmental trajectory and to discover common strategies as well, we describe each infant in terms of our stated three purposes: (1) infants' intrinsic dynamics before first reaches, (2) mechanisms by which infants accomplish first reaches, and (3) modulation of reaching components in the 2 weeks following first reaches.

Gabriel

1. *Intrinsic dynamics.*—Gabriel, whose reach onset was 15 weeks, was the most motorically active infant, and his task in learning to reach was to control his energetic movements. In the 2 weeks before reach onset (onset − 2 and onset − 1), he engaged in frequent, often rhythmical, bilateral "flapping" movements in the presence of the toy. Gabriel produced flaps primarily by shoulder flexions and extensions. These movements had very high velocities (some spikes as high as 200 cm/sec), and generated very high MDT, which were counterbalanced by correspondingly high MUS. Muscle activity was variable, but usually showed phasic bursts of coactivation in arm, shoulder, and back muscles.

The kinematic qualities of these spontaneous movements are illustrated in Figures 2 and 3. The top panels of Figure 2 show the path of the right (14 sec) and left (10 sec) hands in the frontal plane (imagine the path of the hand projected on a screen in front of the infant) during a trial the week before

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[3] Picking peaks by computer program requires arbitrary criteria for determining meaningful changes in direction from inevitable fluctuations in the time series due to noise in the data. The number of peaks is always dependent on the degree of data smoothing. However, since we used standard criteria for data smoothing and for picking peaks, we feel confident that between and among-infant comparisons are valid. Also note here that we use the term *speed* for the first derivative when we use the resultant (3D) displacement of the hand, which results in unsigned values. *Velocity* is conventionally a vector and is used for signed values.

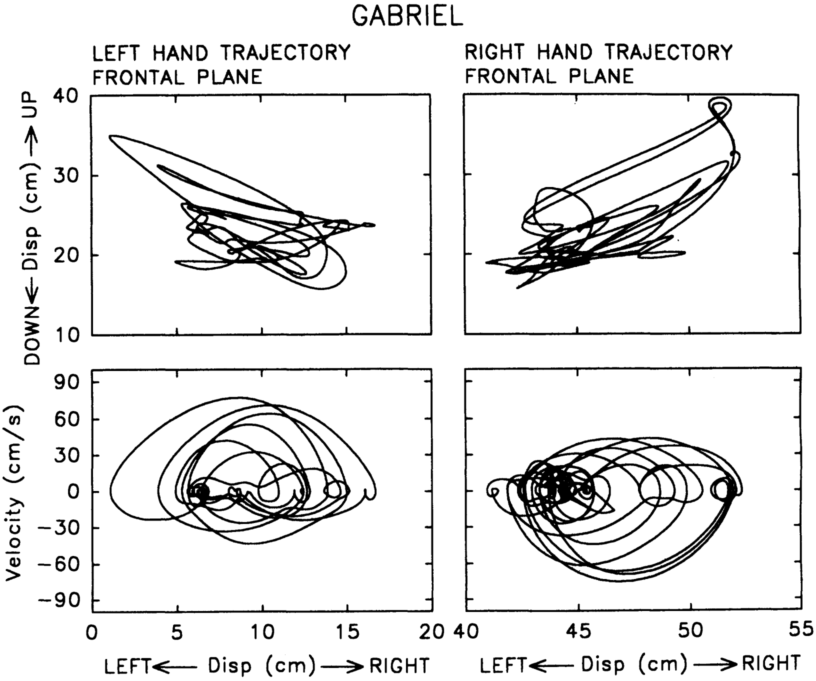

FIG. 2.—Hand trajectories and phase plane plots of 14 sec (right) and 10 sec (left) of Gabriel's spontaneous movements at onset – 1. Top panels: The path of both hands in the frontal plane. There was no toy contact. Bottom panels: The same movements plotted as phase planes with the hand displacement in the left/right direction versus the velocity. The rounded trajectories indicate that the velocity varied smoothly with the displacement, a dynamic characteristic of springs and pendula. The topological similarity of the trajectories suggests behavior of a *limit cycle attractor.*

reach onset where his parent offered the toy, but he did not contact it. Note the symmetrical trajectories in the upward and lateral directions, and how the hands traced remarkably smooth, similar paths. The bottom panels represent the same movements on the *phase plane,* which provides a picture of the changes in hand movement in the right-left direction as a function of the velocity of those changes; phase planes describe the dynamic states of the system. Conventionally, we read the phase plane clockwise, that is, as Gabriel moved from his right to his left, his hand velocity increased smoothly in the negative direction, reached 0 at the direction reversal, and moved in the opposite direction. Note that his velocity was higher in the left to right direction in his left hand and in the right to left direction in his right hand. This means that Gabriel had higher velocity toward the midline than away from it in both hands; movements were mirror-like both in space and in speed. These phase planes have dynamic characteristics similar to those of springs and pendulums, where the force varies smoothly during the trajectory. Figure 3 captures the rhythmical qualities, high speeds, and bilateral synchrony of these movements by comparing the 3D resultant speeds of both hands of another trial at the week before onset. Muscle activation patterns correspond to phasic movement bursts, with activity especially strong in the triceps. Muscle groups sometimes contracted alone (i.e., triceps), but more often showed considerable coactivation, including lower back extensors.

In order to assess the infants' intrinsic dynamics both within the reach itself and in the movements preceding and following the reach, we have summarized in Figure 4 hand speed changes for the entire analyzable trial where the toy was presented for each infant in the weeks before, during, and after reach onset. These measures allow comparisons of average speed, average maximum speed, and the mean rate of speed peaks, an estimate of the number of changes of movement direction (note that because we did not analyze segments of trials where infants did not move at all, these plots likely slightly overestimate the activity of the more quiet infants, for whom we analyzed a

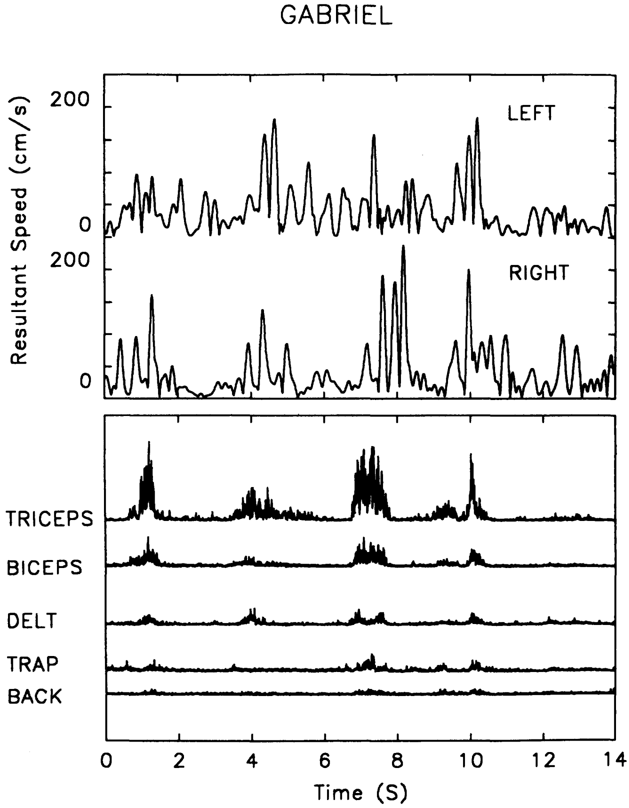

FIG. 3.—Resultant 3D speeds for right and left hands for Gabriel's spontaneous movements at onset − 1 and concurrent EMGs for the left hand. Both arms are activated in nearly simultaneous bursts. Note that the large bursts at 1, 4, 8, and 10 sec have simultaneous activation in all arm and shoulder muscles as well as in the lower back.

smaller percentage of the trial; see Appendix A). Figure 5 presents similar data for MUS torque, an estimate of how much force infants are generating from muscle activity in both their spontaneous and reaching movements. (By our conventions, torques in the negative direction tend to flex the joints; averages are calculated on absolute values and thus represent torques rotating the joints in both flexion and extension.) The rate of MUS torque peaks (bottom row of panels, Fig. 5) is again a measure of movement smoothness and speed. Jerky and/or fast movements usually generate more modulation of MUS. Figures 4 and 5 provide a description of the *movement context* from which reaches emerge and in which they are embedded.

Gabriel's high activity level before reach onset is apparent in these figures. His speed level and rate of speed change were the highest of all the infants. His MUS had very high values at onset − 2, but he appeared to modulate his extreme force values at onset − 1, although average speed remained high. Thus, Gabriel's first reaches emerged from a background movement repertoire characterized by rapid movements associated with high generated forces.

2. *Reach onset.*—Given his cyclic, high energy movements in both weeks before reach onset, how did Gabriel manage to direct his hand to the toy? In Figure 6, we show how a typical reach emerged from these spontaneous movements in the week of reach onset. The top two graphs indicate the trajectory of his right hand for an 8-sec segment, projected on the frontal and lateral plane, where the toy was presented soon after the beginning of the segment. (Most of Gabriel's reaches, like his flaps, were bilateral, with the second hand initiating movement and often contacting the toy nearly simultaneously or with a lag of a few seconds.) In this example, Gabriel produced one large flap back and to his left before approaching the toy from above. On the resultant speed time series (bottom plot), the high speed peaks around 5 sec are the flap; the segment

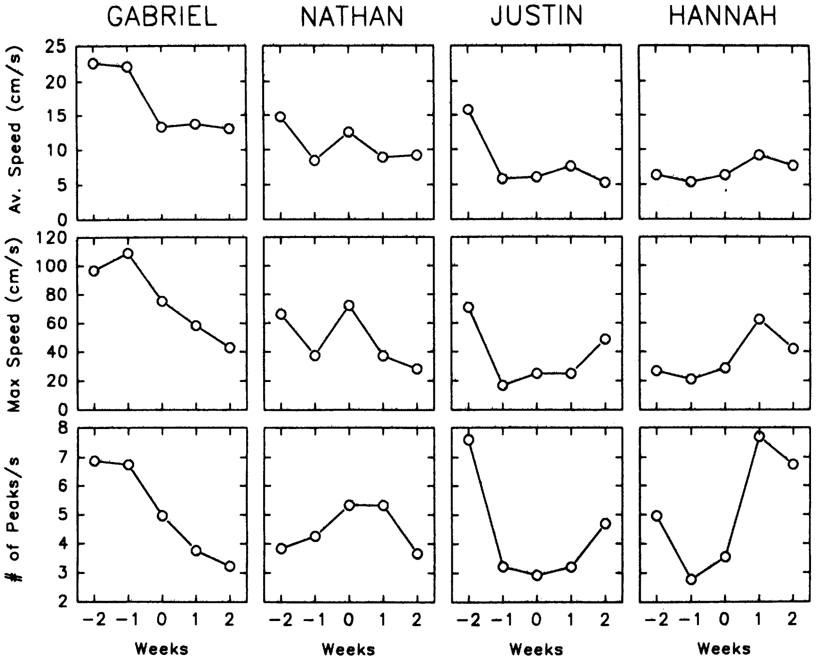

FIG. 4.—Summary of hand speed changes in the overall movement context from which each infant's reach emerged. Top row panel: Averaged resultant speed across trials and hands by week. Middle row panel: Averaged maximum resultant speed across trials and hands by week. Bottom row panel: Averaged number of resultant speed peaks across trials and hands by week. The number of segments used to average hand speed changes is specified in Appendix B.

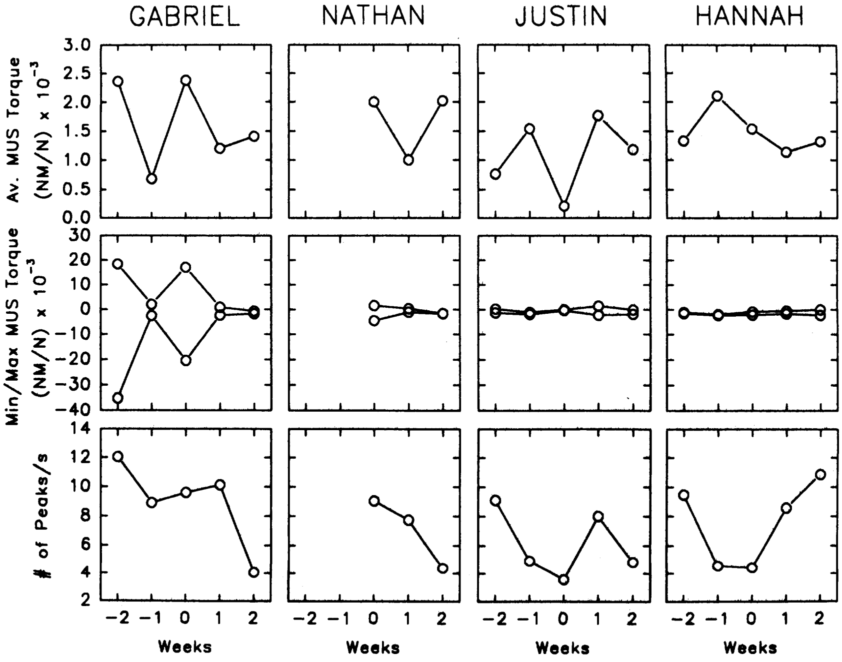

FIG. 5.—Summary of shoulder MUS torques in the overall movement context from which each infant's reach emerged. Top row panel: Averaged shoulder MUS torques computed using absolute values. Torques were averaged across trials and arms by week. Middle row panel: Averaged maximum and minimum shoulder MUS torque across trials and arms by week. Bottom row panel: Averaged number of MUS torque peaks across trials and arms by week. The number of segments used to compute shoulder MUS torque averages is specified in Appendix C.

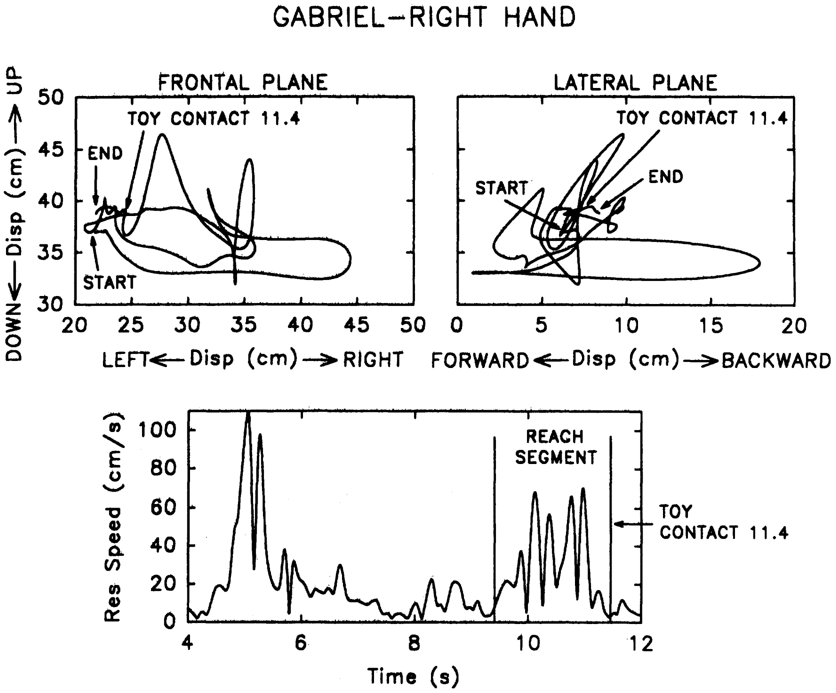

FIG. 6.—Exemplar trial for Gabriel's right hand at reach onset showing transition from spontaneous flapping to reaching for toy. Top panels: 8 sec hand path in the frontal and lateral planes. Bottom panel: Resultant speed for the same segment showing high velocity flaps at 4–6 sec and a flap-into-reach at 9.5 sec.

of the movement directed toward the toy is marked by vertical lines. Gabriel approached the toy with a high velocity swiping movement, with many changes of direction.

Figure 7 (top left) illustrates the pattern of rotations of the shoulder, elbow, and wrist joints in the movement segment directed toward the toy and ending in contact. Note the rapid flexions of the shoulder, which were also characteristic of Gabriel's spontaneous movements before onset. (By our conventions, flexion or smaller joint angles meant lifting the shoulder and bending at elbow and wrist.) Elbow and wrist flexed and extended just before contact in this example, but this was not consistent in all the reaches. The bottom graph in Figure 7 shows the partitioned torques associated with the same segment. Gabriel produced high MUS and MDT, but notable is his successive damping of the shoulder torques as his hand approached the toy. Thus, even in this first week of reaching, Gabriel appeared to be modulating his swiping movements somewhat as he approached the toy, although the movement was still fast and forceful. Finally, we can see in Figure 7 (top) a pattern of coactivation in four of the five muscle groups during the approach toward the toy. (Coactivating muscles works to stiffen the arm.) Within the coactivation, there are rapid modulations of triceps and deltoid, perhaps reflecting muscle responses that damped high MDT. We observed these modulations in all the infants, even in Justin and Hannah, who generated low MDT, so it is also possible these represent muscle activity to correct the path of the hand once it is stiffened.

In sum, Gabriel carved his first reaches from an active movement background of rhythmic, high velocity movements from the shoulder by both stiffening his limbs through muscle coactivation, and lowering both the velocity and the perturbing passive forces. However, his first reaches were more like swipes, with little adjustment as he approached the toy.

3. *Subsequent modulation.*—Gabriel discovered he could obtain the toy by damping down his large, rapid movements. In the 2 weeks subsequent to his reach onset (onset + 1 and onset + 2), Gabriel continued to adapt his intrinsic dynamics to fit the task. In Figures 8–12, we document these changes.

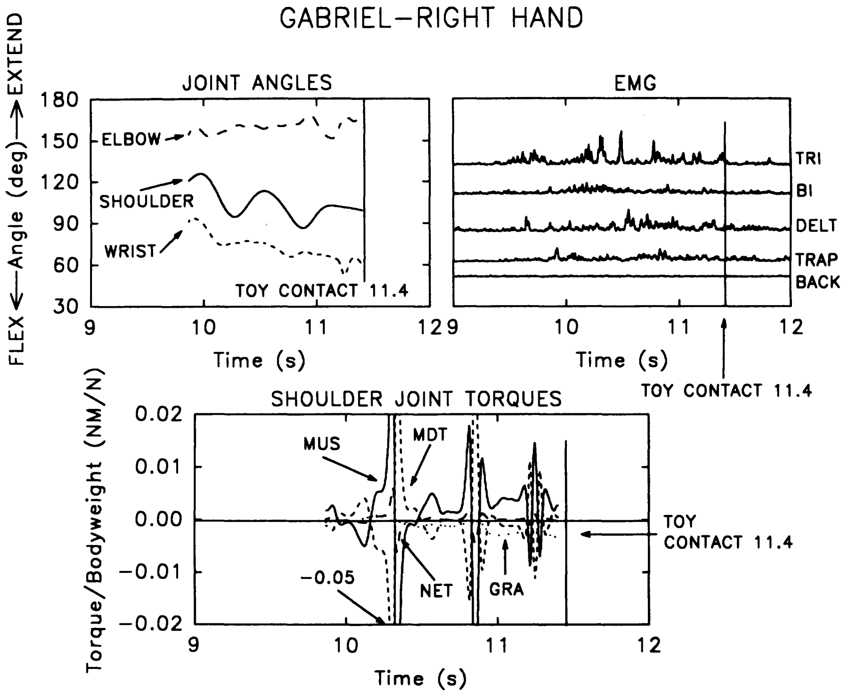

FIG. 7.—Top left panel: Rotations of the shoulder, elbow, and wrist joints of Gabriel's right hand for the flap-and-reach segment indicated in Figure 6. Flexion = decreasing joint angles at elbow and wrist, and lifting the arm at the shoulder. Top right panel: EMGs of five muscle groups for the entire 3-sec reach segment illustrating tonic coactivation. Bottom panel: Torques at the shoulder associated with the same segment. Negative torques work to flex the joints. NET = sum of all torques rotating the shoulder joint. GRA = torques due to the pull of gravity. Note that gravity is extensor at the shoulder. MDT = torques rotating the shoulder that result from the movement of the other, mechanically linked segments of the arm. MUS = torques rotating the shoulder arising from muscle contraction and tissue deformation.

Because we observed young infants in an unconstrained context, reaches were often continuous with other, seemingly non-goal-directed movements. Thus, it was impossible to know when infants actually began each reach. Therefore, we assigned toy contact space and time coordinates of zero and used all kinematic and kinetic data up to 3 sec preceding the contact point. If two hands made toy contact, we used only the first hand. Figure 8 has Gabriel's contact hand trajectories plotted on the plane defined by front-back and left-right movement, and normalized by using the toy contact coordinates as 0,0. (Imagine the infant's head at about the 0 mark on the X axis, and that we are looking down on the path from above.) This figure shows that after 2 weeks of reaching practice, Gabriel was still making large and somewhat indirect movements to the toy. More enlightening is Figure 9, which plots the resultant 3D hand speed using time 0 as toy contact. In the onset week, we see the large, rhythmical peaks, with some evidence of deceleration at contact. Although at onset + 1, Gabriel was still contacting the toy with variable, and sometimes high speed, there is evidence of slowing down before the reach itself at about .5 to 1 sec before contact. In other words, Gabriel gained the ability to inhibit flaps and direct his hand toward the toy in a more discrete movement, although some reaches still contacted with high speed. The notable feature of onset + 2 is the lower speed for the reach itself and at contact compared to the previous week. Figure 4 also illustrates Gabriel's increasing control of his high speed movements in the weeks following onset.

Gabriel's control of the speed of his hand is also dramatically reflected in the amount and direction of his shoulder MUS torque (Fig. 10). Reach onset has huge MUS torques in both flexor and extensor directions. The torques are lower by onset + 1, but are still variable before and during the reach. After 2 weeks of reaching practice,

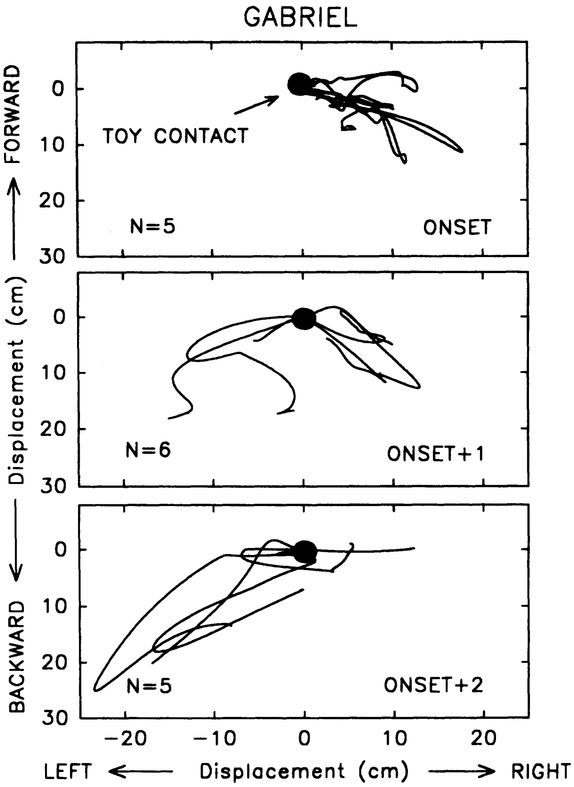

FIG. 8.—Hand trajectories of all analyzable trials at reach onset and the following 2 weeks during which Gabriel contacted the toy. Only the trajectory of the hand making first contact is plotted. Trajectories are depicted from a top view, that is, looking down over Gabriel's head as he faced the toy. Trajectories were normalized to the space-time coordinates of contact and plotted for the 3 sec preceding contact.

however, Gabriel's MUS torques during reaching have converged to similar values, all negative, indicating that he used MUS at the shoulder primarily to raise the arm against the extensor influence of GRA, and that he discovered a more optimal level of MUS for the task. This torque modulation during the reach was also reflected in torque damping during overall movement context (Fig. 5).

As Gabriel learned to modulate the speed and forces of his arm, did he also control the coordination of the segments? Figure 11 reports coordination between the shoulder and elbow rotations as angle-angle plots. In angle-angle plots, the 3D rotation of one joint is plotted as a function of the rotation of the second joint. (These plots do not show where the arm is in space.) Thus, if the rate of movement of one joint is the same as the second, that is, they are perfectly coordinated, the angle-angle plot should trace a diagonal whose direction depends on the relative direction of movement. If movement is entirely in the shoulder, for instance, the curve would be vertical, indicating no movement in the elbow. Conversely, movement only in the elbow would result in a horizontal trace. Also note that the pattern of coordination will depend on the starting position of the arm. Since we did not control for starting position, we subsequently coded from the videotape whether the reach in question began at the infant's *side*, or at the *midline*, either shoulder height (*high*, near mouth and chest) or below (*low*, near lap), and plotted the angle-angle curve as a function of starting position.

As mentioned previously, Gabriel generated his flapping movements at the onset week primarily from the shoulder, which is seen clearly in the top panel of Figure 11. As Gabriel decreased his speed and modulated his muscle torque at onset + 1, he also generated more movement at the elbow. The trajectories available for onset + 2 suggest more diagonal elements, possibly showing more use of both shoulder and elbow

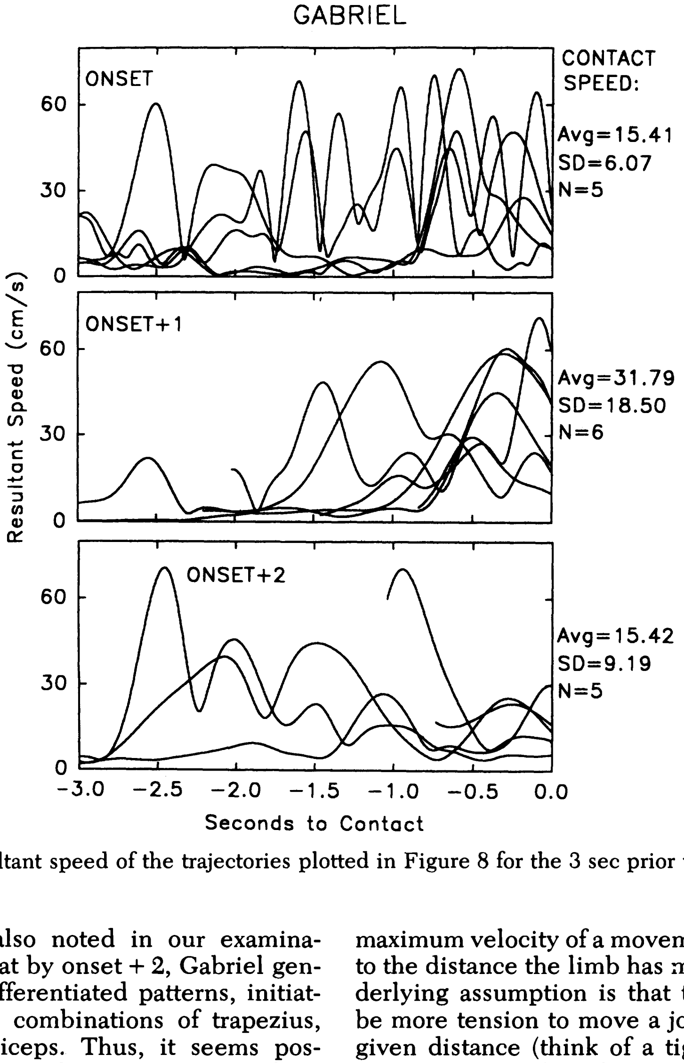

FIG. 9.—Resultant speed of the trajectories plotted in Figure 8 for the 3 sec prior to toy contact

together. We also noted in our examination of EMG that by onset + 2, Gabriel generated more differentiated patterns, initiating reaches by combinations of trapezius, deltoid, and triceps. Thus, it seems possible that joint coordination emerges *along with* or following control of joint forces and stiffness.

This suggestion of the primacy of force control is supported by looking directly at an estimate of arm stiffness. Although the stiffness (tension) cannot be measured directly, it can be estimated by considering the maximum velocity of a movement in relation to the distance the limb has moved. The underlying assumption is that there needs to be more tension to move a joint faster for a given distance (think of a tight vs. loosely coiled spring). Thus, for any discrete movement, we can characterize a peak velocity associated with a corresponding displacement. If stiffness is held constant over a number of discrete movements, then there should be a linear relation among the points so described, while the slope of the regression gives an estimate of the overall stiffness for those movements (Cooke, 1980).[4]

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[4] Although measures of force/velocity versus displacement functions are commonly used to estimate limb stiffness, the measure remains controversial. The controversy lies in whether the infant (or an adult mover of a limb) is in fact adjusting the muscular stiffness characteristics of the limb autonomously from the energetic pulses that drive the oscillations of the limb. If the limb is considered as an undamped mass spring, then the slope of the peak velocity versus the amplitude of oscillation is unambiguously related to the stiffness of the spring. That is, without the need to add energy to overcome friction, the only factor that determines the sine wave of the oscillation is the spring stiffness. But an undamped spring is not a realistic model of a real limb which has damping properties and needs a forcing function—energy delivered at a particular frequency to maintain the oscillation. When this forcing function is added, then the frequency of the observed oscillation is equal to that of the driving frequency. In this case, the amplitude

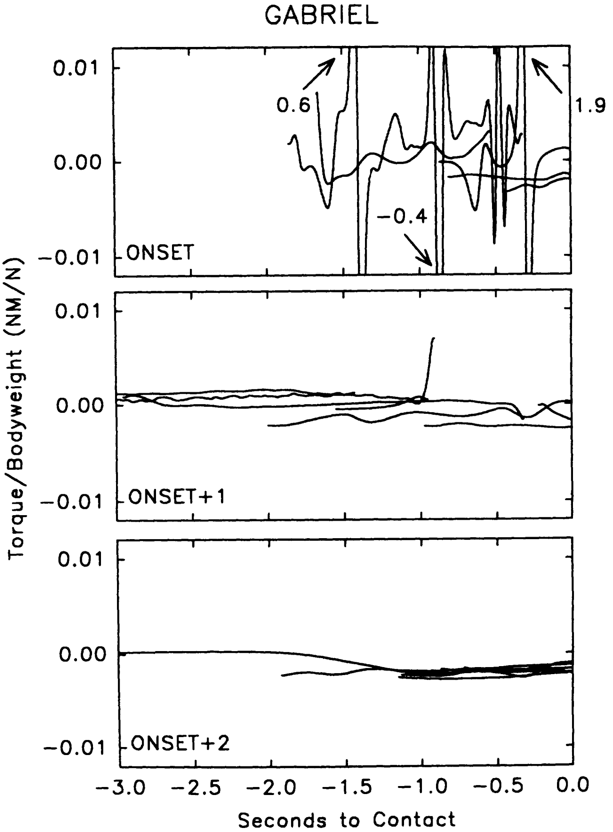

FIG. 10.—Shoulder MUS torques of the trajectories plotted in Figure 8 where dynamic data were available. Negative MUS means that muscles were contracting to flex the shoulder. High spikes of MUS are associated with rapid movements generating high MDT.

To estimate stiffness of the arm in infant reaches, we used the hand displacement and associated speed time series from the 3 sec prior to point of toy contact. Using the speed profile, we identified "movement units" (Brooks, Cooke, & Thomas, 1973), as a speed acceleration and deceleration (partial units at the start and end of the segment were not used), and calculated the associated hand displacement (total path traversed) for that unit. Thus, each point on Figure 12 represents the peak velocity-displacement value for a movement unit, plotted by seconds prior to toy contact and including all the reaches for that session. We have also indicated the best-fit regression line and the slope of the regression line for each group of points.

The stiffness plots suggest two trends for Gabriel. First, at week of onset, his movements became less stiff in the second before the reach contact than in the previous 2 sec. And second, Gabriel was reaching with a more compliant arm in the 2 weeks after reach onset than at onset, indicated by the less steep slope. Although some of these regressions are based on too few points to generate total confidence, the trend seems to be to modulate stiffness with reaching experience.

Nathan

1. *Intrinsic dynamics.*—Nathan was not as motorically active as Gabriel. However, some characteristics of his reaching development were more similar to Gabriel's

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of oscillation is no longer a function of the stiffness alone. Thus, the slope of the peak velocity versus displacement cannot disambiguate whether the infant is adjusting the stiffness or the driving frequency, or both. However, since we observed coactivation, it is likely that infants are adjusting stiffness.

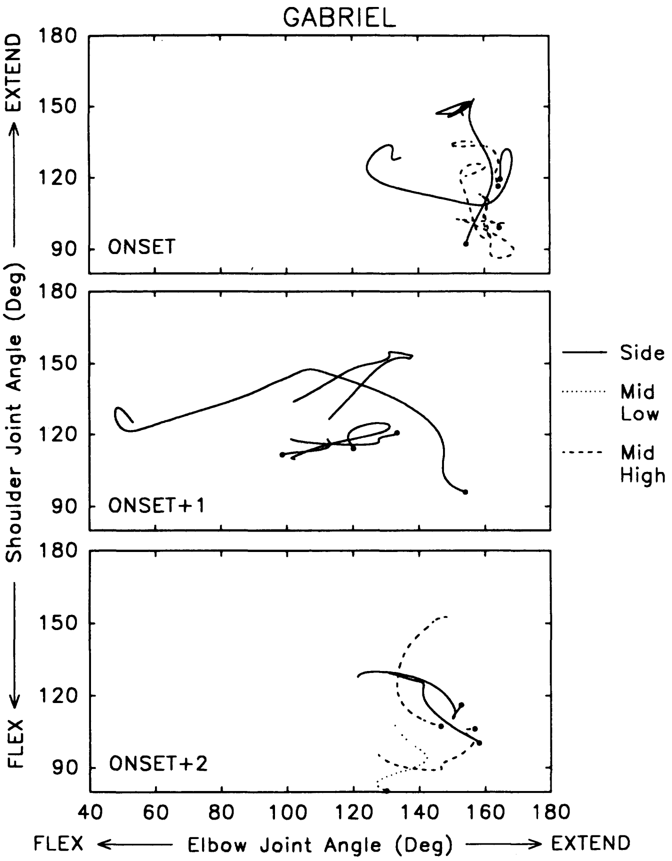

FIG. 11.—Angle-angle plot between the elbow and shoulder joints corresponding to the trajectories plotted in Figure 8. The dots mark the end of each segment and the line types (solid, dashed, or dotted) indicate the position of the hand in space at the beginning of each segment, that is, about 3 sec prior to contact. Hand on side means that the arm is extended down along the side of the body, midline low means that the hand rested on the lap, and midline high refers to the hand starting from a position near the chest or the mouth. Shoulder flexion is an upward motion of the arm and extension a downward motion of the arm.

than to Justin's or Hannah's. Unfortunately, our data for Nathan's transition are less complete than for the other infants for several reasons. First, Nathan, who was the first infant in the study, surprised us by reaching quite early, with several attempts at week 11. At that early age, the elbow IRED was often obscured by his flexed arm posture, so we used the elbow IRED as a second hand marker. Thus, we do not have data on joint angles and dynamics before week 12, which we used as Nathan's onset week. Second, in the weeks after reaching onset, Nathan lost interest in the toy, so we captured only a few reaches. Third, Nathan often held his hands below or behind the chair, adding to the visibility problem. As a consequence, Nathan's data are based on only hand kinematics and EMG for the 2 weeks before onset, and we lack many reaches for the weeks following onset.

In onset – 2, Nathan performed mostly large and fast spontaneous movements in both arms. His arm movements were often cyclical, and mirror-like, as were Gabriel's. Often, Nathan cycled his arms from low at his sides up and toward midline, bringing the hands closer to the toy, although he rarely contacted the toy. As shown in Figure 4, his overall average and maximum hand speeds at this week were higher than in succeeding weeks. Although the arm movements were simultaneous, the left hand often produced faster and larger movements than the right. This left bias continued in the subsequent weeks: when reaching, Nathan almost always contacted the toy with the left

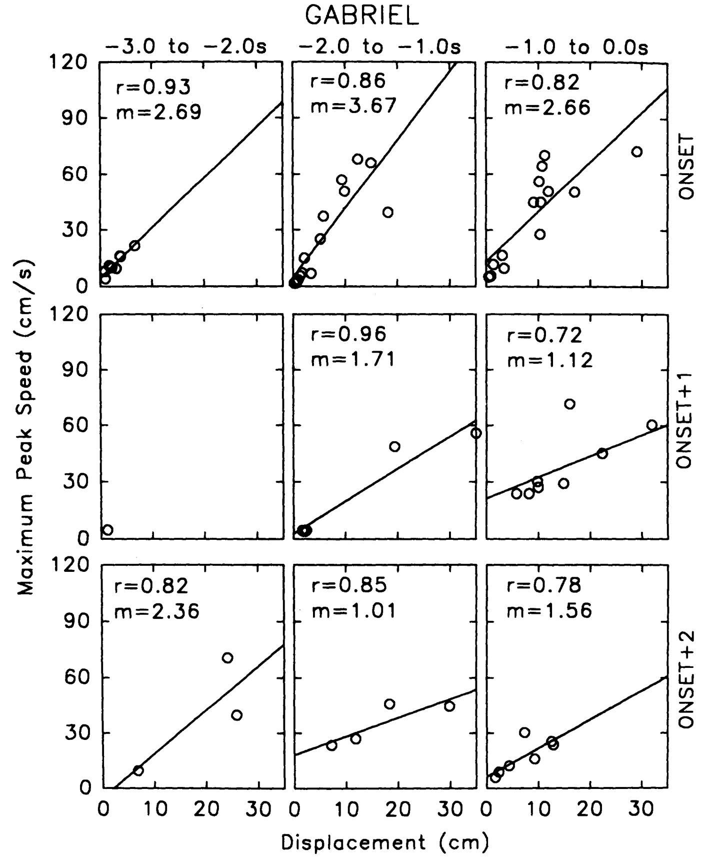

FIG. 12.—Arm stiffness estimation for Gabriel's reach segments at 3 to 2 sec, 2 to 1 sec, and 1 to 0 sec prior to contact during the week of onset and the 2 following weeks. Each point of the scattergram represents the displacement as a function of the maximum peak speed for a single "movement unit." Regression lines give an estimation of arm stiffness. Steep slopes indicate high stiffness; slopes near 0 indicate a lack of stiffness.

hand first. EMGs revealed both phasic activation and coactivation.

Onset – 1 was a transition week. Nathan attempted to contact the toy four times with high velocity swipes when it was presented by his mother. Overall, however, he was somewhat less active than the previous week, and his movements were slower (Fig. 4). Most dramatic was the disintegration of the symmetrical trajectories seen the week before and an increase in spatial variability, perhaps reflecting Nathan's attempts to guide his hands toward the toy. The EMG records were again variable, showing both phasic activation and coactivation.

2. *Reach onset.*—At reach onset, Nathan again became very active (Fig. 4). Nathan's efforts to carve a reach from his more disorganized spontaneous movements are exemplified in Figure 13. The tortuous trajectory to the toy had several large velocity peaks. As shown by the exemplars, he produced primarily fast movements before, during, and after the reach, exploring up-down, back-forth, and right-left space with frequent changes in movement speed and direction. In contrast to Gabriel, Nathan accomplished most of his reaches by large elbow extensions and little shoulder flexion, although he did flex at the shoulder when he started from down at his side (Figs. 14, 18). Moreover, MUS torques were variable. On average, Nathan's MUS torques were higher than Justin's or Hannah's during the reach or in other movements (Figs. 5, 17). However, unlike Gabriel, who used MUS to counteract MDT, Nathan used his MUS to work against both MDT and GRA, as illustrated in Figure 14. Like Gabriel, Nathan often used coactiva-

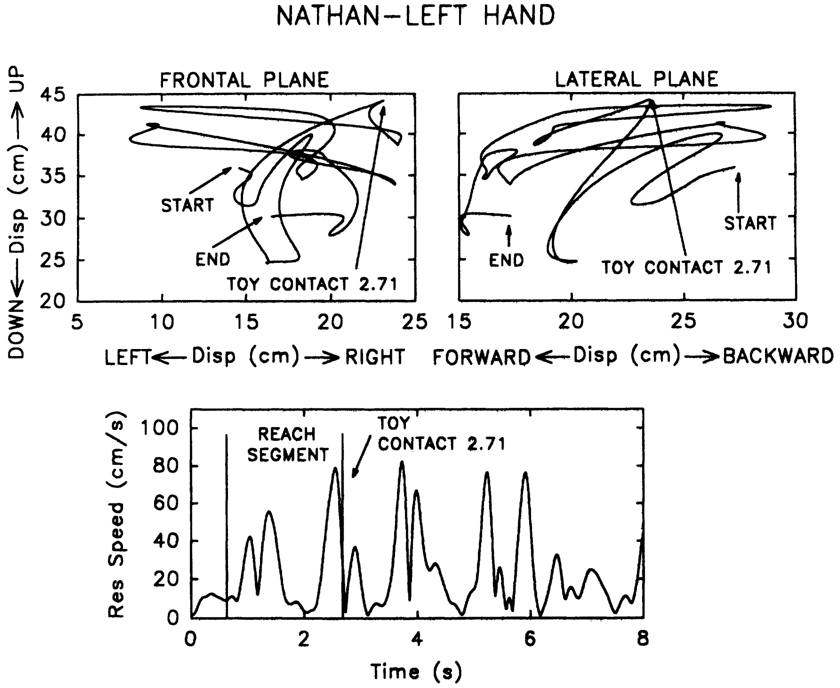

FIG. 13.—Exemplar trial for Nathan's left hand at reach onset showing transition from spontaneous to goal-oriented reaching movement. Top panels: 8-sec hand path in the frontal and lateral planes. Bottom panel: Resultant speed for the same segment.

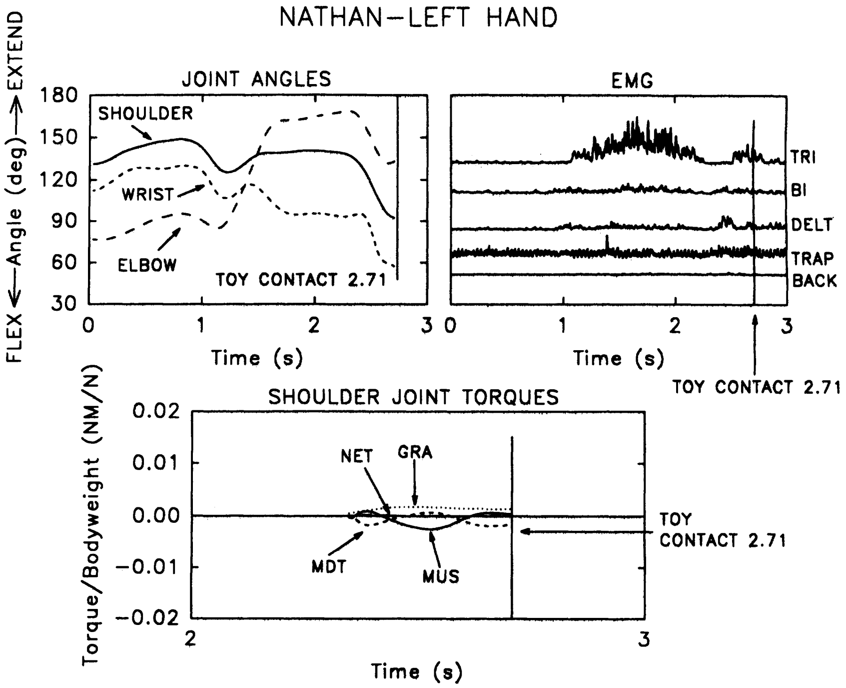

FIG. 14.—Top left panel: Rotations of the shoulder, elbow, and wrist joints of Nathan's left hand for the reach segment indicated in Figure 13. Reach is accomplished primarily by elbow extension. Top right panel: EMGs of five muscle groups for the entire 3-sec reach segment illustrating tonic coactivation. Bottom panel: Torques at the shoulder associated with the same segment.

tion, evidenced in the EMG, to damp down high velocity in the shoulder and upper arm muscles prior to contact. This is consistent with the increased stiffening seen in the 2 sec prior to contact shown in the top panel of Figure 19.

Overall, Nathan's movements at reach onset were variable and showed complicated trajectories. He produced high velocities during movements directed toward the toy, indicating that he, like Gabriel, was swatting the toy. Nevertheless, the kinetics revealed that he was using MUS not only to counteract MDT. His movements were largely at the elbow, and EMG's showed consistent coactivation only before toy contact.

3. *Subsequent modulation.*—Nathan was not very interested in the toy during the 2 weeks following onset. His overall motor activity decreased considerably, indicated by decreased movement speed, MUS, and number of peaks (Figs. 4, 5). Nathan reached for the toy only twice at onset + 1 and four times at onset + 2. Moreover, during both weeks, he reached very slowly, in contrast with his earlier rapid swipes (Figs. 15, 16). Unfortunately, we lacked kinetic data for these few later reaches, but MUS torque data for the entire segment indicated that Nathan, like Gabriel, generated much less MUS after reach onset, and used MUS primarily to counteract GRA (Fig. 5). Similarly, because of sparse data, we saw no clear changes in joint coordination patterns (Fig. 18). Figure 19 indicates an overall modulation of the stiffness estimates with age and a decrease of slope in the last second before contact. We do not have EMG data for the reaching hand at onset + 1. In contrast to the onset week, we detected no clear patterns of muscle coactivation at onset + 2.

Because we could collect only minimal data in the 2 weeks following onset, we are cautious about reporting changes in Nathan's reaching behavior. From the hand speeds and stiffness estimates, we can con-

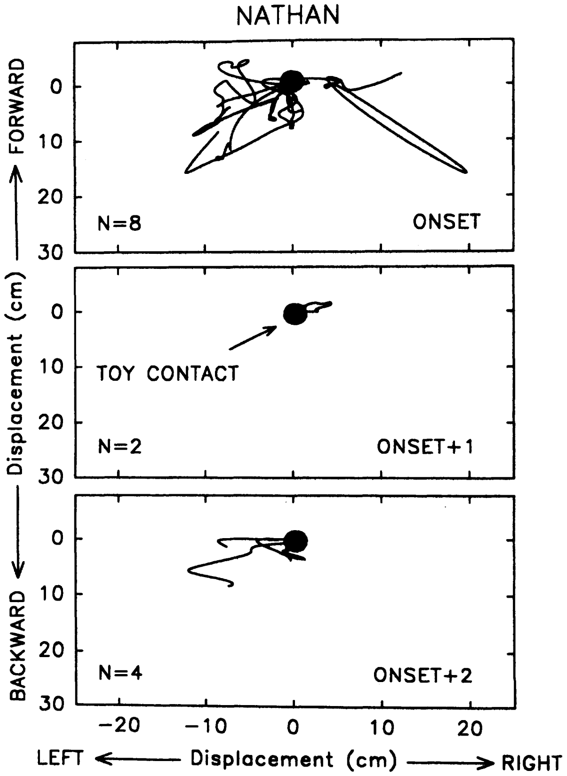

FIG. 15.—Hand trajectories of all analyzable trials at reach onset and the following 2 weeks during which Nathan contacted the toy. Only the trajectory of the hand making first contact is plotted. Trajectories are depicted from a top view, that is, looking down over Nathan's head as he faced the toy. Trajectories were normalized to the space-time coordinates of toy contact and plotted for the 3 sec preceding contact.

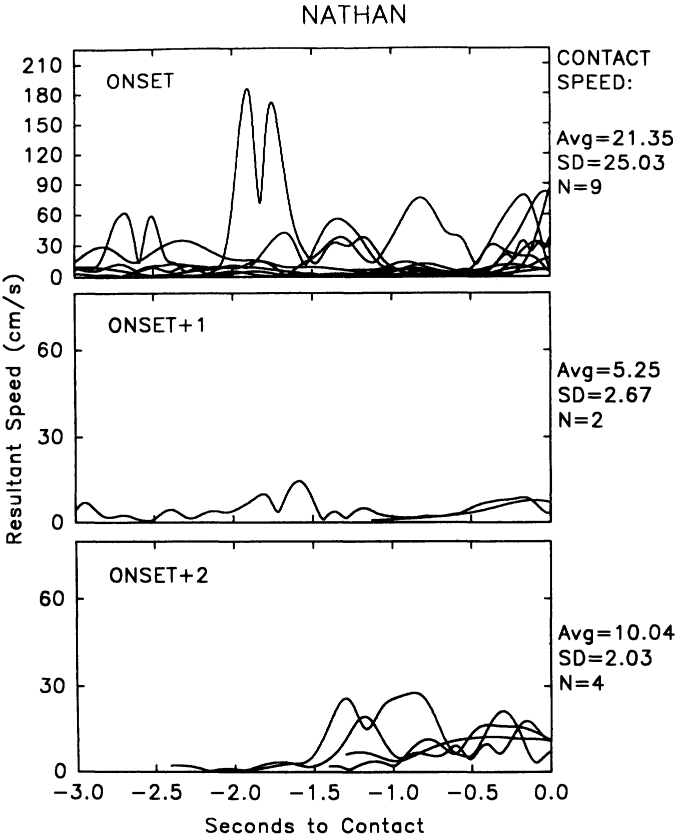

FIG. 16.—Resultant speed of the trajectories plotted in Figure 15 for 3 sec prior to contact

clude that Nathan did dramatically inhibit his large, rapid movements after the week of onset. Indeed, after onset, reaches were generated from a lower-energy movement background where muscles were primarily used to lift the arm against gravity.

Justin

1. *Intrinsic dynamics.*—Justin was a very different infant than Gabriel or Nathan, who faced different challenges in learning to reach. Justin was a moderately active infant who responded more to social stimuli than to objects. He reached first at 21 weeks, considerably later than the two other boys. His preferred posture in the weeks before reach onset was with his hands flexed to his chest, and his movements were smaller and less frequent than Gabriel's or Nathan's. He occasionally waved his arms or extended them forward, especially to social stimulation. He performed more unilateral than bilaterally symmetrical movements, although he produced occasional bilateral flaps. When he did move at onset – 2, his overall movement velocities were comparable to Nathan's, but he rarely produced the same very rapid velocity spikes, and consequently did not generate the high MUS seen in Gabriel and Nathan (Figs. 4, 5). Indeed, MUS worked primarily against gravity, and only occasionally moved into the extensor range where MUS counteracted MDT. At onset – 1, the speed of his movements dropped considerably, with fewer peaks and an even more constrained range of MUS. Justin's muscle activation patterns were especially diverse: tonic activation of the biceps when his arm was flexed close to his body and phasic coactivation of arm and shoulder muscles during flaps in a number of discrete patterns. While Gabriel had a more "all or nothing" pattern of contraction, Justin activated more defined groups of muscles associated with particular movements.

2. *Reach onset.*—At onset, Justin reached both with one arm and with nearly simultaneous bilateral extensions. Justin's lower energy level was evident in his first attempts to reach for the toy as well. In contrast to Gabriel and Nathan, Justin's first

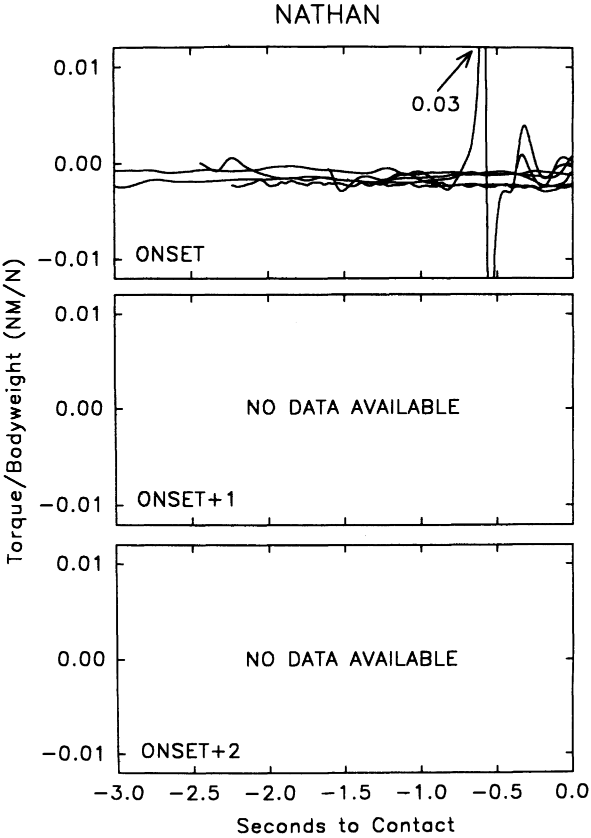

FIG. 17.—Shoulder MUS torques of the trajectories plotted in Figure 15 where dynamic data could be calculated. No data were available for the 2 weeks following onset.

reaches were not high speed swipes, but had relatively slow and seemingly more controlled trajectories (Fig. 20). Note in this exemplar that Justin began the reach from a quiet position rather than an ongoing rapid movement. Although the trajectory was not straight, Justin showed a more adult-like speed profile, with contact at much lower speed than the previous infants. (Compare with the bottom panels of Figs. 6, 13, 20.) Justin also had more coordinated arm segments during the reach (Fig. 21), with shoulder, elbow, and wrist flexing together in the 2 sec before contact. The relative timing and equal use of shoulder and elbow can also be seen in the top panel of Figure 25. The dramatic contrast between Justin and Gabriel and Nathan is in the level of forces moving the arm. Figure 21 shows that, when his MUS were plotted on a comparable scale, Justin moved his arms with much lower torques at the shoulder (and at the elbow as well). Like Nathan, he used his MUS to counteract both MDT and GRA.

Interestingly, however, at the level of the muscle activation patterns during the reach segment itself, it is difficult to distinguish these three infants. All showed examples of tonic coactivation of the muscles we monitored with modulation within the tonic activation. Justin, however, showed more lower back activation and more discrete bursting in the biceps (compare Figs. 7, 14, 21). Justin reached with a somewhat more compliant, less stiff arm than the other boys (Fig. 26).

3. *Subsequent modulation.*—In contrast to Gabriel and Nathan, who damped their movements, in the weeks following onset, Justin scaled up his reach velocity and forces. Consider Figures 22, 23, and 24, which show Justin's evolution from slow, smooth, and more mature-looking reaches at the onset week to much faster, variable, swiping movements at onset + 1 and onset + 2. Movement velocities increased slightly at onset + 1 (Figs. 4, 23), and the

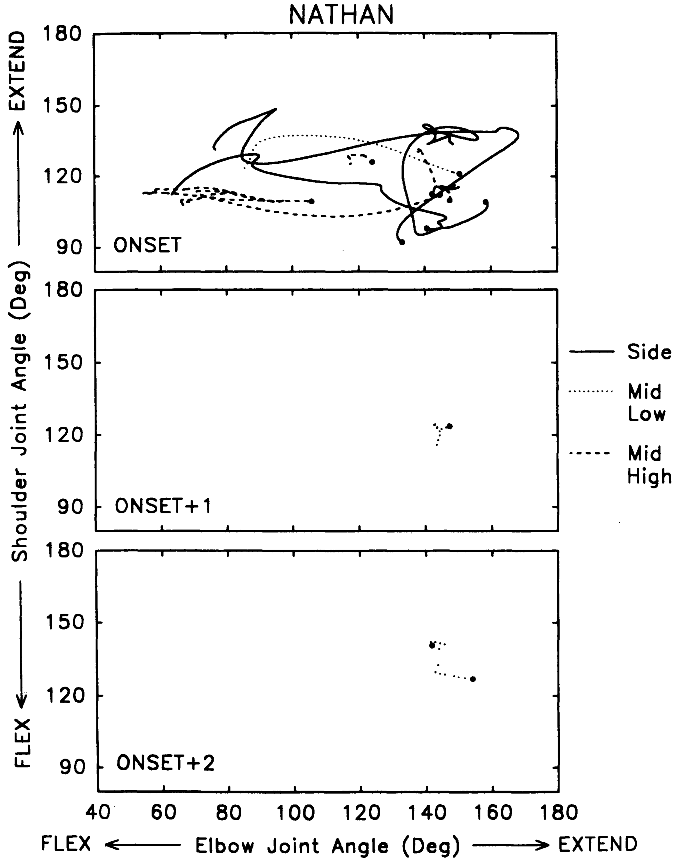

FIG. 18.—Angle-angle plot between the elbow and shoulder joints corresponding to the trajectories plotted in Figure 15. The dots mark the end of each segment and the line types (solid, dashed, or dotted) indicate the position of the hand in space at the beginning of each segment, that is, about 3 sec prior to contact. Shoulder flexion is an upward motion of the arm and extension a downward motion of the arm.

magnitude and range of MUS increased in both the reach itself and in the movement context (Figs. 5, 24). Fluctuating MUS in the postonset weeks indicates that he was using muscle activation in opposition to the MDT generated from higher velocity movements, and not just for flexing the shoulder against GRA. Justin also changed from smooth, coordinated shoulder and elbow flexions seen at onset (Fig. 25) to holding his elbow rigid and using less wrist movement. The increase in velocity at onset + 2 was accompanied by a steeper slope in the stiffness estimate than the other infants, but note how Justin modulated the stiffness as he approached the toy (Fig. 26). He showed a very consistent muscle activation pattern of tonic coactivation in the biceps, trapezius, and deltoid, and no activation of the triceps until just before or after contact. In the more energetic reaches, he contracted his lower back muscles. As a consequence of these stiffer, more energetic swats, Justin paid a price in accuracy and smoothness. Note in Figure 22 that his hand trajectories at onset + 2 were considerably more complex than at onset week.

Thus, Justin switched from a low energy coactivation strategy to one where he increased the energy delivered to the limb while controlling the movement largely at the shoulder. He also became more consistently bilaterally symmetrical. In short, as he produced more energetic reaches, they resembled those of Gabriel and Nathan at onset.

Hannah

1. *Intrinsic dynamics.*—Hannah was the most quiet and contemplative infant. She was visually alert and socially responsive, but rarely displayed vigorous movements.

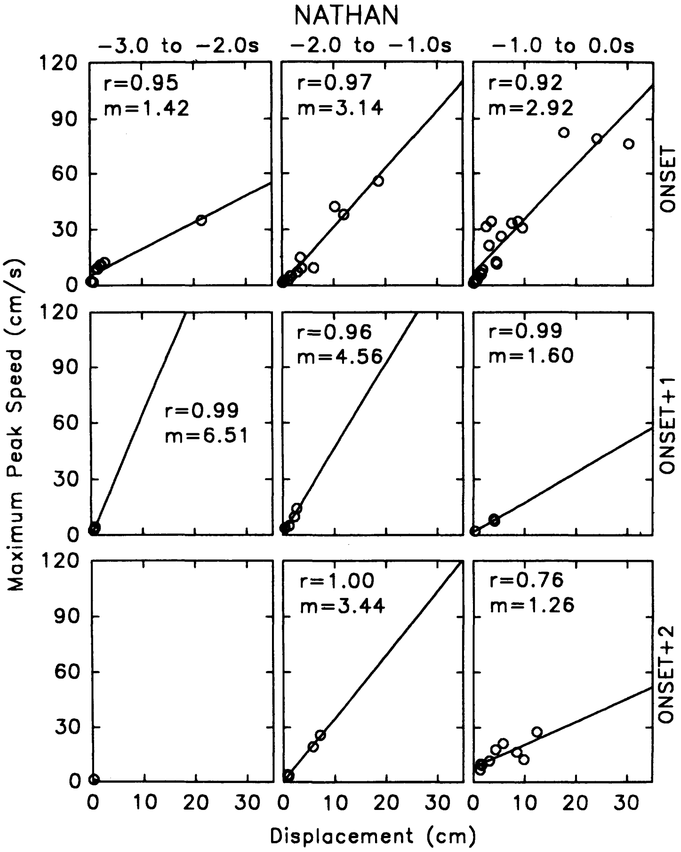

FIG. 19.—Arm stiffness estimation for Nathan's reach segments at 3 to 2 sec, 2 to 1 sec, and 1 to 0 sec prior to contact during the week of onset and the 2 following weeks. Each point of the scattergram represents the displacement as a function of the maximum peak speed for a single "movement unit." Regression lines give an estimation of arm stiffness. Steep slopes indicate high stiffness; slopes near 0 indicate a lack of stiffness.

Before reaching onset at 22 weeks, she preferred sitting with her hands on her chest or in her mouth or engaging in small, slow movements such as dropping her hands to her side. She grasped and manipulated toys handed to her for several weeks before she extended her arm up and forward. Because she was quieter, we analyzed fewer prereaching trials (Appendix A).

Hannah's relatively small and slow movements are reflected in much lower average hand speeds and MUS torques (Figs. 4, 5) than those of Gabriel and Nathan. Indeed, her MUS torques consistently remained below zero, meaning that they were always flexor and counteracting gravity. Most muscle activity was tonic and in the biceps, reflecting her flexed arm position, although occasionally we detected triceps activity associated with elbow extension and shoulder muscle contraction.

2. *Reach onset.*—From this low energy background, Hannah produced first reaches that were quite smooth and mature-looking. Note in Figure 27 that the exemplar reach was initiated from a quiet starting position with a small lateral and backward loop, followed by the hand moving directly to the toy and overshooting. The reach was relatively slow in duration and speed, with few changes of direction. To do this, Hannah lifted her shoulder while first extending and then slightly flexing her elbow (Fig. 28). Figure 32 also shows Hannah's tendency to move joints both alone and in a coordinated fashion; the angle-angle diagrams show horizontal, vertical, and diagonal traces. The MUS torques at the shoulder contributing to the reach were primarily working against GRA, with a small influence of MDT from the rapid elbow extension (Fig. 28). At onset, Hannah's stiffness estimate was the lowest of the infants; she reached with a compliant

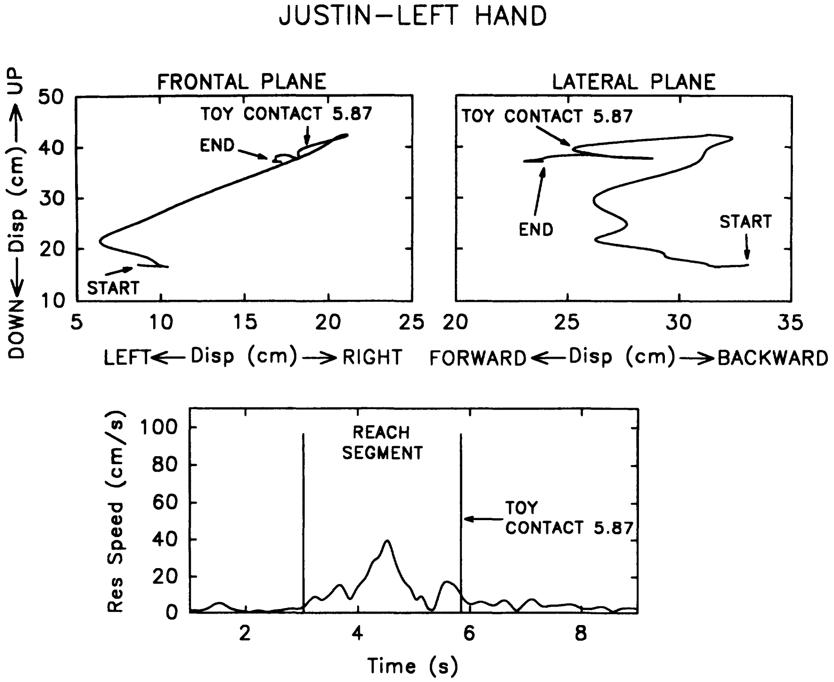

FIG. 20.—Exemplar trial for Justin's left hand at reach onset showing reach segment emerging from small movements. Top panels: 8-sec hand path in the frontal and lateral planes. Bottom panel: Resultant speed for the same segment.

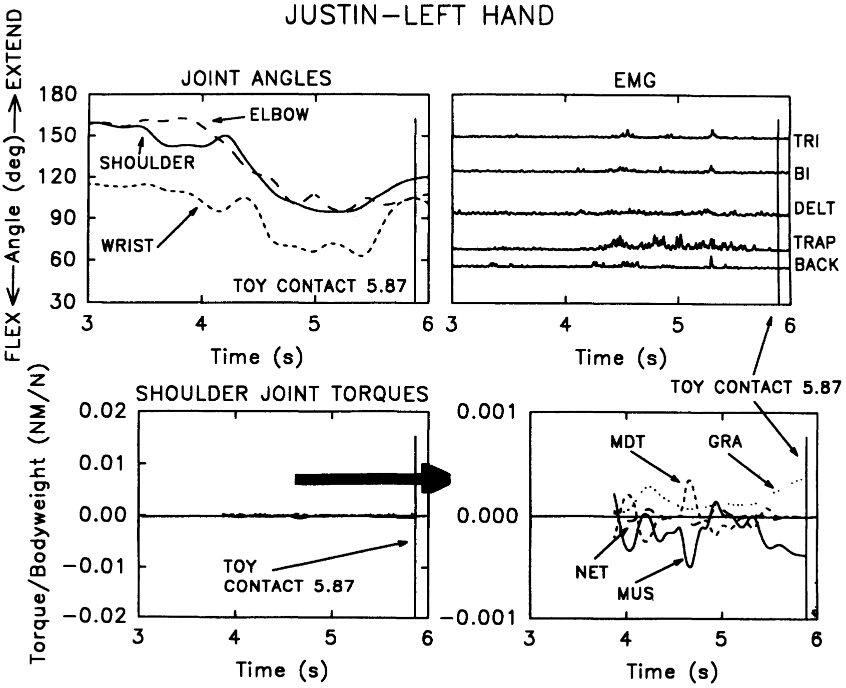

FIG. 21.—Top left panel: Rotations of the shoulder, elbow, and wrist joints of Justin's left hand for the reach segment indicated in Figure 20. Top right panel: EMGs of five muscle groups for the entire 3-sec reach segment illustrating phasic burst of coactivation accompanied by tonic activation of the trapezius and deltoid. Bottom left panel: Torques at the shoulder associated with the same segment. Scales are identical to the other infants' exemplar plots. Bottom right panel: Same segment with reduced scale to magnify details of Justin's shoulder torques.

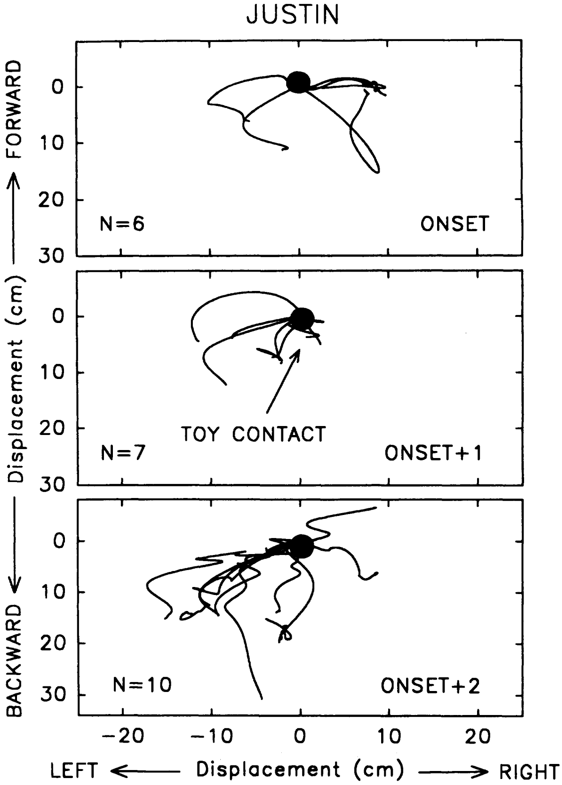

FIG. 22.—Hand trajectories at reach onset and following weeks of all analyzable trials where Justin made contact with the toy. Only the trajectory of the hand making first contact is plotted. Trajectories are depicted from a top view and normalized to the space-time coordinates of toy contact.

arm (Fig. 33). Muscle firing patterns (Fig. 28) showed coactivation in triceps, biceps, and deltoid and some activity in the lower back.

In sum, Hannah's initial reaches looked controlled, but they often overshot the object without slowing down or adjusting to the toy. Many trajectories were smooth, with few reversals, and MUS torques were low, as illustrated in the top panels of Figures 29–31. Notably, Hannah's first reaches were exclusively unilateral. The nonreaching hand was relatively inactive.

3. *Subsequent modulation.*—Hannah, like Justin, also worked on scaling up her reaches in the subsequent 2 weeks. This is reflected in higher mean and higher maximum velocities, with more peaks and greater MUS as well (Figs. 4, 5). Note the dramatic increase in the shoulder stiffness estimate. Although in onset + 1 week, Hannah approached the toy with more active movements, there was little evidence of velocity modulation (Fig. 30). This changed dramatically by onset + 2. Although her approach movements were faster, she consistently slowed down about .5 sec before toy contact. What is especially interesting is that torque patterns underlying these velocity changes revealed a considerable "loosening up" of the system. Whereas in the onset week (Fig. 31), Hannah by her slow movements generated few MDT and used MUS to lift her arm against GRA, later her more rapid movements produced more MDT, and consequently more compensatory MUS at the shoulder. Yet, she tamed these MDT and approached the toy with more controlled trajectories. Not only did Hannah learn to modulate the approach velocity, she also gained control of the reach initiation, reflected in a more consistent initial position (Fig. 29) and a shorter, less variable reach duration. The pathway to the toy was also more direct. Joint angle coordination began to reflect more simultaneous movement by onset + 2 (Fig. 32).

Muscle activation patterns varied depending on the vigor of the reaching movements. In more rapid movements, Hannah

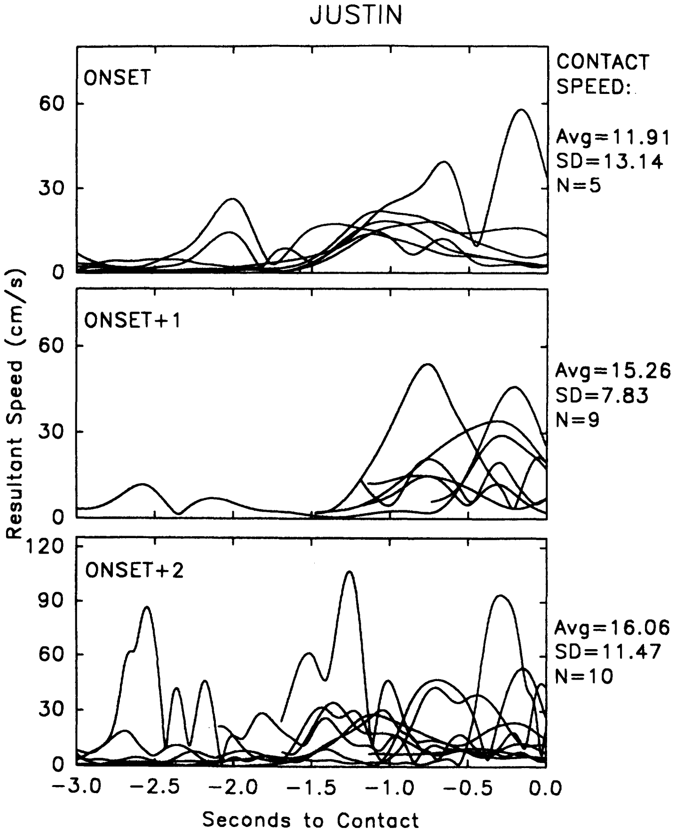

FIG. 23.—Resultant speed of the trajectories plotted in Figure 22 for 3 sec prior to contact

showed phasic coactivation of arm and shoulder muscles. Also common was coactivation in the biceps and shoulder muscles in slower, more sustained reaches. Finally, we noted a clear progression in Hannah's interlimb coordination from nearly all one-handed reaches in onset and onset + 1 to more bilateral movements in onset + 2.

Discussion

In this study, we have opened a window on the dynamic processes of a developmental phase shift, the transition to reaching for an object. We described how four infants individually found solutions to the task of lifting their arms and guiding them toward a desired toy. The infants entered this transition at different ages, and with different activity levels and preferred movement patterns. The process of learning to reach was one of discovering the match between these intrinsic dynamics—the opportunities and constraints of their bodies—and their intention to bring the felt and seen hand to the seen toy. We believe that these individual profiles are enlightening on several levels. First, they suggest potential control parameters for the assembly of this specific skill. Second, they affect contemporary models of mature reaching. And third, these individual stories have implications for developmental theory and methods of understanding change.

The Dynamics of Learning to Reach

Our account of early reaching differs from traditional descriptions of improvement with age by considering reaching, like all perceptual-motor skills, to be *softly assembled* rather than a product of a prefigured reaching device. Soft assembly means that, in this case, the reacher temporarily marshals the dynamic properties of the body in the environment to create a device that is specific to the task at hand (Bingham, 1988; Kelso, Holt, Kugler, & Turvey, 1980; Kugler & Turvey, 1987; Saltzman & Kelso, 1987). Conceptualizing action as softly assembled from multiple available components addresses a number of troubling complexities about how movements are coordinated and

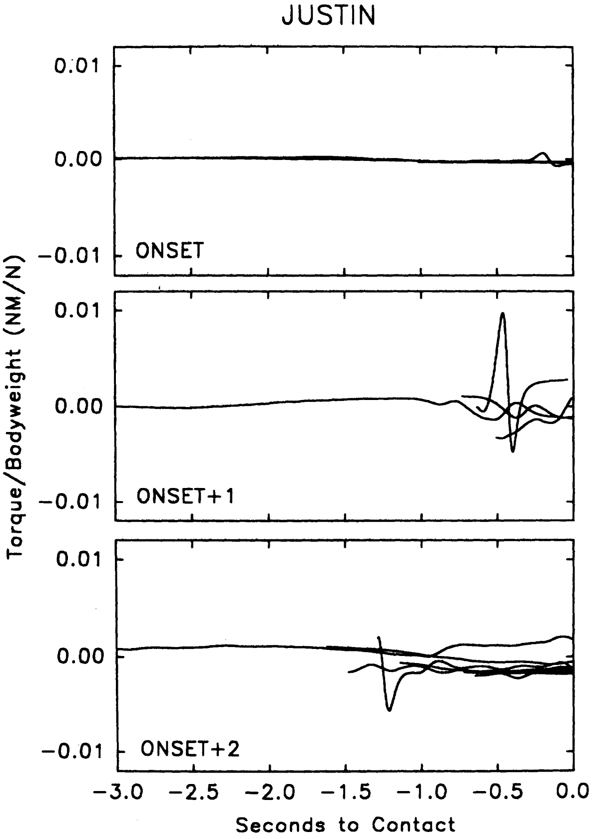

FIG. 24.—Shoulder MUS torques of the trajectories plotted in Figure 22 where dynamic data could be calculated.

controlled (Bingham, 1988). First, this approach sees *function* as imposing the constraints on the inherent degrees of freedom in the human action system. This means that actors choose the patterns for executing a task in a flexible manner, in relation to their dynamic resources and the demands of the task rather than from a preexisting icon of the movement. Second, because of its dynamic properties, a softly assembled system has *self-organizing* and *optimizing* properties. Patterns of behavior need not be prefigured, because organization can arise from the dynamics themselves. In addition, the system autonomously *discovers* good solutions to its task demands through exploring its intrinsic dynamics in relation to the specific function to be performed (e.g., Kugler & Turvey, 1987; Zanone & Kelso, 1991). Fourth, softly assembled systems can be variously parameterized or scaled to meet the scale demands of the task, but the scale relations may be nonlinear: some solutions may be more stable than others. And finally, these systems are open to continual modulation with changes in perceptual information specifying the nature of the task and the qualities of the intrinsic dynamics.

The developmental transition to reaching in Gabriel, Nathan, Justin, and Hannah can be understood within this dynamic framework. At the time of reach onset, each of these infants had characteristic intrinsic dynamics: preferred postures, movements, and energy levels. The two higher activity infants, Gabriel and Nathan, energized their muscles with large coactive phasic bursts, often rhythmical in nature. These periodic energy spurts resulted in large, cyclical, coupled movements of both arms. Although we have not yet tested this model formally, these movements have dynamic characteristics similar to those produced by two oscillating springs or pendulums (see Jensen, Ulrich, Thelen, Schneider, & Zernicke, 1991, for a similar characterization of the spontaneous movement of the legs). Before Gabriel and Nathan reached for the toy, or later, when the toy was not available, their bilat-

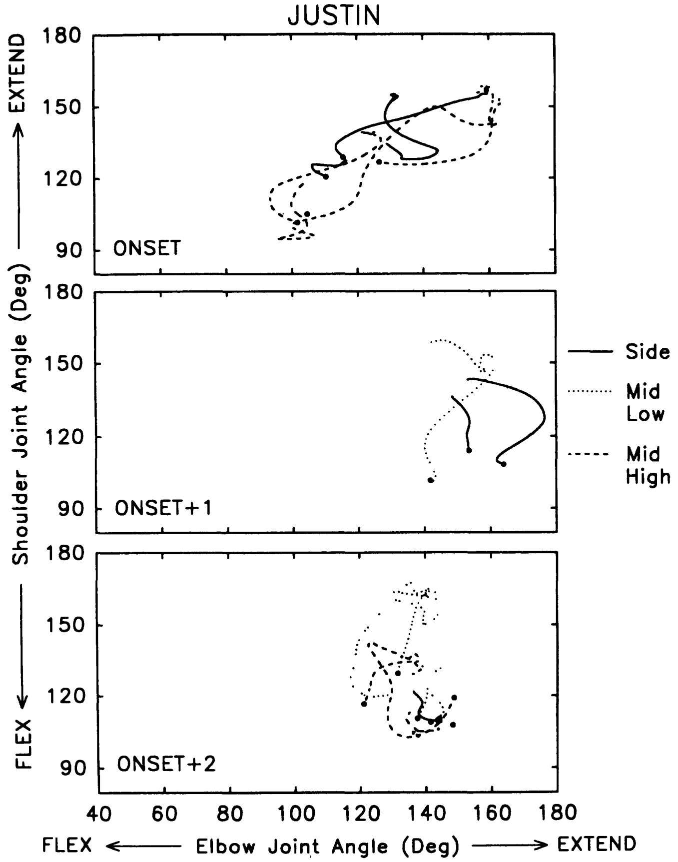

FIG. 25.—Angle-angle plot between the elbow and shoulder joints corresponding to the trajectories plotted in Figure 22. Shoulder flexion is an upward motion of the arm and extension a downward motion of the arm.

eral flapping had stable trajectories, which, in dynamic terms, looked like limit cycle attractors. When the infants perceived the toy and intended to grab it, they faced the problem of converting their seemingly undirected oscillations into a task-specific device (Bingham, 1988), or, put another way, adapting their limit cycle dynamics to those of a point attractor (Saltzman & Kelso, 1987). (Nathan's flaps in onset − 2 were directed toward the direction of the toy, however.) They did this by damping down their oscillations by stiffening the arm through muscle coactivation. With the elbow held rigid and the arm less compliant and thus less subject to uncontrolled motion-dependent forces, they were able to capture the ongoing trajectory, so to speak, and orient the hand toward the toy. That their first reaches were high velocity swipes attests to their opportunistic transduction of their intrinsic dynamics in service of the intended task.

Hannah and Justin faced another problem. In these more quiet infants, the task required that they lift their arms against gravity and extend them forward. To do this, they needed to supply additional muscle power, which they too accomplished through coactivation. The results at reach onset were slow, sustained movements, which, without the perturbations of motion-dependent forces from connected segments, were quite smooth and controlled looking. Since their limbs remained relatively compliant, joints were free to flex and extend. The control was illusory, however, since they initially contacted the toy without subsequent modulation and were not especially accurate.

In all cases, the scaling of the control parameters of limb stiffness and energy allowed reaching to emerge from an ongoing background *as a real-time discovery of a match between infant and task.* The flexibility of the individual solutions (and their subsequent modulation) attests to their dy-

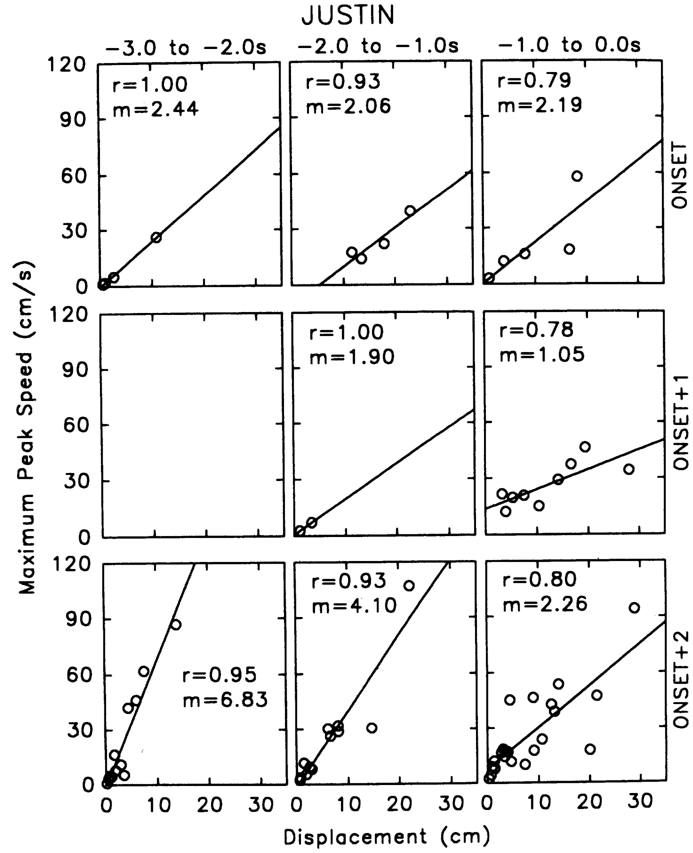

FIG. 26.—Arm stiffness estimation for Justin's reach segments at 3 to 2 sec, 2 to 1 sec, and 1 to 0 sec prior to contact during the week of onset and the 2 following weeks. Regression lines between displacement and maximum speed peaks give an estimation of arm stiffness. Steep slopes indicate high stiffness; slopes near 0 indicate a lack of stiffness.

namic assembly. The first reaches of these infants were highly variable in kinematics, kinetics, and muscle patterning. The only common element in the hand trajectories, speeds, or durations, for instance, was that the hand eventually contacted the toy. Coordination between the arm segments as expressed by rotations of the three joints was also diverse and highly context specific. Infants were clearly not expressing a fixed program of muscle activation patterns, as coactivation was the rule, and we found no evidence of the adult pattern of reciprocal activation of flexors and extensors. Rather, infants were scaling their muscle contractions to provide an adequate level of energy and compliance to adjust their ongoing dynamics to the goal.

What needs to be "represented" beforehand or "constructed" for reaches to emerge? First, these results argue against visual mapping of toy and hand as the primary process in first reaches. The infants behaved as though the first obstacle was getting their arms and hands extended in a controlled fashion somewhere near the toy. Typically, they fixed their gazes on the toy and did not look at their hands, which, in some cases, were moving rapidly and unpredictably around them. We also found no evidence of infants having an innate "prereaching" program either in the form of a hand trajectory, patterns of joint coordination, or centrally encoded muscle synergies. What must be "within" the infant is the desire to obtain the seen toy and some ability to adjust arm forces and stiffness to get the hand "in the ball park" of the object.

But note that by the time the infants produced their first reaches in this context, they had 3 to 5 months of perceptual-motor experience in a visually complex, gravitational environment. They have acquired improved visual tracking, acuity, and binocular vi-

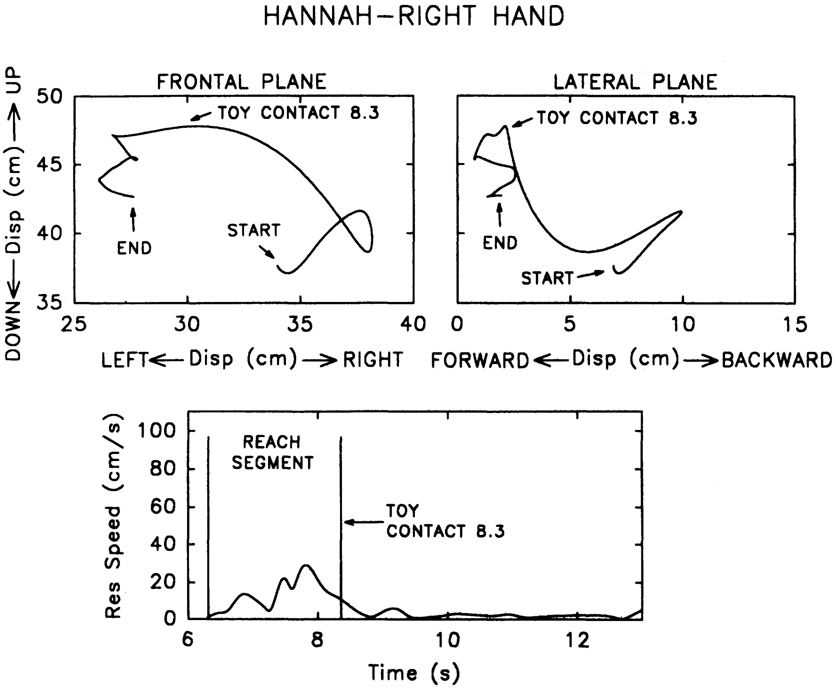

FIG. 27.—Exemplar trial for Hannah's right hand at reach onset showing reach segment initiated from a quiet starting position. Top panels: 8-sec hand path in the frontal and lateral planes. Bottom panel: Resultant speed for the same segment showing fewer reversals than for the other infants.

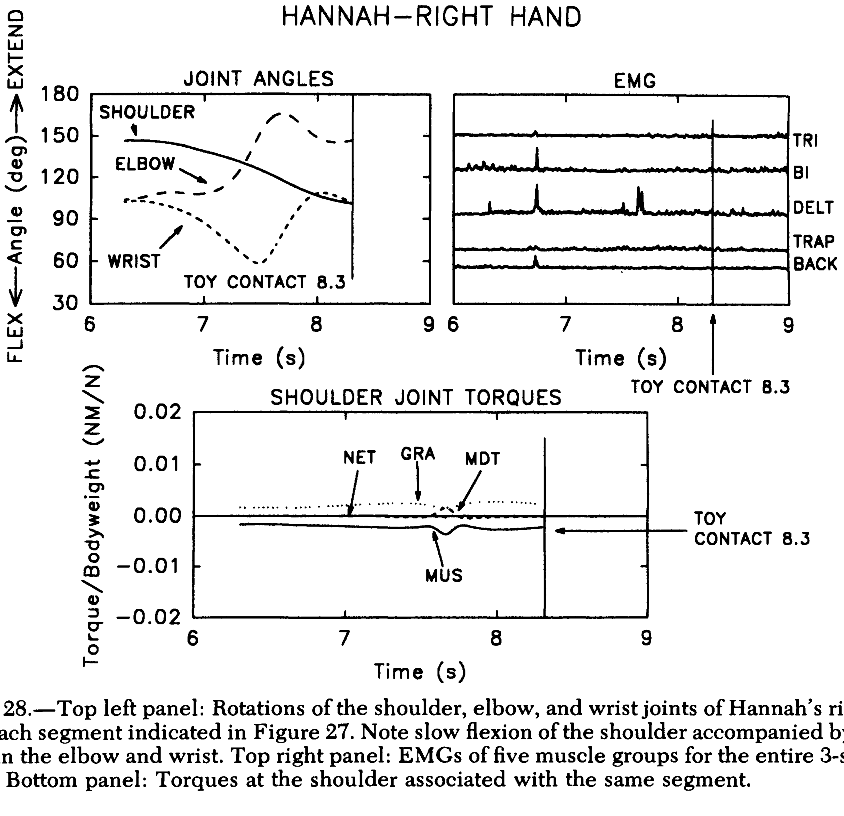

FIG. 28.—Top left panel: Rotations of the shoulder, elbow, and wrist joints of Hannah's right hand for the reach segment indicated in Figure 27. Note slow flexion of the shoulder accompanied by smooth changes in the elbow and wrist. Top right panel: EMGs of five muscle groups for the entire 3-sec reach segment. Bottom panel: Torques at the shoulder associated with the same segment.

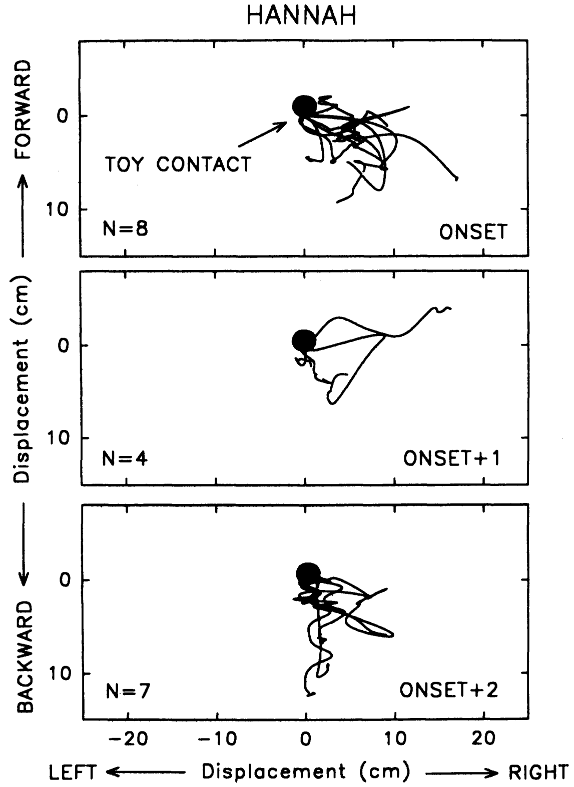

FIG. 29.—Hand trajectories at reach onset and following weeks of all analyzable trials where Hannah made contact with the toy. Only the trajectory of the hand making first contact is plotted. Trajectories are depicted from a top view and normalized to the space-time coordinates of toy contact.

sion. They have stable head control and emerging control of the trunk. Although they did not successfully reach and grasp, hundreds of hours of moving and perceiving provided them with information about their visual world and about their self-produced activity with eyes, heads, mouths, and limbs through receptors in muscles, joints, skin, and vestibular system (Gibson, 1988). They also had considerable experience with a range of energy levels, from being relaxed and drowsy to producing the vigorous, thrashing movements associated with high excitement or crying. Thus, even without goal-corrected movements, infants have explored their dynamics in terms of muscle stiffness and compliance, and have seen and felt the consequences of movements in many situations and gravitational orientations. The imposition of voluntary control may begin at this level.

A natural, mature reach is fast, but exquisitely controlled, especially near the target. The hand traverses nearly a straight path to the target, the joints flex and extend, and the hand opens and grasps in a coordinated manner (see Jeannerod, 1988, for a review). Mature reachers use muscle forces efficiently but not excessively, to initiate and brake movement and stabilize against unwanted MDTs (Schneider, Zernicke, Schmidt, & Hart, 1989). Our evidence from the first weeks of reach onset supports the likelihood that these stable patterns in trajectory, coordination of the joints, and patterns of muscle activation are the later *consequences* of the initial stiffness modulation and are discovered, rather than imposed. Hannah and Justin, for instance, began reaching with remarkably mature-looking velocity profiles and patterns of joint coordination. Both infants looked more disorganized in the succeeding week as they shifted to a more forceful approach, reflected in higher velocity movements and more MDTs. By onset + 2, Hannah had discovered how to control initiation and more efficiently produce a single, directed extension, but Justin was still exploring a wider range of force levels, although with evidence of modulation before the target. Gabriel and

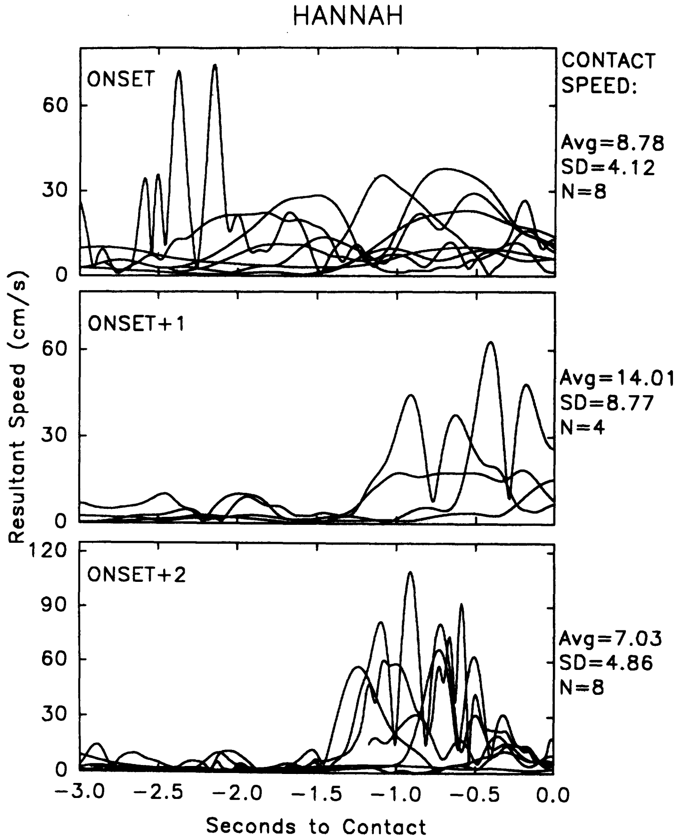

FIG. 30.—Resultant speed of the trajectories plotted in Figure 27 for 3 sec prior to contact

Nathan learned within 2 weeks that their initial swat and swipe strategies were deficient in control and accuracy (and inefficient as well), and their movements became more subdued. Note that as Gabriel damped velocities and torques after 2 weeks, he also had smoother joint excursions, including a coordinated elbow extension before contact.

In addition, data from this transitional window also suggest that interlimb coordination, as well as single arm trajectories and joint coupling, fall out of the natural and intrinsic dynamics of the movements. Recall that both Gabriel and Nathan, the more forceful initial reachers, had highly coupled spontaneous movements and performed nearly all of their first reaches bilaterally, although their hands did not always touch the toy simultaneously. Justin, with intermediate levels of force, used both one and two hands initially. Hannah was exclusively unimanual at first, and only when her reaches became faster did we see occasional bilateral approaches. We speculate that control of the energetic coupling across the limbs may be one clue to understanding the puzzling picture of shifting laterality in hand use in infancy. That is, that the degree of bilateral coupling is a function of the overall excitation of the system, and that unimanual or differentiated hand use will first require that infants bring the limbs into some optimal energetic ranges. Thelen and her colleagues (Thelen, Skala, & Kelso, 1987; Thelen, Ulrich, & Niles, 1987) have demonstrated such an energetic/informational coupling in infants' legs, and Thelen, Ridley-Johnson, and Fisher (1983) have suggested that this coupling may explain bilateral coordination shifts. Further experimental studies are warranted.

In sum, all of these infants did the best they could with what they had to initially make that "ball park" reach. In these examples, smooth trajectories and coupling of the joints did not emerge through some black-box process of maturation, but were a by-product of particular levels of force and arm stiffness or compliance. These dynamic parameters are good candidates for develop-

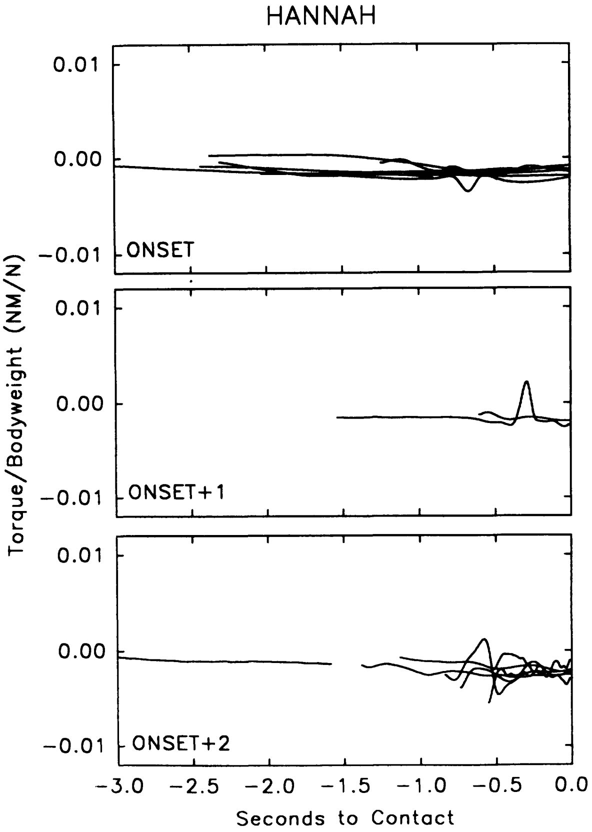

FIG. 31.—Shoulder MUS torques of the trajectories plotted in Figure 27 where dynamic data could be calculated.

mental control parameters: scalar changes led to more (and less!) mature forms. Finally, our evidence shows that even within 2 weeks of reaching onset, infants were exploring their dynamics and matching levels of force and stiffness to the task. The scaling demands for executing a more optimal reach were unique to each infant in the task context, and the infants generated individually appropriate solutions.

Implications for Models of Skilled Reaching

We believe that understanding the developmental process of how infants discover first reaches also provides insight into the control and coordination of skilled reaching. There is considerable debate among movement scientists as to how the brain controls the arm and hand in order to reach and grasp. Does the central nervous system plan reaches to be smooth and graceful, by minimizing the irregularities in the path of the hand (Hogan, 1984)? Is the direction of the hand path controlled (Morasso, 1981)? Does the CNS calculate the course to the target in terms of the positions of the joints (e.g., Soechting & Ross, 1984)? Or does the relative timing of the agonist-antagonist muscle bursts determine the fundamental pattern (Gottlieb, Corcos, & Agarwal, 1989)? A common criticism leveled at all of these models, however, is that they cannot explain how actions remain flexible and skilled in the face of inevitable and often unpredictable perturbing forces arising internally from the movement of the limb or externally from the environment.

Our results potentially support an alternative group of models. These models suggest that the CNS is actually working on the dynamic characteristics of the controlled limb rather than its movement pathway or the firing patterns of the muscles. More specifically, they propose that limbs behave like mass springs where the nervous system changes the overall response dynamics by altering the limb's compliance (dynamic stiffness) (Berkinblit, Feldman, & Fukson, 1986; Feldman, 1966; Hogan, Bizzi, Mussa-Ivaldi, & Flash, 1987; Polit & Bizzi, 1978).

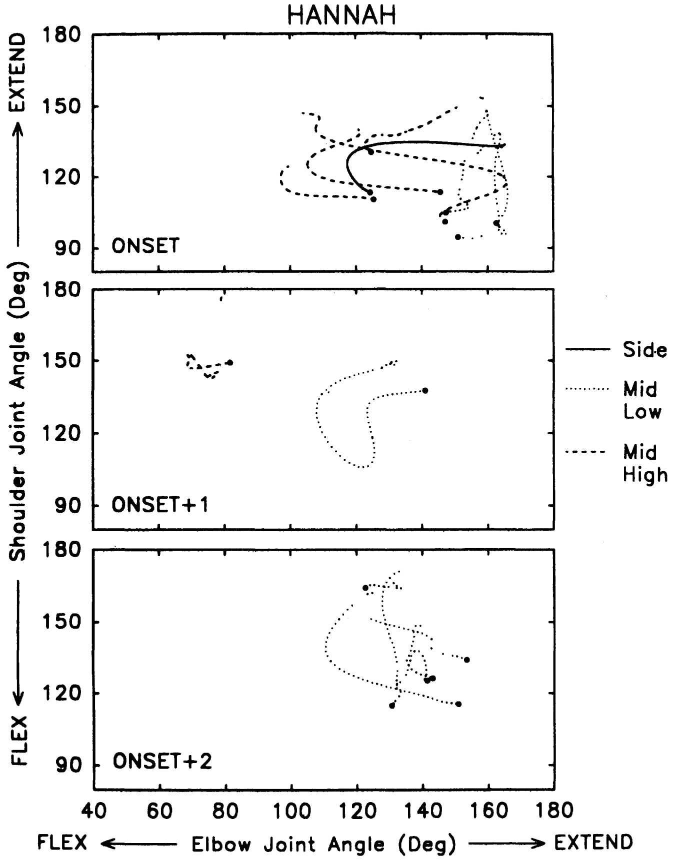

FIG. 32.—Angle-angle plot between the elbow and shoulder joints corresponding to the trajectories plotted in Figure 27.

In this view, neither the trajectory of the hand, joint angles nor muscle patterns are explicitly planned ahead of the movement. Rather, the CNS sets up initial conditions in the limb in relation to the position of the arm and the target, much like setting the stiffness of a spring. Details of the space-time behavior of the joints and hand are emergent properties of the dynamics, just as the behavior of a spring is determined by its mass and stiffness. Additionally, our data are consistent with dynamic computational models that derive trajectories from dynamics (Saltzman & Kelso, 1987). In particular, the neural network model of Bullock and Grossberg (1990) explicitly predicts that speed and limb compliance control are crucial in skill learning.

Most important for the developmental story is that the physiological mechanisms for detecting dynamic force fields and imposing compliance control of the limb appear to be in place in young infants. These likely include lower level stretch reflexes, probably mediated at the spinal level, which function to control the length of muscles in response to changes in load (Houk, 1979; Myklebust, Gottlieb, & Agarwal, 1986) and the use of agonist-antagonist coactivation, which stiffens the entire limb or limb segment (Feldman, 1980; Hogan et al., 1987). Coactivation was a very common strategy in our new reachers, and, indeed, in even younger infants for moving their legs (Thelen & Fisher, 1983). We have earlier suggested (Schneider et al., 1990) that the compensatory muscle torque response to motion-generated torques, seen in reaching and also in leg movements, was mediated through such stretch reflexes.

Thus, although the dynamic properties of infant arm movements await formal modeling, it seems reasonable to propose that infants are creating their task-specific devices through adjusting the tension on the spring and the energy they deliver to it.

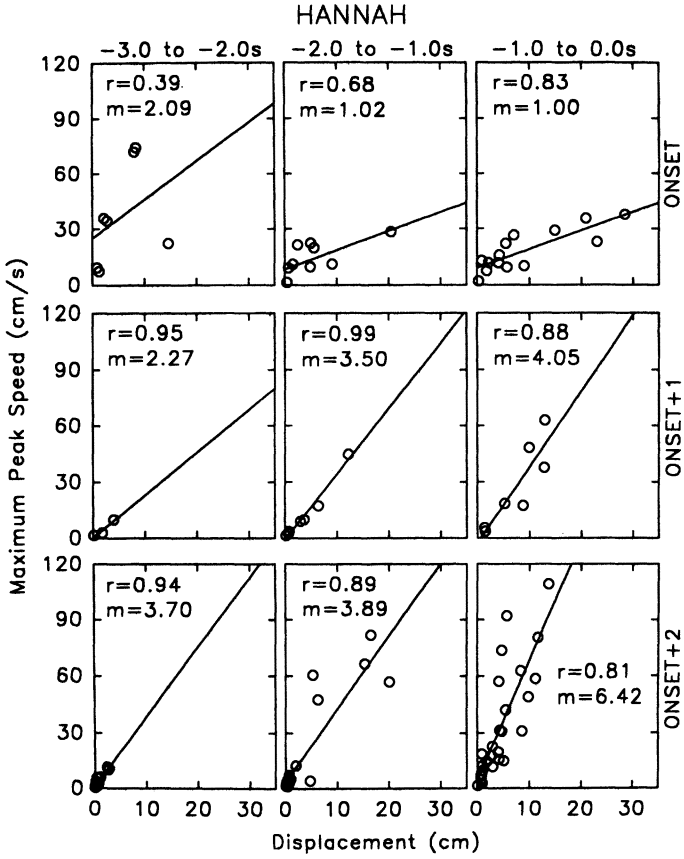

FIG. 33.—Arm stiffness estimation for Hannah's reach segments at 3 to 2 sec, 2 to 1 sec, and 1 to 0 sec prior to contact during the week of onset and the 2 following weeks. Regression lines between displacement and maximum speed peaks give an estimation of arm stiffness.

Their initial attempts were rather crude, but they got the hand close enough to the toy to start the process of more precise calibration.

Implications for Development

We believe this study illustrates the utility of the operational principles of a dynamic systems approach to development (Thelen & Ulrich, 1991). First, this account of early reaching would have been impossible with cross-sectional, group data or traditional analyses. Neither the infants' ages nor their actual performance (they were equally effective in contacting the toy) could predict the dynamic parameters of reaching. Infants did not uniformly improve on these variables. Indeed, the infants were so variable that averaging them together on any measure would have only obscured their individual solutions. Frequent sampling was necessary; we observed important developmental transitions within a span of a few weeks, and even within this span infants differed in the rate and direction of their changes.

More important, this study demonstrated that infants assembled reaching skill in a dynamic, context-specific fashion, using whatever components they individually had available for the task. Although reaching appeared as a discontinuous phase shift, the skill emerged from the confluence of components that were continuous and manifest: the ability to visually locate the toy in space, intention to reach and grab the toy and transport it to the mouth, growing control of the head and trunk, and the increasing ability to modulate the force and compliance of the arms. It is unnecessary to add other constructs such as prefigured devices, innate knowledge, or maturational programs. We suggest that infants assemble other cognitive, social, and perceptual-motor skills in a similar dynamic, problem-solving, and opportunistic manner. However, this can only be discovered by tracking developmental transitions in individual infants and by characterizing not only the level of performance, but also the dynamics of the contributing components.

Our data here clearly illustrate the continuity of time scales between the real-time appearance of a new form—the actual transformation of a flap into a reach—and the discovery and loss of behavioral forms over the time scales of development. Developmental change is engendered by the same process of exploration and discovery that led to the first reaches (Gibson, 1988). Each reach is an effort to match current abilities to some desired goal. By repeating this matching effort over days, weeks, and months, infants find increasingly efficient and stable solutions. Once they are in the ball park of the object, they can work to scale their movements to the size, shape, orientation, distance, and weight of the object. Each new solution, in turn, opens up new task domains, which require new body-environment matches. Thus, the developmental landscape unfolds from the activity of the infant as an individual problem solver working each day.

Finally, this account of the discovery of solutions and the matching of individual dynamics to a task provides strong empirical support to Edelman's selectionist theory of neural and behavioral development (Edelman, 1987; Sporns & Edelman, 1993, in this issue). As Sporns and Edelman show in this volume, computational solutions to the difficult problems of arm trajectory control are not necessary, and indeed incapable of dealing with the flexibility, complexity, and adaptability of real movers in the real world. They propose a theory and model to show how a primary movement repertoire (our intrinsic dynamics) can be transformed into adaptive actions through the continual process of exploration of the perceptual consequences of self-generated movement. Even in the few weeks around reaching onset, Gabriel, Nathan, Justin, and Hannah showed evidence of this learning by doing.

Appendix A

NUMBER OF TOY TRIALS AND PERCENT OF TOTAL TIME ANALYZED

SUBJECT, WEEK, AND TRIAL TYPE	TRIALS ANALYZED/ TOTAL OF TYPE	% OF ANALYZED/ TOTAL TRIAL TIME: Right	% OF ANALYZED/ TOTAL TRIAL TIME: Left
Gabriel:			
Onset – 2:			
PP	2 of 2		
APP	1 of 2	77.7	70.1
Onset – 1:			
PP	2 of 2		
APP	4 of 4	80.6	82.3
Onset:			
PP	1 of 2		
APP	4 of 6	63.0	63.3
Onset + 1:			
PP	2 of 2		
APP	6 of 7	66.0	45.1
Onset + 2:			
PP	2 of 3		
APP	4 of 5	60.3	85.7
Nathan:			
Onset – 2:			
PP	2 of 4		
APP	1 of 4	97.5	93.5
Onset – 1:			
PP	4 of 5		
APP	0 of 2	60.7	66.2
Onset:			
PP	5 of 5		
APP	5 of 6	85.2	82.4

Appendix A (*Continued*)

Subject, Week, and Trial Type	Trials Analyzed/ Total of Type	% of Analyzed/ Total Trial Time	
		Right	Left
Onset + 1:			
PP	1 of 4		
APP	3 of 6	46.5	67.3
Onset + 2:			
PP	3 of 4		
APP	2 of 4	50.3	38.4
Justin:			
Onset − 2:			
PP	1 of 2		
APP	6 of 8	66.7	57.1
Onset − 1:			
PP	6 of 7		
APP	2 of 4	51.9	1.2
Onset:			
PP	6 of 7		
APP	0 of 4	64.5	62.6
Onset + 1:			
PP	4 of 6		
APP	4 of 5	47.3	42.5
Onset + 2:			
PP	2 of 2		
EP	7 of 7		
APP	1 of 1	97.7	85.2
Hannah:			
Onset − 2:			
PP	4 of 5		
APP	1 of 4	72.8	85.6
Onset − 1:			
PP	4 of 5		
EP	1 of 2		
APP	2 of 2	55.6	71.1
Onset:			
PP	4 of 4		
EP	4 of 7		
APP	0 of 2	35.8	35.4
Onset + 1:			
PP	6 of 6		
EP	0 of 4	52.4	58.4
Onset + 2:			
PP	5 of 5		
EP	3 of 6	75.1	88.1

Note.—PP = parent presents; EP = experimenter presents; APP = apparatus presents.

Appendix B

NUMBER OF SEGMENTS USED TO AVERAGE HAND RESULTANT SPEED

Subject and Week	Number of Segments
Gabriel:	
Onset − 2	RH: *N* = 3 LH: *N* = 6
Onset − 1	RH: *N* = 9 LH: *N* = 11
Onset	RH: *N* = 6 LH: *N* = 6
Onset + 1	RH: *N* = 8 LH: *N* = 17
Onset + 2	RH: *N* = 16 LH: *N* = 7
Nathan:	
Onset − 2	RH: *N* = 5 LH: *N* = 6
Onset − 1	RH: *N* = 6 LH: *N* = 4
Onset	RH: *N* = 12 LH: *N* = 13
Onset + 1	RH: *N* = 4 LH: *N* = 4
Onset + 2	RH: *N* = 6 LH: *N* = 9
Justin:	
Onset − 2	RH: *N* = 11 LH: *N* = 9
Onset − 1	RH: *N* = 8 LH: *N* = 1
Onset	RH: *N* = 8 LH: *N* = 6
Onset + 1	RH: *N* = 10 LH: *N* = 10
Onset + 2	RH: *N* = 10 LH: *N* = 19
Hannah:	
Onset − 2	RH: *N* = 11 LH: *N* = 5
Onset − 1	RH: *N* = 13 LH: *N* = 7
Onset	RH: *N* = 8 LH: *N* = 8
Onset + 1	RH: *N* = 6 LH: *N* = 7
Onset + 2	RH: *N* = 13 LH: *N* = 9

Appendix C

NUMBER OF SEGMENTS USED TO AVERAGE SHOULDER MUS TORQUES

Subject and Week	Number of Segments
Gabriel:	
Onset − 2	RH: *N* = 4 LH: *N* = 8
Onset − 1	RH: *N* = 23 LH: *N* = 3
Onset	RH: *N* = 8 LH: *N* = 8
Onset + 1	RH: *N* = 16 LH: *N* = 10
Onset + 2	RH: *N* = 7 LH: *N* = 11
Nathan:	
Onset	RH: *N* = 27 LH: *N* = 30
Onset + 1	RH: *N* = 5 LH: *N* = 4
Onset + 2	LH: *N* = 2
Justin:	
Onset − 2	RH: *N* = 9 LH: *N* = 7
Onset − 1	RH: *N* = 11
Onset	RH: *N* = 10 LH: *N* = 6
Onset + 1	RH: *N* = 6 LH: *N* = 4
Onset + 2	RH: *N* = 19 LH: *N* = 23
Hannah:	
Onset − 2	RH: *N* = 3 LH: *N* = 13
Onset − 1	RH: *N* = 5 LH: *N* = 7
Onset	RH: *N* = 10 LH: *N* = 8
Onset + 1	RH: *N* = 6 LH: *N* = 2
Onset + 2	RH: *N* = 16 LH: *N* = 14

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