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Lateral Biases and Fluctuations in Infants' Spontaneous Arm Movements and Reaching

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ABSTRACT: *The development of hand preference in infant reaching is marked by several lateral fluctuations. This study investigated whether similar lateral fluctuations were present in infants' spontaneous, nonreaching, and freely performed movements. We collected reaching and nonreaching movements kinematics in 4 infants that we followed longitudinally during their 1st year. In their 4th year, we assessed the direction of their hand preference. We found that lateral biases in spontaneous, nonreaching movements in the 1st year showed several shifts that were similar to those observed in reaching. Despite these shifts, all 4 infants traversed a short period of right-handedness. This right-handedness matched the direction of their hand preference at 3 years of age. We propose that shifts in the development of hand preference in the 1st year are linked to successive reorganizations of the motor system. These reorganizations take place as infants learn to sit, crawl, and walk.* © *1999 John Wiley & Sons, Inc.* Dev Psychobiol 34: 237–255, 1999

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INTRODUCTION

How does hand preference develop? Despite decades of research in this area, this question is still not well answered. Part of the puzzle lies in the difficulty of establishing a direct link between adults' hand preferences and the lateral instabilities that are typical of infants' hand use. For example, parents who observe their child on a daily basis frequently report having difficulties predicting the direction of their infant's hand preference because it changes so often. Predicting the direction of hand preference has been the focus of many developmental studies. One approach has been to search for early precursors of hand preference in newborns' spontaneous behavioral asymmetries. For instance, some studies related the origins of hand preference to the tendencies of newborns to orient their heads asymmetrically either to the right or left side (Coryell, 1985; Coryell & Michel, 1978; Gesell, 1938; Hopkins et al., 1990; Michel, 1981; Michel & Harkins, 1986; Turkewitz, 1977). Others searched for asymmetries in primary hand activities such as spontaneous hand closure (Cobb, Goodwin, & Saelens, 1966) or grasping behaviors (Caplan & Kinsbourne, 1976; Hawn & Harris, 1983). Still other studies related the development of lateral asymmetries to the position of the fetus in utero (Michel & Goodwin, 1979; Previc, 1991) or to early mother–infant social interactions (Harkins & Michel, 1988; Harkins & Uzgiris, 1991).

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Overall, this research has defended one of two major interpretations of the development of hand preference. One attributes early asymmetries and later hand preference to biologically rooted tendencies in the system (Annett, 1981; McManus, 1985; Schonen, 1977). The other explanation links the origins of hand preference to biased perceptual–motor experience acquired early in development (Harkins & Michel, 1988; Previc, 1991; Provins, 1997).

This developmental link between newborns' preferred behavioral asymmetries and the direction of later hand preference is not straightforward, however. Whether the explanation is genetic or experience-related, one would expect these newborn lateral tendencies to develop either into stable and consistent asymmetries, or into increasingly greater asymmetries, such as using one hand progressively more than the other. But this is not what happens when we follow the development of hand preference during infancy. Studies that tracked changes in hand use in reaching and object manipulation during the first two years of life found a rather complicated and fluctuating developmental picture. Just as parents have often noticed, there was no consistent preference for one side or the other (Carlson & Harris, 1985; Gesell & Ames, 1947; Provins, Dalziel, & Higginbottom, 1987; Ramsay, 1984, 1985b; Ramsay & Willis, 1984; Young, 1977). One day, infants use their right hands to attain an object located at midline. The next day or even on the next trial, they use their left hands to reach for the same object. And often, infants show periods in which they use both arms repeatedly to attain a small target, as if their lateral preferences disappeared (Corbetta & Thelen, 1996; Fagard & Pezé, 1997; Gesell & Ames, 1947). Clearly, these studies suggest that if spontaneous asymmetries or lateral tendencies exist from the 1st days of life, they may be unstable, or may undergo several reorganizations before settling into a defined and preferred direction.

The current literature, therefore, leaves a central question unresolved: Do these shifts and fluctuations in reaching reflect actual developmental changes in underlying lateral tendencies or are they the result of infants' poor arm control? The newborns' studies assume that the lateral tendencies seen in spontaneous movements express the natural, preferred bias of the organism in absence of task constraints. However, the connection between such spontaneous biases and actual hand preferences in reaching and object manipulation has not been made. Does the hand used for reaching match the preferred asymmetries of the organism? Indeed, one still may argue that lateral fluctuations in reaching may result not from any inborn tendency, but from infants' inabilities to control their arms appropriately when the action is goal-oriented and requires spatial and temporal accuracy. As we know, reaching patterns, unlike nonreaching spontaneous behaviors, are subject to complex perceptual–motor processes that infants need to learn and master before they can produce stable motor responses adapted to the task demands. Especially during the months following reaching onset, infants cannot generate straight arm trajectories to the target, they cannot calibrate movement speed to the task demand, and often lack proximal and distal joints coordination (Hofsten, 1991; Thelen et al., 1993; Thelen, Corbetta, & Spencer, 1996). It is therefore possible that this lack of arm control not only alters infants' abilities to bring their arms efficiently to a desired location, but also interferes with infants' preferred lateral biases. For instance, infants may shift arms in the course of reaching, or use two arms instead of one to increase their chances of intercepting the desired target. If this is the case, the hand used for reaching may not accurately reflect the preferred lateral bias of the organism. In contrast, spontaneous, freely performed movements that are not subject to specific external constraints or task demands may better describe the natural evolution and formation of lateral preferences during infancy.

Hence, a first aim of this study was to examine the time course of spontaneous, nonreaching, freely performed movements in infancy throughout the 1st year in order to assess how lateral biases in hand activity develop. In addition to learning to reach and manipulate objects, infants continue to produce a high rate of non-object-oriented movements or object-related activities that do not require fine arm control. Like newborns who prefer to spontaneously rotate their head to the right, close their right hand, or kick with the right leg, infants may display asymmetrical limb activity when jiggling their arms, shaking a rattle, throwing a toy, or when generating arm movements in absence of specific task demands. Our goal was to discover whether these nonreaching movements show stable lateral biases or if they show the fluctuating asymmetries seen in reaching. Because these natural jigglinglike patterns are not subject to movement accuracy or specific arm control problems, they may provide a more reliable way to predict the developmental direction of hand preference.

A second aim of this study, related to the first one, was to understand the correspondence between the preferred asymmetries emerging from freely performed movements and the lateral fluctuations observed in reaching for objects. As we explained earlier, nonreaching movements represent an important part of infants' movement repertoires and like other movements, they provide motoric and perceptual experience. Although this experience is not necessarily object-oriented, it may contribute considerably to the formation and establishment of lateral preferences. Accordingly, we examined to what degree nonreaching movement asymmetries relate to preferred hand use in reaching in the 1st year and to what extent they relate to later hand preference in object manipulation. Do asymmetries in nonreaching and reaching behaviors evolve in unison or do they show separate developmental trends because of the specific perceptual–motor processes involved? And, will preferred bias in the 1st year match preferred hand use later in development? In particular, examining in detail the development of both reaching and nonreaching arm movements in the 1st year will help to disambiguate these issues of intrinsic lateral asymmetries and emergent motor control. If both reaching and nonreaching patterns show similar shifts and fluctuations in activity, this suggests that the development of hand preference is not an established process that shows a clear direction from the 1st days of life, but rather an unstable process that undergoes significant reorganizations in early life. On the contrary, if nonreaching, self-generated movements reveal increasing and/or stable asymmetries across the 1st year while reaching does fluctuate, this indicates that infants' initial lack of arm control in reaching temporarily conflicts with infants' preferred asymmetries.

Finally, a third aim of this study was to evaluate the later outcome of these 1st-year lateral tendencies and preferences. We compared the direction of reaching and nonreaching lateral tendencies in the 1st year with the direction of hand preference at 3 years of age in the same children. As established by previous studies, 3 years old is an appropriate age to accurately assess the direction of hand preference (McManus et al., 1988).

To address these goals, (a) we present a detailed kinematic account of the evolution of infants' nonreaching, spontaneous upper-arm activity and reaching during the 1st year of life; (b) we compare the pattern of the nonreaching lateral tendencies with the development of hand use in reaching; and (c) we link these 1st-year observations in reaching and nonreaching activity with the direction of hand preference at 3 years of age.

The data reported here are an extension of previous investigations on the development of infant reaching and nonreaching activity in 4 infants whom we followed during their 1st year, from 3 to 52 weeks old (Corbetta & Thelen, 1996; Thelen et al., 1993; Thelen et al., 1996). These reports described changes in the transition to reaching, in the kinematics of the reach, and in interlimb coordination but did not investigate changes in the direction of upper-limb asymmetries. To fulfill the specific goals of this article, we collected additional data from these 4 participants when they were older than 3 years in order to assess the outcome of their hand preference.

From the previous longitudinal reports, we know that during the 1st year, these 4 infants traversed periods in which they tended to reach more with one hand while at other periods they reached more with two hands (Corbetta & Thelen, 1996). We also know that these tendencies in one- versus two-handed reaching were related to predominant patterns of interlimb coordination in their spontaneous movement repertoires. When they reached more bimanually, spontaneous patterns were more synchronous, and when they reached more unimanually, the synchrony tendencies dissolved to give rise to a broader range of patterns of interlimb coordination. Based on these previous findings, we can make a certain number of predictions regarding the development of hand preference and lateral bias in reaching and nonreaching activity. First, we expect to find stronger lateral differences between hands during the unimanual periods than during the bimanual periods; however, bimanual periods may still reveal some lateral biases. Second, because reaching and nonreaching interlimb movements fluctuated similarly in a coherent pattern throughout the 1st year, we expect a similar relation between hand use in reaching and lateral bias in nonreaching movements. That is, if the right arm is more active during nonreaching activity, we expect infants to use their right arms more for reaching. If the left arm is more active, we expect infants to use predominantly their left hands for reaching. And if both hands are equally active, we expect infants to reach more bimanually.

Our last prediction involved changes in arm control in reaching throughout the 1st year. In a previous report (Thelen et al., 1996) we found that all 4 infants demonstrated rather poor and unstable arm control during the first half of the 1st year. From Weeks 30–36 however, they began to produce fairly stable and smooth reaching trajectories. If change in arm control matters and interferes with preferred biases in nonreaching activity, we should see a stronger link between spontaneous biases and hand preference in reaching toward the end of the 1st year as arm control improves. This link between reaching and nonreaching activity should be weaker during the 1st months following reach onset because lack of arm control may eventually interfere with preferred hand use, as explained above.

The 1st-year longitudinal study and the 3-year-old hand preference assessment are presented as two separate studies because the questions asked by each period required different methods.

PART 1: THE 1ST-YEAR LONGITUDINAL STUDY

Methods

Participants. Four infants, 3 boys (GS, NQ, and JA) and 1 girl (HR) from Caucasian, middle-class families, participated in the 1st-year longitudinal study. They were normal, full-term infants with no known sensory or motor impairments. We recruited them through local advertisements and through letters sent to expectant parents. Parents who responded to our advertisement were invited to visit the laboratory setting prior to the birth of their child. During this meeting, we introduced them to the longitudinal procedure, equipment, and goal of the study. Parents who consented to participate with their infants received $15.00 per visit. We began the longitudinal study when the infants were 3 weeks old and ended it when they were 52 weeks old. GS, JA, and HR never missed a session. NQ missed one session at 25 weeks old because of illness, and had an additional session at Week 51 to replace Week 50, when he cried.

Materials. We collected the kinematic data of the activity of both arms when moving freely and when reaching with a four-camera motion analysis system (WATSMART optical electronic system, Northern Digital, Ontario, Canada). WATSMART tracks small infrared light-emitting diodes (IREDs) attached to the infants' arms. We attached a total of eight IREDs on the rotational center of each shoulder, elbow, and wrist of the infants' arms and on the knuckle of each hand. The IREDs pulsed at 150 Hz and were individually tracked by the cameras as the infants moved their arms within a precalibrated area of 53.5 cm × 53.5 cm × 65.5 cm. The cameras, located in pairs on either side of the infant, recorded the IREDs' pulsed position of each arm as two-dimensional coordinates. The third dimension was mathematically reconstructed a posteriori using a direct linear-transformation technique.

During movement recording, participants were seated on a specially designed infant chair that was narrow, armless, and adjustable. The chair was located at the center of the precalibrated volume and was reclined 30 degrees from vertical to provide full trunk and head support while allowing free arm movements. We used two chairs of identical design but of different sizes to fit infants' increasing body size. Also, in the early weeks, the chair was equipped with a headrest similar to the one used by Hofsten (1982, 1984). This headrest helped support and stabilize the infants' heads at midline. This was necessary to maintain focus during the task and prevent attention from shifting because of lack of head control. Thus, we minimized any arm asymmetry due to head asymmetry. The headrests were removed when infants developed stable head control, that is within the first 7 weeks (see Vereijken, Spencer, Diedrich, & Thelen, 1998).

The reaching targets were a set of 10 small toys, that infants could easily grasp with one hand. They were lightweight, colorful, and of various shapes including a bell-shaped and a round-shaped baby rattle, four solid balls ranging from 4.5 to 5.5 cm diameter, a set of small metallic measuring spoons, and three "silent" laboratory-made toys such as strings of colorful beads knotted in flower-shaped patterns.

We simultaneously videotaped the sessions using two video cameras that provided concurrent side and either front or overhead views of the infants' activities. We recorded both views on the same image using a split-screen device. The video cameras and WATSMART were connected to a frame counter that insured synchronization of video and kinematic data.

Design and Procedure. The participants came to the Infant Motor Development Laboratory 39 times, that is, every week from 3 to 30 weeks old (28 visits) and every other week from 30 to 52 weeks old (11 visits). Parents and infants also participated in longitudinal naturalistic play sessions during 39 separate visits to the laboratory. We only report some of these data in the final discussion of this article. For more details regarding the naturalistic play sessions, see Vereijken et al. (1998).

At the start of each session, we removed the infants' shirts and attached the IREDs on the hand and joints of each arm. Then, we secured the infants in the chair with a wide strap around their torso to prevent them from leaning forward or sideways. At every session, we collected 8 to 12 trials of 14 s that included either both 1 to 2 s of reaching and 12 to 13 s of nonreaching movements, or only 14 s of nonreaching movements. In particular, during the weeks preceding reach onset, our data contained only nonreaching movements. In our setting we did not observe prereaching behaviors as described by Hofsten (1982, 1984). Typically, a trial began by triggering the WATSMART system. Then, a few seconds after, an experimenter brought a small attractive toy to the infants' reaching space, at midline and shoulder height. We always presented a toy regardless of infants' ability to reach. We allowed infants the full duration of the trial to initiate a reach. Only reaches and successful contacts with the target were considered as goal-oriented movements targeted to specific external constraints (i.e., location). The other movements, whether performed before or after the reach, were always considered as nonreaching movements because they were not performed to accommodate any consistent or specific task demand that was imposed by our setting. After they reached for the toy, the infants were free to jiggle, wave, flap their arms, or explore and manipulate the toy in any desired way (i.e., shake, rotate, or throw the toy). All of these nonreaching movements were lumped together because we could not make specific assumptions or predictions regarding infants' intentions. Thus, before the onset of reaching, we recorded all movements as nonreaching. After reach onset, we identified the reach itself, and then classified all other movements as nonreaching.

We always presented the reaching toys one at a time and in random order. At the end of each trial, we removed the toy from the infants' hands or view before starting the next trial.

Data Selection and Filtering. Because infants were free to move anywhere they chose, sometimes IREDs were obscured from the cameras' views. Likewise, sometimes infants remained momentarily uncooperative, inactive, or fussy. Therefore, before filtering and analyzing the data we needed to select which trials or portions of trials contained usable and visible data. This entailed a double selection process. First, we selected behaviorally usable data from the video. Behaviorally usable data corresponded to whole trials or portions of trials that contained any ample movements of one or both arms performed either in relation to the toy or independently from the toy. These movements generally included upper-arm rhythmical activities (i.e., flapping), random arm waving, clapping, energetic object-related activities such as shaking and throwing a toy, and reaching behaviors. We excluded from our data set trials or portions of trials in which infants were inactive, asleep, or crying, when they were pulling on wires, looking around (which was generally accompanied by no arm movements), sucking on their fingers, or moving only extremities (i.e., fingering, small hand movements, hand rotations, etc.). This behavioral selection was performed by two coders working together. They coded each arm in separate passes. At each pass, they marked on coding sheets the onset/offset values of the video frame counter corresponding to the usable behavioral segment. If behavioral segments were unequal for each arm, they always matched the hand with the shorter behavioral segment to the hand containing the longer segment. Thus, usable data contained behavioral segments where both hands were active and behavioral segments when only one hand was active while the other was not. The only data left out were segments where both arms were inactive, or when infants were fussy or uncooperative. During this entire process, coders had no knowledge that these data were going to be used for assessing lateral biases.

Once behaviorally usable data were selected from the video we began our second data- selection process, which concerned IRED visibility within our kinematic files. We needed to check whether the kinematic data corresponding to the usable behavioral segments had visible x, y, and z coordinates. A custom program counted the number of visible and obscured position coordinates for each IRED within each trial or segment of trial. A double criterion was used to determine usability of the kinematic data: (a) IREDs had to be seen through at least 70% of the behavioral segment and (b) gaps of missing data had to be smaller or equal to 50 frames (one third of the sampling frequency). Previous pilot studies indicated that such gaps could be interpolated and filtered without distorting the original signal, while larger gaps could not. If the 70% criteria could not be met, we discarded the trial or segment of trial. If the 70% criteria passed but there were gaps of 50 frames or more, we used the segments of data around the gaps. These shorter segments were again checked for the 70% visibility criterion.

Finally, to reduce the loss of data related to this data-selection process, we compared the amount of data seen between hand IRED and wrist IRED for a given segment. In our analyses we used the IRED providing higher visibility; however, if visibility between hand and wrist IRED was identical, we chose the hand IRED.

The interpolation and filtering of the data were performed for the entire 14-s trial. However, we stored and used only the segments of data matching our previous behavioral and visibility criteria. We first interpolated the obscured data of each IRED's coordinate by using a linear spline (straight line). Linear splines do not alter the actual frequency component of the original data. Then we determined a filtering cutoff frequency for each coordinate of each IRED from the spectral analysis of each coordinate. The cutoff frequency corresponded to 97% of the integral value of the spectral density. Each coordinate was then filtered using its corresponding cutoff frequency with a fourth-order Butterworth filter and then differentiated to obtain x, y, and z movement velocities.

Two more steps were taken before analyzing the data. First, because our selection process for IRED visibility may have led to unequal kinematic data files between hands, we only used selected segments of data that contained overlapping information from both hands in the same time in order to prevent any bias in the computation due to different amounts of data between hands. By doing so, we lost nonreaching movements in one arm for HR Weeks 5, 6, 11, and 18 and for JA Weeks 5, 9, and 11 because the IREDs of that arm gave us consistent unusable data during these sessions.

Second, because our data selection process lumped together reaching and nonreaching movements, we needed to identify which portions of kinematic data were specific to the act of reaching in order to separate these data from the continuous stream of nonreaching activity and make possible the comparison between reaching and nonreaching movements. To do so, we first identified the start and end of each reach from the video. A reach was identified when the following criteria were met: (a) the object was located in the infant's reachable space, (b) the infant was looking at the object or noticed it before reaching, and (c) the arm movement resulted in one or both hands contacting the target. Then, the coder searched for the frame of reach initiation and reach end. Reach initiation was assessed by playing the video backward from the point of hand–toy contact until the hand went back to its initial reach position. Reach end was always defined as the first hand–toy contact. Because reach initiation could be ambiguously defined, we compared both the frame of reach start and reach end to their kinematic profiles. To do so, we applied a method described in a previous article (Corbetta & Thelen, 1995). This method also allowed us to extract the reach from the continuous stream of kinematic data. In brief, this method used an interactive computer program that allowed matching video events (in our case the frame of initiation and end of the reach) to corresponding kinematic data. The specific video frame numbers were entered in the program. The program converted these video frame numbers into the corresponding frame numbers in the kinematic files and generated a graphic display of the 14 s of data or portion of data by plotting the position of the hand relative to the toy location and the corresponding resultant velocity profile. It also indicated on the plots where the defined start and stop of the reach occurred. The program always matched the video frame of reach initiation to the closest velocity minima on the kinematic profile. The user always had the option to modify these values for accuracy and check these events against the video to ensure correctness. When infants reached bimanually, each arm was analyzed separately. The kinematic frames of reach initiation and reach end were then stored in data files for further processing. In later analyses assessing lateral biases in nonreaching movements, we instructed the program to skip the portion of data corresponding to the reach. This method to identify a reach within a continuous stream of behavior led to highly reliable results (for more details see Corbetta & Thelen, 1995).

The final kinematic data set for the 4 infants, after selection and elimination of segments behaviorally unusable or lacking visible coordinates, included a total of 8410.32 s of data, spanning both reaching and nonreaching interlimb activity from 5 to 52 weeks of age. This corresponded to an average of 2102.58 s of data per infant (*SD* = 180.13). These data included an average of 6.7 (*SD* = 0.41) reaches per infant and per session from the week the infants began to reach.

Scoring.

Hand Preference in Reaching. Our method to identify a reach within a continuous stream of behavior gave us the exact frames of reach initiation and hand–toy contact. Hence, the assessment of which hand initiated and/or contacted the target first was based on these numbers. Previous studies defined hand preference using either the hand initiating the movement or the hand making initial contact with the target (i.e., Carlson & Harris, 1985; Michel, Ovrut, & Harkins, 1986; Morange & Bloch, 1996). Our data showed that the hand initiating the reach was also the hand contacting the toy first in 78% of the cases. Therefore, we computed hand preference in reaching by using only the hand making initial contact with the target because that hand was first to successfully attain the goal. Hand preference in reaching was scored using the following formula (Carlson & Harris, 1985):

$$\frac{(\Sigma_{\text{Right Hand reaches}} - \Sigma_{\text{Left Hand reaches}})}{(\Sigma_{\text{Right Hand reaches}} + \Sigma_{\text{Left Hand reaches}})}$$

This formula provides a single value varying between +1 and −1 that captures the predominant lateral bias across all reaching trials within a session. A positive value indicates a rightward bias with more right-handed reaches; a negative value depicts a leftward bias with more left reaches. A value of +1 corresponds to 100% right-handed reaches, −1 reflects 100% left-handed reaches, and a value of 0 indicates an equal amount of right- and left- handed reaches.

Lateral Biases in Nonreaching Movements. Laterality in spontaneous movements might be expressed in several ways: moving one limb more frequently or moving it farther distances. We chose to use the relative speed of the limbs because it directly reflects the forces activating the limbs (Thelen et al., 1993; Thelen et al., 1996). Also, if one hand was consistently more active than the other, we assumed that that hand was the one providing more perceptual–motor feedback to the system and therefore was the one to likely express a lateral dominance. Therefore, we analyzed the continuous stream of nonreaching activity to capture lateral bias in upper-arm movement patterns by applying a moving-window technique to the continuous resultant velocity profiles of both hands. A 1-s window size (150 data points) was shifted frame by frame along the entire velocity profile of the segment of data. At every shift of the window, we calculated the average speed performed by each hand within the 1-s window size and computed a laterality index using the same formula used to assess hand preference in reaching:

$$\frac{(\text{Average speed}_{\text{right hand}} - \text{Average speed}_{\text{left hand}})}{(\text{Average speed}_{\text{right hand}} + \text{Average speed}_{\text{left hand}})}$$

As for reaching, this formula provided a single value varying between +1 and −1 that described at every window shift which hand was more active (see Figure 1). A positive value indicated a rightward bias with a right hand more active; a negative value depicted a leftward bias with a left hand more active; a value of zero indicated no bias with both hands moving at the same speed. Likewise, a value of +1 indicated that only the right hand was active and −1 indicated that only the left hand was active. This way of computing the nonreaching data gave us a continuous description of speed difference performance between hands over time as illustrated in Figure 1. The kinematic data of Figure 1 show that both hands moved at similar speeds. This was captured by the laterality function that fluctuated around a zero value. In such a case, where the movements were obviously performed bimanually and in a synchronous fashion, we concluded that the movements expressed no lateral preference. However, if one hand moved consistently faster than the other, the laterality function would become positive or negative depending on which hand was the more active.

To reduce the continuous lateral function describing the evolution of speed differences between hands into a single value, we first condensed the laterality curves into a single frequency histogram (shown on Figure 1 for the 9-s segment of movement). The frequency histogram was obtained by dividing the continuous laterality scale from +1 to −1 into 20 equal ordinal categories and by summing within each category the number of data points observed within a category. These frequency values per week were then normalized by the total number of data points obtained during that week. Finally, we obtained a single laterality value per week by summing separately the positive and negative normalized frequency values and by computing their difference. That way, if the right hand was more active than the left, the final number was a positive value ranging from 1 to 100, where 100 meant that only the right hand was active. A negative value, ranging from −1 to −100, meant that the left hand was more active than the right hand, and a value close to zero meant that both hands were equally active. In the example provided in Figure 1, the frequency histogram is rather symmetrical. Therefore, the computation of the difference between the positive and negative values of the histogram would lead to a small

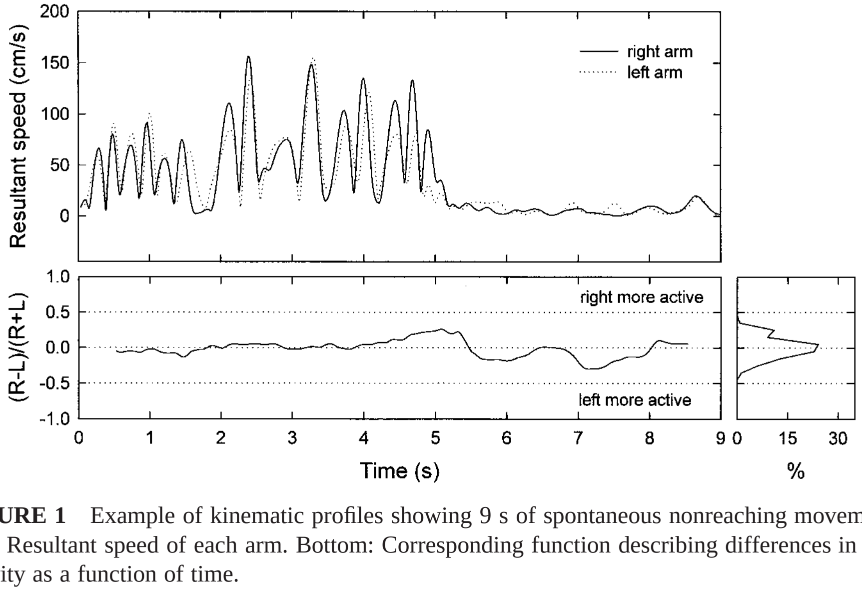

FIGURE 1 Example of kinematic profiles showing 9 s of spontaneous nonreaching movements. Top: Resultant speed of each arm. Bottom: Corresponding function describing differences in hand activity as a function of time.

number neighboring a zero value, confirming for that segment of data that there was no predominant lateral bias.

Results

Does the Development of Spontaneous Nonreaching Movements Show Fluctuating Asymmetries as Does Reaching? To compare reaching and nonreaching lateral biases as they evolved in the 4 subjects during the 1st year, we present both the reaching and nonreaching data in parallel for each infant separately. In addition, for each infant we briefly report our previous findings on interlimb coordination regarding changes between one- and two-handed reaching periods (Corbetta & Thelen, 1996). This allows examining in detail how lateral biases map onto patterns of interlimb coordination across the 1st year.

Infant HR. HR began to reach at 20 weeks old. From Week 20 to Week 27, she did not use a preferred unimanual or bimanual pattern for reaching; she reached for the toys indiscriminately with either one or two hands. Then, from Week 28, she alternated between periods of one- and two-handed reach preference. As shown on Figure 2a, HR had two bimanual reaching periods, one between 28 and 32 weeks old, and the other at Weeks 40 and 42. In between, from Week 30 and later from Week 44, she reached predominantly with one hand (Corbetta & Thelen, 1996).

HR's hand preference in reaching followed similar fluctuations (Figure 2a). During the two one-handed periods, from Week 34 and after Week 42, HR reached exclusively with her right hand. This rightward bias was weaker or even absent during the periods she reached with two hands or during the early weeks that followed reach onset. We calculated an overall index of hand preference for each infant that included all the reaches performed during the entire year using the same (R−L)/(R+L) formula. HR's overall hand-preference index for the year was .437, which was the highest index of the 4 infants.

A similar developmental picture emerged from the analysis of her nonreaching activity (Figure 2b). Her right arm was clearly more active than her left arm during the two unimanual periods. A rightward bias in nonreaching activity was also present during the first period following reaching onset. Surprisingly, however, before reach onset HR's spontaneous nonreaching activity revealed no consistent lateral bias.

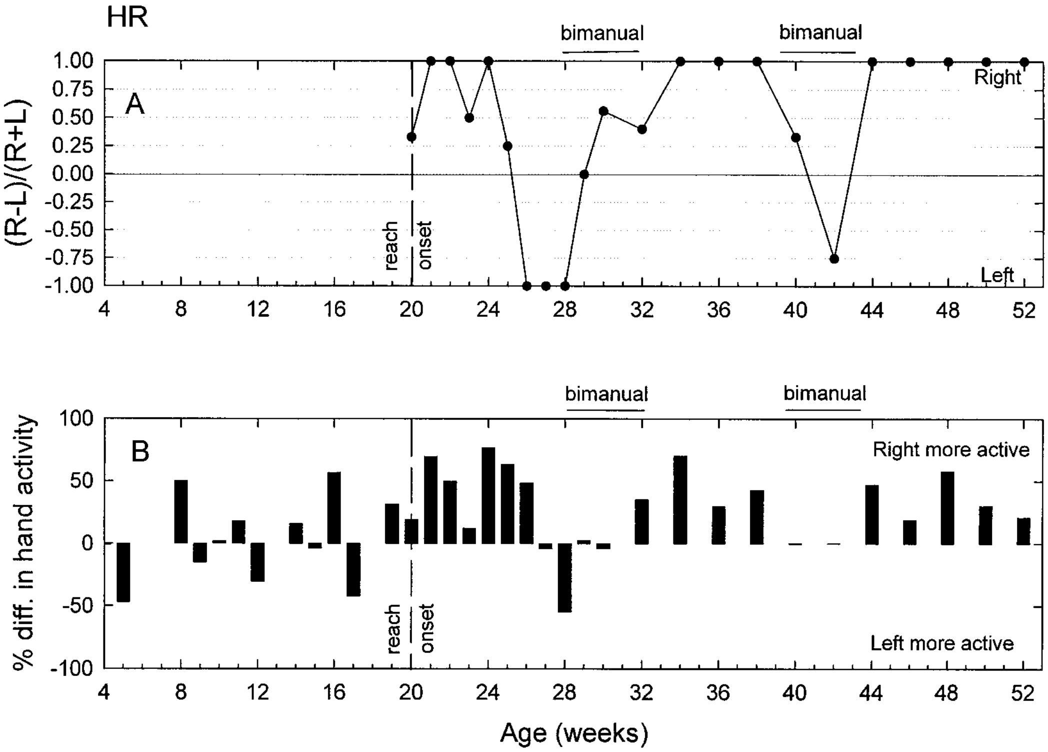

FIGURE 2 Lateral biases in reaching and nonreaching movements in Infant HR throughout the 1st year. (A) Hand preference in reaching. (B) Lateral biases in nonreaching movements.

Infant GS. Unlike HR, GS never showed clear periods of one-handed reaching. As described in previous reports (Corbetta & Thelen, 1996; Thelen et al., 1993; Thelen et al., 1996), GS was an active child who tended to jiggle and flap his arms around most of the time, often using symmetrical movements. His reaching patterns also remained predominantly bimanual from reach onset until the end of the year.

Accordingly, GS's hand preference in reaching showed weak and unstable lateral tendencies (Figure 3a). The development of GS's hand preference in reaching can almost be divided into two periods. A first period following reach onset seemed to reveal the progressive establishment of a rightward bias, where the right hand increasingly contacted the target first. The second period that began around Week 32, however, reflected the disappearance of this progressive rightward bias. From Week 32, GS's hand preference began to shift between right and left hand use. Although GS's overall hand-preference index for the year was positive, indicating a slight rightward bias, this index remained rather weak (= .206), which reflects his predominant bimanual behavior.

GS's nonreaching interlimb activity also revealed weak lateral differences between hand speeds (see Figure 3b). This result is consistent with the fact that GS was a highly bimanually active infant. Similar to his reaching tendency, GS's nonreaching activity revealed a predominant rightward bias during the weeks that followed reach onset. After Week 32, however, this rightward bias disappeared. As with HR, no consistent lateral biases were observed during the weeks preceding reach onset.

Infant NQ. NQ began to reach at 12 weeks of age using primarily two-handed patterns. He then shifted to one hand for reaching at Week 21 and maintained that behavioral mode until Week 42. Finally, between Weeks 44 and 52, he returned to two-handed reaching.

NQ's overall hand preference in reaching was also very unstable. Similarly to GS, NQ showed a first period with a predominant rightward bias during the weeks following reach onset. This rightward bias, however, disappeared after Week 30 (see Figure 4a). It is interesting to note that, when NQ shifted from two- to one-handed reaching at Week 21, he also shifted to a clear right-hand preference. However, he maintained this right-hand preference only for 1 month. Similarly to GS, NQ's overall index of hand preference for the year was rather weak (= .240).

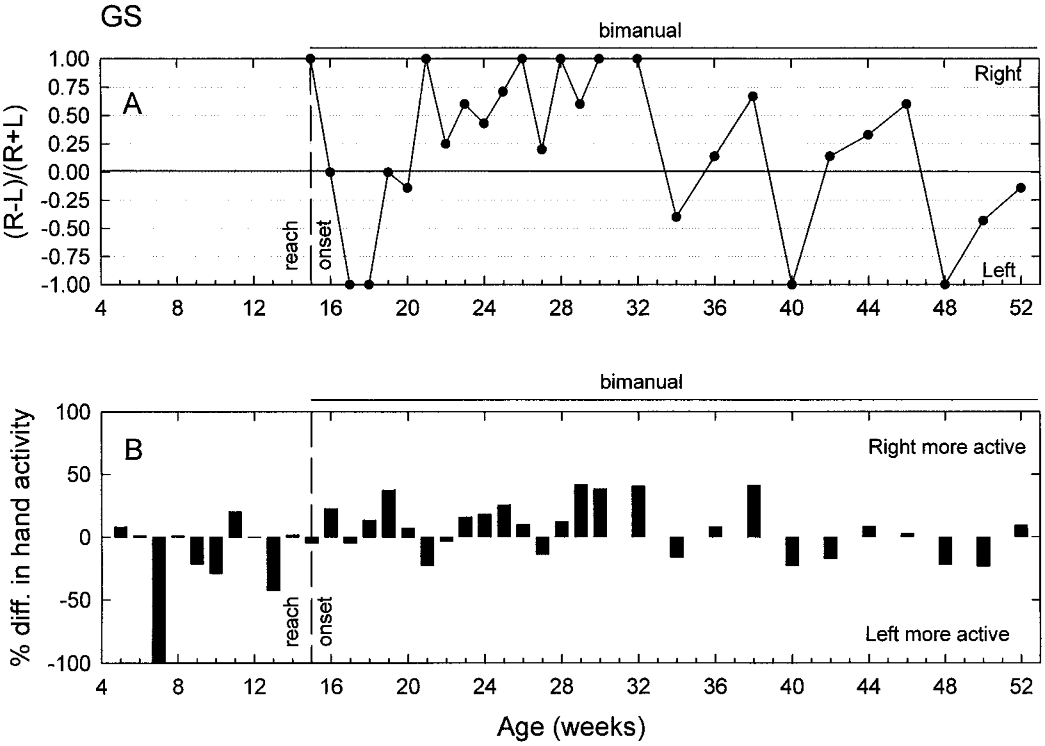

FIGURE 3 Lateral biases in reaching and nonreaching movements in Infant GS throughout the 1st year. (A) Hand preference in reaching. (B) Lateral biases in nonreaching movements.

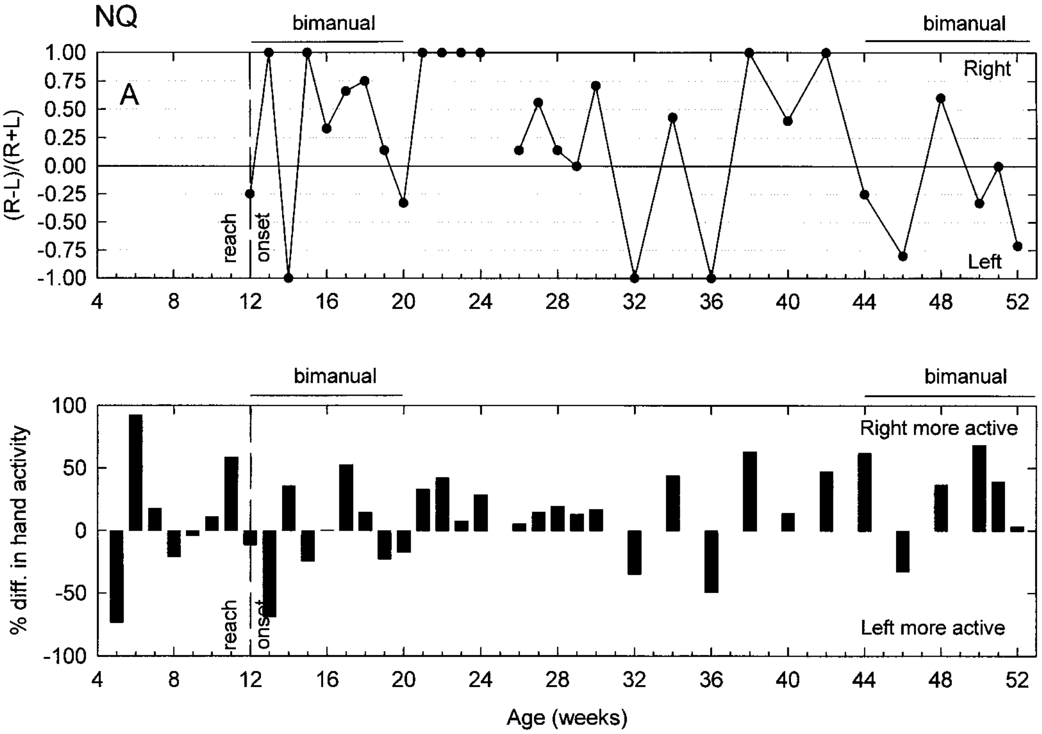

FIGURE 4 Lateral biases in reaching and nonreaching movements in Infant NQ throughout the 1st year. (A) Hand preference in reaching. (B) Lateral biases in nonreaching movements.

NQ's overall nonreaching activity revealed a much more predominant rightward bias than in reaching (see Figure 4b). NQ's right arm tended to move faster than his left most of the year except for a few weeks here and there. This nonreaching rightward bias seemed to become slightly predominant and consistent from Week 21 when NQ shifted from two- to one-handed reaching. Similarly to HR and GS, NQ did not show consistent lateral bias during the weeks preceding reach onset.

Infant JA. JA, like GS, never showed a clear period of one-handed reaching activity. JA began to reach at 21 weeks of age using predominantly two hands. From Week 25 to Week 38, he reached mixing either one- or two-handed reaching patterns. Finally, from Week 40 until the end of the year, he returned to two-handed reaching (Corbetta & Thelen, 1996).

JA's development of hand preference in reaching was also very unstable (see Figure 5a). From reach onset, JA's hand use continuously fluctuated between right and left. He never seemed to show a consistent preference for one side. As a result, JA's overall hand-preference index for the year was one of the lowest (= .172).

JA's nonreaching activity did not reveal consistent lateral biases either, except during the weeks preceding reach onset where JA demonstrated a clear rightward bias (see Figure 5b). After reach onset until the end of the year, JA's nonreaching lateral tendencies shifted continuously between right- and left-predominant activities.

Do Changes in Arm Control Throughout the 1st Year Increase the Lateral Coherence Between Reaching and Nonreaching Activity? We suggested that when infants learn to reach and have poor control of their arms, they may not always use the arm matching their preferred or more-active side because they are still solving the complex perceptual–motor processes involved in the act of reaching. If this prediction is true, we should find a greater coherence between reaching and nonreaching lateral biases later in the year than following reach onset. To assess the degree of coherence between reaching and nonreaching lateral biases as a function of changes in arm control, we divided the 1st-year data into two periods—a first unstable reaching period and a second stable reaching period—based on findings from a previous report (Thelen et al., 1996). In that report we analyzed the movement kinematics of the reaching arm making first contact with the target. We found that all 4 infants developed

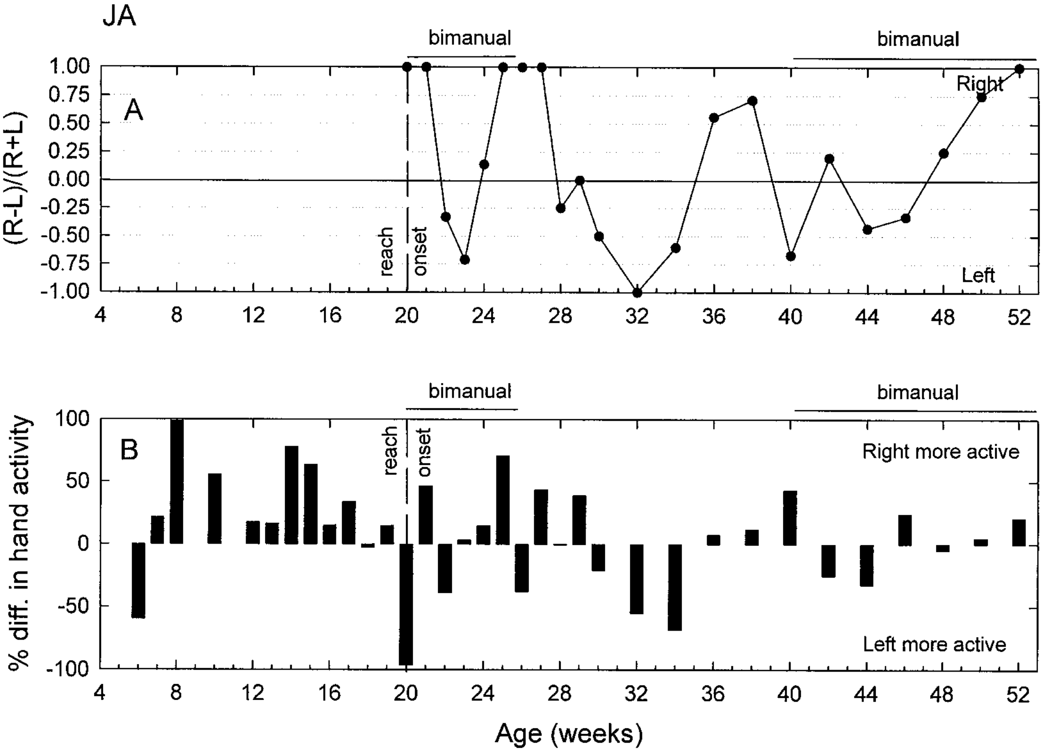

FIGURE 5 Lateral biases in reaching and nonreaching movements in Infant JA throughout the 1st year. (A) Hand preference in reaching. (B) Lateral biases in nonreaching movements.

rather stable reaching trajectories after 30–36 weeks of age. Before 30–36 weeks, infants showed highly variable reaching trajectories with tortuous paths composed of several and radical changes in movement speeds, indicating lack of stable arm control. The degree of coherence between reaching and nonreaching lateral biases was obtained by applying a Spearman rank order correlation on the lateral biases corresponding to the unstable and stable reaching periods of each infant. The results of this analysis are presented in Table 1.

Results are suggestive, but not conclusive in this small sample. Three of the 4 infants demonstrated a significant correlation between reaching and nonreaching lateral biases during the stable reaching period. Only HR revealed a significant correlation between reaching and non-reaching lateral biases during the initial unstable reaching period. JR had weak correlations in both periods. No infants had negative correlations. This suggests, as predicted, that improvements in arm control increased the lateral coherence between reaching and nonreaching movements. Thus, as infants begin to solve the issues of arm control, the more active arm is more likely to be used for reaching. But this relation between arm control, arm activity, and arm used for reaching is apparently independent from the formation of a stable direction in hand preference.

Discussion of Study 1

All 4 infants demonstrated unstable and fluctuating developmental lateral biases in both reaching and nonreaching movements during the 1st year. This con-

Table 1. Correlations between Reaching and Nonreaching Lateral Biases as a Function of Period of Reaching Stability Per Infant

Infant	Unstable Reaching Period	Stable Reaching Period
HR	Weeks 20–34	Weeks 36–52†
r	0.675*	0.707*
n	13	9
GS	Weeks 15–30	Weeks 32–52†
r	−0.001	0.813**
n	16	11
NQ	Weeks 12–30	Weeks 32–52†
r	0.107	0.656*
n	18	12
JA	Weeks 20–30	Weeks 32–52†
r	0.305	0.355
n	11	11

†Stable and unstable reaching periods as defined in Thelen et al., 1996.

*$p < .05$. **$p < .001$.

firms previous findings that hand preference does not develop in a progressive, linear manner, but rather is marked by highly individually defined discontinuities, shifts, and abrupt transitions (Gesell & Ames, 1947). Despite these individual fluctuations, the data showed common trends as well. First, in all 4 infants, reaching and nonreaching lateral tendencies were to some extent related to each other. However, the coherence between reaching and nonreaching was stronger toward the end of the 1st year, when overall arm control in reaching was more stable, than in the weeks following reach onset when reaches were less smooth and straight and more variable. Second, these data revealed that when we detected somewhat consistent biases in reaching, they also showed up in nonreaching movements. Likewise, when these reaching biases disappeared or became inconsistent, these inconsistencies also appeared in the nonreaching activity. Finally, these data revealed that despite their highly individual and changing developmental curves, all infants traversed periods where rightward tendencies predominated for several weeks in a row. Leftward tendencies, in contrast, appeared more sporadically and were usually of short duration.

Our next question thus concerns the later outcome of these rightward tendencies. Are these 1st-year rightward biases, even though ephemeral, predictors of later right hand preference? This question is addressed in the second part of the study. When HR, GS, JA, and NQ were beyond 3 years old, we visited them again in order to assess the direction of their hand preference. As shown by previous studies, the degree to which hand preference is established in 3-year-olds is still quite variable, but the direction of the preference can be identified (McManus et al., 1988). However, because there are no standard tests to assess hand preference in young children (as there are for adults) and because we could not just rely on parents' and children's verbal reports regarding their hand use, we designed our own assessment tasks. To validate these tasks and make sure that they provided us with accurate tools to assess the direction of hand preference, we extended our assessment to additional 3-year-old children (including the 4 longitudinal ones) and a group of adults.

PART 2: THREE-YEAR-OLD HAND-PREFERENCE ASSESSMENT

Methods

Participants. The 4 longitudinal infants were contacted again in their 4th year to assess the direction of their hand preference. NQ, GS, and HR were respectively 3:8, 3:8, and 3:6 (years:months) at the assessment time. JA, who moved out of town and was harder to locate, was 4:1 when assessed. Twenty-one participants were added to this part of the study to validate our tasks. They were ten 3-year-olds (5 boys and 5 girls aged between 3:1 and 3:8, $M = 3{:}4$) and 11 adults (6 males and 5 females aged between 19:1 and 26:1 years old, $M = 20{:}4$). They were recruited through local advertisements and received a small gift for their participation.

Materials. We used 12 children's toys to assess hand preference in both children and adults. Some toys required one-handed object manipulation while others necessitated a complementary two-handed activity. We chose all toys because (a) they required simple and specific manipulations that made the identification of hand preference easy; (b) they were colorful, fun, and engaging to the children; and (c) they were not difficult to manipulate by 3-year-olds. The list of toys we used included a "Bozo" board with a foam ball that stuck to the board covered with velcro material, a colorful xylophone with a small mallet, two yellow plastic buckets with a green plastic shovel and a bag of dried beans, a set of color crayons and a coloring book, a "Teddy-Beddy Bear" contained in a box that popped up when a front roller was turned, a child's cordless phone, a set of 15 yellow, red, green, and blue large Legos, 10 small blocks of different shapes that could be inserted in a cylindrical container through corresponding holes in the lid, a small house with five different colored doors which had matching colored plastic keys to unlock the doors, a puppy bank with coins, a doll with a baby spoon and a baby bowl, and a child's puzzle with handles on each piece.

We recorded the entire session with a portable video camera. The videotapes were used for later behavioral analysis.

Design and Procedure. We tested all the adults and a few children in the Infant Motor Development Laboratory. The other children were tested in their homes following their parents' preferences. Testing always took place on a low coffee table with the participant and one experimenter sitting on the floor on either side of the table and facing each other.

We assessed handedness by presenting the participants with the 12 different toys/tasks (hidden in a black bag) one at a time and in a random order. We presented every task as a game and repeated each task at least four times in order to obtain repeated measures of hand use for reaching an object and for manipulating that object in specific ways. We always offered

Table 2. Criterion Used to Score Hand Preference for Each Task According to Each Category of Behavior (Reaching vs. Specialized Activity)

Tasks	Reaching	Specialized Activity
Bozo board	Hand that reached for ball presented at midline	Hand that threw ball at board
Xylophone	Hand that reached for mallet presented at midline	Hand that used mallet to play tune
Buckets	Hand that reached for shovel presented at midline	Hand that held shovel to transfer beans
Crayons	Hand that reached for crayons at midline	Hand that held crayon to color
Teddy Bear	n/a	Hand that spun roller to open box
Cordless phone	n/a	Hand that dialed phone number
Legos	Hand that removed Lego pieces from block	Hand that added Lego pieces to block
Cylinder	Hand that retrieved blocks from cylinder	Hand that inserted block through lid
Keys	Hand that reached for keys presented at midline	Hand that manipulated key to open door
Puppy bank	Hand that reached for coin presented at midline	Hand that inserted coin in bank
Doll	Hand that reached for spoon presented at midline	Hand that held spoon to feed doll
Puzzle	Hand that reached for puzzle piece at midline	Hand that inserted puzzle pieces on board

toys to the participants at midline in order to not influence the use of one hand over the other. Table 2 provides a brief description of the tasks and behaviors involved. Each task contained two behavioral components used for assessing hand preference: (a) reaching for an object and (b) manipulating that object in a specific way, which we defined on Table 2 as specialized activity. Reaching always corresponded to the hand used to reach for the crayon, mallet, ball, or block at midline. The specialized activity corresponded to the hand used for a specific task, such as coloring with the crayon, hammering with the mallet, throwing the ball, or inserting the block in the appropriate hole.

The adults performed these 12 tasks in the same way as the children. However, adults were also asked to answer the Bryden's (1977) hand-preference questionnaire in order to evaluate whether our custom-made tasks were leading to a comparable hand-preference assessment.

Scoring: The videotapes were viewed and coded by two experimenters who worked together. For each task, hand preference was scored according to the two categories of behavior defined in Table 2: the hand used for reaching versus the hand used to perform a specialized activity. The "Teddy Bear" and cordless phone tasks were coded only for specialized activity; there was no reaching involved in turning the front roller of the Teddy Bear and the phone was reached for only once.

We scored each behavior as right, left, or bimanual. Bimanual was used when both hands were used together to perform the same task (for example, when both hands were holding the key while inserting it in the door). Only the first four relevant actions for each completed task were coded. For each repeated measure, a score of 1 was assigned to the hand used. If the behavior was bimanual, each hand received a score of .5. Then, we computed a hand-preference score by task and by subject using the same formula as in Part 1 of the study. That is, we summed the number of right-handed behaviors versus the number of left-handed behaviors and computed these values as follow: $(R-L)/(R+L)$. Reliability in analyzing the tapes was obtained by recoding randomly across subjects 20% of the previously coded tasks. The overall reliability coding was above 90% for both reaching and specialized activities.

Results

Did Our 12 Tasks Appropriately Measure Hand Preference? To answer this question, we correlated the pairs of individual hand-preference scores obtained for each adult by using both our 12 custom tasks and the Bryden's questionnaire. If our testing is a good measure of hand preference, we should find comparable hand-preference scores across tests for the same participants; that is, adults who rated high on Bryden's questionnaire should also rate high in our tasks, and adults who rated low on one test should also rate low on the other test.

The correlation coefficient between assessment scores (Bryden vs. our 12 tasks) obtained using a linear regression equation were .73 for reaching and .78 for the specialized activities (both correlation values were significant at $p < .01$). In other words, our 12 tasks led to a hand-preference assessment that was comparable to Bryden's questionnaire when used with mature individuals with established lateral preferences.

Would Some Tasks Provide a More Consistent and Less Variable Hand-Preference Assessment than Others? Our second concern was to determine how our tasks would measure hand preference in 3-year-olds, knowing that children of this age still show a lot of variability in their lateral preferences (McManus et al., 1988). To address this issue, we compared the adults' hand-preference scores with those of the 3-year-olds by grouping the individual scores per task into one of three categories: (a) Clear right- or left-hand preference, which included the scores ranging between .75 and 1.0 and between −.75 and −1.0; (b) right- or left-biased, which included the scores ranging between .25 and .74 and between −.25 and −.74; and (c) no preference, which included the scores ranging between −.24 and .24. We used the number of subjects whose scores fell within one of these three categories for each task to identify whether all 12 tasks provided an equally reliable measure of hand preference, or, if some tasks appeared to show less consistent and more variable hand-preference responses across subjects. Figures 6 and 7 show the frequencies of these ranked hand-preference scores by task and per group (adults vs. children) for both reaching (Figure 6) and specialized activities (Figure 7).

Both figures display similar results whether the behaviors were reaching or specialized activities and whether the subjects were adults or children. The tasks that showed high and consistent hand preference across subjects were the xylophone, the buckets, the Bozo board, the crayons, the keys, and the puppy bank. The other tasks (the cylinder, the Teddy Beddy Bear, the puzzle, and Legos) revealed more intersubject variability.

Were HR, GS, NQ, and JA Predominantly Right-Handed as We Predicted from Their 1^st^-Year Longitudinal Data? Figure 8 displays the individual hand- preference scores of HR, GS, JA, and NQ for each task according to reaching or specialized activity. All 4 children displayed a clear right-handed dominance, even though this dominance was modulated by certain tasks and resulted in different degrees of hand preference depending on the behavior (reaching vs. specialized activities). Note that HR, who showed the strongest rightward lateral index in the 1st year, also revealed a more consistent, dominant right-hand use for reaching and manipulating toys at 3 years old (average index across tasks for reaching = .740; for specialized activity = .850). JA, who revealed the weakest lateral bias in his 1st year, also had the lowest lateral index in his 4th year (average index across tasks for reaching = . 540; for specialized activity = .723).

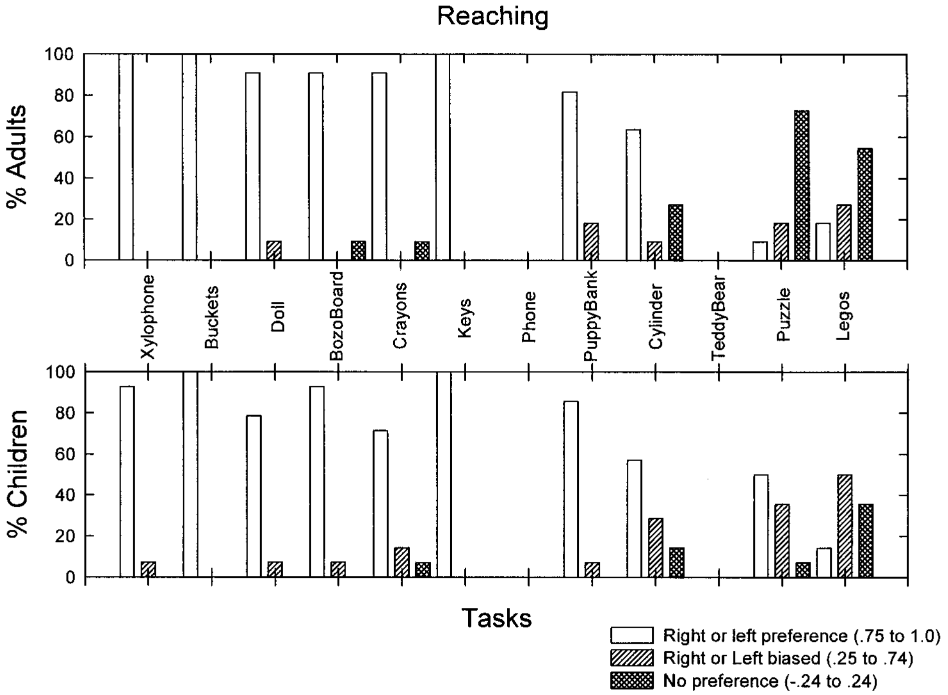

FIGURE 6 Distribution of hand-preference scores for reaching in children and adults as a function of task.

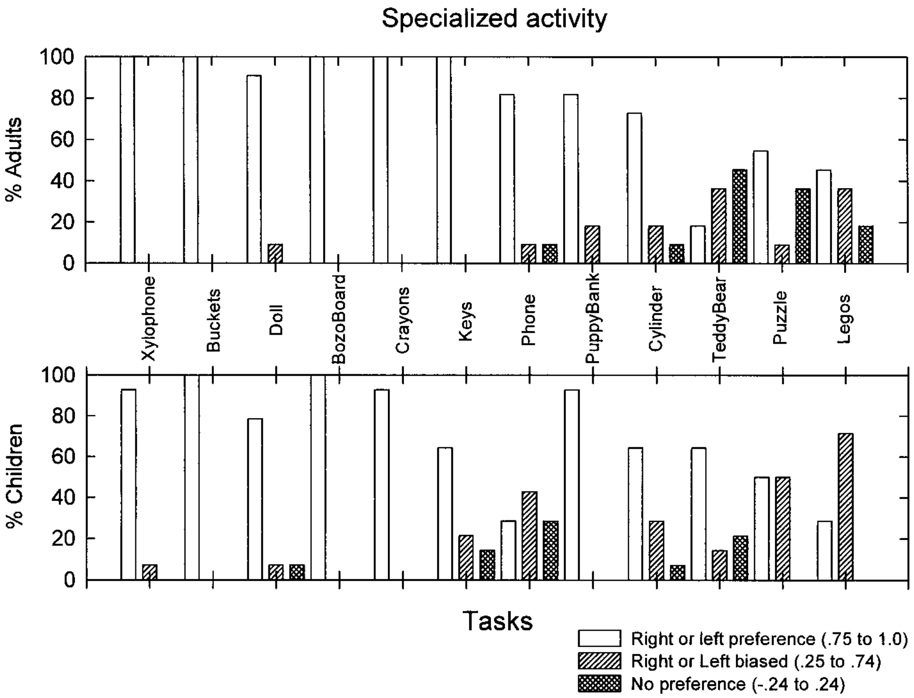

FIGURE 7 Distribution of hand-preference scores for specialized activities in children and adults as a function of task.

DISCUSSION

How does hand preference develop? This question motivated the present article and was primarily addressed through the examination of three aspects of the development of hand preference. The first concerned the natural evolution and formation of lateral asymmetries in spontaneous, nonreaching movements throughout the 1st year of life. As stated previously, several studies have pointed out the fluctuating, highly changing, and unstable characteristics of hand preference in infant reaching. This study revealed that

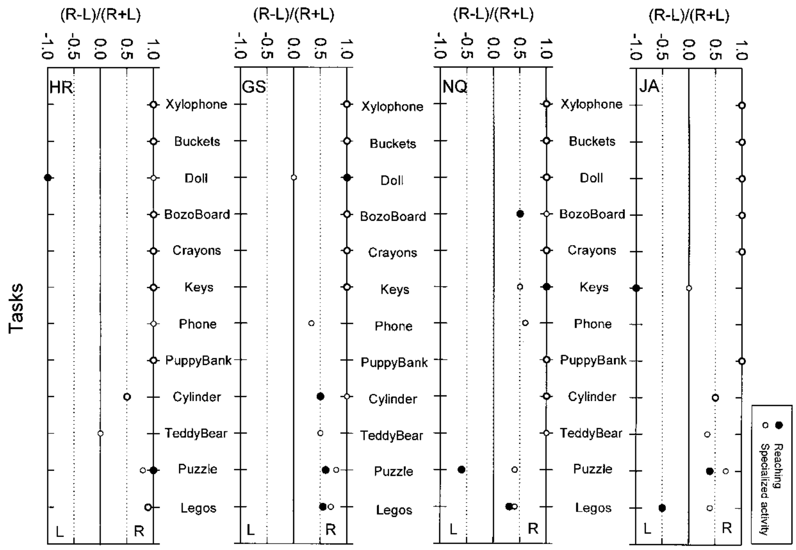

FIGURE 8 Hand-preference scores of HR, GS, NQ, and JA as a function of task and behavior (reaching vs. specialized activities) at 3 years of age.

spontaneous, nonreaching patterns similarly fluctuated throughout the 1st year and demonstrated extremely unstable lateral tendencies.

These shifts and fluctuations in nonreaching movements occurred despite our efforts to maintain our weekly sessions and conditions of testing as identically as possible throughout the 1st year. Therefore, these changes and shifts in hand activities were minimally related to variations in testing. In addition, our measure of spontaneous movement asymmetry was based on speed differences between arms. Speed difference between arms was entirely defined and self-generated by infants' spontaneous levels of activity and was not induced by any specific external asymmetrical task constraints or postures. For that reason, we believe that our speed measure between arms was an appropriate measure to capture the naturally developing asymmetries of the organisms in absence of task constraints. The fact that these spontaneous asymmetries fluctuated throughout the 1st year confirmed that the development of hand preference is not straightforward, but instead is marked by a series of shifts and transitions at least throughout the 1st year.

Second, we compared reaching and nonreaching asymmetries in connection with learning to reach and the associated problems of controlling the limb to reach a target. Because learning to reach is a difficult and rather long process that involves the mastery and control of both perceptual and motor coordination, we assumed that the lateral discrepancies between reaching and nonreaching asymmetries would be greater in the weeks following reach onset than at the end of the 1st year. Our argument was that poor arm control would interfere with the emergence of preferred asymmetries in reaching and reveal a greater mismatch between the more active arm and the arm used for reaching. Except for JA, who never showed coherent lateral biases between reaching and nonreaching movements, our longitudinal infants did verify this prediction. As arm control in reaching improved, the lateral coherence between reaching arm and more active arm in nonreaching movements also increased. What was surprising and rather unexpected, however, was that stable asymmetries tended to be more manifest earlier during the unstable arm control period than later during the stable arm control period. In other words, progress in controlling the arm and increased stability in reach trajectory did not correlate with the formation of hand preference or the establishment of more stable asymmetries.

Nonetheless, over a longer time scale, stable asymmetries did emerge. The third issue raised by this research asked whether temporary lateral tendencies observed during the 1st year predicted the direction of later hand preference. The 1st year data revealed that all infants traversed at least one period where they demonstrated a predominant rightward bias, while they never showed a consistent leftward bias. Our assessment of hand preference performed with these same children in their 4th year clearly indicated their predominant right-hand preference.

The question that remains to be answered, then, is how to reconcile the fluctuating patterns of hand use in the 1st year with the establishment of right-handedness in the 4th year? And how can we reconcile these data with other studies that showed, for example, that preferred head rotations correlate with later hand preference (see Coryell, 1985; Michel, 1981; Turkewitz, 1977)? We think these data are best understood from a dynamic systems perspective. Dynamic systems views changes and transitions as the result of complex interactions between multiple behavioral components. Therefore, within this perspective, changes that occur at one behavioral level may be influenced by changes occurring at other behavioral levels (Thelen, 1986). For instance, we could speculate that developmental shifts in lateral biases may be influenced by postural shifts as infants learn to sit, crawl, and walk. Previous studies have already suggested that changes in interlimb coordination or lateral preference during the 1st year may be linked to changes in postural control (Corbetta & Thelen, 1996; Goldfield, 1993; Rochat, 1992). Rochat (1992), for example, found that infants reach more unimanually when they are able to sit alone, while they tend to reach more bimanually before the emergence of independent sitting. Goldfield (1993) reported that infants produce more lateralized and unimanual behaviors following the onset of crawling. Additional observations on our longitudinal infants provide similar evidence supporting the view of possible interactions between postural transitions and shifts in hand preference and lateral biases in the 1st year. Thelen and Smith (1994), for instance, provided data on NQ's postural shifts throughout the 1st year as he learned to reach. NQ's onset of unimanual and right-handed reaching coincided with the onset of hand and knee posture. The later disruption and disappearance of NQ's rightward bias at Week 26 and return of two-handed reaching at Week 46 coincided with the respective onsets of crawling and walking. Similar links between crawling onset and disruption of hand preference were observed for the other 3 children (Vereijken et al., 1998). HR began to adopt a hand and knee posture at Week 38 and began to crawl shortly after at Week 42. This period between Weeks 38 and 44 corresponded to the second period during which HR's right-hand preference was disrupted. GS's crawling onset emerged at

Week 30. Again, following this period GS's rightward bias in reaching and nonreaching movements disappeared. For JA, this link between crawling and hand preference is not as clear because he never showed a clear period of stability in hand use after reach onset. However, consistently with the other children, JA's crawling onset which appeared at Week 36 was followed by an unstable hand preference in reaching and nonreaching movements. Only NQ began to walk toward the end of the 1st year matching a return to two-handed reaching. This coincident return to two-handedness during the onset of walking was recently tested by Corbetta (1997) with a larger number of infants. That study was specifically designed to assess whether patterns of interlimb coordination and hand preference would change as infants learn to walk. In that study, Corbetta (1997) followed 10 infants longitudinally throughout the transition from crawling to independent walking. She discovered that during the crawling period, infants displayed relatively consistent unimanual and lateral patterns in reaching for small objects, although hand preference was not always stable. When they began to walk independently, however, they lost these lateral tendencies and began to reach for small objects primarily bimanually for several weeks in a row. When infants gained relatively stable gait patterns and developed relatively stable balance control, unimanual patterns reappeared. These observed links between the onsets of crawling and walking and the development of hand use for reaching and manipulating objects are consistent with the hypothesis that lateral preferences may reorganize several times during the 1st year as other motor abilities develop. Crawling, in particular, seems to break coupling between arms favoring alternate and unimanual responses while walking may increase coupling, replacing the rate of unimanual responses by increasing bimanual responses in reaching. In addition, both crawling and walking seem to contribute to the reduction of stable lateral preferences. The data in the present article do show that lateral biases tend to disappear in the second half of the 1st year, when infants are indeed developing crawling and walking skills successively.

If postural shifts affect lateral tendencies in development, how can we explain that many studies, including the present study, still found a coherent match between early lateral biases and later hand preference? And how can we account for the fact that 90% of the population becomes right-handed besides these early fluctuations in hand preference? A possible explanation could be that newborns begin to develop preferred initial lateral asymmetries while in the womb and that these asymmetries are already biased to the development of a right-sided dominance in the system (Previc, 1991). But, we contend that these early asymmetries are not rigid and certainly not resilient to significant postural perturbations that would destabilize these preferred asymmetries. Note that preferred head rotations in newborns were identified when infants were lying supine and resting on a surface that provided stable postural support. Activity performed against gravity tends to disrupt the manifestation of these early lateral tendencies. Once infants gradually gain successive stable postures, each new postural milestone can be seen as a new destabilizing period that requires recalibration or reorganization of the whole system. This cascading process or "snowball effect" to reuse Hellige's (1993) expression, may, in turn, affect the expression of stable or latent lateral tendencies. Clearly, additional investigations will be necessary. Nonetheless, that both reaching and nonreaching patterns fluctuated somewhat similarly throughout the 1st year is consistent with the explanation that lateral biases may be sensitive to more general and pervasive motor changes such as the reorganization of the overall postural system. We can only speculate on what happened in the 2nd and 3rd year of these infants because we did not continually follow the development of their upper arm activity during that time. But it may not be a coincidence that hand preference begins to stabilize around 3 years of age when most of these fundamental reorganizations of the postural system have already taken place in a child's life.

This work obviously calls for additional investigations and especially for more studies that would parallel the concomitant development of several behavioral skills. Because we had a small sample of only 4 infants during the 1st year, we need to be cautious in our interpretations. We argued that shifts in posture may be a factor influencing the developmental stability of early lateral biases. Although some data are suggestive of such interpretation, more evidence is needed to substantiate it. Also, we are aware that posture may not be the only factor. As we know, the lateralization of function of upper arm coordination may be linked to other developing subsystems such as the emergence of speech (Ramsay, 1984, 1985a), the refinement of hand control and manipulative skills (Napier, 1980), or even social factors such as the interaction between caregiver and child (Harkins & Michel, 1988; Harkins & Uzgiris, 1991). Recently, Provins (1997) provided compelling evidence that lateral preferences may not be predetermined but rather progressively shaped as a function of practice and experience throughout one's life development. This practice and experience is primarily developed in a world favoring right-hand use, although the development of left-hand use may also be influenced by children's surrounding environment (Harkins & Michel, 1988; Harkins & Uzgiris, 1991). What is certain is that this study showed that the development of hand preference is not a rigid behavioral dimension that is inherent in the system and does not change. The highly fluctuating lateral biases documented in the present article suggest that early movement asymmetries are rather flexible and subject to significant changes before settling into a preferred direction. These changes may be linked to new developing motor experiences such as learning to sit, crawl, and walk. Provins (1997) also suggested that what is inherent in the system and possibly inherited is the strength of the lateral preferences, not the direction. Again, our data would be consistent with such interpretation. HR had stronger lateral biases early and later in development, and JA had weaker lateral preferences early and later in development, although we may again caution the validity of such interpretation given our small sample. However, regardless of sample size, this study clearly demonstrates that extreme care needs to be taken in interpreting cross-sectional studies that assess hand preference in infants at one given point in time. That point in time may not reflect the predominant tendencies of the system and certainly does not reflect the complex developmental history of the system.

NOTES

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