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Infants Return to Two-Handed Reaching When They Are Learning to Walk

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ABSTRACT. The authors examined whether infants of about 1 year return to 2-handed reaching when they begin to walk independently. Infants ($N = 9$) were followed longitudinally before, during, and after their transition to upright locomotion. Every week, the infants' reaching responses and patterns of interlimb coordination were screened in 3 tasks involving different adaptive reaching responses. Before the onset of upright locomotion, the infants responded to each task adaptively. Following walking onset, they increased their rate of 2-handed responses in all tasks. The 2-handed responses declined when the infants gained better balance control. The results suggest that infants' return to 2-handed reaching is experience dependent. Those findings are discussed in terms of the integration of new developing motor skills into existing cognitive and motor repertoires.

Key words: developmental discontinuities, infancy, interlimb coordination, reaching, walking

Infants discover and learn about their environment through their actions as they sit, reach, crawl, and walk. The emergence of reaching, in particular, promotes infants' discovery and understanding of objects' physical properties, knowledge that is later needed for using and manipulating objects. During the 1st year, infants' progress in reaching clearly demonstrates their growing abilities to understand and adapt to their environment. When infants begin to reach at around 4 months of age, their attempts are poorly controlled, poorly adapted to objects' properties, and are often performed with two hands regardless of the objects' sizes (Corbetta, Thelen, & Johnson, in press; Thelen et al., 1993; von Hofsten, 1979, 1991; White, Castle, & Held, 1964). Within a few months, however, infants greatly refine their responses to fit the environment. For instance, by 8 months, infants preshape their handgrip configurations to accommodate objects' shapes and orientations before contacting the target (Lockman, Ashmead, & Bushnell, 1984; Piéraut-Le Bonniec, 1985; von Hofsten & Fazel-Zandy, 1984). They anticipate objects' trajectories so that they can intercept moving targets successfully (von Hofsten & Lindhagen, 1979; von Hofsten, Vishton, & Spelke, 1998). They also select distinct groups of muscles across the shoulder girdle to reach for small or large objects with one or two arms, respectively (Corbetta et al., in press; Fagard & Pezé, 1997; Newell, Scully, McDonald, & Baillargeon, 1989; Siddiqui, 1995).

Despite that dramatic behavioral progression, many infants return to two-handed reaching near the end of the 1st year—particularly when objects are presented at midline (Fagard & Pezé, 1997; Flament, 1975; Goldfield & Michel, 1986; Ramsay, 1985a, 1985b). They do so even when reaching for small and familiar objects and even after extensive one-handed reaching practice (Corbetta & Thelen, 1996). Moreover, the resurgence of those two-handed motor responses in infancy is not unique to reaching. It has been observed also in spontaneous, non-goal-oriented movements, as if all upper arm movements were driven by a pervasive and generalized coupling tendency (Corbetta & Thelen, 1996). In other words, that change in patterning happens as if infants temporarily forget how to integrate anticipated sensory information into their movement patterns to differentiate and select distinct muscle groups across the shoulder girdle despite knowing objects' properties.

Gesell and Ames (1947) first documented that return to two-handed reaching in the mid-1940s. Since then, many authors (Corbetta & Thelen, 1996; Fagard & Pezé, 1997; Flament, 1975; Goldfield & Michel, 1986; Ramsay, 1985a,

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1985b) have reported that finding; but until now, no one has been able to offer a plausible explanation as to why infants activate two arms again when reaching for small objects toward the end of their 1st year. To date, the only proposed account for that developmental phenomenon comes from Gesell's seminal work. Gesell (1939, 1946) posited that the developmental fluctuations in interlimb activity between periods of uni- and bilateral motor responses are the result of ongoing neuromotor reorganizations. According to him, those "recapitulatory" patterns and return to bilateral responses, which he called "reciprocal interweaving," are the "functional expressions of transient but necessary stages in the organization of the neuromotor system" (Gesell, 1946, p. 307). However, lacking evidence for identifying the origins of those neuromotor reorganizations, he surmised that they are the product of orderly sequences of brain maturation. Despite repeated evidence for Gesell's reciprocal interweaving, the origins of those behavioral reorganizations still remain rather unclear.

In the present research, we examined the possibility that infants' tendency to return to two-handed reaching around the end of the 1st year is associated with the development of a new motor skill, specifically, the emergence of upright locomotion. In previous studies, the acquisition of new motor skills such as sitting, crawling, or walking have been shown to dramatically reorganize infants' existing motor, perceptual, and cognitive abilities (Adolph, 1997, 2000; Campos et al., 2000; Kermoian & Campos, 1988; Rochat, 1992). The fact that infants return to two-handed reaching toward the end of their 1st year, which is a time when infants usually begin to stand up and attempt to perform their first independent steps, may not be coincidental. Such coincidence between return to two-handed reaching and the onset of upright locomotion was reported before in one case study (Corbetta & Thelen, 1996). Moreover, it is known that the emergence of upright locomotion imposes new constraints on balance control, quadrupedal cross-coordination, and head and arm position (Bril & Brenière, 1992; Burnett & Johnson, 1971; Ledebt, 2001). It is plausible, therefore, that the postural reorganization and development of new coordination skills associated with the transition to upright locomotion temporarily affect infants' abilities to reach adaptively.

The view that the emergence of new skills might alter the organization of previously established patterns of response is compatible with a dynamic systems perspective. According to that perspective, development is a complex process that entails multileveled and multirelational changes between the components of an organism and its environment (Thelen, 1986; Thelen & Ulrich, 1991). That means that one or several component changes associated with the development of a new motor skill can potentially alter pattern formation and modify established responses, even if the organism is acting within a familiar environment. In the case of the emergence of upright locomotion, for example, several components, such as tonus, posture, balance control, muscle strength, and motivation, are known to change (Thelen, 1986). Those component changes are determinant for the emergence of upright locomotion, but because those components are not isolated and independent from other motor responses generated by the same organism, they can potentially alter other responses such as reaching. Here, we began to investigate that complex developmental issue between reaching and walking by asking the first and most foundational question: Do changes in reaching patterning co-occur when infants begin to walk independently?

Specifically, our aim in this study was to assess whether infants increase their rate of two-handed reaching at the end of the 1st year when they begin to walk and whether they resume adaptive reaching when they have gained better balance control. To do so, we observed infants longitudinally from the age of 8 months to about 12 to 14 months, that is, from before they were able to walk independently until they were able to perform relatively stable walking patterns. Every week, we screened infants' progress in posture and locomotor activity and observed their reaching behavior in three tasks requiring differentiated coordination between hands: reaching for small and large objects and retrieving an object in a box with a lid. Because we hypothesized that two-handed reaching might increase when infants begin to walk, we used the emergence of upright locomotion rather than age as our developmental marker. Our predictions were threefold: (a) Before the onset of upright locomotion, the infants would develop adapted and well-coordinated movement patterns to reach for objects of different sizes and to retrieve the toy concealed in the box; (b) the infants who were able to respond adaptively to those reaching tasks before walking would show a significant rise in bimanual reaching following the onset of upright locomotion; and (c) the rise in bimanual reaching would decline once the infants had developed relatively stable gait patterns, as evidenced by the lowering of their arm position during locomotion.

Method

Participants

Participants were 10 healthy infants (6 girls and 4 boys) who had prior reaching experience but were not capable of performing any independent steps at the beginning of the study. They were on average 8 months old (range = 7:0 to 8:2 [months:weeks]) when they visited the laboratory for their first session (see Table 1). The infants were recruited via birth announcements published in the local newspaper. Parents were sent a letter explaining our goal and the procedures of the study before their infant was 7 months old. Parents voluntarily enrolled their infant in the study after meeting with the principal investigator and visiting the Infant Motor Development Laboratory at Purdue University. Parents and their infants received a small gift for their participation.

Procedure and Tasks

The infants, accompanied by their parents, came to our laboratory every week for a period of 4–8 months (the total number of visits to the laboratory ranged between 14 and 33 weeks, depending on the infant). The infants were followed until they were able to walk independently, and thereafter for another 2- to 3-month period until they resumed adaptive reaching patterns for 3 consecutive weeks. During each visit, we tested the infants' locomotor, reaching, and bimanual coordination skills separately.

Before the infants were able to walk, we screened their ability to control their posture and adopt an upright posture. The screening was performed in the laboratory on a hard, carpeted surface and included the following tasks: rolling over, crawling, and creeping; pulling up on a padded crate or wooden chair with or without assistance; cruising upright between chairs while holding onto them; pushing a toy cart; standing alone; and attempting to take independent steps. Walking onset was based on parents' report and consistent follow-up observations in the laboratory. We determined walking onset as the week during which the infants took their first unsupported steps either in the laboratory or in the parents' home, regardless of the number of steps performed and as long as we could witness systematic and continuous attempts to walk independently while in the laboratory. Next, we monitored progress in upright locomotion by counting the number of steps performed successively in a single sequence up to 20 steps. When the infants performed a minimum of 5 successive steps without stopping or falling, they were solicited to cross a 3-m-long surface two times. That procedure allowed us to capture weekly changes in arm position relative to the body during walking, which we used to index the infants' progress in locomotor balance control (Burnett & Johnson,1971; Ledebt, 2001; McGraw, 1989/1945).

Every week throughout the study, we used a consistent procedure to test the infants' reaching and bimanual coordination skills. Reaching and bimanual coordination tasks were performed while the infants were seated on a specially designed infant chair that provided full trunk support while allowing free upper arm movements. The chair did not have arm rests, it was reclined 15° from vertical, and the infants were securely strapped and supported in the chair with a 15-cm-wide foam band around their torso. We assessed reaching patterns by presenting the infants with repeated single, colored, small (5 cm diameter), and large (13 cm diameter) balls at midline and shoulder height. Reaching patterns were categorized as unimanual or bimanual on the basis of the number of arms (one or two) that were extended to reach for the balls. There were eight trials per condition, and size order was counterbalanced each week.

We assessed bimanual coordination by using an object-retrieval task requiring complementary hand activity. In that task, the infants watched the experimenter hiding a small, easy-to-grasp, symmetrical rattle in a 20.5- × 12.5- × 5.5-cm opaque plastic box with a hinged lid. Next, the experimenter brought the closed box to the infants' reaching space at midline. Bimanual coordination was captured as distinct retrieval strategies involving different levels of timing and sequencing between the arms (Fagard & Pezé, 1997). The most mature and efficient object-retrieval strategy was one involving a bimanual complementary activity with good timing between arms; that is, one hand opened and maintained the lid open while the other hand retrieved the toy from the box. In that strategy, the infants did not exhibit interference between movements. The object-retrieval task was performed three times per session. We considered that the infants had achieved success at that task when they were able to use a bimanual complementary strategy on all three trials and to maintain good timing between hands on at least two out of the three trials.

Postural screening, progress in locomotion (number of steps and arm position), and interlimb coordination in reaching and object retrieval were all recorded on videotape.

TABLE 1
Age at Beginning of Study and at Walking Onset for Each Infant

Infant	Age at beginning of study (mo:wk)	Age at walking onset (mo:wk)
BB	8:2	10:1
CH	8:0	12:0
MP	7:3	12:0
GD	8:0	13:2
DC	8:0	12:0
KL	7:3	9:2
LC	7:3	13:1
EG	8:0	9:3
CO	8:2	10:3
MG	7:0	9:3

Note. mo = months, wk = weeks.

Video Coding

Two independent coders analyzed the video recordings to extract the following dependent variables:

1. Arm position was assessed as the position of the hand relative to the body according to five categories: above shoulder, shoulder level, above waist, waist level, and below waist (see Figure 3A). Interrater reliability was 86%.

2. Reaching for balls was coded as unimanual or bimanual, depending on how many arms (one or two) were extended toward the target. Reaching was coded only when successful contact with the target occurred. Distinction between uni- and bimanual reaching was entirely on the basis of the presence or absence of interlimb co-activation in object-orientedness (Corbetta & Thelen, 1996). That is, if the infants extended only one arm to reach for the ball without coactivating the other arm or if the second arm was acti-

vated after the first one made contact with the target, the reach was coded as unimanual. On the contrary, if the infants extended both arms simultaneously toward the target, whether movements started in the same time or with a lag, the reach was coded as bimanual. In the bimanual code, we did not take into account the number of hands making contact with the target. Interrater reliability was 92% for small and 96% for large objects.

3. Object retrieval was coded according to four behavioral strategies, as defined by Fagard and Pezé (1997): (a) *Failure*. The infants failed to retrieve the toy from the box. (b) *Unimanual retrieval*. The infants used the same hand to open the lid and retrieve the toy from the box. (c) *Bimanual complementary retrieval with weak timing*. The infants used one hand to open the lid and the other to retrieve the lid, but displayed difficulties maintaining the lid steadily open while the other hand retrieved the toy. (d) *Bimanual complementary retrieval with good timing*. The infants displayed good timing and sequencing between arms. Interrater reliability was 95%. The number of hands used (one or two) to open the lid of the box was also coded. Interrater reliability was 97%.

Data Analyses

Because the infants began to walk at very different ages and were followed afterward for different extents of time, infants made unequal numbers of visits to our laboratory. For instance, before the emergence of independent walking, longitudinal observations between the infants ranged from 7 to 23 weeks. Moreover, from the time they began to walk until they resumed adaptive reaching for 3 consecutive weeks (which was our criterion for ending our study), longitudinal observations ranged from 7 to 13 weeks. Those large individual differences in time span required that we find an objective way to address our research questions and compare performance across the infants over comparable time spans so that our analyses would not be affected by varying amounts of data between participants.

We solved that problem by using two different cutoffs. First, to assess adaptive reaching before the onset of locomotion and measure change in reaching around the transition to upright locomotion, we took the week when the infants performed their first independent steps (regardless of the number of steps performed) as our developmental marker and standardized our analyzes by comparing the infants' reaching responses over a 7-week period immediately preceding and a 7-week period immediately following the week of walking onset. We chose the cutoff of 7 weeks because it corresponded to the shortest observation time before and after walking in some infants. Indeed, 3 infants performed their first independent steps on their eighth visit to our laboratory, whereas the other infants took longer. Equally, 3 infants resumed adaptive reaching within 7 weeks postlocomotion, whereas the others took longer.

Second, to assess change in arm position in walking during the postlocomotor weeks (which was our index for evaluating progress in gait and balance control), we compared arm position during the first 3 weeks following the production of five consecutive steps and the last 3 weeks of the study. The cutoff of 3 weeks was chosen because some of the infants who resumed adaptive reaching within 7 weeks had as few as 6 data points for arm position,[1] although others had as many as 12 data points before the end of the study. Moreover, the cutoff of 3 weeks corresponded to our criterion that our longitudinal observations should end when the infants resumed adaptive reaching. That particular cutoff allowed us to determine whether the infants gained better balance control when they resumed adaptive reaching. In the Results section, we report the behavioral characteristics observed within those specific cutoff periods.

Results

The infants began to walk at different ages from the onset of the study. In Table 1 are shown each infant's age at both the beginning of the study and when each began to take her or his first independent steps in the laboratory. Walking onsets ranged from age 9:2 (months:weeks) to age 13:2 (months:weeks). Those walking onsets fell within the expected normal developmental range (Bayley, 1993).

Reaching and Object Retrieval Before the Onset of Upright Locomotion

To assess whether changes in reaching patterning are associated with the emergence of upright locomotion and not with other possible confounding behavioral factors, we needed to determine first that, before the emergence of independent walking, the infants could respond adaptively to the different reaching tasks. During the 7 weeks preceding the onset of upright locomotion, 9 of the 10 infants ($p <$ .022, two-tailed binomial test) developed differentiated interlimb patterns for reaching for objects of different sizes and developed complementary bimanual patterns to retrieve the toy from the box. As expected, those 9 infants displayed significantly more bimanual patterns for the large objects than for the small objects—Wilcoxon Signed Rank Test = 45.00; p(exact) = .004—and they learned to sequence and coordinate their arms differentially so that the could open the lid, hold the lid open, and retrieve the toy from the box well before they began to walk independently. They achieved the object-retrieval task by using consistent bimanual complementary patterns with good timing by an average of 3.88 weeks (SD = 2.66) from the onset of the study (i.e., by a mean age of 8:3 months:weeks) and began to walk by an average of 15.55 weeks (SD = 6.6) from the onset of the study (that is, by a mean age of 11:2 months:weeks). Those onsets were significantly different, $t(8) = -4.616$, $p = .002$ (paired t test).

One infant girl (CO), however, never differentiated reaching patterns for small and large objects before the onset of upright locomotion and never sequenced her movement patterns to retrieve the toy from the box before walking independently. When reaching, 80% of her responses were consistently bimanual regardless of the size of the object, and in the object-retrieval task, she never held the lid with one hand while retrieving the object with the other hand. Because in this study it was imperative that the infants display adaptive responses before the onset of walking and because we could not assess from her responses whether she could differentiate her movements to meet the changing task demands, we removed her from our participant pool.

Reaching and Object Retrieval Following the Onset of Upright Locomotion

When the infants began to walk, reaching behavior changed. The 9 infants who displayed adaptive responses before independent walking increased their rate of two-handed responses for reaching and for opening the lid of the box following the onset of upright locomotion. Figure 1A displays exemplars of weekly data from 3 infants for the 7 weeks before and the 7 weeks after the onset of upright locomotion. In Figure 1B, we present the individual mean percentage of bimanual reaching responses performed over the two consecutive 7-week periods preceding and following the onset of upright locomotion for all 9 infants.

Those figures illustrate the finding that before the onset of upright locomotion, the infants primarily used unimanual reaching for small objects. Following the onset of upright locomotion, however, the infants significantly increased their rate of two-handed responses while reaching for the same small objects, Wilcoxon Signed Rank Test = 39.00, $p(\text{exact}) = .020$. Two-handed reaching also increased significantly in the large-object condition, although the infants were already predominantly responding bimanually in that condition before the onset of upright locomotion, Wilcoxon Signed Rank Test = 34.00, $p(\text{exact}) = .016$.

In Figure 2, we present similar results for opening the lid in the object-retrieval task. The three exemplars in Figure 2A and the averaged data in Figure 2B show that 7 weeks before the onset of upright locomotion, most of the infants opened the lid of the box with one hand and used the other hand to retrieve the toy from the box. After the onset of upright locomotion, however, many of the infants began to open the lid of the box by using two hands, Wilcoxon Signed Rank Test = 35.00, $p(\text{exact}) = .039$, as if role-differentiated activity had disappeared.

Progress in Locomotion and Decline of Two-Handed Reaching

How long did the increase in two-handed reaching last, and how did it match progress in upright locomotion? The exemplars presented in Figure 1 show that the intensity and the extent of the increase in bimanual coupling varied enormously from child to child. A few infants maintained the two-handed patterning in reaching for as little as 4 weeks, then resumed adaptive reaching for 3 consecutive weeks (i.e., Infant MP, Figure 1A). In most cases, however, two-handed reaching lasted beyond the 7-week period displayed on these figures, sometimes up to 9 or 10 weeks following the onset of upright locomotion (i.e., Infants EG and CH, Figure 1A). Regardless of its duration, however, the increase in two-handed reaching almost always occurred during the weeks immediately following the onset of independent locomotion. That period is when the infants typically walked holding their arms above waist level and when their balance control was the most precarious. Our data showed that by the end of the study, when the infants resumed adaptive reaching during the last 3 weeks, they also began to walk with their arms at or below waist level, which means that by that time they had acquired better upright balance control during locomotion.

In Figure 3B, we illustrate that change in arm position in 1 infant, EG, during 11 weeks following the onset of upright locomotion. Those data are shown in conjunction with changes in her reaching for small objects. Records for arm position during walking began when EG was able to perform at least five consecutive steps (Week 9 in Figure 3B). From that time, EG walked maintaining her arms above waist level except during the last 3 weeks of the study. Recall that during those last 3 weeks, the infants had to show a decline in the rate of two-handed reaching for small objects to enable us to determine whether we should end our longitudinal observations.[2] EG was not the only one to lower her arms while walking during the last 3 weeks of the study. In Figure 3C are shown the walking arm positions adopted by all 9 infants during the first 3 weeks following the production of five steps or more and during the last 3 weeks of the study. Figure 3 shows that following walking onset, most of the infants maintained their arms above waist level; however, during the last 3 weeks of the study, when the infants reduced their rate of two-handed reaching for small objects most of them held their arms at or below waist level during walking (Fisher exact test, $p = .015$).

Individual Differences

As in many developmental studies in which individuals are followed over time, our results were not exempt of individual differences (Adolph, 1997; Corbetta & Thelen, 1996; Thelen & Ulrich, 1991). Although most infants revealed the expected increase in two-handed reaching following the onset of upright locomotion, there were some notable variations in our data, especially in the small-object condition. The individual averages on reaching between pre- and post-locomotion presented in Figure 1B revealed that 1 infant, KL, did not increase her bimanual reaching for small objects following the onset of upright locomotion and that 2 infants, BB and MG, revealed only a weak increase in bimanual reaching. The absence of an increase in two-handed reaching might suggest that change in reaching patterning did not systematically occur when the infants were learning to walk. A closer look at the developmental curves of those 3 infants, however, reveals that that was not the case. In Figure 4 are displayed the individual reaching and walking data for those 3 infants for the entire period they came to our laboratory. That figure shows that the individ-

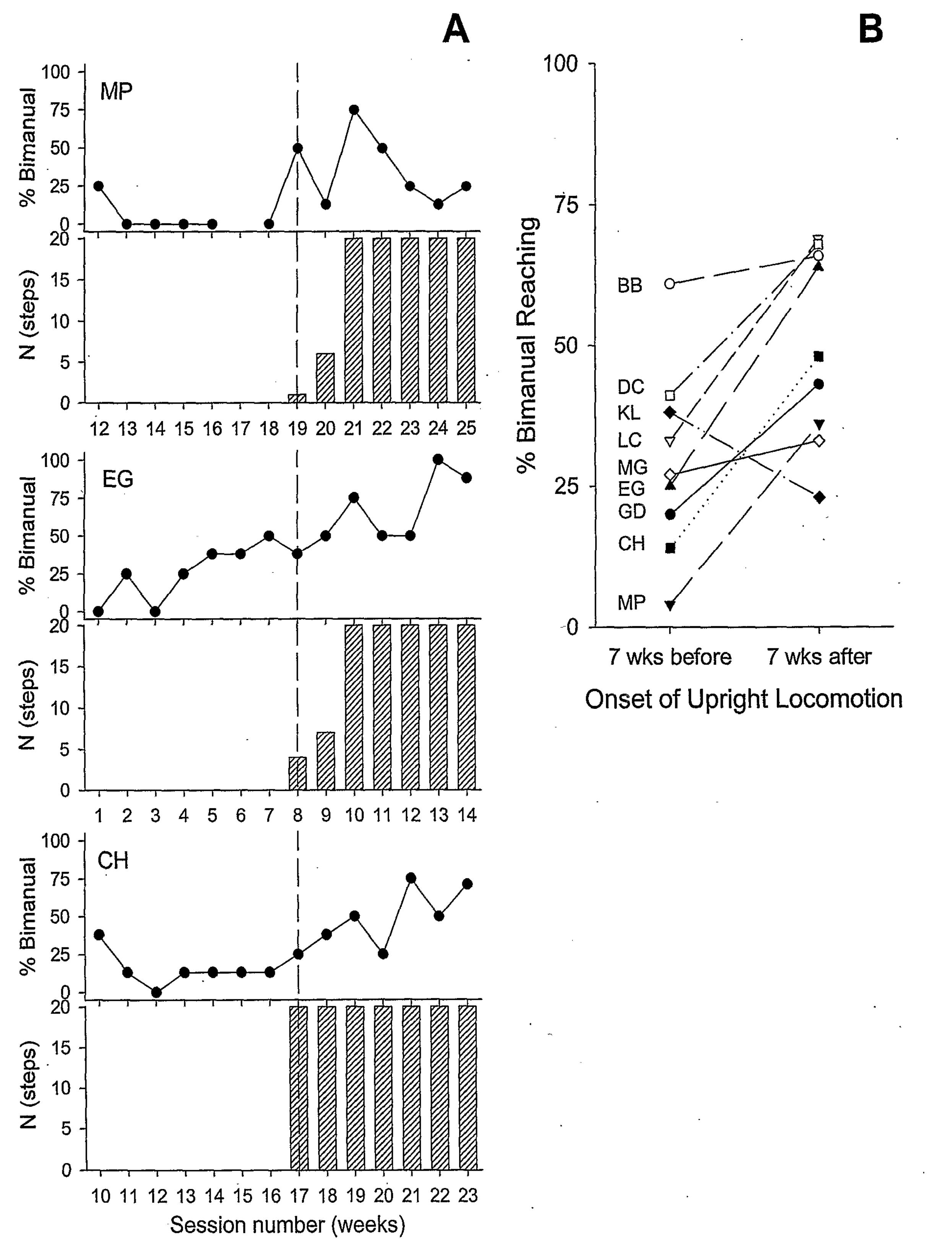

FIGURE 1. Reaching for small objects before and after the onset of upright locomotion. (**A**) Exemplars of weekly data from 3 infants over a period of 14 weeks (7 weeks before and 7 weeks after the emergence of upright locomotion). In the three exemplars, the percentage of bimanual reaching responses for small objects performed during each weekly session (top line graphs) is compared with the number of independent steps performed on the same sessions (bottom bar graphs). (**B**) Mean percentage of bimanual reaching responses used during the 7 weeks preceding and the 7 weeks following the emergence of upright locomotion by infants.

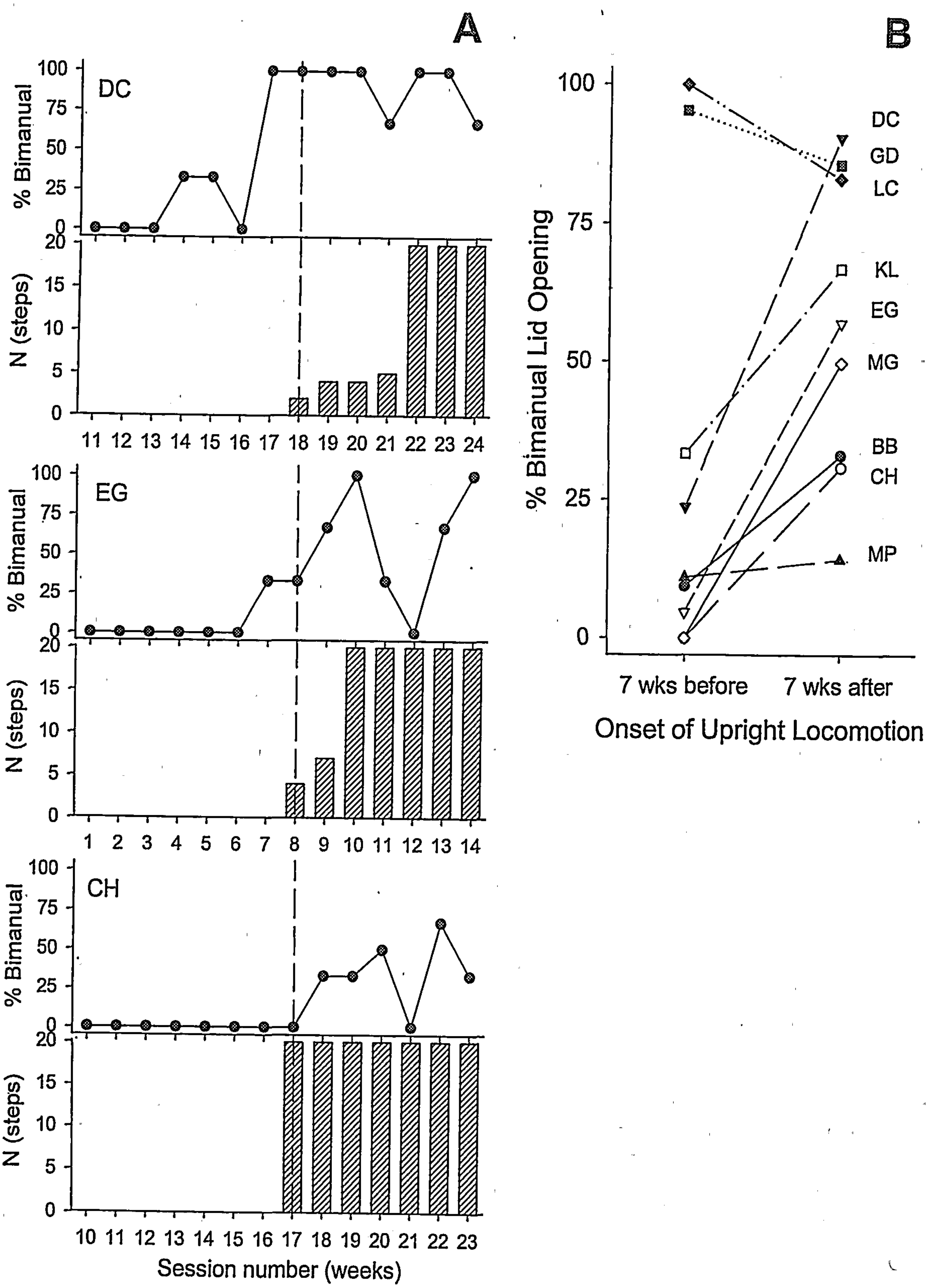

FIGURE 2. Object-retrieval task: Lid opening before and after the onset of upright locomotion. (A) Exemplars of weekly data from 3 infants over a period of 14 weeks (7 weeks before and 7 weeks after the emergence of upright locomotion). In the three exemplars, the percentage of bimanual lid openings performed during each weekly session (top line graphs) is compared with the number of independent steps performed on the same sessions (bottom bar graphs). (**B**) Mean percentage of bimanual lid openings used during the 7 weeks preceding and the 7 weeks following the emergence of upright locomotion by infants.

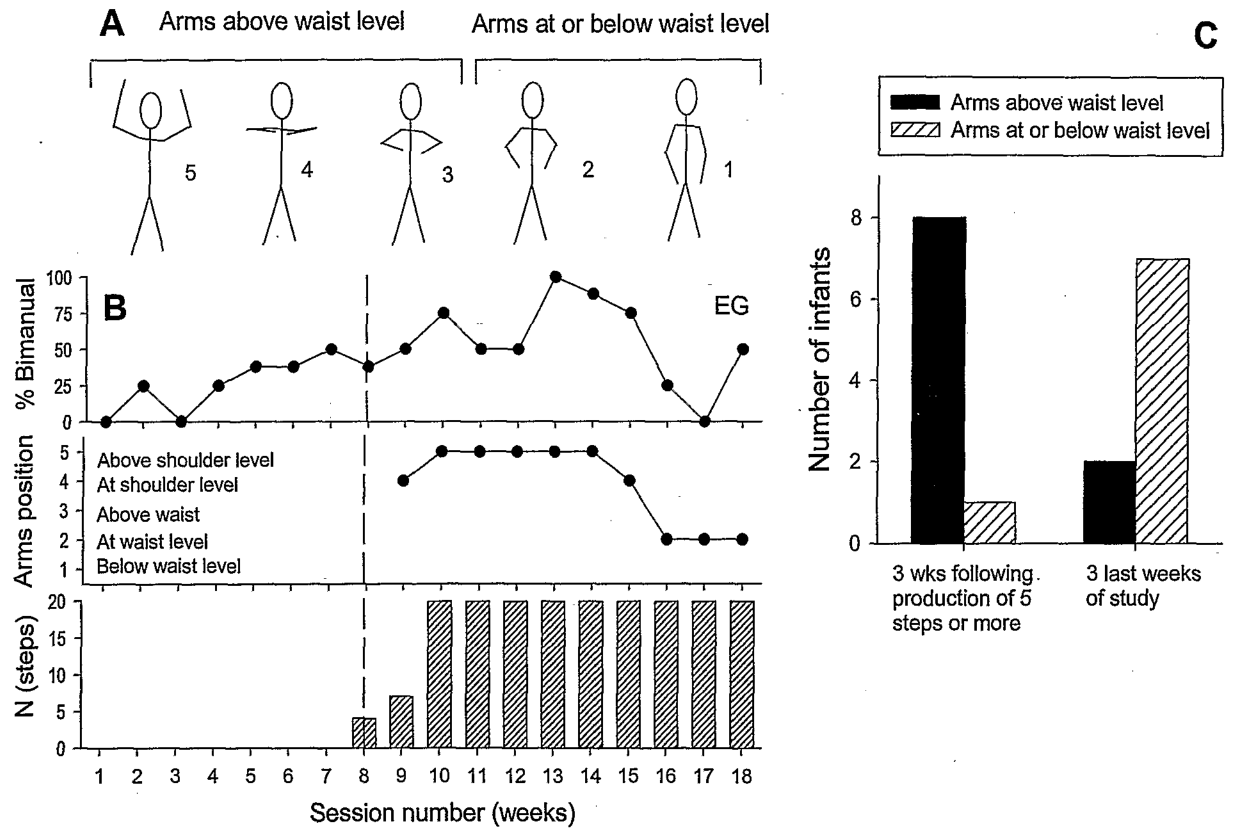

FIGURE 3. Position of arms relative to body as a function of weeks of independent upright locomotion. (**A**) Illustration of the five different arm position categories coded during walking. (**B**) Example of how those arm positions changed in 1 infant during 10 weeks of independent upright locomotion, that is, until completion of the study (middle line graph). The data are displayed in conjunction with the percentage of bimanual reaching for small objects performed each week (top line graph) and the progress in number of steps from walking onset (bottom bar graph). (**C**) Number of infants who adopted an arm position above versus at or below waist level during the first 3 weeks following the production of five consecutive steps and during the last 3 weeks of the study.

ual variations obtained in our averaged results with regard to those 3 infants were mainly caused by two factors: fluctuations in reaching patterning before the onset of upright locomotion and variations in timing onsets between increase in two-handed reaching and walking.

Indeed, Figure 4 reveals that those infants also displayed an increase in two-handed reaching around the transition to upright locomotion. Unlike the other infants, however, their reaching transition occurred either right before the onset of upright locomotion (Infant KL),[3] was embedded in highly fluctuating patterns (Infant BB), or occurred well after the onset of upright locomotion (Infant MG).

Discussion

Our main goal in the present research was to establish whether infants increase their rate of two-handed reaching when they begin to walk independently. Our findings were consistent with our predictions. Most of the infants were able to produce competent and adaptive reaching responses before the onset of upright locomotion. When they began to walk, however, those infants increased their rate of two-handed reaching. Then, a few to several weeks later, when the infants showed progress in upright locomotion and began to walk holding their arms at or below waist level, they resumed adaptive, unimanual reaching for small objects. Those findings were not specific to age, because the infants began to walk at very different times from the onset of the study. They were not task specific either, because the infants significantly increased their two-handed reaching responses across all three reaching tasks (small- and large-object reaching, and object retrieval).

Although the present findings are suggestive of a developmental link between reaching and walking, we must be cautious in our interpretation. As stated in the introduction, this study represents the initial and most foundational step in assessing changes in reaching patterning in relation to the emergence of upright locomotion, namely, to verify whether those two developmental events co-occur in a predictable pattern. However, observing co-occurrence between two developmental events does not provide information about the causal relations that might link them to each other. As a result, at this point we can only speculate about the potential

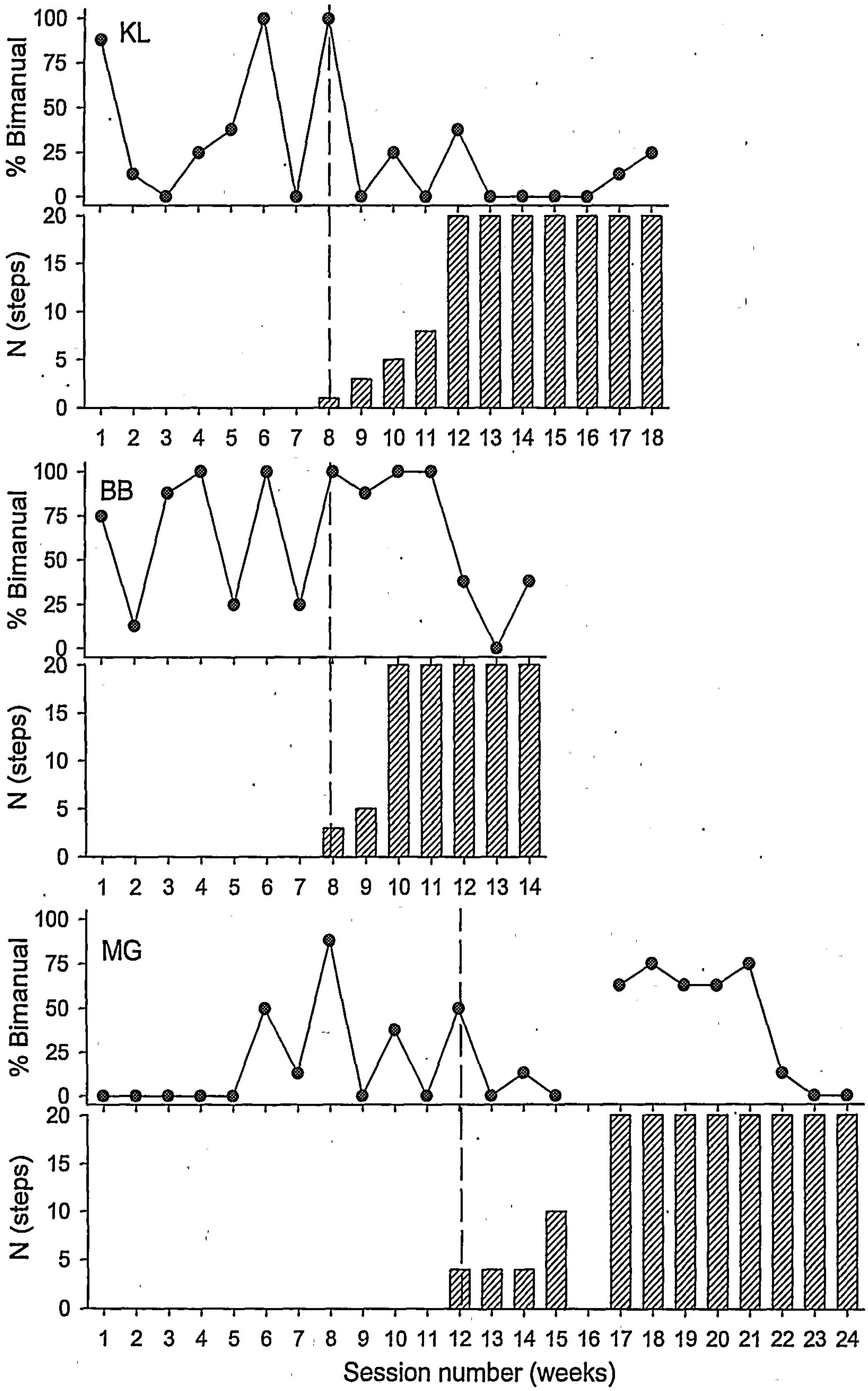

FIGURE 4. Reaching for small objects before and after the onset of upright locomotion in the 3 infants who showed different reaching changes in relation to walking onset. In the three exemplars, the percentage of bimanual reaching responses for small objects performed during each weekly session (top graphs) is compared with the number of independent steps performed on the same sessions (bottom graphs) for the entire period of the study.

underlying processes that might account for the observed developmental changes. Second, because some infants showed notable variations in timing between the rise in two-handed reaching and the onset of upright locomotion, we need to consider the possibility that another factor related to the development of walking might have played a role in the observed developmental changes in reaching. Indeed, some infants already demonstrated an increase in two-handed responses before the onset of upright locomotion (i.e., EG in Figure 1A, DC in Figure 2A, and KL in Figure 4) or revealed highly fluctuating two-handed behaviors before walking (i.e., BB and MG in Figure 4). How can we explain the observed developmental changes in reaching during the transition to upright locomotion?

Next we discuss two complementary scenarios that might potentially account for the observed developmental changes in reaching in relation to the emergence of walking. The first one relates to the development and mastery of upright balance control when learning to walk. We argue that the new postural constraints linked to the adoption of the upright posture temporarily transfer to reaching until balance is mastered and fully integrated into the developing postural system. In the second scenario, we attempt to explain the origins of the transfer between emerging constraints in upright balance control and the fact that the change in reaching occurred while the infants were sitting. We propose that a behaviorally driven neural mechanism might be at the origins of such behavioral transfer.

The Emergence of Walking, Postural Constraints, and the Mastery of Balance Control

We know from previous research that the emergence of upright locomotion in infancy is a novel behavior that imposes new constraints and challenges to the postural and neuromotor systems (McGraw, 1989). To walk, infants must develop muscle strength to support their body weight and control their upright balance. Achieving such a milestone also imposes new tasks on the brain, which has to solve the problem of how to coordinate and sequence new sets of muscles properly. The process of coordinating and sequencing new sets of muscles is a difficult one, especially during the early stage of walking onset. As described in the literature, infants achieve that transition and manage to control their upright balance by maintaining their arms in a high guard position, by increasing tonus, by generating small steps to prevent falling, and by adopting a wide stance to reduce oscillations of their center of gravity (Bril & Brenière, 1992; Burnett & Johnson, 1971; Ledebt, 2001). We found that right around that transition of important postural and neuromuscular reorganizations, the infants increased their rate of two-handed reaching.

Two main features in our data suggested that change in reaching patterning might be associated with the mastery of upright balance control as infants prepare to or begin to walk. First, most of the infants increased two-handed reaching in the first weeks following walking onset when balance control was the most precarious and when they held their arms upward in a high guard position. Likewise, the infants regained adaptive reaching when they began to lower their arms along their body sides, which means that they had gained greater upright balance control and had acquired higher coordination flexibility by that time (Burnett & Johnson, 1971; Ledebt, 2001). Although balance control is an integral component of walking, infants' attempts to control upright balance may begin before walking onset, especially in preparing infants to achieve this important motor milestone. If change in reaching patterning is linked to the emergence and mastery of upright balance, then we should see some instances of increased two-handed responses before the infants actually begin to walk independently. Our data showed that those responses did occur for some infants, especially for BB, DC, and KL. More interesting, during our prelocomotor weekly postural screening, we noticed that those infants were attempting to get up on their feet on their own without support and frequently were testing their balance by shortly releasing the support surface onto which they were holding. Two other infants, MG and EG, also began to show a rise in two-handed reaching before independent walking. Similarly, they demonstrated some attempts to maintain their balance when upright before walking onset, but their attempts were more cautious. KL was also unique in being able to get up on her feet from sitting on the floor without using any help or without relying on any surface or furniture to stabilize her upright posture. Unlike the other infants, she demonstrated a much greater ability to control her upright balance before walking than her peers did. Coincidentally, she was the 1 infant who did not extend two-handed reaching beyond walking onset, as if her rapid mastery of upright balance facilitated her rapid return to adaptive reaching.

Taken together, those data suggest that upright balance control might have acted as a control parameter on the return to two-handed reaching. Yet, more detailed analyses will be necessary in subsequent studies to enable us to be conclusive about the link between upright balance control and changes in reaching patterning. For now, one possible interpretation that stems from our initial observations is that the temporary return to two-handed reaching reflects the progressive integration of upright balance control into the developing postural system. Reaching, like many goal-oriented behaviors, is anchored into a postural system. Any reorganization of that system, whether caused by new developing motor milestones or by temporary perturbations, can potentially affect the formation of goal-oriented behaviors.

The interpretation that change in reaching patterning might be associated with the mastery of balance control, postural integration, and reorganization is compatible with conclusions from other studies in which developing motor milestones such as sitting, crawling, and walking have been found to affect existing motor, perceptual, and cognitive skills (e.g., Adolph, 1997, 2000; Rochat, 1992, to cite a few). Those studies have revealed that changes in infants' perceptual and adaptive responses depend on their ability to control their posture when sitting or walking. Rochat, for example, demonstrated that success at producing adaptive reaching responses in 5- to 8-month-olds emerged when the infants were able to adopt a stable sitting posture. Moreover, Adolph found that success at perceiving gaps of different widths or slopes of various steepnesses was directly correlated with infants' ability to control their sitting or upright posture.

Although the present study on reaching and walking conveys a similar idea—that change in reaching patterning might be associated with the development and mastery of upright balance and locomotion—our study reveals a novel feature: Pattern reorganization can occur seemingly independently from the new postural requirements being learned. Indeed, it was striking to observe that changes in the infants' reaching responses took place while the infants were sitting and fully supported around their torso, that is, in a context where there was no threat or danger that balance and postural stability could be compromised and could interfere with reaching. Because lack of balance in the upright posture did not directly apply to reaching, an explanation based on balance alone does not seem to fully account for the observed developmental transition in reaching. To solve that problem and explain why infants returned to two-handed reaching during the transition to upright locomotion, although they were not standing or walking during reaching, we propose a second complementary account to the one proposed for upright balance control. In particular, we suggest that changes in reaching patterning might reflect changes in the neuromotor organization of the system, as surmised by Gesell (1939, 1946) in his seminal work. Unlike Gesell, however, we hypothesize that those neuromotor reorganizations are the product of the highly practiced upper arm postures that are adopted by infants when learning to control their upright balance. It is the practice of those upper arm postures during early standing and walking that might have transferred to reaching.

Postural Transition, Experience-Dependent Brain Reorganizations, and Behavioral Transfer

For nearly 6 decades, the only explanation that has been brought forward to account for developmental fluctuations in interlimb activity was the one proposed by Gesell (1939, 1946). Gesell assumed that changes in interlimb patterning are related to autonomous changes in the central nervous system. A strict maturationist account cannot be entirely true, however, because many developmental changes in the brain also occur as a result of behavioral learning. In the last decade, there has been a growing body of literature on humans and nonhuman mammals that has demonstrated that the brain reorganizes itself, particularly following novel motor skill learning (Greenough, Black, & Wallace, 1987; Jenkins, Merzenich, Ochs, Allard, & Guic-Robles, 1990; Karni et al., 1998; Kleim, Barbay, & Nudo, 1998; Petersen, Mier, Fiez, & Raichle, 1998). Moreover, behaviorally driven changes in the brain, in turn, have been found to affect motor performance (Dorris, Paré, & Munoz, 2000). Such reorganization has even been documented in human infants following the emergence and consolidation of a motor milestone such as crawling (Bell & Fox, 1996).

In the present study, we have no evidence of brain change in our participants; but given the growing number of discoveries concerning brain plasticity, we cannot exclude the possibility that certain neuromotor changes associated with specific skill learning, that is, walking, might interfere with established skills, for example, reaching, especially if in both the newly learned and the preexisting behaviors common groups of muscles are used. It was indeed astonishing to discover that upper arm interlimb coupling arose and declined at similar developmental times in both walking and reaching, even though both behaviors were used in different contexts. Is it conceivable that the upper arms' coupled neuromuscular activity, newly practiced during early locomotion in response to novel balance constraints, temporarily transferred to reaching?

Some recent neurophysiological correlates can possibly lead to an answer to that question. In two recent studies, frequent practice of movement patterns involving muscle coactivation was shown to result in magnified coupled response representations in the motor cortex and greater functional coupling between hemispheres (Andres et al., 1999; Nudo, Milliken, Jenkins, & Merzenich, 1996). Moreover, it has been argued that greater experience-dependent representations in the cortex increase the likelihood that some specific behavioral solutions will be selected over a range of other possible behavioral solutions (Sporns & Edelman, 1993). In the context of the present study, one could argue that the greater upper arm coupling activity associated with the development and mastery of upright balance might have strengthened the neural representation of the coupled response for that particular group of muscles. Because in reaching an identical group of muscles is used, arm coupling associated with walking may have transferred to reaching, increasing the probability that coupled, bimanual reaching responses were selected over unimanual, noncoupled responses. Again, such an interpretation will deserve careful attention in follow-up studies. Nonetheless, the fact that increased coupling in reaching was observed across tasks and has been documented even in earlier studies when infants began to walk (Corbetta & Thelen, 1996) is consistent with such an interpretation.

We think that one must use the second explanation of brain and behavioral development to account for the observed behavioral transfer between walking and reaching. Clearly, the infants did not return to two-handed reaching in response to specific or changing task requirements while sitting. Reaching and object retrieval were consistently tested the same way during the whole duration of the study. The only change that occurred during the study was that the infants learned to walk and had to learn to adopt a new posture.

Conclusions and Implications

The present findings provide clear evidence that development is not necessarily continuous and that existing and established skills are not immune to modification. We think that the present findings have broader developmental implications than simply providing a new interpretation of the resurgence of two-handed reaching in the 1st year. First, the results showed that depending on the developmental period, perception and cognition may not always guide or command action. In the present study, the infants returned to two-handed reaching although they knew and responded to the tasks adaptively before the onset of locomotion. Thus, perception and cognition alone were not sufficient to enable them to correct or prevent change in reaching patterning. Rather, our data suggest that novel motor constraints arising from the development and mastery of the upright posture might have played an important and decisive role in the developmental reorganization of reaching. Second, our findings suggest that change in reaching patterning and developmental discontinuities might be linked to critical periods of learning, when underlying brain and behavioral reorganizations are more likely to occur. In other studies, a similar argument has been raised: that developmental fluctuations in manual activities are related to novel skill learning. In particular, those other studies revealed that hand preference in infancy is reorganized several times during the 1st year as infants undergo successive postural recalibrations (Corbetta & Thelen, 1999, in press) or as infants progress through milestones of language development such as babbling, producing new words, and forming sentences (Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; Ramsay, 1980a, 1980b, 1984, 1985a). Finally, the current findings suggest that the emergence of new skills might not be simply added to existing skills but might be built upon and might necessitate the reorganization of already acquired skills so that the infant will be able to complete and coherently integrate new forms of responses in the overall behavioral repertoire. The process of integration might involve the dynamic reorganization of multiple systems, that is, neural, motor, sensory, and cognitive.

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NOTES

1. Often we could not determine arm position during the 1st week of independent walking because infants performed less than the required five steps.

2. Similar declines in two-handed reaching during the last 3 weeks of the study can be seen in Figure 1A (Infant MP) and in two exemplars in Figure 4 (Infants BB and MG).

3. Note that we should have stopped following KL's walking and reaching progresses after Week 11 because, by that week, KL met our criterion of resuming adapting reaching patterns for small objects for 3 consecutive weeks. She was the only infant that we followed beyond that 3-week behavioral criterion. We did so because her two-handed period unexpectedly occurred before the transition of upright locomotion and was very short. Because we could not exclude the possibility that she still might have returned to two-handed reaching in her postlocomotor period, we followed her for another additional 7 weeks. To maintain equivalence with the other infants, we still computed her reaching patterns over 7 weeks pre- and postlocomotion.

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