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PAPER

Posture and the emergence of manual skills

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Abstract

In this paper, we examine how infants' natural manual and postural activities – what they prefer and do week by week – are related to developmental transitions in reaching skill and its neuromuscular control. Using a dense, longitudinal design, we tracked the manual and postural activities of four infants in a natural, free-play setting across the first year of life, and related these activities to two transitions in reaching as measured in a structured laboratory setting: the transition to reaching and the transition to stable reaching. Our data indicated that specific advances in the free-play setting preceded both transitions. Head and upper torso control, the ability to extend the arm and hand to a distant target, and the ability to touch and grasp objects placed nearby were all precursors to the onset of reaching, whereas sitting independently was associated with the transition to stable reaching. We also found important individual variability in when these 'components' were in place, indicating that it is the ensemble of components that is essential, not the order in which they develop or the timing of their contribution. These findings suggest that subsequent experimental manipulations should be planned with respect to infants' individual constellations of skills, rather than looking at only a single precursor to change.

When researchers first began studying infant reaching, the problem was conceived, somewhat simply, as one of establishing accurate eye–hand coordination: matching the sight of the hand to the sight of the target (Piaget, 1952; White, Castle & Held, 1964). With increased study and improved technology for recording infant movements, the complexity of these early behaviors has become more apparent. For instance, infants are initially just as successful reaching in the dark as to a seen target (Clifton, Muir, Ashmead & Clarkson, 1993). Thus, the 'feel' of the hand and arm as they move in relation to the body and to external objects is an important factor. Likewise, infants must be able to adjust not just the spatial position of the arm, but also the forces or amount of energy delivered to the muscles in order to get their hands in the vicinity of desired objects (Thelen *et al*., 1993; Thelen, Corbetta & Spencer, 1996; Spencer & Thelen, in press). Finally, there is growing agreement that other components such as binocular vision, postural control, and motor planning and memory all contribute to the emergence of this skill.

A central challenge for understanding the development of reaching skill is how to conceptualize the contributions of these multiple components. In the last decade, a dynamic systems approach to development has been proposed to meet this challenge (Thelen & Ulrich, 1991; Thelen & Smith, 1994). From a dynamic systems perspective, new behaviors such as reaching arise from the interaction of multiple, interdependent components under particular task and environmental constraints. Although many components may contribute to a behavioral pattern at any one time in development – binocular vision, postural control, motor memory – one or more elements may be especially critical in shifting the qualitative form of the behavior. These components can be non-obvious; that is, components seemingly unrelated to manual skill may be central to change. And because developing systems can be highly

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nonlinear, a very small change in such a component can cascade into large developmental effects. One goal of developmental research, then, is to identify these critical components and to determine when, and under what circumstances, they contribute to developmental change.

A second useful principle of the dynamic approach is that the system's own activity leads to developmental change. This is because developing systems are both open and dynamic, creating activity, and in turn being modified by activity. This suggests that in order to identify relevant contributors to changes in manual skill, researchers must attend to what an infant is currently experiencing and what has been experienced in both the near and more distant past.

In a series of previously published papers, Thelen and her colleagues have used these dynamic systems principles to explore how infants learn to reach across the first year (Thelen *et al.*, 1993; Corbetta & Thelen, 1996; Thelen *et al.*, 1996; Thelen & Spencer, 1998; Spencer & Thelen, in press). These papers all report on data from a year-long, dense longitudinal study of four infants learning to reach, using multiple measures. The infants were studied in a structured laboratory setting in which they were positioned nearly upright in a special chair with their torsos stabilized and with toys presented in a standardized way. In the present report, we add another level of analysis to this emerging picture of how infants learn to reach. Here we report on the same infants' manual and postural behaviors in a natural, free-play setting, collected and coded independently from the structured laboratory sessions that yielded information on the kinetic, kinematic and neuromuscular bases of reaching. From these free-play data we asked how infants' natural manual and postural activities – reflecting what they prefer and do week by week – were related to changes in reaching and its control measured in the more structured setting. The guiding assumption was that developmental changes in the reaching system were intimately tied to infants' experiences both in the specific action of reaching but also in other non-reaching manual movements and in the related skill of developing postural control.

Two transitions in the development of reaching skill

Analyses of the kinetic, kinematic and neuromuscular bases of infants' reaching skill have identified two distinct transitions common to the four infants studied by Thelen and colleagues. First, all infants showed a transition from arm movements that did not end in contact with distant objects to the onset of the first reaches. This transition involved changes in infants' abilities to modulate torques, or the forces needed to successfully extend the arm toward the object (Thelen *et al.*, 1993). Infants also changed the muscles they used to move their hands in the spaces around the toy. Before infants were able to touch the toy, they primarily used the biceps and triceps to flex and extend the arm when near the toy. During the first weeks of reaching, however, the infants used combinations of shoulder and neck muscles to stabilize the head and lift and extend the arm toward the toy. In addition, the infants co-activated shoulder, neck and arm muscles to stabilize the arm at the toy's location (Spencer & Thelen, in press).

The second transition seen in all four infants – the transition to 'stable' reaching – occurred at about 7 months. Before this transition, there was little week-to-week consistency in how infants reached for toys. Although sometimes infants' reaches were smooth and straight, other times their reaches were jerky, with several changes in direction and increases and decreases in movement speed. After the transition, infants' reaches were consistently smooth and straight from week to week (Thelen *et al.*, 1996).

In addition to these characteristics that were common to all infants, we noted important individual differences in the timing of the developmental transitions as well as in the general style of movement across the transition periods. Two of the infants – Nathan and Gabriel – first reached for toys relatively early in the first year, at 12 and 15 weeks respectively. Before these transition weeks, both infants had characteristically fast and forceful non-reaching movements (Thelen *et al.*, 1993). This highly active movement style continued throughout the first year (Thelen *et al.*, 1996). By contrast, Hannah and Justin moved their arms less vigorously early in the first year and did not reach for toys until week 20. The less active movement styles of these two infants continued throughout the first year, although there were several weeks prior to the stable period when Hannah's movements were more vigorous.

Specific goals

The first issue we address in this paper is what changes in manual behaviors preceded the abrupt transition to reaching seen in the structured laboratory sessions. As discussed in Thelen *et al.* (1993), successful reaches did not arise *de novo*, but were selected and sculpted from the previous and ongoing non-reaching movements. Nevertheless, because infants were relatively constrained in the structured sessions, we may not have had a good sample of these earlier important manual activities. In this paper, we look more closely at how infants moved their arms when in different postures and when interacting in a play situation with a parent. From these data, we ask whether infants were producing arm extensions toward objects, with or without contact, in the weeks before they demonstrated reaching in the structured setting. Similarly, we ask what other types of arm movements, e.g. to the mouth or face, preceded or accompanied the onset of reaching.

The second transition in reaching skill – the transition to stable reaching – may also have been related to infants' manual activities outside of the structured laboratory setting. For instance, Thelen (1979, 1981) suggested that manual stereotypes such as banging and waving are indicators of transitions in arm and hand control: these movements are seen after infants gain some ability to make voluntary movements, but before they are very skilled. Such rhythmical movements may provide feedback about the feel of the arms as infants modulate forces. Thus, in this paper we examine how infants' manual activities in a natural play setting are related to stable reaching late in the first year.

In addition to manual abilities, it has been increasingly recognized that posture and postural control are intimately tied to the control of the arm in reaching and grasping (see Thelen & Spencer, 1998). For instance, Rochat (1992) found that infants who were stable self-sitters were more likely to use one-handed reaches than those who could not sit alone. Rochat and Goubet (1995) showed that sitting and non-sitting infants stabilized at the hip would lean when reaching for an object, but non-sitters could not coordinate the trunk and the reach. Similarly, Savelsbergh and van der Kamp (1994) showed that body orientation with respect to gravity influenced both the quantity and quality of reaching. The reaching of younger infants became more similar to that of older infants when they were sitting upright rather than sitting in a reclined position or lying supine. On the other hand, in a direct manipulation of postural stability, Kamm (1994) found no differences in the trajectories of reaching movements when postural support was removed.

In the present study, we look at the association of naturally occurring developmental changes in head and torso postures with transitions in reaching and its neuromuscular control. Can we identify critical postural milestones and preferred postural states that may act as necessary precursors to upper limb control or that may contribute to improvements in reaching skill?

To answer these questions about naturalistic manual and postural behaviors, we developed a coding system that targets the manual and postural behaviors identified by previous research as potentially important to the development of reaching skill. Here we examine the week when infants first engaged in these behaviors, and the amount of time infants spent engaged in these behaviors from week to week across the first year.

Method

Participants

Four infants – one girl (Hannah) and three boys (Gabriel, Justin and Nathan) – participated in this study. These infants were all full term and had no known sensory or motor impairments. Infants and their families were recruited through local prenatal classes or from published birth announcements. The infants were from white, middle-class families. All families visited the laboratory before consenting to participate in the study. Parents were paid $15 for each observation session.

Materials

Infants were placed on a 3×6 ft mat in the center of a large viewing area. A fixed set of large and small toys were placed randomly around the infant on the mat. In addition, a $12 \times 12 \times 14$ inch high box was placed next to the mat. The box was designed to help scooting and crawling infants pull to a stand. Parents sat to one side of the mat and were allowed to change their location during the session as they desired. Two video cameras were positioned on either side of the mat to provide two different views of the activity in the play area. These views were recorded on one videotape using a Pelco (Model VSS100DT) screen-splitter. This was useful when behaviorally coding events, because one view was occasionally blocked by the parent or by nearby toys. A time counter (30 Hz) was also added to the videotapes to assist with behavioral coding.

Procedure

We observed each infant twice per week from 3 to 30 weeks of age and twice every other week from 32 to 52 weeks. In the first session each week, infants were videotaped in a quasi-naturalistic free-play session. Data from these sessions form the basis of the present report. In the second session each week, we collected position–time and electromyographic data as infants reached for objects presented at midline. These data and associated methods have been reported elsewhere (Thelen *et al.*, 1993, 1996; Corbetta & Thelen, 1996; Spencer & Thelen, in press).

Each free-play session consisted of four trials in a predetermined order. Some sessions early in the first year included a fifth trial. We do not report data from these trials, because we did not have a full data set to analyze. During each trial, infants were videotaped interacting with their parents and nearby toys for 5 min. We asked parents to present toys to their infants during the 5 min trials. Aside from these instructions, the interactions were unstructured. A few trials early in the first year were stopped before 5 min had elapsed because the infants became fussy. Conversely, several trials at the end of the year were stopped early because the infants walked outside the viewable area and were more interested in the laboratory than in the 'attractive' toys on the mat.

The first two trials of each play session were *supine* trials. At the beginning of these trials, infants were placed on the mat lying in a supine position. Trials 3 and 4 were *seated* trials. At the beginning of these trials, infants were placed in an age-appropriate infant seat. Around week 27, the infants started to become fussy when placed in the infant seat because they preferred to sit on the mat. Thus, from that point on, we placed them in a seated position on the mat at the start of trials 3 and 4. These changes in procedure during the seated trials are noted in Figure 3.

It is important to note that the four trials during each play session differed in the position of the infants at the *beginning of each trial*, but not necessarily later in the trial after several minutes had passed. For instance, even though we placed the infants in a supine position at the start of a supine trial, after about 4 months of age they often rolled from a supine to prone position early in the 5 min collection period. Similarly, once infants were able to crawl, they often moved from a seated position at the start of a seated trial to a crawling position to play with different toys.

Behavioral coding

To characterize changes in infants' manual and postural abilities across the first year, we developed a coding system consisting of 11 manual codes (see Table 1) and 12 postural codes (see Table 2).

Manual codes

The 11 manual codes in our coding system (see Table 1) capture changes in manual skill from early 'pre-reaching' movements to object-directed actions. Codes 1–3 identify three manual actions infants typically perform prior to their first reaches – movements ending with the hand on the face/head (HOF), movements ending with the hand in the mouth (HOM) and movements ending with the hands touching one another (HOH). By contrast, codes 4–8 identify movements that are more object-directed. These codes include the three segments of a reach that could be reliably coded from videotape – the initial extension of the arm toward an object (AEO), followed by a touch (TCH) and finally a grasp (GOB). It is important to note that these segments were not contingent on one another. Before the infants were skilled reachers, they often extended their arms toward objects but failed to touch or grasp them. By contrast, once infants were quite skilled, they often dropped one toy and grabbed another without an intervening arm extension. The last two 'object-directed' codes capture two typical forms of object manipulation – bringing the object to the mouth (MOO) and manipulating specific object characteristics (MAN) such as levers and buttons on toys. In addition to pre-reaching and object-directed actions, we included two codes to capture rhythmical manual stereotypies during the first year (RAN, RAO).

Table 1 *Code descriptions for manual actions*

Action	Code	Description
1. Hand on face/head	HOF	Hand resting on the face/head or rubbing/scratching the face/head
2. Mouth hand	HOM	Hand in the mouth
3. Hand on hand	HOH	Both hands touching one another
4. Arm extension – object	AEO	Arm extending away from body toward an object
5. Touch	TCH	Infant touches, but does not grasp, an object
6. Grasp object	GOB	Infant wraps fingers around object and holds on to it
7. Mouth object	MOO	Infant mouths or sucks on object. If holding object but mouthing hand, code MOO, not HOM
8. Manipulate object	MAN	Infant explores or uses some aspect or property of object
9. Rhythmical activity – no object	RAN	Infant does stereotypic movement without an object. Includes waving and banging of hand. Must have at least three repetitions
10. Rhythmical activity – object	RAO	Infant does stereotypic movement with an object in hand. Includes shaking, banging, waving. Must have at least three repetitions
11. No activity	NOA	General category for when there is no movement of the arms and hands. Includes hands at sides and hands resting on body

Table 2 *Code descriptions for postures*

Posture	Code	Description
1. Supine	SUP	Infant lying on back. Both sides of upper torso on support surface
2. Supine – hip up	SHU	Infant lying on back. Upper torso on support surface but pelvis lifted off surface
3. Side	SID	One side of upper torso off surface, the other side on surface. Pelvis on or off surface. May be supported by one arm
4. Prone – head up	PHU	Infant lying on stomach with head raised. At least one arm must be on surface, but not supporting
5. Prone – on arms	POA	Infant lying on stomach, supported by both arms which are extended
6. Head at midline	MID	Head facing forward
7. Slouch	SLO	Infant's torso and shoulders supported by seat. Shoulders and torso curved to the right or left
8. Seated erect	SER	Infant's torso, shoulders, and head supported by seat. Head is erect and controlled
9. Sits forward	SFR	Infant in seat, but head, head and shoulders or entire upper and lower back off seat
10. Supported sitting	SUS	Infant sitting without a seat, but with support from one or both arms, pillows, parents or other objects
11. Sit alone	SIA	Infant sits without support for more than 3 s
12. Hands and knees	HKN	Infant in hands-and-knees position. Stomach off surface

Finally, we included a code to capture periods of time when infants were not moving their arms and hands (NOA).

Postural codes

The 12 postural codes in our coding system (see Table 2) were developed to identify changes in infants' postural skill in both the supine and seated trials. The first five codes captured early changes in infants' ability to roll over when placed in a supine position. We coded how often infants were in a supine position (SUP) or in a prone position (PHU, POA). In addition, we coded early postural flexibility, i.e. infants' ability to move from a supine position to nearby postures (SHU, SID).

The next group of postural codes – codes 6–9 – were developed to identify changes in infants' postural skill when they were seated in the small or large seat. Our postural coding system captured when infants were first able to hold their heads at midline (MID, coded to week 20) and to sit straight in the seat (SER), as opposed to slouching over to one side (SLO). A final code in this group (SFR) captured when infants were able to lift their head, shoulders and upper torso off the seat – an important milestone in emerging postural control. Once infants were moved out of the large seat and onto the mat during the seated trials, we used two codes to identify changes in infants' ability to sit independently. One code (SUS) captured when infants used support to assist them as they sat on the mat, while a second code (SIA) captured when infants sat independently for more than 3 s.

The final skill identified by the postural coding system was the transition to crawling. We coded how much time infants spent in a hands-and-knees posture (HKN). In addition, we coded the week of onset of hands-and-knees crawling, defined as the first week during which an infant crawled on hands and knees or feet for three or more continuous cycles (see Adolph, Vereijken & Denny, 1998). This differed from the other codes in that crawling onset was a discrete event as opposed to a proportion of total trial time.

Coding method and reliability

During each coding session, coders first watched the to-be-coded trial to place the infant's manual or postural activity in the real-time context of what happened during the trial. Next, coders returned to the beginning of the trial and stepped through it frame by frame (30 frames per second). Using the timer encoded on each video, they marked the beginning and end time of each event they observed from the manual or postural coding systems. All codes within each coding system were mutually exclusive. During pilot coding, we determined that it was too difficult to monitor the activity of both hands simultaneously. Therefore, manual actions were always coded in two passes – one for the right hand, one for the left hand. After coding the four trials of each session, we computed the proportion of time per trial each infant spent performing the coded manual actions across the first year, as well as the proportion of time per trial each infant spent in the coded postures across the first year.

Given the immense size of the data set analyzed in the current report, it was necessary to code the videotapes using multiple coding teams across multiple years. This made it challenging to obtain good inter-coder reliability. This challenge was met in several ways. First, the manual and postural coding systems focused solely on clearly defined behaviors. Thus, the number of judgments coders were required to make was minimized as much as possible. Initial pilot coding helped identify problem areas, which were then eliminated by modifying the coding rules. Second, a team of coders each year used the manual coding system, while a different team used the postural coding system. Thus, each coder had to master at most 12 codes. This was further simplified with the manual coding system because some codes were more frequent early in the first year (HOF, HOM), while other codes were more frequent later in the year (MAN, RAO). Similarly, the postural codes were split across trials: a subset of codes applied to the supine trials, a different subset applied to the seated trials with the large and small seat, and a third subset applied to the seated trials in which the infant was placed directly on the mat. Finally, the sessions were coded in a pseudo-random order rather than chronologically to avoid clear expectations about what behaviors would occur from week to week.

Each year, a team of undergraduate coders from Indiana University was recruited and assigned to a coding system. Coders were trained for several weeks, after which they were assigned to coding pairs. During the first coding year, pairs were tested for reliability against one another. After the first coding year, pairs were tested for reliability against coding from the previous years. For each pair, we computed the percentage co-occurrence across each test trial, i.e. the percentage of time that coders selected the same coding event in the same time interval (30 frames per second). Coding teams continued to train until there was greater than 75% co-occurrence across each test trial for the given coding week. All discrepancies with coding from previous years were corrected in the direction of the previous year's coding to avoid systematic drift in the coding systems. Reliability data for the last week of training across all coding years are reported in the Appendix. On two testing trials, a coding pair was lower than 75% co-occurrence; however, these coding pairs were considered to be reliable since their reliability measures were consistently above the 75% criterion on the other trials of the testing week.

Results

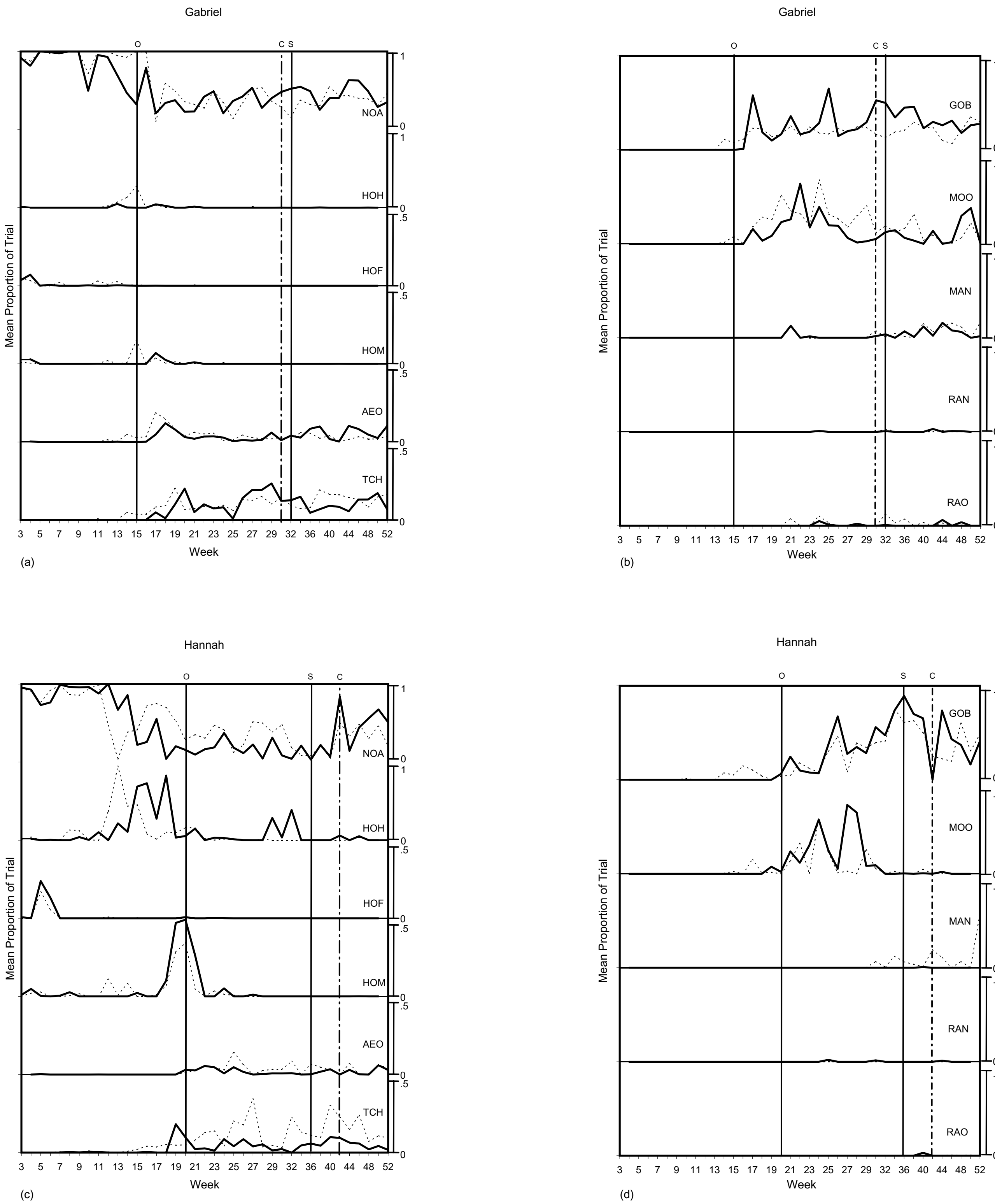
In the next two sections, we describe changes in infants' naturally occurring manual and postural abilities across the first year, focusing first on manual abilities, then on postural abilities. Within each section, we describe the general pattern of change across the first year. Then we focus on each transition in turn – the transition to reaching and the transition to stable reaching. The goal in each transition section was to identify coded behaviors that emerged in development just before the given transition.

Changes in manual activities across the first year

Figures 1(a)–1(h) show the developmental profiles of the infants' coded manual activities in the free-play sessions, expressed as a mean proportion of trial time. Each panel in Figure 1 shows the average proportion of time an infant spent performing a coded manual activity during the two trial types (supine and seated) of each free-play session. The scale bars on the right edge of each panel indicate the range of proportions displayed for each coded behavior. The scales were adjusted to make the developmental changes in manual behaviors across the first year more visible. Although the proportion of time several codes occurred was relatively small, it is important to note that even small proportions may be meaningful. For example, an average proportion of 0.05 indicates that an infant engaged in the coded behavior for 30 s across the two supine or seated trials for the given week. Although 30 s of behavior is a relatively brief duration, given that infants were free to engage in a wide variety of behaviors, this brief duration may mark the emergence of a new ability.

In the early months, infants were generally inactive (see NOA in Figures 1(a), 1(c), 1(e), 1(g)) with their arms in a flexed position and held close to the body and face. When they did move, Gabriel, Hannah and Nathan generally moved their hands to the face (HOF), to the mouth (HOM), or they held their hands clasped together (HOH; see Figures 1(a), 1(c), 1(g)). These behaviors were especially prominent in Hannah, who had tightly flexed arms in the structured laboratory sessions, and who was motorically less active than the other babies. Justin engaged in some hand-on-hand (HOH) behaviors in the seated condition early in the first year, but in general he did not engage in HOF and HOM until 5–6 weeks before he began reaching for toys in the structured laboratory sessions (see line labeled O in Figure 1(e)). In all infants, HOF, HOM and HOH occurred less frequently after reach onset.

After several months of engaging in face- and mouth-centered actions, infants' manual behaviors became more object-centered. Infants began touching (TCH) and grasping (GOB) toys several weeks before the onset of reaching in the structured laboratory sessions, and grasping increased dramatically after this transition week (Figure 1). Touching and grasping objects emerged earlier in the seated versus the supine trials. This may reflect the increased biomechanical demands of reaching from supine (Savelsbergh & van der Kamp, 1994) or infants' increased social engagement when seated (Fogel, Dedo & McEwen, 1992). The amount of time infants spent with objects in their mouths (MOO) also increased at reach onset and remained at fairly high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(a)
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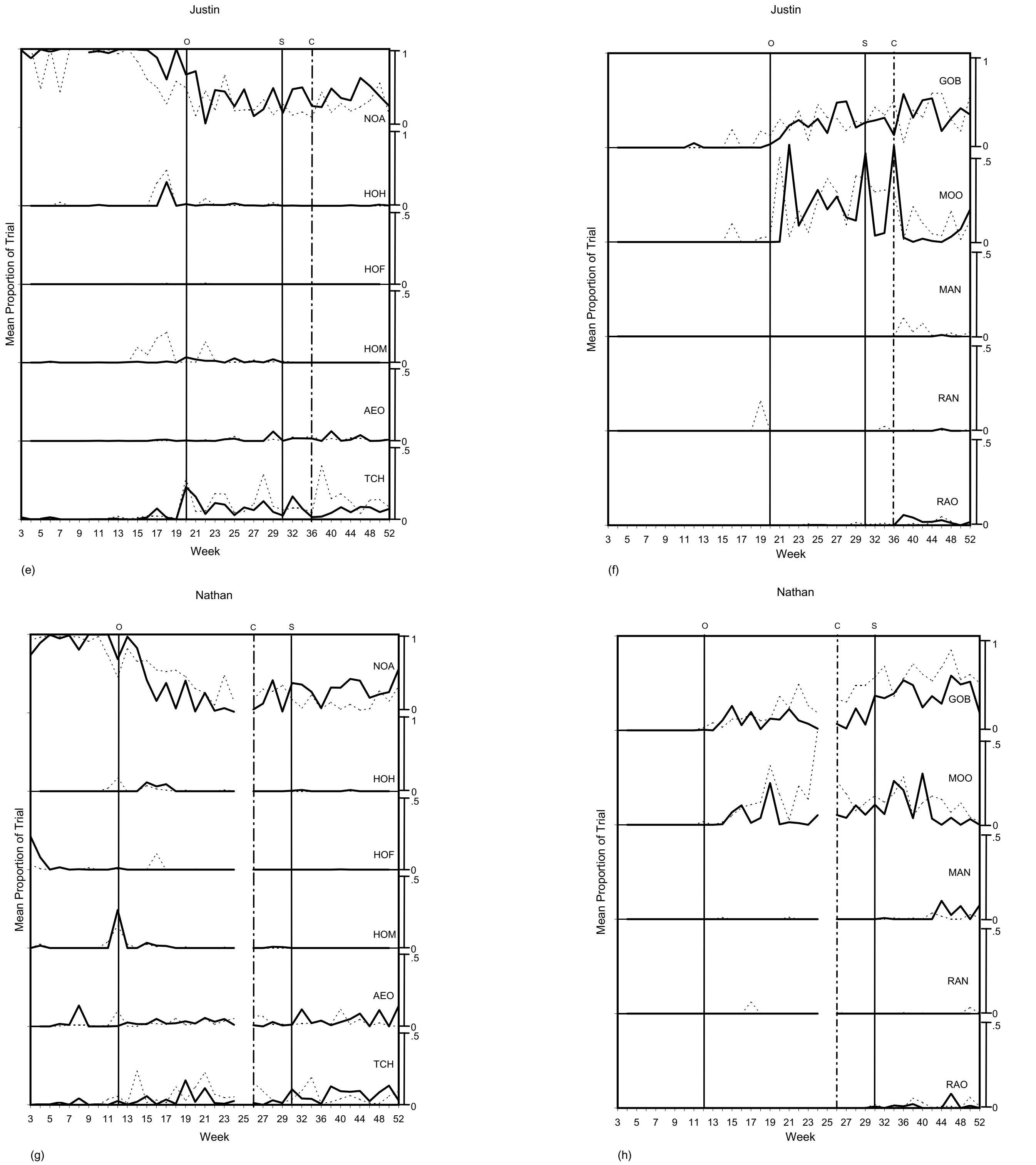


Figure 1 *Average proportion of trial time each of the infants spent in each of the manual activities (NOA, no activity; HOF, hand on face; HOM, hand in mouth; HOH, hand on hand; AEO, arm extension toward object; TCH, touch object; GOB, grasp object; MOO, object in mouth; MAN, manipulate object; RAN, rhythmical activity; RAO, rhythmical activity with an object) in the supine trials (solid line) and seated trials (broken line) across the first year. Vertical lines indicate the transition to reach onset (O) and the transition to reach stability (S) in structured laboratory sessions, and the onset of hands-and-knees crawling (C). The scale for each panel is shown to the right.*

levels throughout the first year. This suggests that reaching, grasping and mouthing objects became frequent and functional in infants' free-play activities at the same time that we observed them reaching reliably in the more constrained laboratory sessions.

After the onset of reaching, infants began moving their arms rhythmically, both with and without objects (RAN and RAO), although Justin engaged in some rhythmical activity before the transition to reaching (see Figure 1(f)). Rhythmical activity was sporadic for Hannah and Nathan until late in the first year when these infants began reliably waving and banging objects (see RAO in Figures 1(d), 1(h)). Finally, infants did not manipulate objects (MAN) until relatively late in the first year, around the transition to stable reaching (see line labeled S in Figures 1(b), 1(d), 1(f), 1(h)). Indeed, the proportion of object manipulation did not increase consistently until *after* the transition to stable reaching for all four infants.

Manual activities associated with reaching onset

Given that reaching emerged in the structured laboratory sessions at a specific week for each infant, we asked what manual activities were well synchronized with this transition in the free-play sessions. That is, what activities first emerged (or increased in frequency) in the free-play sessions just before the onset of reaching? We assume here that, although reaching onset is a discrete, identifiable milestone, this transition in action emerges from infants' continuous, ongoing activities before the transition.

It is clear from Figure 1 that infants engaged in a variety of manual activities well before the onset of reaching. However, it is difficult to identify which behaviors shown in Figure 1 were 'well-synchronized' to this transition given the large amount of week-to-week variability. Thus, we identified the first time infants reliably engaged in each manual activity. Then we determined if the onset of these manual activities preceded the transition to reaching in all four infants. We used two criteria to determine the onset of each coded behavior. First, we used a 'consecutive' criterion: we determined the first time each infant engaged in a manual behavior for 2 weeks in a row. Second, we used a 'duration' criterion: we identified the first time each infant engaged in a manual behavior for at least 10 s during the supine or seated trials. These two criteria were used to eliminate the few cases where the infants engaged in a behavior for a few seconds on a single trial early in the year and did not engage in that behavior again for several weeks.

Figure 2 shows the number of weeks before or after reaching onset that the infants first engaged in seven manual activities based on the consecutive (2(a) and 2(c)) and duration (2(b) and 2(d)) criteria. Data for three other manual activities are shown in Figure 2 – MAN, RAN and RAO. These behaviors are discussed below because they generally emerged after reaching onset but before the transition to stable reaching.

The onset of three manual activities in the supine condition – HOF, HOM, HOH – was variable across infants using both the consecutive (Figure 2(a)) and duration (Figure 2(b)) criteria. Grasping (GOB) and mouthing objects (MOO) were better synchronized with reaching onset in the supine trials, although all of the infants except Justin engaged in these behaviors *after* reaching onset. The onset of the remaining manual activities in the supine trials – AEO and TCH – was variable based on the consecutive criterion, but showed some synchronicity with reaching onset using the duration criterion. Again, however, several infants did not engage in AEO and TCH reliably until after reaching onset.

The onset of manual activities in the seated condition more consistently preceded reaching onset. As in the supine condition, HOF, HOM and HOH emerged relatively early for some infants. However, all of the infants extended their arms toward objects (AEO), touched (TCH) or grasped (GOB) objects, and put objects in their mouths (MOO) *before* reaching onset based on either the consecutive (Figure 2(c)) or duration (Figure 2(d)) criterion. Thus, these four behaviors in the free-play session may be important precursors to the transition to reaching.

Reaching itself involves extending the arm toward the desired object (AEO), touching the object (TCH), and then grasping it (GOB). As such, the four behaviors shown in Figures 2(c) and 2(d) may simply reflect early reaches in the free-play sessions. Alternatively, these behaviors may reflect infants' heightened interest in toys just before they learned to reach. For instance, before reaching onset, infants may have spent time extending their arms toward, but not contacting, toys. This could give infants experience moving their hands away from the body in the vicinity of nearby toys. Similarly, infants may have touched and grasped objects placed in their hands before reaching onset, but not reached for objects extended away from the body. This could enhance infants' interest in toys and give them experience with the feel of different objects.

To investigate whether the data shown in Figure 2 reflect early reaches, we computed the number of touches and grasps 5 weeks before and 5 weeks after reaching onset, and the number of touches and grasps

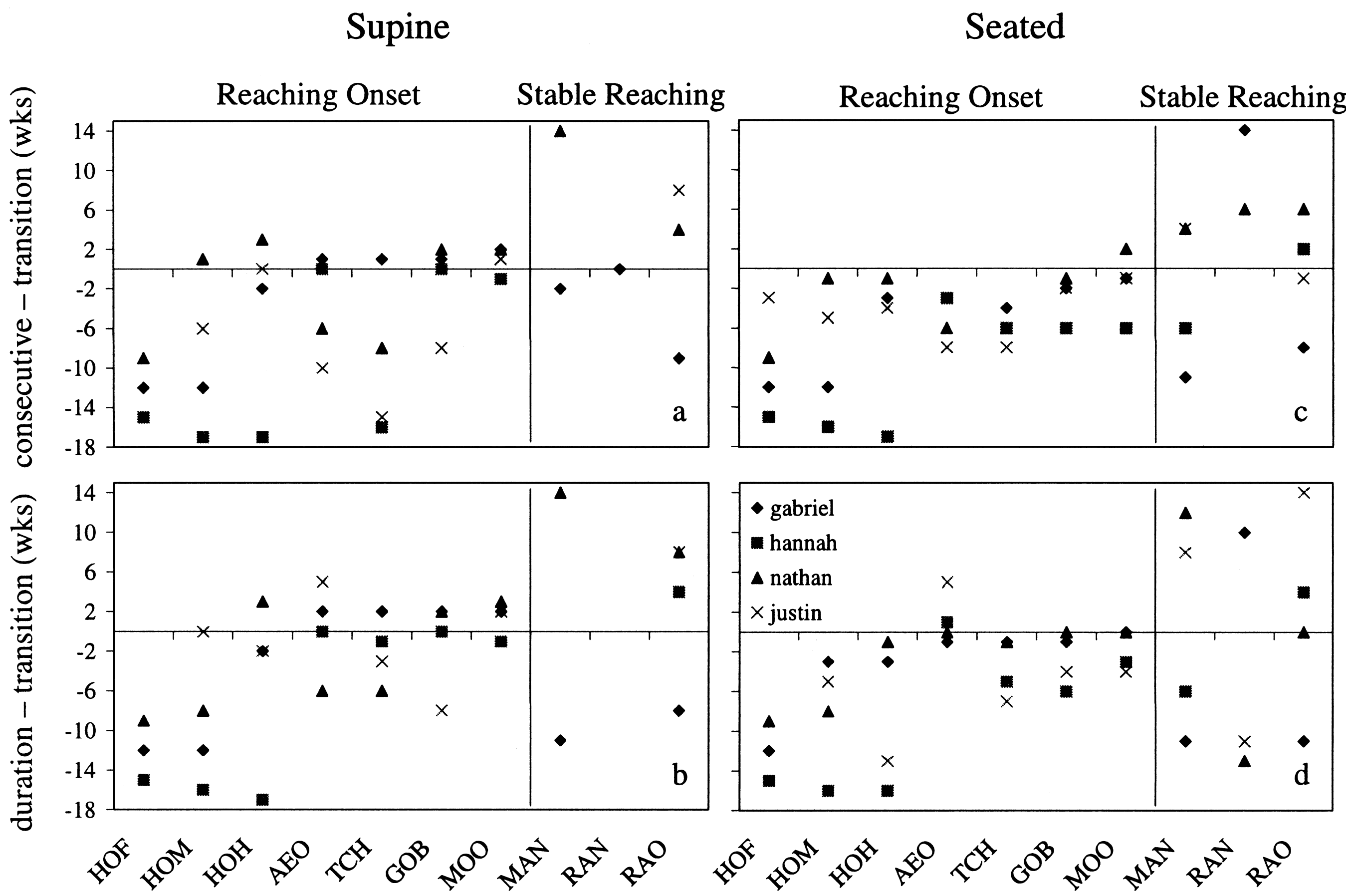


Figure 2 *The number of weeks before/after reaching onset or stable reaching that the infants first engaged in each manual activity based on the consecutive ((a) and (c)) and duration ((b) and (d)) criteria in the supine (left column) and seated (right column) conditions. The onset of HOF, HOM, HOH, AEO, TCH, GOB, MOO were synchronized to reaching onset. The onset of MAN, RAN, RAO were synchronized to the onset of stable reaching. The vertical line in each panel separates these groups of manual codes.*

preceded by arm extensions 5 weeks before and 5 weeks after reaching onset. These data are shown in Table 3. We used a range of 5 weeks because all four infants engaged in AEO, TCH and GOB within this range. As was apparent in Figure 1, infants touched and grasped objects more frequently before reaching onset in the seated versus the supine condition (see Table 3). Furthermore, there was an increase in touching and grasping in both the supine and seated trials before versus after reaching onset. To determine if these increases across conditions and development were statistically reliable effects, we conducted a two-way analysis of variance (ANOVA) for both manual activities with condition (supine, seated) and developmental period (before, after) as within-subjects factors. There was significantly more touching ($F(1, 3) = 16.9$, $p < 0.05$) and grasping ($F(1, 3) = 46.8$, $p < 0.01$) of objects in the seated condition. In addition, there was a significant increase in both touching ($F(1, 3) = 10.7$, $p < 0.05$) and grasping ($F(1, 3) = 34.7$, $p < 0.01$) over development. No other effects reached significance.

The data in parentheses in Table 3 indicate the number of touches and grasps that were preceded by arm extensions. If the touches and grasps before reaching onset reflect early reaches, then the majority of these manual actions should have been preceded by arm extensions. Consistent with this interpretation, a high proportion of Gabriel's touches were preceded by arm extensions. However, in general, the majority of touches and grasps before the onset of reaching in Table 3 were *not* preceded by arm extensions. By contrast, after reaching onset, there was an increase in the number of touches and grasps preceded by arm extensions for all infants except Justin. He showed only a modest increase. This was primarily due to the way he interacted with his parents. Rather than presenting toys extended away from his body, Justin's parents generally brought toys close to his hands.

Table 3 *Total number of touches and grasps and the number (in parentheses) that were preceded by arm extensions for each infant in supine and seated trials, 5 weeks before reach onset (Before) and 5 weeks after reach onset (After)*

		Touches and number of touches preceded by arm extension		Grasps and number of grasps preceded by arm extension	
	Reach onset	Supine	Seat	Supine	Seat
Gabriel	Before	2 (1)	34 (21)	0 (0)	16 (3)
	After	65 (30)	185 (96)	65 (12)	120 (22)
Hannah	Before	8 (0)	46 (6)	0 (0)	26 (0)
	After	46 (46)	61 (48)	43 (12)	59 (22)
Justin	Before	35 (11)	69 (8)	2 (0)	11 (0)
	After	96 (11)	194 (14)	58 (2)	126 (3)
Nathan	Before	4 (3)	15 (5)	1 (1)	1 (0)
	After	19 (10)	73 (24)	37 (10)	84 (17)

We examined whether there was a significant increase in touches and grasps preceded by arm extensions before and after infants learned to reach. As above, we conducted a two-way ANOVA for each type of manual activity with condition (supine, seated) and developmental period (before, after) as within-subjects effects. There was a significant increase in the number of grasps preceded by arm extensions after reaching onset ($F(1, 3) = 12.2$, $p < 0.05$). There was also a trend toward more grasps preceded by arm extensions in the seated condition ($F(1, 3) = 6.7$, $p < 0.08$). No other effects reached significance.

In summary, the data in Table 3 demonstrate that, although infants did reach for toys before the onset of reaching, they spent more time engaged in manual activities that might be considered sub-components of successful reaches – extending their arms toward toys, and touching and grasping objects placed in their hands.

Manual activities associated with stable reaching

Figure 2 shows the three manual activities that first emerged after the transition to reaching – MAN, RAN and RAO. Given that these behaviors emerged after reaching onset, the data shown in Figure 2 were synchronized to the transition to stable reaching. Thus, Figure 2 shows the number of weeks before or after the transition to stable reaching that the infants first engaged in MAN, RAN and RAO based on the consecutive (2(a) and 2(c)) and duration (2(b) and 2(d)) criteria. As can be seen in this figure, the onset of all three coded behaviors was quite variable across the supine and seated trials using both the consecutive and duration criteria. Thus, none of the coded manual behaviors was a consistent precursor to the onset of stable reaching.

Changes in postural abilities across the first year

Manual activities are performed within the context of particular postures, which may facilitate or inhibit actions of the hands and arms. Figures 3(a)–3(h) illustrate developmental changes in the infants' postural abilities across the first year. In this section, we focus primarily on infants' control of head position and the upper torso. Head control allows for stable visual fixation of the target object and facilitates the tracking of moving objects. A stable torso is needed to counteract the forces generated by lifting the arm up and away from the body.

When supine, newborn and very young infants characteristically turn their heads to one side, usually the right. As is seen in Figure 3, the infants' ability to keep their heads centered at midline (MID) rather than turned developed gradually in the months before reach onset. We saw centered head positions more frequently when the infants were seated. This probably reflects the physical support of the seat.

Although we began two free-play trials with infants supine, early in the first year infants were starting to turn onto their sides (SID) and occasionally raise their legs up off of the mat (SHU; see Figures 3(a), 3(c), 3(e), 3(g)). By weeks 14–18, Gabriel, Hannah and Nathan were rolling over into a prone position and remaining in that position for considerable amounts of time, with head erect (PHU) and, later, supported on their arms (POA). Justin showed the same developmental trend but at a later age. As SID, PHU and POA increased, the amount of time infants spent in a supine (SUP) posture decreased.

Concurrent with these changes in the supine trials, infants' posture in the seated trials indicated increasing control of the upper torso. The typical newborn slouched position (SLO) generally decreased in frequency over the first few months (see Figures 3(b), 3(d), 3(f), 3(h)); however, Justin showed an increase in this behavior just before reach onset (Figure 3(f)). Infants again returned to a slouched position later in the year. Although this looks like a developmental regression, it was primarily caused by the increased postural demands placed on the infants when we moved them to the larger sling seat (see 'sling seat' label in Figure 3). In contrast to SLO, the time infants spent sitting erect with head controlled (SER) increased over the first few months. Similarly, all infants increased the amount of time they spent sitting forward in the infant seat (SFR). This increase was closely linked to the onset of reaching in Gabriel, Nathan and Justin (see Figures 3(b), 3(f), 3(h)). Between weeks 25 and 28, the infants began sitting with support from nearby objects (SUS) or sitting independently (SIA). Nathan began crawling and moving into a hands-and-knees posture (HKN) at about the same point in the first year (Figure 3(h)). The other three infants did not crawl or move into the HKN posture until a few weeks after sitting independently.

Postures associated with reaching onset

Figure 4 shows the number of weeks before or after reaching onset that the infants first assumed different postures in the supine and seated trials based on the consecutive (4(a) and 4(c)) and duration (4(b) and 4(d)) criteria. As in Figure 2, the vertical line in each panel distinguishes postures that emerged before reaching onset from postures that emerged later in the first year (SUS, SIA, HKN).

In the supine trials, infants assumed several postures early in the year. All four infants could keep their heads at midline (MID) while maintaining a supine (SUP) posture 2–3 months before reaching onset (see Figures 4(a), 4(b)). In addition, two of the infants were able to roll onto their sides (SID) 4 months before reaching onset. Infants' ability to raise their legs while supine (SHU) was more closely linked to the onset of reaching, although Hannah achieved this posture relatively early. Finally, infants' ability to roll over and remain in a prone position (PHU, POA) was not directly related to reaching onset. The three boys attained these postural milestones after the reach transition, while Hannah was rolling to prone several months before reach onset.

As in the supine trials, infants could keep their heads at midline (MID) in the seated trials early in the first year (Figures 4(c), 4(d)). Furthermore, although they often slouched in the infant seat (SLO), the infants were able to achieve an erect posture relatively early (SER). The most dramatic result in Figures 4(c), 4(d) was the tight synchronicity between reaching onset and the first week Gabriel, Nathan and Justin were able to sit forward in the seat (SFW): these three infants first sat forward two weeks before reaching onset (see circles in Figures 4(c), 4(d)). Although this postural ability may be an important precursor to reaching onset, data from Hannah demonstrate that it is not sufficient – Hannah spent a high proportion of time in this posture well before reaching onset (see Figure 3(d)).

Postures associated with stable reaching

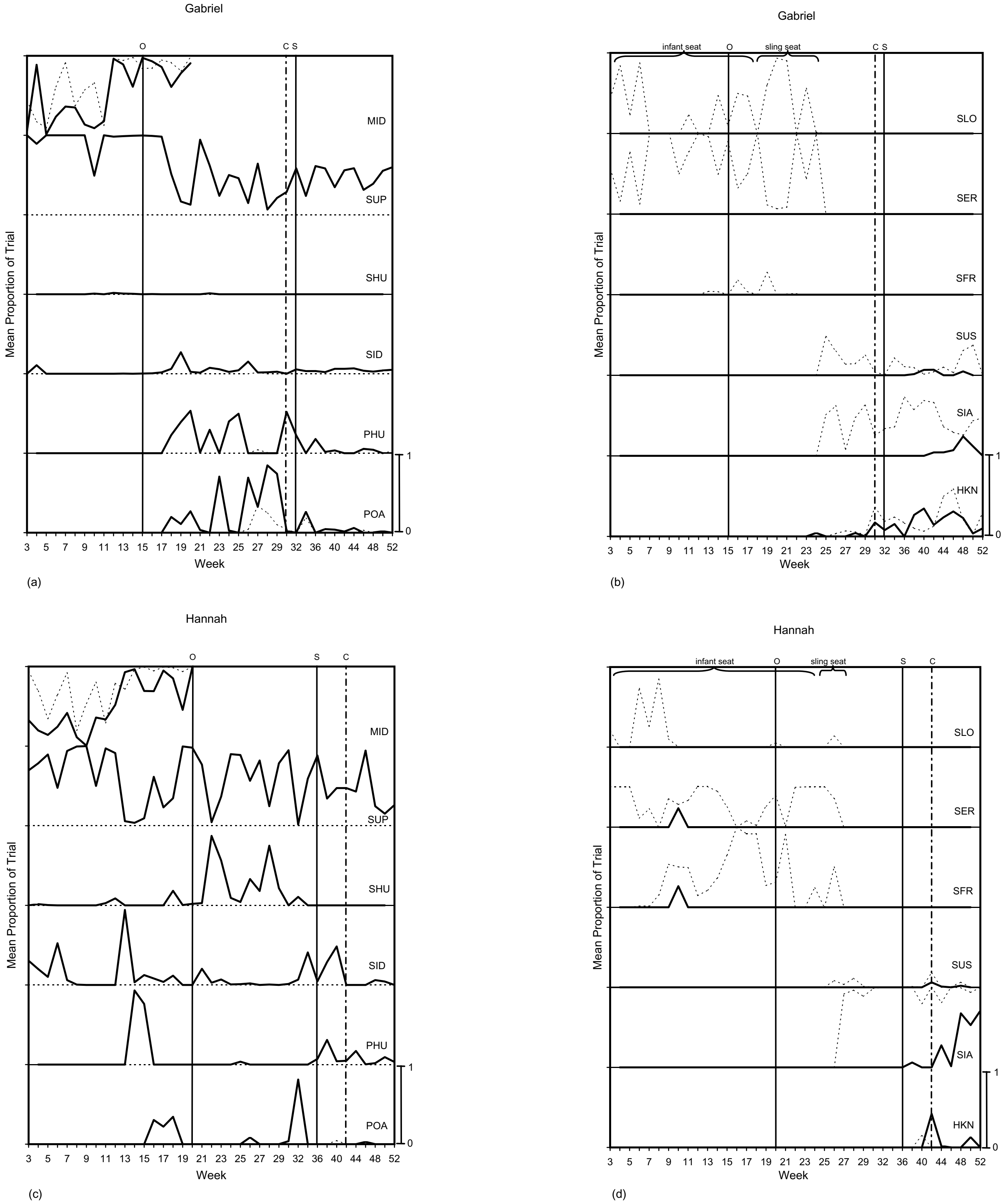
Previous research has implicated good control in sitting with better coordination of the hands and arms in reaching (Rochat, 1992). Consistent with these previous results, all four infants in the seated trials could sit supported (SUS) and alone (SIA) several weeks before the transition to stable reaching (see Figures 4(c), 4(d)). Interestingly, it took Gabriel, Hannah and Justin several additional weeks to sit by themselves during the supine trials (see Figures 4(a), 4(b)). These trials required the infants to roll over from supine to prone and pull themselves up to a seated position. In contrast to the seated posture, infants' ability to assume the hands-and-knees posture (HKN) was not clearly related to the transition to stable reaching. Both hands-and-knees posture and crawling first emerged several weeks *after* stable reaching for Hannah. This was also the case for Justin in the seated trials, although he assumed a hands-and-knees posture in the supine trials before the onset of stable reaching (see Figure 4(a)). Crawling and the hands-and-knees posture were evident several weeks before the transition to stable reaching in Nathan and Gabriel.

Discussion

The goal of the present study was to map developmental changes in naturally occurring manual and postural activities to major transitions in the development of reaching skill. Although the present study is strictly descriptive, we identified several manual activities and postures closely linked to two transitions in reaching skill, and others that appear to be less directly related. Importantly, we did not find evidence that a single, critical variable preceded each transition across all four infants. Instead, an ensemble of abilities was in place before each transition and the timing of each 'component' in the ensemble was variable across infants.

Onset of reaching

Before the transition to reaching, all infants were able to maintain a midline head position both when seated and when supine and to sit erect in the infant seat. This is


Gabriel
O
C S
MID
SUP
SHU
SID
PHU
POA
Mean Proportion of Trial
1
0
3 5 7 9 11 13 15 17 19 21 23 25 27 29 32 36 40 44 48 52
Week
(a)
Gabriel
infant seat
O
sling seat
C S
SLO
SER
SFR
SUS
SIA
HKN
Mean Proportion of Trial
1
0
3 5 7 9 11 13 15 17 19 21 23 25 27 29 32 36 40 44 48 52
Week
(b)
Hannah
O
S
C
MID
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SHU
SID
PHU
POA
Mean Proportion of Trial
1
0
3 5 7 9 11 13 15 17 19 21 23 25 27 29 32 36 40 44 48 52
Week
(c)
Hannah
infant seat
O
sling seat
S
C
SLO
SER
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SIA
HKN
Mean Proportion of Trial
1
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3 5 7 9 11 13 15 17 19 21 23 25 27 29 32 36 40 44 48 52
Week
(d)

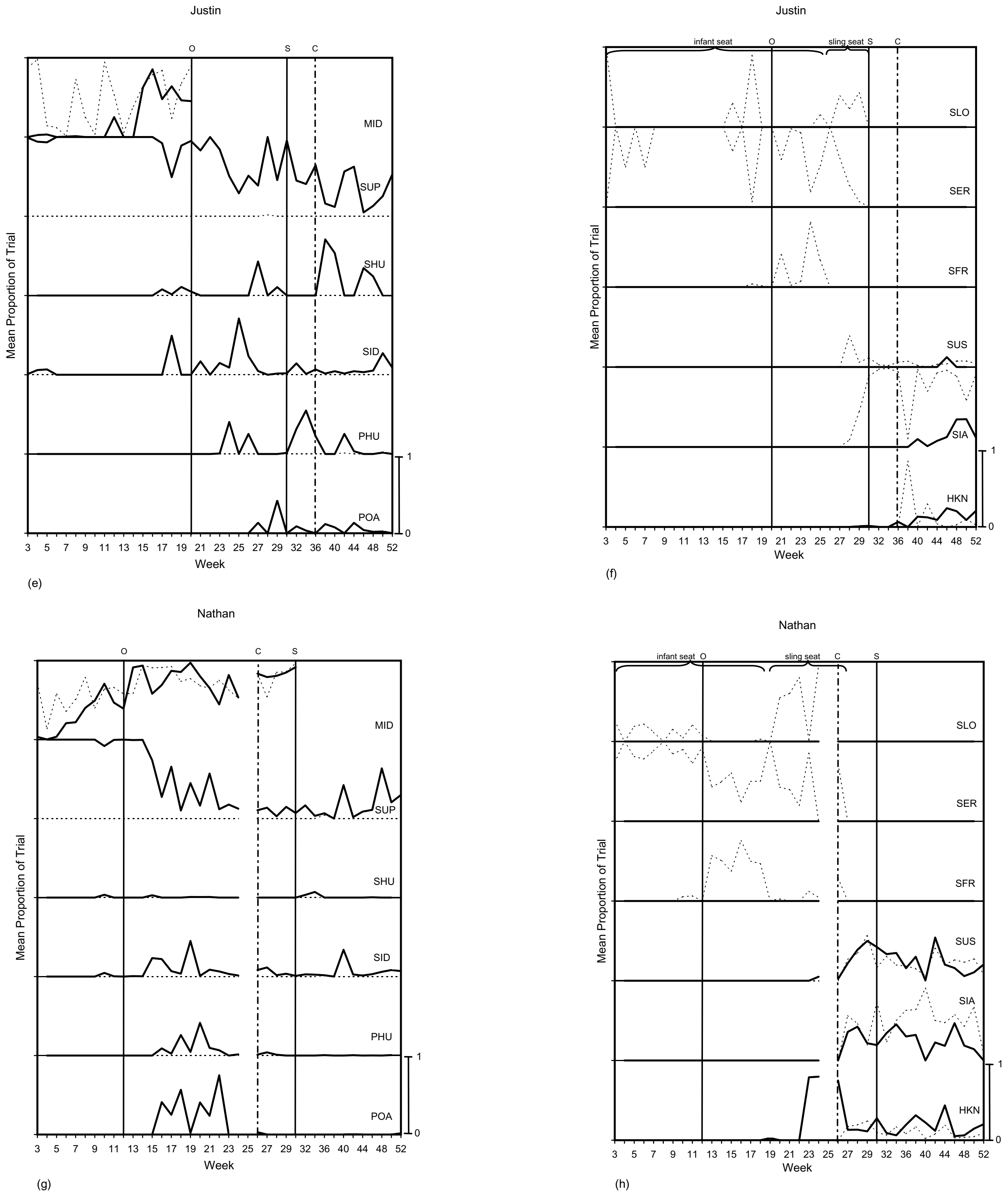

Figure 3 *Average proportion of trial time each of the infants spent in each of the postural activities (MID, head at midline; SUP, supine; SHU, supine, hip up; SID, side; PHU, prone, head up; POA, prone, on arms; SLO, slouched; SER, seated erect; SFR, sits forward; SUS, supported sitting; SIA, sits alone; HKN, hands and knees) in the supine trials (solid line) and seated trials (broken line) across the first year. Vertical lines indicate the transition to reach onset (O) and the transition to reach stability (S) in structured laboratory sessions, and the onset of hands-and-knees crawling (C). All panels were scaled from 0 to 1. Labels in (b), (d), (f) and (h) show when infants were moved from the infant seat to the sling seat in the seated trials. After the sling seat, infants were placed on the mat.*

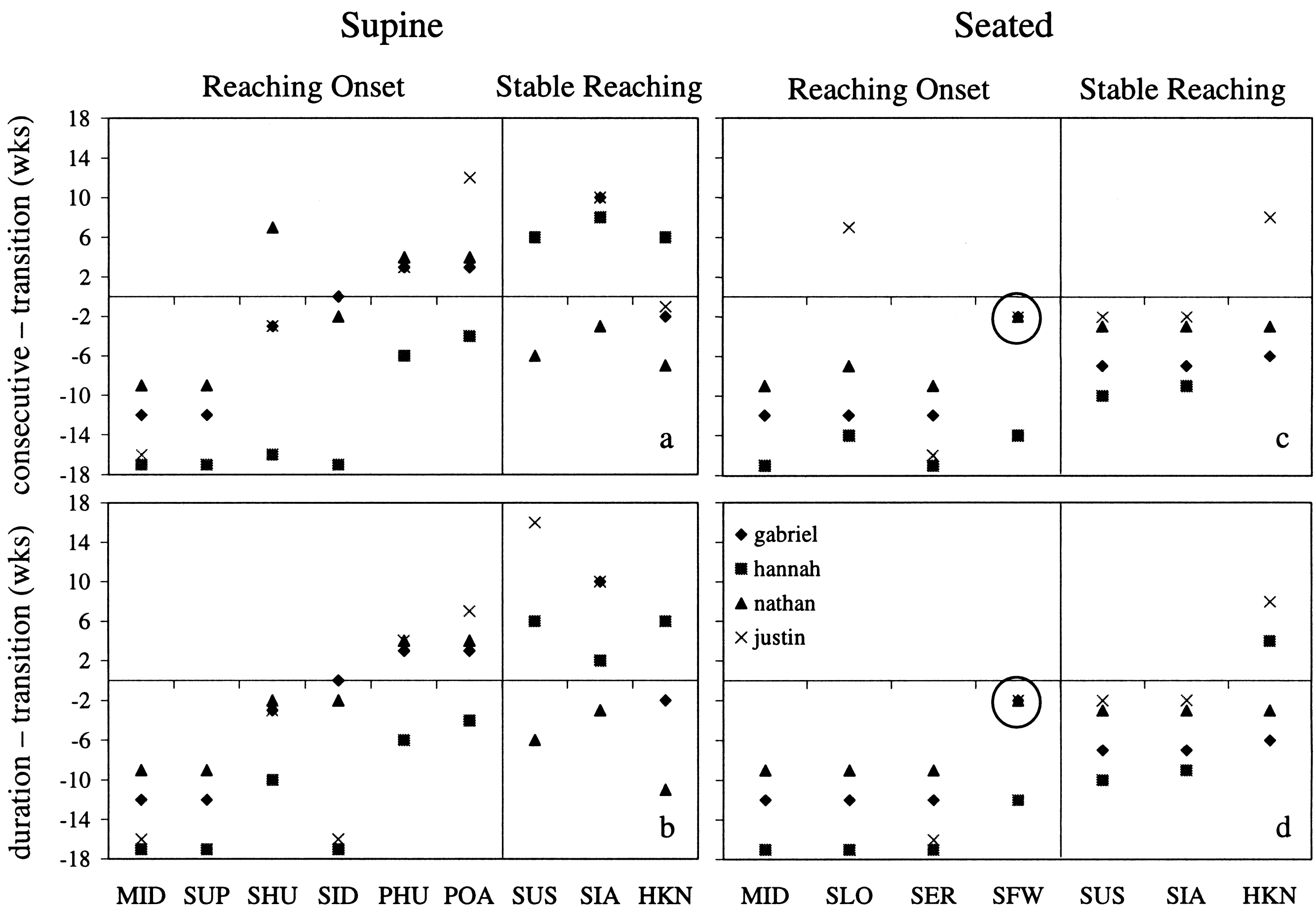

Figure 4 *The number of weeks before/after reaching onset or stable reaching that the infants first engaged in each posture based on the consecutive ((a) and (c)) and duration ((b) and (d)) criteria in the supine (left column) and seated (right column) conditions. The onset of MID, SUP, SHU, SID, PHU, POA, SLO, SER, SFW were synchronized to reaching onset. The onset of SUS, SIA, HKN were synchronized to the onset of stable reaching. The vertical line in each panel separates these groups of postural codes. The circle in (c) and (d) indicate that three data points are superimposed on one another.*

consistent with previous suggestions that head control is important for early reaching (Amiel-Tison & Grenier, 1986; Bullinger, 1990). Both developments were in place well in advance of reaching onset and may have provided the basis for a stable visual field. However, the postural change most closely linked to the onset of reaching was the emergence of forward sitting. Three of the four infants began sitting forward in the infant seat 2 weeks before the first successful reaches in the structured laboratory sessions. Forward sitting requires good head control and good control of the upper torso. Thus, the emergence of this behavior indicates that infants had a stable postural base from which to extend the arm just before the transition to reaching.

If we had looked at the three boys only, we might conclude that these postural milestones were the developmental 'switch' that turned on reaching – when these components were in place, reaching emerged. However, Hannah's developmental profile suggests otherwise: she showed upper torso control about 2 months before reach onset. Thus, while head and torso control may have been necessary for all four infants, other factors must have played a key role in the development of Hannah's reaching skill.

The manual codes help identify other relevant factors. First, before reaching, all infants spent time holding objects provided by their caregivers as well as exploring objects with their mouths. Thus, they had experience with the feel of objects as well as with the correlated actions of looking at toys and grasping them. In this way, they learned to grasp objects placed very close to their hands. But successful reaching also requires extending the arm and hand to more distant visual targets. All infants extended their arms away from the body before the onset of reaching. Although some of these early arm extensions ended in contact with distant toys, many of them did not.

Taken together, these postural and manual data suggest that head control, upper torso control and the ability to extend the arm toward distant objects all contribute to the onset of reaching, but there is individual variability in when these component skills emerge during the first year. For Hannah, head and upper torso control were in place well before the transition to reaching, but arm extension did not emerge until 3 weeks before reaching onset. The other three infants were extending their arms toward objects, touching and grasping objects, and putting objects in their mouths before the transition, but did not have good upper torso control until just before the transition.

The importance of head and torso control and arm extension to the onset of reaching is consistent with several recent studies. Spencer and Thelen (in press) analyzed the muscle activation patterns the four infants used in the structured laboratory sessions before and after they learned to reach. They found that the transition to reaching was associated with a dramatic increase in the participation of the muscles used to both stabilize the neck and shoulder girdle (trapezius) and extend the arm forward from the shoulder (anterior deltoid). Similarly, Berthier, Clifton, McCall and Robin (1999) reported that infants largely used shoulder and torso rotation to move their hands toward toys in the first few weeks after reaching onset.

Transition to stable reaching

More stable reaching was associated with changes in infants' manual activities. Before this transition, infants nearly always put grasped objects into their mouths and explored them orally. Although infants continued to engage in this behavior after the transition, the time spent manipulating objects increased. This suggests that skilled reaching facilitated more advanced manipulation and exploration of object properties.

Less clear was the relationship between stable reaching and rhythmical movements. Thelen (1981, 1996) suggested that rhythmicities are associated with transitions in motor control, when infants can initiate some voluntary posture or limb movements but before they acquire finely differentiated control. Thus, these oscillations appear first just as trajectory control is being established. Later, oscillations recur as infants can readily grasp objects but where manipulation is still developing. We did observe rhythmical activities in all four infants after reaching onset and before the transition to stable reaching. However, these behaviors were sporadic for Hannah and Nathan. After the transition to stable reaching, rhythmical movements with objects occurred more frequently, although, once again, the proportion of time spent engaged in these behaviors was quite small. Thus, the data from the present report are generally consistent with Thelen's proposal, although conclusions from these data must be tentative given the low proportions we observed. It is important to note that the early rhythmical actions reported here differed from the 'flapping' movements described in Thelen *et al.* (1993). Flapping movements in the structured sessions occurred early in the first year in conditions of high postural support – infants were secured in an infant seat using a broad torso strap. In the present report, infants did not wave and bang their arms and hands until after they had achieved some measure of upper torso control, i.e. after reaching onset.

In contrast to the manual codes, there was a clear relationship between the transition to stable reaching and postural advances. Infants did not reach stably from week to week until they could sit independently. In addition, some infants were able to assume a hands-and-knees posture at or before this transition. Good reaching requires upper arm and torso strength and differentiated control of both limbs, as well as the ability to stabilize the trunk against the forces generated by moving the arm. These abilities are also needed for sitting and crawling. It is important to note, however, that the direction of influence between sitting and stable reaching is not clear. Experience reaching in different contexts, with the associated postural demands, may contribute to back strength and flexibility. Likewise, turning over and assuming the prone and hands-and-knees posture may contribute to the differentiation of neck and shoulder muscles needed for stable reaching.

Conclusion

A small sample longitudinal design, even with a dense observation schedule, has many limitations. We do not know how the four developmental profiles reported here generalize, nor how many other individual patterns we would discover could we take these detailed measurements on many more infants. In addition, even though we have examined the development of reaching skill at multiple levels of analysis, the picture is still incomplete. We did not take into account changes in infants' visual systems or in their attention, motivation or memory. It is likely, for instance, that infants' visual acuity and the onset of depth vision play an important role in the onset of reaching (Shimojo, Birch, Gwiazda & Held, 1984; Held, 1985). Depth vision develops quite abruptly around 3 months of age, and would appear to be an important component skill needed before the onset of reaching. Nevertheless, we predict from the present results that depth vision is not the single, critical precursor to the onset of reaching. Instead, depth vision is an important component skill like head control, upper torso control and arm extension abilities. Justin and Hannah, for example, reached long after we would have expected the normal onset of depth vision.

Although the present study has several limitations, the data presented here make important contributions to our understanding of how Gabriel, Hannah, Justin and Nathan learned to reach, and, more generally, to our understanding of the processes involved in the development of reaching skill across the first year. Transitions and individual dispositions that we discovered earlier in the precise kinematic and kinetic analyses were reflected in the infants' activities in a more natural play setting. This gives us confidence that what we measured in the structured sessions was a reflection of infants' more general ongoing activities. Moreover, the picture from the present report was consistent with neuromuscular analyses of infants pre-reaching and reaching movements.

Beyond the four infants we studied, the present report suggests novel ways of untangling developmental processes experimentally. We discovered here that for reaching to emerge and stabilize, multiple components interacted, but not necessarily in an ordered fashion. One way to further test this result is to use infants' individual developmental histories and preferred movements and postures rather than age as a predictor of transitions. For example, pre-reaching infants might be characterized not by age but by a combination of their preferred arm posture, movement vigor, and head and trunk control. Infants with more components 'on line' would be expected to reach at earlier ages than those who are yet to develop the constituent skills (for related ideas, see Bril & Breniere, 1992; Rochat & Goubet, 1995; Adolph, 1998).

Furthermore, to test which component skills are truly critical, it should be possible to provide support for missing components and induce transitions earlier than expected. For instance, Rochat and Goubet (1995) provided non-sitting infants with increased hip support during a reaching task. They found an increase in coordination between the trunk and arm not normally seen until infants have been sitting alone for several weeks. Again, however, the lesson from the present study is that it may be especially fruitful to plan these manipulations with respect to infants' individual constellations of skills. For instance, while providing postural support or trunk stability may accelerate reaching onset or skill in some infants, it may be less effective with other infants who may require support for arm extension or enhanced practice reaching in novel situations. If we are able to identify the contributing components and their multiple interactions, we may get closer to understanding both the global similarities and the individual variations that underlie the development of reaching skill.

Appendix

Reliability (% co-occurrence) following training weeks for each coding pair

Coding pair	Test trial no.	% Co-occurrence
1	1	85.62
	2	91.31
	3	85.95
	4	91.54
	5	86.98
	6	75.80
2	1	91.90
	2	86.21
	3	84.14
	4	85.79
	5	86.15
3	1	94.62
	2	94.42
	3	88.14
4	1	47.20
	2	84.44
	3	75.40
	4	87.73
5	1	77.56
	2	97.40
	3	95.91
	4	87.84
6	1	82.94
	2	93.38
	3	97.15
7	1	70.43
	2	75.46
	3	89.22
	4	76.19
8	1	100.0
	2	97.78
	3	85.37
	4	100.0

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