Postural Influences on the Development of Infant Lateralized and Symmetric Hand-Use

By: Iryna Babik, Julie M. Campbell, George F. Michel

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Abstract:

Within-individual variability is such an apparent characteristic of infant handedness that handedness is believed to consolidate only in childhood. Research showed that manifest handedness is influenced by emerging postural skills (sitting, crawling, and walking). In this investigation, it was proposed that symmetric hand-use (tendency to acquire objects bimanually), rather than lateralized hand-use (the use of one hand more than the other), may be influenced by postural changes. Trajectories of lateralized and symmetric hand-use for object acquisition were examined in 275 infants tested monthly from 6 to 14 months. Multilevel modeling revealed that change in lateralized hand-use is unrelated to developmental transitions in infant posture, whereas the trajectory of symmetric hand-use changes significantly with the development of postural skills.

Keywords: handedness | hand preference | infant | toddler | bimanual

Article:

Handedness represents an easily observable sensorimotor skill that reflects a distinct lateralized asymmetry in hemispheric functioning (Serrien, Ivry, & Swinnen, 2006). Thus, the early development of handedness (or lateralized hand-use) could serve as a model for the exploration of the development of other forms of hemispheric lateralization (Michel, 1983, 1988). However, many have argued that handedness in infancy is not a stable trait and cannot be reliably identified until the ages of 3–4 years (McManus et al., 1988) or even 8–9 years (Fennell, Satz, & Morris, 1983). Indeed, within-individual variability has been reported to be a prominent characteristic of infant manual asymmetries and interlimb coordination development (Corbetta & Thelen, 1999, 2002; Fagard, 1998; Fagard & Lockman, 2005; McCormick & Maurer, 1988; Piek, 2002; Thelen, 1995; Thelen, Corbetta, & Spencer, 1996). Across observation periods, infants appear to change their preferences in hand-use for reaching and manipulating objects as well as their choice of one-handed versus two-handed strategies (Fagard & Lockman, 2005).

Several researchers have proposed that fluctuations in handedness development could be explained from a dynamic systems perspective as a function of developing postural skills (Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996, 2002; Fagard & Lockman, 2005). As infants acquire new skills like sitting, crawling, and walking, they must control their posture and movements, as well as explore new ways of using their hands. Such exploration interferes with the established patterns of handedness. Rochat (1992) and Goldfield (1993) reported that the mastery of sitting as well as the emergence of crawling shifts infants' hand-use toward unimanual reaching, thereby increasing the lateralization of hand-use. Goldfield (1989), when examining the transition from rocking to crawling, argued that infants rock during a period when they show mostly bimanual reaching, and start crawling when they exhibit a strong hand preference for reaching.

According to Thelen's dynamic systems perspective (e.g., Corbetta & Thelen, 1996), as an infant's system makes a transition to building a skill in posture (locomotion), manual actions are recruited into that process. Thus, if an infant exhibits a unimanual or bimanual hand-use when reaching for and acquiring objects, that pattern will be either facilitated or disrupted depending upon the posture (locomotion) skill that the infant is in the process of mastering. If the infant initiates crawling with a preferred hand, then the act of crawling facilitates the infant's unimanual hand-use, and he or she will show a facilitated asymmetric hand-use when reaching for toys during play while sitting at a table. Similarly, when the infant starts walking, the arms must be recruited in a symmetric manner to sustain balance, and the same pattern of increased manual symmetry is proposed to occur when the infant is reaching for toys (e.g., Corbetta & Bojczyk, 2002).

Corbetta and Thelen (2002) proposed that infant hand-use might become less lateralized by the end of the 1st year because they undergo several postural changes as they develop from mainly a sitting postural position toward an upright standing or walking posture. Corbetta and Bojczyk (2002) reported that infants significantly increase bimanual reaching at the onset of independent walking toward the end of their 1st year; thereafter, the proportion of both-hand reaches declines as upright locomotion improves and infants gain better balance control. Similarly, Berger, Friedman, and Polis (2011) found that infants decreased in their lateral preferences for reaching with the emergence of walking. Thus, since upright locomotion imposes new constraints on balance control, which has consequences on head and arm control, it may interfere with established reaching preferences (Corbetta & Bojczyk, 2002).

It is important to distinguish between lateralized and symmetric hand-use for the current investigation. Lateralized hand-use for acquiring objects refers to the use of one hand more than the other hand (when using only one hand and not engaging in bimanual movements). Thus, we suggest that an infant using primarily the right (or left) hand for reaching and acquisition is more lateralized than another infant frequently alternating between the hands. In contrast, symmetric hand-use to acquire objects refers to the simultaneous use of both hands. An infant who reaches for and acquires toys mostly bimanually is more symmetric in his or her hand-use than another infant that is doing mostly unimanual reaches and acquisitions.

When describing fluctuations in infants' handedness, researchers typically refer to shifts between unimanual and bimanual reaching during development. Thus, some reported a shift of infant handedness toward unimanual reaching at the onset of sitting and crawling (Goldfield, 1993; Rochat, 1992), whereas others reported a shift toward bimanual reaching by the end of the 1st year (Corbetta & Bojczyk, 2002). We suggest that the fluctuations that are often reported in studies measuring hand-use are fluctuations in manual symmetry rather than fluctuations in manual lateralization. Therefore, one of the goals of this study is to explore whether lateralized or symmetric (or both) hand-use changes significantly with acquisition of motor milestones such as sitting, crawling, and walking.

Another goal of this study is to examine the relation of the infant's sex to the manifestation of hand-use since handedness has been reported to vary between the sexes. Although males were previously reported to be less lateralized than females when handedness was assessed with a questionnaire (e.g., Annett, 1985), males seem to be more lateralized than females in hemispheric specialization of function in the majority of pioneer studies that used a variety of methodologies such as dichotic listening, tachistoscopic presentation, electrophysiology, and the assessment of brain damaged individuals (Lake & Bryden, 1976; Lansdell, 1962; McGlone, 1978; Shaywitz et al., 1995; Van Dyke et al., 2009; Witelson, 1976).

Moreover, handedness seems to interact with sex when assessing lateralized differences in hemispheric functions. Thus, Herron (1980) reported that left-handed females have less functional differentiation between the two hemispheres than left-handed males, whereas right-handers do not show any sex differences. Moreover, a large-scale meta-analysis (Papadatou-Pastou, Martin, Munafò, & Jones, 2008) found that the odds of a male being left-handed were significantly greater than for females, irrespective of the mode of handedness classification. Therefore, this study includes the infant's sex, handedness status, and their interaction as possible predictors in the modeling of the development of lateralized and symmetric hand-use during the acquisition of objects.

The previous studies that examined the influence of postural constraints on the development of reaching involved small samples (4–10 subjects). This study employs a large sample of 275 infants tested longitudinally at monthly intervals from 6 to 14 months of age to examine the relation of postural development to the developmental trajectories of lateralized and symmetric hand-use for object acquisition while controlling for the sex and handedness status of participants.

Method

Participants

Two hundred seventy-five infants (155 males, 120 females) from full-term pregnancies (a minimum of 37 weeks gestation) and uncomplicated single births completed participation in the study. The sample represents a subset of approximately 330 infants who visited the lab for testing. Selection for this subset involved completion of at least eight of the total nine monthly visits (85% provided data for all nine time points). The sample was ethnically diverse: 53% of Caucasian, 28% of African American, 3% of Hispanic or Latino, 3% of Asian, and 13% of mixed ethnicity. All infants were tested monthly between 6 and 14 months of age within ± 7 days from infants' monthly birthdays. Mean age at the beginning of the study was 6.08 months (SD = 0.16) and at the end of the study was 14.23 months (SD = 0.17).

Procedure

For each observation visit, infants' handedness patterns and development of postural control were assessed in the Infant Development Center at the University of North Carolina at Greensboro. The procedure for recruitment, obtaining informed consent, data collection, and presentation was in accordance with the regulations set by the UNCG Institutional Review Board for the protection of human subjects. Parents received a $10 gift certificate as compensation for each of their visits to the laboratory.

Assessment of the development of postural control

Infants were tested on three items from Touwen's (1976) Group III Neurological Assessment Scale: (a) duration of sitting, (b) locomotion in prone position (crawling), and (c) walking (for the full description of these items and their scoring, see Table 1). Touwen demonstrated that these three skills have a distinct developmental course and exhibit individual differences in the rates of development during the interval between 6 and 14 months. Moreover, Touwen's scale of postural and motor development has excellent reliability and validity scores.

1. Duration of sitting: 0 = unable to sit without support; 1 = sits free for some seconds; 2 = sits free for 30 s; 3 = sits free for 1 min; 4 = sits free for longer than 1 min
2. Locomotion in prone position: 0 = no change in spatial position; 1 = wriggling or pivoting movements; 2 = abdominal progression using the arms only; 3 = abdominal progression using arms and legs; 4 = progression by way of abdominal creeping and creeping on all fours; 5 = creeping on all fours
3. Walking: 0 = unable to walk; 1 = walks if held by both hands; 2 = walks if held by one hand; 3 = walks few (< 7) paces; 4 = walks seven or more paces

Table 1. The three items from Touwen's (1976) Group III Neurological Assessment Scale

Assessment of a hand-use preference

At each monthly visit, a reliable and validated handedness assessment (Michel, Ovrut, & Harkins, 1985) was administered while infants were sitting on their parents' laps, at navel height and in an upright posture to a table. This posture permitted free movements of the infant's arms. Parents were requested to hold the infant with both hands at the waist level so that the infant could maintain a steady posture, and not to interfere with the infant's movements. Instances of accidental parental interference were excluded from coding and analysis.

Assessment of hand-use patterns consisted of separate, random-order, presentations of 34 infant toys: 10 double presentations involving two identical toys presented in line with the infant's shoulders (7 pairs of toys presented on the table and 3 pairs suspended by string at the level of the infant's eyes), and 24 single toys presented midline to the infant (19 toys presented on the table and 5 toys presented in the air). Alternating double and single presentations as well as air and table presentations ensured that infants were unlikely to establish any repetitive response bias. The toys selected for the study were brightly colored, of medium size so that they could be easily grasped, and contained features that produced noise or movable parts that increased the likelihood that the infants would reach for them.

Each toy presentation lasted approximately 15 s before the toy was taken away and the next one was presented, which resulted in a 20- to 25-min procedure. Infants' hand-use when acquiring the toys was digitally recorded using two synchronized cameras that provided a split screen with an overhead and a side view.

Measures

Development of postural control

For analyzing patterns of postural control development, the raw scores obtained from the Touwen's Group III assessment were dummy-coded into binary units. For sitting status, raw scores < 4 were coded as 0, indicating a "presitting" status; raw scores of 4 were coded as 1, indicating "post onset of sitting" status. The same coding scheme was used for the other two scales. Thus, for the onset of crawling, the score 5 was used as a cutoff point between pre- and postcrawling, whereas for the onset of walking the cutoff score was 4. One might argue that "walks few (< 7) paces" (score 3) rather than "walks seven or more paces" (score 4) reflects the emergence of walking. We found that the transition from the score of 2 to the score of 4 on the walking scale happens very quickly so that a score of 3 is often skipped in our monthly records. Thus, score 4 was used as an onset of walking in this study.

Lateralized and symmetric hand-use

The coding for hand-use was done in The Observer® XT (Noldus Information Technology, Wageningen, Netherlands), which permitted frame-by-frame coding of reaching and manipulation behaviors. Coders viewed all recordings in slow motion to identify precisely the hand used for a toy acquisition (lifting the toy from the surface of the table, or having control of a toy during air presentations). During a single-toy presentation, if the infant was observed to pick up the toy using both hands within an interval of < 0.25 s, this acquisition action was coded as bimanual; beyond the 0.25 s interval, the action was coded as unimanual (only the hand that acquired the toy first was coded). During a double-toy presentation, if an infant's two hands each acquired a toy (or toys) within an interval of < 0.25 s, a bimanual acquisition was coded; otherwise, a unimanual acquisition was coded for the faster hand. The quarter-second time window permitted a greater opportunity to observe bimanual acquisitions. Also, this quarter-second time window is well within the ability of the nervous system to coordinate the movements of the two arms.

Some previous research (e.g., Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996) used initiation of reaching movement as a criterion for identification of unimanual or bimanual hand-use. That is, if both hands moved before the object was contacted the reach was coded as bimanual, irrespective of whether the second hand contacted the object. We considered that using an acquisition of the object (when the hand controls a toy) would permit better distinction of goal-directed acts from non-goal-directed bimanual incidental and associated movements. Therefore, although we address general conceptual issues raised by previous research, we do it with related, albeit different, measures of bimanual actions. Consequently, any direct comparisons of our current findings to those of previous research should be done with caution.

A random selection of 20% of the videos were recoded by a second coder for interrater reliability, which reached a mean Cohen's kappa of 0.91 (Mdn = 0.91, range = 0.82–0.99). Also, another 20% of the videos were recoded by the same coder to check for intrarater reliability, which resulted in a mean Cohen's kappa of 0.94 (Mdn = 0.94, range = 0.88–0.99). All coding was done blind to the predicted hand preference of infants.

To chart the development of lateralized hand-use for object acquisition in our sample, a handedness index (HI) was calculated as a ratio of the number of right-hand acquisitions over the sum of right- and left-hand acquisitions across the 34 toy presentations for each infant at each monthly visit (resulting in 8–9 estimates for each infant): HI = Right/(Right + Left). The HI provided an estimation of the infant's lateralized hand-use preference for acquisition at that month. The possible values for HI ranged from 0 to 1, and the value of 0.5 was considered to be a baseline of no preference.

Some might suggest including bimanual actions while estimating the HI: HI = Right/(Right + Left +Both). In this study, however, bimanual acquisitions were deliberately excluded from the estimation of the lateralized hand-use since we defined "lateralized hand-use for acquiring objects refers to the use of one hand more than the other hand (when using only one hand and not engaging in bimanual movements)." Therefore, this measure is determining the proportion of right-hand acquisitions over all unimanual acquisitions, whereas all bimanual acquisitions are accounted for by the symmetry index (SI) described next.

To explore the change in symmetric hand-use for acquiring objects, a SI was calculated as a proportion of bimanual acquisitions over the total number of acquisitions for each infant at each visit: SI = Both/(Right + Left + Both). In contrast to the HI, which allows us to observe age changes in an infant's manual lateralization, the SI focuses on an infant's change in manual symmetry with age. As the SI increases, the symmetric hand-use of an infant (proportion of bimanual acquisitions) also increases. Although the HI and the SI were calculated from the same hand-use acquisition assessment sessions and are consequently related, they do represent different measures of the infant's hand-use.

Handedness status

Handedness status of each participant was determined with group-based trajectory modeling (Nagin, 2005) that was conducted on infants' 6- to 14-month hand-use preference z scores: z = (Right − Left)/(Right + Left)1/2, using SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001; see Michel, Sheu, & Brumley, 2002, for the explanation of the appropriateness of using z scores for this type of the analysis). Group-based trajectory modeling is a statistical method designed to discover distinctive patterns in the distribution of a sample's trajectories. Although this classification tends to ignore the continuous character of handedness development, group-based trajectory modeling enabled us to take into account infants' handedness trajectories while estimating their handedness status. We hypothesized the presence of unobserved latent groups with distinct developmental trajectories of hand-use preference for acquisition in our sample. It was also hypothesized that infants with different-handedness status may have different patterns of lateralized and symmetric hand-use development.

Results

Gross Motor Development

Table 2 shows the ages of onset for sitting, crawling, and walking. Only 82.9% of infants (80.6% of males and 85.8% of females) demonstrated confident walking (score 4 in Touwen's Neurological Assessment Scale) by the age of 14 months.

Table 2. The development of sitting, crawling, and walking (in months)

Motor skills	Minimum age of skill acquisition	Maximum age of skill acquisition	Mean age of skill acquisition	Standard deviation
Sitting	6	11	7.11	0.95
Crawling	6	15	8.83	1.52
Walking	9	18	12.83	1.66

The analysis of bivariate correlations among the onsets of sitting, crawling, and walking revealed significant correlations between the onset of sitting and crawling, $r(273) = .385$, $p < .01$; sitting and walking, $r(273) = .374$, $p < .01$; as well as between crawling and walking, $r(273) = .591$, $p < .01$. Thus, variables describing the development of postural control (sitting, crawling, and walking) are not independent from each other.

Latent Groups in the Trajectories of Infant Handedness

Using the group-based trajectory modeling devised by Jones et al. (2001) and described in detail in Michel, Babik, Sheu, and Campbell (in press), the best fitting model has three latent groups underlying infant handedness: around 26.5% of infants being right-handed, 10.5% left-handed, and 62.9% of infants exhibiting no significantly distinct hand-use preference for object acquisition. The distribution of handedness statuses did not significantly differ between males and females, $\chi2(2, N = 275) = 0.40$, $p = .819$. To identify possible differences in the trajectories of lateralized and symmetric hand-use between infants with different handedness status, we used multilevel modeling that accounts for nonindependence of multiple observations of the same subject.

Multilevel Model of Change in Lateralized Hand-Use

Multilevel models of change allow the simultaneous analyses of different research questions: (a) Level 1 describes within-person variability in the sample and focuses on the individual change over time in lateralized hand-use for object acquisition and (b) Level 2 describes between-person portion of variability and addresses questions of how individual changes in lateralized hand-use vary across infants, and how grouping variables such as sex and handedness status can add to the explanation of this change (Singer & Willett, 2003). In this study, all multilevel analyses were conducted using the HLM program (Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004).

For the multilevel analysis of lateralized hand-use development, in the within-individual level (Level 1) of the model, we entered age variables representing linear, quadratic, and cubic trends of change. To avoid effects of multicollinearity, we coded infants' age using orthogonal polynomials (Kleinbaum, Kupper, Nizam, & Muller, 2008). In the "between-individual" level of the multilevel model (Level 2), we included the dummy-coded handedness status variable HS (HS1 would compare right-handers to left-handers; HS2 would compare right-handers to infants without a stable hand-use preference; infants with a right-hand preference were chosen as a reference group), as well as dummy-coded sex variable (0 = males, 1 = females) SEX, and interactions between the sex variable and handedness status variables (SEX × HS1, SEX × HS2). In the process of model building, we went through a sequence of models including the unconditional means model, the unconditional growth model, the full Level 1 model, and, finally, the full Level 1 and Level 2 model (Singer & Willett, 2003). A model comparison framework was then used to reduce statistically nonsignificant fixed effects in the model, beginning with higher order interactions and working down to lower order interactions and main effects (Appelbaum & Cramer, 1974; Cramer & Appelbaum, 1980).

The final model is presented below, and its estimated parameters are displayed in Table 3.

Table 3. Estimated Fixed and Random Effects for Handedness Index

Level 1 effects	Level 2 effects	Parameters	Model estimates
Fixed effects			
Initial status, π_{0i}	Intercept	β_{00}	0.705***
	HS1	β_{01}	−0.319***
	HS2	β_{02}	−0.130***
AGE, π_{1i}	Intercept	β_{10}	0.005†
	HS1	β_{11}	−0.015*
	HS2	β_{12}	0.004
$(\text{AGE})^2$, π_{2i}	Intercept	β_{20}	−0.002***
	HS1	β_{21}	0.003***
	HS2	β_{22}	0.002***
Random effects			
Level 1	Within-person, ε_{ij}	$\sigma\varepsilon^2$	0.031
Level 2	Intercept, δ_{0i}	σ_0^2	0.002***
	AGE, δ_{1i}	σ_1^2	0.0003***

Note. HS1 = comparison of right-handers and left-handers; HS2 = comparison of right-handers and infants without a stable hand-use preference.
†$p < .10$. *$p < .05$. ***$p < .001$.

HS1 = comparison of right-handers and left-handers; HS2 = comparison of right-handers and infants without a stable hand-use preference. †p < .10. *p < .05. ***p < .001.

$$\text{Level 1 model: } HI_{ij} = \pi_{0i} + \pi_{1i} * (AGE)_{ij} + \pi_{2i} * (AGE)^2_{ij} + \varepsilon_{ij}$$

$$\begin{aligned} \text{Level 2 models: } \pi_{0i} &= \beta_{00} + \beta_{01} * HS1_i + \beta_{02} * HS2_i + \delta_{0i} \\ \pi_{1i} &= \beta_{10} + \beta_{11} * HS1_i + \beta_{12} * HS2_i + \delta_{1i} \\ \pi_{2i} &= \beta_{20} + \beta_{21} * HS1_i + \beta_{22} * HS2_i \end{aligned}$$

In this model, HIij represents the proportion of right-hand acquisitions over the sum of right- and left-hand acquisitions for child i at time j. The residual εij corresponds to the portion of infant i's lateralized hand-use that is unpredicted at time j. The random effects for the intercept and the age variable, δ0i and δ1i, respectively, allow accounting for heterogeneity of infants in their intercepts and linear components of change. A nonsignificant random effect for the quadratic trend of change was dropped from the model. The sex variable was not statistically significant, $t(271) = -0.066$, $p = .948$, and was dropped from the model.

The multilevel analysis revealed significant quadratic trends of change for right- and left-handed infants (Table 3 and Figure 1). Thus, right-handers increase their right-handedness during the period from 6 to 10–11 months and decrease thereafter, left-handers increase their left-handedness until the age of 11 months and slightly decrease it thereafter, and infants initially without a hand-use preference increase their right-hand use during the entire 6- to 14-month interval.

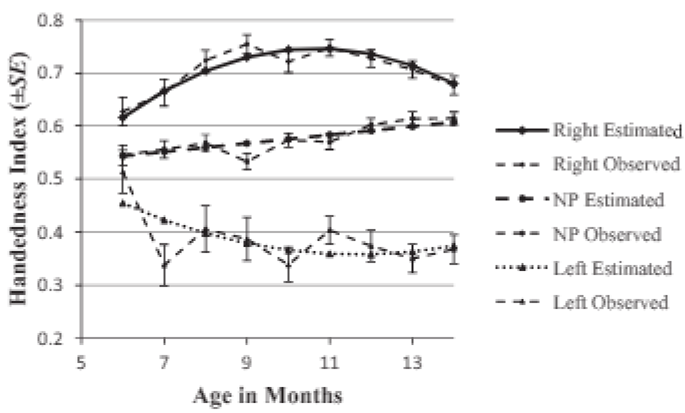

Figure 1. Observed and estimated trajectories of lateralized hand-use for infants with different handedness status. NP = no preference.

Then we explored a possible change in the trajectory of lateralized hand-use in relation to developing postural and locomotor skills—the onset of sitting (SIT), crawling (CRW), and walking (WLK). For control, we also included interactions between the linear age variable and variables describing the onset of sitting, crawling, and walking. Interestingly, the multilevel analysis showed no significant changes in HI at the onset of sitting, $t(274) = -0.204$, $p = .839$;

crawling, t(274) = −0.976, p = .330; or walking, t(2423) =−0.718, p = .473. In addition, none of the interactions between orthogonal age and dummy-coded posture variables was statistically significant: Age × Sitting, t(2414) = 0.350, p = .726; Age × Crawling, t(2414) =−0.802, p = .423; and Age × Walking, t(2414) = 0.261, p = .794. Thus, lateralized hand-use preference for object acquisition appears to be unrelated to our measures of the development of postural control and locomotion.

Multilevel Model of Change in Symmetric Hand-Use

The relation between the development of symmetric hand-use and postural control was examined next. Increase in the SI (calculated for each monthly visit for each infant) represents an increase in bimanual hand-use, whereas decrease represents an increase in unimanual hand-use. The observed mean trajectory of the symmetric hand-use has a nonlinear trend with the least amount of symmetric (bimanual) hand-use at the age of approximately 10 months (Figure 2). Considering the average age of onset for sitting, crawling, and walking (Table 2), the decrease in manual symmetry approximately coincides with the onset of sitting and crawling, whereas the increase in manual symmetry coincides with the onset of walking. However, this apparent trend should be treated with caution since mean trajectories delineate only means for the entire sample and ignore the variability in the data.

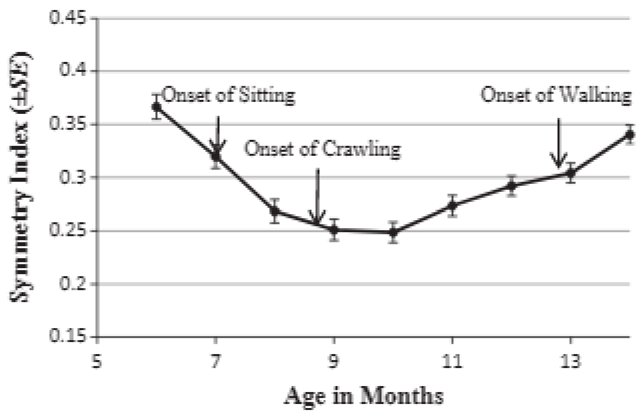

Figure 2. Observed mean trajectory of symmetric hand-use

The observed mean trajectories of symmetric hand-use for males and females (Figure 3A) suggest that females tend to acquire toys bimanually more frequently than males in the interval between 8 and 13 months. In general, for both males and females, trajectories of symmetric hand-use have a similar U-shaped form with a sharp decline in the proportion of bimanual acquisitions in the first half of the observation period and an increased tendency to acquire with both hands thereafter. Interestingly, this developmental change happens on average about 1 month sooner for females compared to males (9 vs. 10 months). We might suspect that the observed shift in the trajectory is a developmental milestone that is achieved sooner by females since they typically develop faster than males (Waber, 1977, 1979).

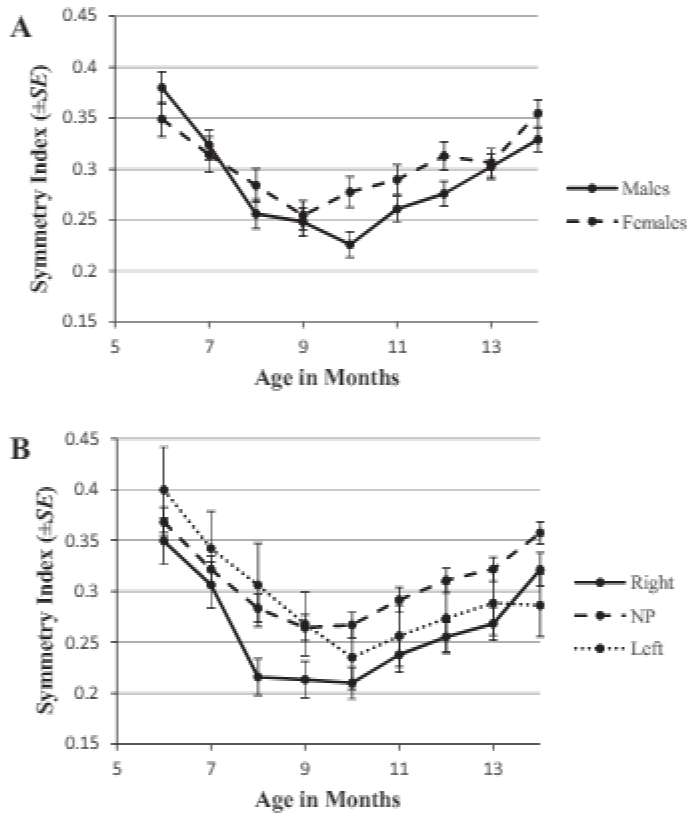

Figure 3. Observed mean trajectories of symmetric hand-use for males and females (A) as well as for infants with different handedness status (B). NP = no preference.

The observed mean trajectories of symmetric hand-use for infants with different handedness status (Figure 3B) revealed that until the age of 9 months the trajectory of left-handed infants is very similar to the trajectory of infants without a stable hand-use preference, while after the age of 10 months lateralized (left- and right-handed) infants seem to be more alike compared to "no preference" infants. Note that the observed mean trajectories can only be exploratory, whereas true patterns of change in hand-use with age are better revealed using the multilevel statistical analysis.

For the multilevel analysis of symmetric hand-use development, in the within-person level of the model, we entered age variables representing linear, quadratic, and cubic trends of change, as well as three time-varying predictors defining the development of postural control in infancy: SIT, CRW, and WLK. Again, infants' age was coded using orthogonal polynomials (Kleinbaum et al., 2008). For control, we also included interactions between the linear age variable and variables describing the onset of sitting, crawling, and walking. In the between-person level, we entered variables HS1 and HS2 defining differences between handedness groups, a dummy-coded sex variable SEX, and interactions between the sex variable and handedness status variables. The final reduced multilevel model is presented next, and the estimated parameters of this model are available in Table 4.

Level 1 effects	Level 2 effects	Parameters	Model estimates
Fixed effects			
Initial status, π_{0i}	Intercept	β_{00}	0.263***
	SEX	β_{01}	−0.051*
	HS1	β_{02}	0.035
	HS2	β_{03}	0.047***
AGE, π_{1i}	Intercept	β_{10}	−0.015**
	HS1	β_{11}	−0.013*
$(AGE)^2$, π_{2i}	Intercept	β_{20}	0.001***
SIT, π_{3i}	Intercept	β_{30}	−0.045*
	SEX	β_{31}	0.073*
CRW, π_{4i}	Intercept	β_{40}	0.020
AGE*CRW, π_{5i}	Intercept	β_{50}	0.023***
Random effects			
Level 1	Within-person, ε_{ij}	σ_{ε}^2	0.014
Level 2	Intercept, δ_{0i}	σ_0^2	0.021***
	AGE, δ_{1i}	σ_1^2	0.0004***
	SIT, δ_{3i}	σ_3^2	0.018***
	CRW, δ_{4i}	σ_4^2	0.009*

Note. HS1 = comparison of right-handers and left-handers; HS2 = comparison of right-handers and infants without a stable hand-use preference; CRW = onset of crawling; SIT = onset of sitting. *$p < .05$. **$p < .01$. ***$p \leq .001$.

Table 4. Estimated Fixed and Random Effects for Symmetry Index

HS1 = comparison of right-handers and left-handers; HS2 = comparison of right-handers and infants without a stable hand-use preference; CRW = onset of crawling; SIT = onset of sitting. *p < .05. **p < .01. ***p ≤ .001.

$$\text{Level 1 model:} \ SI_{ij} = \pi_{0i} + \pi_{1i} * AGE_{ij} + \pi_{2i} * (AGE)^2_{ij} + \pi_{3i} * SIT_{ij} + \pi_{4i} * CRW_{ij} + \pi_{5i} * (AGE * CRW)_{ij} + \varepsilon_{ij}$$

$$\text{Level 2 models:} \ \pi_{0i} = \beta_{00} + \beta_{01} * SEX_i + \beta_{02} * HS1_i$$

$$.9 + \beta_{03} * HS2_i + \delta_{0i}$$

$$\pi_{1i} = \beta_{10} + \beta_{11} * HS1_i + \delta_{1i}$$

$$\pi_{2i} = \beta_{20}$$

$$\pi_{3i} = \beta_{30} + \beta_{31} * SEX_i + \delta_{3i}$$

$$\pi_{4i} = \beta_{40} + \delta_{4i}$$

$$\pi_{5i} = \beta_{50}$$

In this model, SIij represents the proportion of bimanual acquisitions over the total number of acquisitions for child i at time j. The residual εij corresponds to the portion of infant i's manual symmetry that is unpredicted at time j.

The model suggested that symmetric hand-use has a quadratic trend across age. The influence of the variables describing the onset of sitting and crawling was statistically significant, whereas the variable describing the change in SI at the onset of walking was not significant and was dropped from the model. Significant differences in the trajectories of symmetric hand-use were observed between males and females, as well as between infants with different handedness status. According to Figure 4A, males in our sample on average decrease in their frequency of bimanual acquisitions at the onset of sitting, while at the onset of crawling they increase the use of both hands. Also, the slope of the trajectory after the onset of crawling is significantly steeper in right-handers and males without a stable hand-use preference compared to left-handers. Note that this model explores a step-like change in symmetric hand-use with the onset of sitting, crawling, and walking by analyzing parts of the trajectory before and after the onset of each skill. Thus, breaks in the trajectories represent change in symmetric hand-use during the infant's transition from presitting to postsitting status.

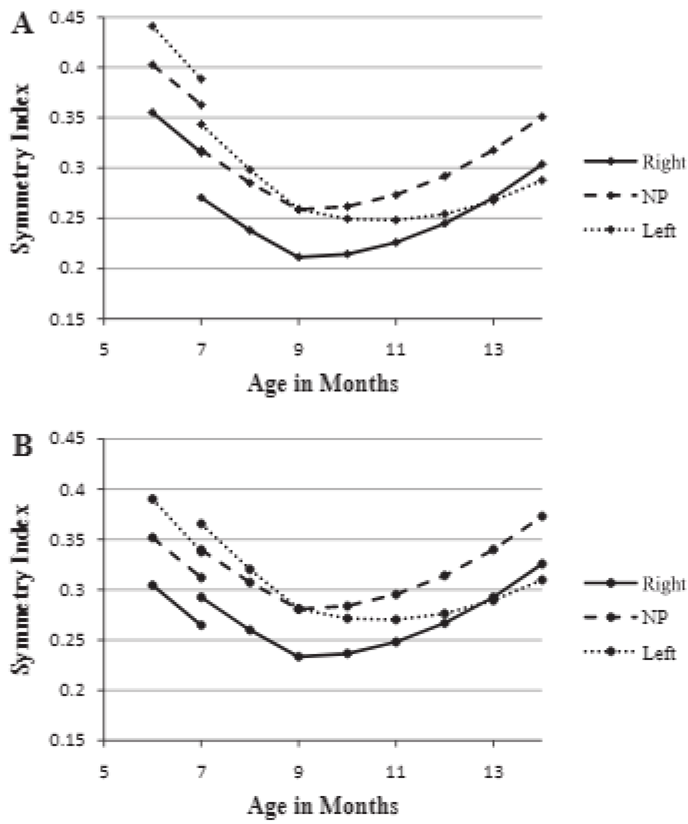

Figure 4. Estimated trajectories of symmetric hand-use for males (A) and females (B) with different handedness status. NP = no preference.

In contrast to males, females tend to increase their use of both hands while acquiring objects after the onset of sitting (Figure 4B). After the onset of crawling, females, similar to males, on average increase bimanual acquisition with left-handers again having a less steep slope compared to other females. In general, left-handed infants, both males and females are more similar to no preference infants in the period between 6 and 10 months, while their trajectory of symmetric hand-use resembles that of right-handers after 11 months. Note that right-handers and infants without a distinct hand-use preference on average change their trajectory of symmetric hand-use about 2 months earlier than left-handers (9 vs. 11 months). Moreover, while males' hand-use is on average more symmetric than that of females before the age of 7 months, females are more symmetric in their hand-use in the period between 7 and 14 months. Previous research (Corbetta & Bojczyk, 2002; Goldfield, 1993; Rochat, 1992) suggested the decrease in manual symmetry at the onset of sitting and crawling (irrespective of the infant's sex and handedness status), and an increase at the onset of walking. However, our results do not seem to support these findings.

Multilevel Model Comparing Trajectories of Symmetric Hand-Use in Infants Developing Gross Motor Skills at Different Rates

To directly examine whether the observed change in posture is responsible for changes in symmetric hand-use, we compared the patterns of manual symmetry in infants developing each postural transition either early versus late. We need to emphasize that although this analysis allows us to become more confident while attributing the observed changes in manual symmetry to postural transitions, in contrast to the previous analysis that tested all postural skills in one model, it does not inform us about the direction of change in manual symmetry at the onset of each skill.

We divided the sample approximately into quartiles and compared the upper quartile of infants who developed postural control skills earlier with the lower quartile who developed these skills later. If patterns of symmetric hand-use for object acquisition are associated with postural changes, we would expect that infants with early postural development would have a change toward more symmetry in their trajectories of symmetric hand-use sooner than those with later developing postural skills. Inversely, if the same patterns of symmetric hand-use are observed in both groups, we may infer that the apparent relation between postural changes and manual symmetry may be accounted for by some other factors. Note that we do not expect changes due to postural development to be observed only during some limited periods of time. Therefore, we again explore trajectories of symmetric hand-use for infants that acquired postural skills earlier or later in the entire 6- to 14-month age interval.

Using multilevel modeling in HLM, we compared trajectories of change in symmetric hand-use in infants who started sitting at 6 months or earlier (early sitters, 81 total, 41 males) and infants who started sitting at 8 months or later (late sitters, 82 total, 53 males), approximately the upper and lower quartiles of our sample. In the within-individual level of the model, we entered orthogonal age variables representing linear, quadratic, and cubic trends of change. In the between-individual level of the multilevel model, we included the dummy-coded variable SIT_EL representing the assignment of the infant to the group of early or late sitters (0 = early, 1 = late), two dummy-coded handedness status variables (HS1 and HS2), dummy-coded sex variable SEX, as well as interactions between the sex variable and handedness status variables (SEX × HS1, SEX × HS2) and interaction between the sex variable and the variable describing the timing of sitting onset (SEX × SIT_EL). The final multilevel model is presented next, and the results are reported in Table 5.

Level 1 effects	Level 2 effects	Parameters	Model estimates
Fixed effects			
Initial status, π_{0i}	Intercept	β_{00}	0.256***
	SIT_EL	β_{01}	0.007
	SEX	β_{02}	0.019
	HS2	β_{03}	0.034*
AGE, π_{1i}	Intercept	β_{10}	−0.0002
	SIT_EL	β_{11}	−0.007
	SEX	β_{12}	0.002
	HS2	β_{13}	0.002
$(\text{AGE})^2$, π_{2i}	Intercept	β_{20}	0.003***
	SIT_EL	β_{21}	−0.0001
	SEX	β_{22}	−0.0009*
	HS2	β_{23}	−0.0009*
$(\text{AGE})^3$, π_{3i}	Intercept	β_{30}	−0.001**
	SIT_EL	β_{31}	0.002*
Random effects			
Level 1	Within-person, ε_{ij}	σ_ε^2	0.014
Level 2	Intercept, δ_{0i}	σ_0^2	0.009***
	AGE, δ_{1i}	σ_1^2	0.0004***
	$(\text{AGE})^2$, δ_{2i}	σ_2^2	0.000001***

Note. SIT_EL = comparison of early and late sitters; HS2 = comparison of right-handers and infants without a stable hand-use preference.
*p < .05. **p < .01. ***$p \leq$ .001.

Table 5. Estimated Fixed and Random Effects for the Multilevel Model of Symmetric Hand-Use in Early and Late Sitters

SIT_EL = comparison of early and late sitters; HS2 = comparison of right-handers and infants without a stable hand-use preference. *p < .05. **p < .01. ***p ≤ .001.

$$\text{Level 1 model:} \, \text{SI}_{ij} = \pi_{0i} + \pi_{1i} * (\text{AGE})_{ij} + \pi_{2i} * (\text{AGE})_{ij}^2 + \pi_{3i} * (\text{AGE})_{ij}^3 + \varepsilon_{ij}$$

$$\begin{aligned} \text{Level 2 models:} \quad & \pi_{0i} = \beta_{00} + \beta_{01} * \text{SIT\_EL}_i + \beta_{02} * \text{SEX}_i \\ & .8 + \beta_{03} * \text{HS2}_i + \delta_{0i} \\ & \pi_{1i} = \beta_{10} + \beta_{11} * \text{SIT\_EL}_i + \beta_{12} * \text{SEX}_i \\ & .8 + \beta_{13} * \text{HS2}_i + \delta_{1i} \\ & \pi_{2i} = \beta_{20} + \beta_{21} * \text{SIT\_EL}_i + \beta_{22} * \text{SEX}_i \\ & .8 + \beta_{23} * \text{HS2}_i + \delta_{2i} \\ & \pi_{3i} = \beta_{30} + \beta_{31} * \text{SIT\_EL}_i \end{aligned}$$

The results of the multilevel analysis indicated that trajectory of symmetric hand-use differ significantly between early and late sitters, between males and females, as well as between lateralized (right- and left-handers) and nonlateralized (no preference) infants (Figure 5). Right-handers on average do not differ from left-handers in the development of symmetric hand-use, whereas those two groups perform significantly fewer bimanual acquisitions compared to infants without a stable hand-use preference in the interval from 8 to 14 months. Early sitters (both males and females) increase their frequency of bimanual acquisitions around the age of 9 months, whereas in late sitters this change does not happen until about 11 months. Moreover, early sitting females tend to acquire objects bimanually more often than early sitting males and the same pattern of sex differences is true for late sitters. Although our findings generally agree with previous research suggesting a significant change in symmetric hand-use with the onset of sitting (Rochat, 1992), they also highlight the role of sex and handedness status that was missed in previous research.

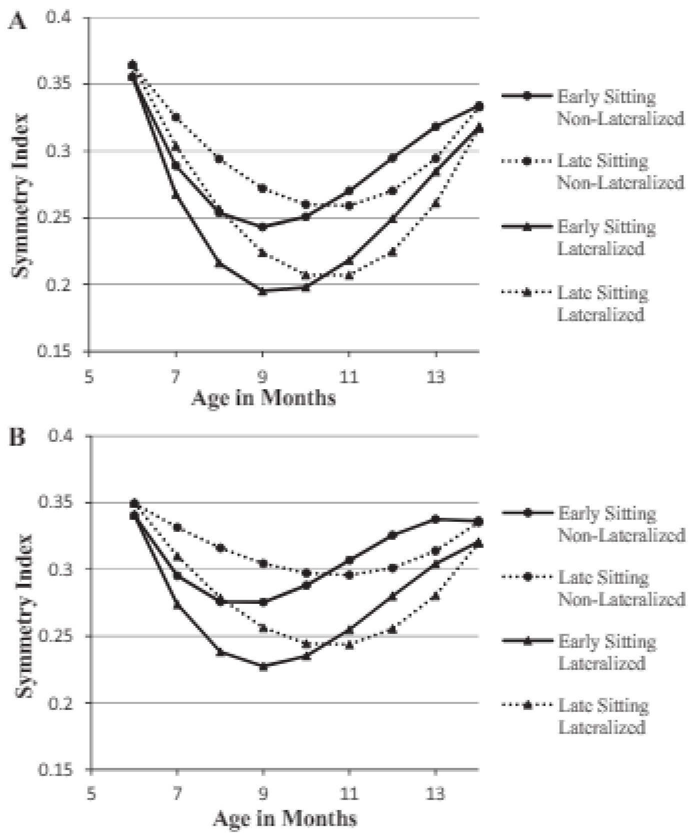

Figure 5. Estimated trajectories of symmetric hand-use for early and late sitting males (A) and females (B). Lateralized = right- and left-handers; nonlateralized = no preference infants

We also compared trajectories of change in symmetric hand-use between infants who started crawling at 6–8 months (early crawlers, 75 total, 37 males) and those who started crawling at 10–14 months (late crawlers, 76 total, 42 males), approximately the upper and lower quartiles of our sample. The tested model was similar to one that explored the change in symmetric hand-use with sitting acquisition. A dummy-coded variable CRW_EL representing the assignment to the group of early or late crawlers (0 = early, 1 = late) was included in the analysis. The multilevel analysis showed that the intercept along with the slope for quadratic age were significantly different from zero: intercept, β = 0.265, t(149) = 19.5, p < .0001; AGE, t(150) = 0.033, p = .974; (AGE)2, β = 0.002, t(150) = 9.63, p < .0001. However, no significant difference between right- and left-handers in their frequency of bimanual acquisitions was found (HS1 not significant). Statistically significant handedness status variable HS2, β = 0.068, t(149) = 3.92, p < .0001, revealed that on average lateralized infants (right- and left-handers) acquire toys bimanually significantly less often than infants without a stable hand-use preference. Importantly, the difference between the two groups of early and late crawlers was not statistically significant—CRW_EL, t(148) = 0.038, p = .970—indicating that the analysis did not support the hypothesis that the onset of crawling is associated with a significant change in symmetric hand-use.

In the analysis of early and late walkers, we compared trajectories of change in symmetric hand-use for infants who started walking at 9, 10, or 11 months (early walkers, 45 total, 20 males), infants who started walking at 14 months (late walkers, 42 total, 28 males), and infants who did not start walking by the end of the study at 14 months (very late walkers, 47 total, 30 males). We built a model similar to those used for the analysis of symmetric hand-use in early and late sitters and crawlers. Two dummy-coded walking variables (WLK_EL1 comparing late walkers to early walkers, and WLK_EL2 comparing late walkers to very late walkers) were included in the model. The final multilevel model is presented next, and the results are reported in Table 6.

Level 1 effects	Level 2 effects	Parameters	Model estimates
Fixed effects			
Initial status, π_{0i}	Intercept	β_{00}	0.253***
	WLK_EL1	β_{01}	0.024
	HS2	β_{02}	0.072***
AGE, π_{1i}	Intercept	β_{10}	−0.008**
	WLK_EL1	β_{11}	0.012**
$(\text{AGE})^2$, π_{2i}	Intercept	β_{20}	0.002***
	WLK_EL1	β_{21}	−0.001**
$(\text{AGE})^3$, π_{3i}	Intercept	β_{30}	−0.001**
Random effects			
Level 1	Within-person, ε_{ij}	σ_ε^2	0.014
Level 2	Intercept, δ_{0i}	σ_0^2	0.010***
	AGE, δ_{1i}	σ_1^2	0.0004***
	$(\text{AGE})^2$, δ_{2i}	σ_2^2	0.000001**

Note. WLK_EL1 = comparison of late walkers and early walkers; WLK_EL2 = comparison of later walkers and very late walkers; HS2 = comparison of right-handers and infants without a stable hand-use preference.
** $p \leq .01$. *** $p < .001$.

Table 6. Estimated Fixed and Random Effects for the Multilevel Model of Symmetric Hand-Use in Early and Late Walkers

WLK_EL1 = comparison of late walkers and early walkers; WLK_EL2 = comparison of later walkers and very late walkers; HS2 = comparison of right-handers and infants without a stable hand-use preference. **p ≤ .01. ***p < .001.

$$\begin{aligned} \text{Level 1 model: } SI_{ij} = \;& \pi_{0i} + \pi_{1i} * (\text{AGE})_{ij} + \pi_{2i} * (\text{AGE})_{ij}^{2} \\ & + \pi_{3i} * (\text{AGE})_{ij}^{3} + \varepsilon_{ij} \end{aligned}$$

$$\begin{aligned} \text{Level 2 models: } \pi_{0i} = \;& \beta_{00} + \beta_{01} * \text{WLK\_EL}_i \\ & + \beta_{02} * \text{HS2}_i + \delta_{0i} \\ & \pi_{1i} = \beta_{10} + \beta_{11} * \text{WLK\_EL}_i + \delta_{1i} \\ & \pi_{2i} = \beta_{20} + \beta_{21} * \text{WLK\_EL}_i + \delta_{2i} \\ & \pi_{3i} = \beta_{30} \end{aligned}$$

From the results of the multilevel analysis, we can infer that late walkers did not differ in the trajectories of symmetric hand-use from the group of very late walkers. However, these two groups of late walkers differed significantly from early walkers. Figure 6 shows that the shift in the trajectory of symmetric hand-use happens at the age of about 9 months in early walkers and at 10 months in late walkers with no significant difference being observed between trajectories of males and females. Again, both right-handed and left-handed infants perform fewer bimanual acquisitions than infants without a distinct hand-use preference. Although these results generally agree with previous findings suggesting a significant change in symmetric hand-use at the onset of walking (Corbetta & Bojczyk, 2002), this investigation revealed the important contribution of the infant's handedness status to this association.

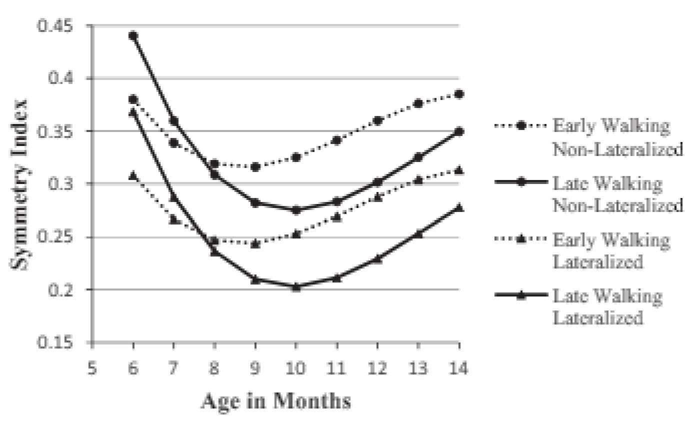

Figure 6. Estimated trajectories of symmetric hand-use for early and late walkers with different handedness status. Lateralized – right and left-handers; nonlateralized = no preference.

Although the last set of analyses explored the development of each postural milestone separately, we do not consider these skills as independent. Indeed, early sitters may become early crawlers and walkers, whereas late sitters may be delayed in achieving other milestones. We identified that 73% of early sitters become early crawlers, whereas only 38% of early sitters had early onset of walking. Moreover, 47% of late sitters are late crawlers, and 49% of late sitters are late walkers. Although there is a significant overlap in the composition of the groups of early sitters and early crawlers, we observed significant differences between early and late sitters, but not between early and late crawlers. Therefore, we propose that there is sufficient variability in group composition to justify separate analyses for the onset of sitting, crawling, and walking skills in relation to manual symmetry.

Discussion

The primary goal of this study was to examine the expression of lateralized and symmetric hand-use for acquiring objects in relation to the development of markers of postural and locomotor control in infancy while taking into account between-subject differences such as handedness status and sex. As noted, lateralized hand-use refers to an infant's use of one hand more than the other when acquiring objects, whereas symmetric hand-use refers to the tendency of a subject to acquire objects bimanually rather than unimanually.

Although the goal of this investigation was to examine some ideas reported in previous research, we need to emphasize that we used different measures of hand-use involving object acquisition (HI and SI), different levels of postural proficiency, different sampling intervals and sample sizes, and our statistical analyses differed from those implemented in previous research. Therefore, any comparison of our results with previous findings of postural constraints on hand-use development should be treated with caution.

We observed that according to the group-based trajectory modeling, a majority (62.9%) of the infants in our sample did not manifest a distinctive hand-use preference in the period between 6 and 14 months, whereas 26.5% of infants could be considered right-handed, and 10.5% were left-handed. The results of this study demonstrated that, in general, right-handed infants in our sample become more right-handed during the 6- to 11-month period and decrease their right-handedness thereafter. Left-handed infants have a similar pattern of becoming more lateralized (in this case, left-handed) from 6 to 11–12 months, and slightly decreasing their lateralization afterward. In contrast, infants without a distinctive hand-use preference for acquisition tend to increase their right-handedness during the entire 6- to 14-month interval. Thus, we concluded that infant handedness is still developing during the 1st year of life, which is supported by some previous research (e.g., McManus, 2002).

No significant sex differences were observed in trajectories of lateralized hand-use in our sample. Perhaps, sex differences in handedness only begin to be manifested after the infant's 1st year. Also, we found no evidence that change in lateralized hand-use is related to the onsets of sitting, crawling, or walking. However, the association of posture and handedness may become more obvious with more frequent assessments (e.g., weekly). Unfortunately, more frequent assessments, in our situation, would necessarily reduce the sample size to levels that would make effective statistical modeling of the developmental patterns more problematic. Moreover, if more frequent assessments were to reveal a postural influence on handedness expression, then it might be suggested that postural transitions disrupt the expression of the infant's handedness rather than its development as revealed by the general trend across monthly assessments that we observed.

Although transitions in posture appeared to be unrelated to changes in lateralized hand-use, we did hypothesize that they may affect developmental trajectories of symmetric hand-use. The mean trajectory of the observed SI scores suggested a decrease in symmetric hand-use during the 6- to 10-month interval when acquisition of sitting and crawling are usually observed, and increase during the 10- to 14-month interval coinciding with the emergence of walking. Similar trends were described by previous research (Corbetta & Bojczyk, 2002; Goldfield, 1993; Rochat, 1992). However, exploration of mean trajectories can be misleading since they highlight the mean trend in the sample while ignoring individual variability in developmental trajectories. In contrast, the multilevel analysis allows accounting for variability in data and nonindependence of individual observations in the longitudinal design, thus providing a more realistic picture of development. The multilevel analysis of symmetric hand-use indicated a significant decrease in the proportion of bimanual acquisitions at the onset of sitting in males, but the reversed pattern in females. In both sexes, left-handers performed significantly more bimanual acquisitions than other infants, followed by no preference infants. Note that based on previous research (e.g., Rochat, 1992), we predicted a decrease in manual symmetry at the onset of sitting. The results of this study suggest that the pattern of change in symmetric hand-use is more complex and cannot be interpreted without taking into consideration the infant's sex and handedness status.

Also, based on previous research (e.g., Goldfield, 1989), our initial hypothesis was that the onset of crawling would coincide with the decrease in symmetric hand-use. In contrast, we found that although the emergence of crawling happens at the nadir of symmetric hand-use trajectory, there is a significant increase, not decrease, in manual symmetry starting at the onset of crawling for right-handers and infants without a distinct hand-use preference (89% of the sample), but not for the left-handers (10.5%). Thus, although we observed an association between crawling and symmetric hand-use development, it was opposite to the manner predicted from previous research.

Furthermore, a decrease in the symmetry of the manual motor system has been proposed to facilitate the initiation of crawling (Goldfield, 1993). That is, infants that have a well-defined hand-use preference (in this case, right- and left-handers), while in a crawling posture, would be more likely to initiate reaching for a toy placed in front of them, and by doing this, throw themselves out of balance and, thus, initiate crawling. However, with more experience in crawling, infants should increase alternation between hands, thus increasing their lateralized hand-use, which this analysis did not reveal. Moreover, the infant's emerging tendency to alternate between hands after the onset of crawling cannot account for the observed increase in infant's symmetric hand-use (SI).

On the basis of previous research (e.g., Corbetta & Bojczyk, 2002), we also predicted a significant increase in the manual symmetry at the onset of walking. In contrast, the multilevel analysis suggested no significant change at the onset of walking. To check the reliability of the obtained results, we proposed that if the change in manual symmetry had been related to the emergence of sitting, crawling, and walking skills rather than some other events, then we should have observed timing differences in the trajectory of symmetric hand-use between infants acquiring these skills earlier and later in age.

We found that the change in symmetric hand-use happens about 2 months sooner in early sitters (at 9 months) compared to late sitters (at 11 months). Although these results generally agree with previous research, note that both sex and handedness status influence the relation between symmetric hand-use and the onset of sitting. Similarly, early walkers in our sample change their trajectory of symmetric hand-use about 1 month sooner (at 9 months) compared to late walkers (at 10 months). In contrast, the additional analysis did not show significant differences in trajectories of symmetric hand-use between early and late crawlers. Thus, we see disparate results produced by different types of analyses. When all postural skills were analyzed together in one model, we found a significant change in symmetric hand-use at the onset of sitting and crawling, but not walking. In contrast, separate examination of each postural skill suggested that symmetric hand-use is significantly related to sitting and walking, but not crawling. Further investigation (perhaps with more frequent sampling) is needed to clarify the relation between symmetric hand-use and the development of postural skills.

Thus, the large sample size and the longitudinal design of this investigation provide unique data about the relation between postural transitions and manual control. We observed that postural transitions affect symmetric rather than lateralized hand-use. Importantly, multilevel analysis revealed that lateralized hand-use, in the categorical form of the infant's handedness status, influences the relation between posture and symmetric hand-use for acquiring objects. Early development of handedness likely coacts with sex and developmental transitions in posture to affect manual symmetry.

References

Annett, M. (1985). Left, right, hand and brain: The right shift theory. Hove, UK: Erlbaum.

Appelbaum, M. I., & Cramer, E. M. (1974). Some problems in the nonorthogonal analysis of variance. Psychological Bulletin, 81, 335–343.

Berger, S. E., Friedman, R., & Polis, M. C. (2011). The role of locomotor posture and experience on handedness and footedness in infancy. Infant Behavior and Development, 34, 472–480.

Corbetta, D., & Bojczyk, K. E. (2002). Infants return to two-handed reaching when they are learning to walk. Journal of Motor Behavior, 34,83–95.

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

Corbetta, D., & Thelen, E. (1999). Lateral biases and fluctuations in infants' spontaneous arm movements and reaching. Developmental Psychobiology , 34, 237–255.

Corbetta, D., & Thelen, E. (2002). Behavioral fluctuations and the development of manual asymmetries in infancy: Contributions of the dynamic systems approach. In S. J. Segalowitz & I. Rapin (Eds.), Hand-book of neuropsychology. Amsterdam: Elsevier.

Cramer, E. M., & Appelbaum, M. I. (1980). Nonorthogonal analysis of variance—Once again. Psychological Bulletin, 87,51–57.

Fagard, J. (1998). Changes in grasping skills and the emergence of bimanual coordination during the first year of life. Clinics in Developmental Medicine, 147,123–143.

Fagard, J., & Lockman, J. (2005). The effect of task constraints on infants' (bi)manual strategy for grasping and exploring objects. Infant Behavior and Development,28, 305–315.

Fennell, E. B., Satz, P., & Morris, R. (1983). The development of handedness and dichotic ear listening asymmetries in relation to school achievement: A longitudinal study. Journal of Experimental Child Psychology, 35, 248–262.
Goldfield, E. (1989). Transition from rocking to crawling: Postural constraints on infant movement. Developmental Psychology, 25, 913–919.
Goldfield, E. (1993). Dynamic systems in development: Action systems. In L. B. Smith & E. Thelen (Eds.), A dynamic systems approach to development: Applications (pp. 51–70). Cambridge, MA: MIT Press.
Herron, J. (1980). Two hands, two brains, two sexes. In J. Herron (Ed.), Neuropsychology of left-handedness (pp.233–262). New York: Academic Press.
Jones, B. L., Nagin, D. S., & Roeder, K. (2001). A SAS procedure based on mixture models for estimating developmental trajectories. Sociological Methods and Research, 29, 374–393.
Kleinbaum, D. G., Kupper, L. L., Nizam, A., & Muller, K.E. (2008). Applied regression analysis and other multivariate methods. Belmont, CA: Thomson Brooks/Cole.
Lake, D. A., & Bryden, M. P. (1976). Handedness and sex differences in hemispheric asymmetry. Brain and Language, 3, 266–282.
Lansdell, H. (1962). A sex difference in effect of temporal lobe neurosurgery on design preference. Nature, 194,852–854.McCormick, C. M., & Maurer, D. M. (1988). Unimanual hand preferences in 6-month-olds: Consistency and relation to familial handedness. Infant Behavior and Development, 11,21–29.
McGlone, J. (1978). Sex difference in functional brain asymmetry. Cortex, 14, 122–128.
McManus, C. (2002). Right hand, left hand: The origins of asymmetry in brains, bodies, atoms, and cultures. Cam-bridge, MA: Harvard University Press.
McManus, I. C., Sik, G., Cole, D. R., Mellon, A. F., Wong, J., & Kloss, J. (1988). The development of handedness in children. British Journal of Developmental Psychology,6, 257–273.
Michel, G. F. (1983). Development of hand-use preference during infancy. In G. Young, S. Segalowitz, C. Corter,& S. Trehub (Eds.), Manual specialization and the developing brain (pp. 33–70). New York: Academic Press.
Michel, G. F. (1988). A neuropsychological perspective on infant sensorimotor development. In L. P. Lipsitt & C.K. Rovee-Collier (Eds.), Advances in infancy research (Vol. 5, pp. 1–37). Norwood, NJ: Ablex.
Michel, G. F., Babik, I., Sheu, C.-F., & Campbell, J. M.(in press). Latent classes in the developmental trajectories of infant handedness. Developmental Psychology.
Michel, G. F., Ovrut, M. R., & Harkins, D. A. (1985). Hand-use preference for reaching and object manipulation in 6- through 13-month-old infants. Genetic, Social, and General Psychology Monographs, 111, 407–427.
Michel, G. F., Sheu, C.-F., & Brumley, M. R. (2002). Evidence of a right-shift factor affecting hand-use preferences from seven- to eleven-months of age as revealed by latent class analysis. Developmental Psychobiology, 40,1–12.
Nagin, D. (2005). Group-based modeling of development. Cambridge, MA: Harvard University Press.
Papadatou-Pastou, M., Martin, M., Munafò, M. R., &Jones, G. V. (2008). Sex differences in left-handedness: A meta-analysis of 144 studies. Psychological Bulletin,134, 677–699.
Piek, J. P. (2002). The role of variability in early motor development. Infant Behavior and Development, 25, 452–465.

Raudenbush, S., Bryk, A., Cheong, Y. F., Congdon, R., &du Toit, M. (2004). HLM 6: Hierarchical linear and nonlinear modeling. Lincolnwood, IL: Scientific Software International.

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

Serrien, D. J., Ivry, R. B., & Swinnen, S. P. (2006). Dynamics of hemispheric specialization and integration in the context of motor control. Nature Reviews Neuroscience , 7,160–166.

Shaywitz, B. A., Shaywitz, S. E., Pugh, K. R., Constable,R. T., Skudlarski, P., Fulbright, R. K., et al. (1995). Sex differences in the functional organization of the brain for language. Nature, 373, 607–609.

Singer, J. D., & Willett, J. B. (2003). Applied longitudinal data analysis: Modeling change and event occurrence. Oxford, UK: Oxford University Press.

Thelen, E. (1995). Motor development: A new synthesis. American Psychologist, 50,79–95.

Thelen, E., Corbetta, D., & Spencer, J. P. (1996). Development of reaching during the first year: Role of movement speed. Journal of Experimental Psychology: Human Perception and Performance, 22, 1059–1076.

Touwen, B. (1976). Neurological development in infancy. Suffolk, UK: Lavenham Press.

Van Dyke, S. A., Zuverza, V., Hill, L. A., Miller, J. B.,Rapport, L. J., & Whitman, R. D. (2009). Gender differences in lateralized semantic priming. Developmental Neuropsychology, 34, 381–392.

Waber, D. P. (1977). Sex differences in mental abilities, hemispheric lateralization and rate of physical grow that adolescence. Developmental Psychology, 13,29–38.

Waber, D. P. (1979). Cognitive abilities and sex-related variations in the maturation of cerebral cortical functions. In M. A. Witting & A. C. Petersen (Eds.), Sex-related differences in cognitive functioning: Developmental issues. New York: Academic Press.

Witelson, S. F. (1976). Sex and single hemisphere: Specialization of the right hemisphere for spatial processing. Science, 193, 425–427.