Latent classes in the developmental trajectories of infant handedness

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Abstract:

Handedness for acquiring objects was assessed monthly from 6 to 14 months in 328 infants (182 males). A group based trajectory model identified 3 latent groups with different developmental trajectories: those with an identifiable right preference (38%) or left preference (14%) and those without an identifiable preference (48%) but with a significant trend toward right-handedness. Each group exhibited significant quadratic trends: Those with a right preference increased to asymptote at about 10 months and began decreasing thereafter; those with a left preference increased to asymptote at about 11 months; those without a preference exhibited increasing right-hand use. Since adult handedness reflects different patterns of neural organization which relate to differences in psychological functioning, the observed differences in infant handedness development may relate to differences in the development of infant neurobehavioral organization and functioning. Several methods were used to explore the relation of latent classes to more conventional ways of classifying infant handedness. Classification into handedness groups according to either a monthly z-score or a combination of 4 or fewer months for a handedness index failed to provide reliable estimates of handedness identified by the trajectory analysis. If identified trajectories of handedness development relate to the development of the infant's neurobehavioral organization, researchers who assess infant handedness only once in order to relate it to cognitive, social and emotional functioning may risk misclassifying the handedness of as many as 37–45% of infants. (PsycINFO Database Record (c) 2016 APA, all rights reserved)

Keywords: infant handedness | infant manual skills | group based trajectory models | latent classes | hemispheric specialization

Article:

Although we have two hands, handedness is not a categorical trait. Nevertheless, adults readily classify themselves as right- or left-handed, with a few acknowledging some mixture. However, because handedness is not a categorical trait, not all right-handers are alike. Whether it is measured by multiple item questionnaires or proficiency differences between the hands, handedness distributes continuously among individuals (Annett, 2002). When measures of equivalent proficiency or equivalent preferred use for each hand are used as a zero-point for examining the distribution of handedness, the distributions always show significantly more individuals with rightward handedness scores than those with leftward scores. Hence, there is a distinct rightward bias in human handedness. The exact proportion of right-handed individuals depends on the criteria used to define right- and left-handers (Annett, 2002). The proportions of right-handers can vary from 95% to 65% of the sample (depending on criteria), and the remainder is usually defined as "non-right-handed" but is a much more heterogeneous group than the "right-handers." The continuous character of handedness and the "criterion" dependency for identifying categories of handedness has plagued studies that have examined the relation of handedness to either other functions or neural anatomy (Bryden & Steenhuis, 1991). Although classification of adults into handedness categories can be problematic, most researchers try to categorize handedness in order to relate handedness to other forms of hemispheric specialization such as language, cognitive, emotional and social abilities.

Handedness is a distinctly lateralized asymmetry of hemispheric functioning (Volkmann, Schnitzler, Witte, & Freund, 1998; Willems & Hagoort, 2007; Willems, Hagoort, & Casasanto, 2010; Willems, Toni, Hagoort, & Casasanto, 2009) that is often used as a convenient marker for other forms of hemispheric specialization. For example, right-hemisphere control of speech and other language abilities is associated more with left-handedness than right-handedness (e.g., Annett, 2002; G. V. Jones & Martin, 2010; Knecht et al., 2000). Willems et al. (2010) discovered (using fMRI) that during a language task involving differences between manual and nonmanual action verbs, left-handers activate their right-hemisphere in contrast to right-handers, who activate their left hemisphere. Willems et al. (2010) concluded that as a consequence of their handedness, individuals have embodied their cognitive functions differently, and, hence, the hemispheres are functionally organized according to the individual's handedness. Presumably, the development of handedness should be contributing to the embodiment of such functions.

Since handedness is readily observable and can be assessed throughout most of the lifespan, Michel (1983, 1988, 2002) proposed that knowing how handedness develops, particularly during infancy, could serve as a model for the exploration of the development of other forms of cerebral asymmetry. During infancy, manual abilities change dramatically, making it especially challenging to obtain consistent measures of an individual infant's handedness (Michel, 1988). Therefore, it is not surprising that many consider infant handedness to fluctuate with state or postural control (cf. Corbetta & Thelen, 2002). Indeed, few theories of either handedness or hemispheric specialization of function incorporate information about the early development of handedness because most consider early handedness to be nonexistent. Consider the following: "Infants initially use both hands indifferently (Corbetta & Thelen, 1999; Rönnqvist & Domellof, 2006), then preference for one hand becomes clear generally from 18 months of age on (Fagard & Marks, 2000) and is more and more pronounced during the following years (Ingram, 1975)" (Dubois et al., 2009, p. 414).

However, variability in the type of handedness assessed (e.g., reaching, role-differentiated bimanual manipulation), sample sizes, and methodology (ages of assessment, frequency of assessments, and time between longitudinal assessments) is likely to have contributed to the conventional notion that infant handedness is not identifiable or inconsistent (cf. Ferre, Babik, & Michel, 2010; Schaafsma, Riedstra, Pfannkuche, Bouma, & Groothuis, 2009). Michel (1991, 2002) argued that even how the preference is defined can affect its apparent consistency (Michel, Sheu, & Brumley, 2002). For example, defining a hand-use preference by a difference between hands (Ramsay, 1980), via a handedness index, may reveal less consistent preferences across assessment ages than a preference defined by statistical estimates of whether the intermanual differences are unlikely to have occurred by chance (cf. Ferre et al., 2010; Michel et al., 2002; Michel, Tyler, Ferre, & Sheu, 2006). Also, Ferre et al. (2010) found that nine monthly longitudinal assessments reveal a different pattern of handedness development for acquiring objects during the period from 6 to 14 months of age than do four bimonthly assessments. Thus, unlike adult handedness, which can function somewhat like a personal trait, infant handedness reflects the consequences of an immature but rapidly developing nervous system that is sensitive to various assessment procedures and conditions. Nevertheless, this does not mean that infant handedness cannot be identified or characterized.

Two recent reports (Ferre et al., 2010; Michel et al., 2006) indicate that handedness for object acquisition seems to be identifiable for the 6- to 14-month age period. Although there is much individual variability in the trajectories of handedness for object acquisition, many infants remain relatively consistent in their preference, whereas others exhibit rightward or leftward trajectories. However, the group as a whole exhibits a quadratic function of increasing right handedness until 12 months and thereafter a decline in right-handedness (Ferre et al., 2010). The observed individual variability in the trajectories of object acquisition handedness during the period from 6 to 14 months of age prompted the question addressed by the current study. Can a group based trajectory model reveal any underlying patterns in the individual variability of the developmental trajectories for the handedness infants manifest when acquiring objects?

Object acquisition was examined because this is the manual skill upon which all other manipulation skills (e.g., tool-use) depend—the object must be acquired before it can be manipulated. The 6- to 14-month age range was chosen because infants exhibit robust object acquisition skills during this period and their hand-use preference for acquisition is less likely to be influenced by how the object is going to be manipulated after acquisition. Before 12 to 13 months of age, infants engage in very little role-differentiated bimanual manipulation (RDBM) actions, and they do not manifest a hand-use preference for RDBM (Kimmerle, Kotwica, Ferre, & Michel, 2010; Kimmerle, Mick, & Michel, 1995). However, by 13 months, the hand-use preference for object acquisition of certain objects begins to become subordinate to the hand-use preference for RDBM. That is, some infants may begin to acquire certain objects with their nonpreferred hand in order to more efficiently initiate RDBM with their preferred hand.

For the current study, a very large sample of infants was chosen to be tested at nine monthly visits in order to provide the data that would enable identification of potentially different developmental trajectories among infants. Also, a large sample would permit evaluation of whether data from some subset of ages can approximate the results obtained by using data from all nine ages. Since we propose that infant handedness is an early precursor to adult handedness, we predicted that there would be a right hand-use bias during infancy resembling the pattern typical for adults. However, since handedness continues to develop beyond infancy (Michel, 2002) and since handedness is a continuously distributed trait, we hypothesized that assessment of hand-use preference for acquiring objects would reveal a substantial proportion of infants for whom their hand-use would not permit statistically reliable categorization into particular handedness groups.

Thus, the primary aim of the current study was to examine the developmental patterns of hand-use preferences for acquiring objects during the period from 6 to 14 months of age by identifying the number and characteristics of any latent classes that might be present in their developmental trajectories. If we found different classes of developmental trajectories underlying the individual variability of handedness development, then we also would attempt to identify whether a conventional handedness assessment at any particular month (or combination of months) during this developmental period would reliably predict the infant's membership in a specific latent group (i.e., a particular trajectory of handedness development). Our large sample size, large number of trials for each assessment, and frequent assessment schedule should permit careful examination of the developmental patterns of handedness for object acquisition.

Method

Participants

Participants were 328 normally developing infants (182 males, 146 females) from full-term pregnancies and uncomplicated single births. The sample was drawn from 403 infants who were tested in cohorts of approximately 60 infants, rolling every 8 to 9 months during a 5-year period beginning in 2007. In an effort to expand our sample size, 75 infants (38 males) were included from a previously published study of 85 infants (Ferre et al., 2010), assessed with the same procedure and providing nine complete data points. Infants were excluded from the study if they accumulated more than two missed visits or if an infant's total number of actions during more than one visit was fewer than 17 (about 19% of infants). The ethnic composition of the tested infants was 57% Caucasian, 25% African American, 12% mixed ethnicity, 3% Hispanic or Latino, and 2% Asian. All infants were tested monthly between 6 and 14 months of age (±7 days from their monthly birthdays). Mean age (in months) at the beginning of the study was 6.09 (SD = 0.15) and at the end of the study was 14.24 (SD = 0.18). Eighty-four percent of the 328 infants (275 infants) provided data for all nine ages, whereas the remaining 16% provided data for eight assessments.

Procedure

At each monthly visit, a handedness assessment with demonstrated test–retest reliability and validity (with spontaneous block play) was administered while infants were sitting on their parents' laps at the table (Michel, Ovrut, & Harkins, 1985). This posture allowed free movements of the infant's arms. Assessment of hand-use preferences was based on a quasi-random-order presentation of 32 medium sized infant toys: 10 pairs of identical toys presented in line with the infant's shoulders (seven pairs presented on the table and three pairs in the air at the level of the infant's eyes), as well as 22 single toys presented midline to the infant (17 toys presented on the table and five toys in the air). Quasi-random presentations of single and double toys as well as table and air presentations reduced the probability of biased repetitive responses. During each presentation, the presenter ensured that the infant's hands were equidistant from the toy(s). Moreover, the infant's hands frequently were shaken simultaneously by the presenter in order to reduce response bias. Each toy presentation allowed enough time for toy acquisition (about 12 s), after which the toy was removed and the next one presented. Duration of the entire procedure was approximately 20 min. All infants' movements were digitally recorded with two synchronized cameras providing an overhead and a side view. Frame-by-frame coding for hand-use was done in Noldus Observer. Coders identified the hand that was the first to lift the toy from the surface of the table or move the toy in the air. Interrater reliability (Cohen's kappa M = 0.91, Mdn = 0.91, range = 0.80 to 1.0) was calculated for 20% of all videos. Another 20% of all videos were recoded for intrarater reliability (Cohen's kappa M = 0.95, Mdn = 0.95, range = 0.87 to 1.0). Coders were blind to any anticipated hand-use preference.

Figure 1 shows the mean number (and SEs) of acquisitions for each month—right-handed (R) + left-handed (L) + bimanual (B)—as well as the mean number of unimanual (R + L) and bimanual acquisitions. Of the 32 presentations, the smallest mean number of acquisitions was 22.5 at 6 months and the largest number was 28.1 at 12 months. The mean number of bimanual acquisitions ranged from 6.3 at 9 months to 9.4 at 14 months. Therefore, on average, the infants provided between 15 and 21 unimanual acquisitions for calculating their hand-use preference.

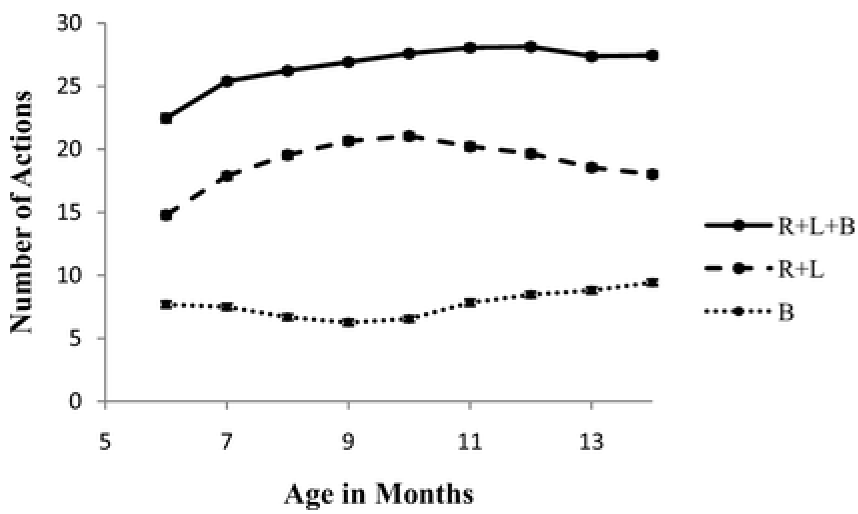

Figure 1. Mean (and SE) number of object acquisitions (R + L + B), as well as unimanual (R + L) and bimanual (B) acquisitions for each age of the 328 infants. R = right-handed; L = left-handed.

Hand-use preferences for the 328 infants were identified in two ways:

1. A Handedness Index (sometimes called a lateral asymmetry quotient [LAQ]) comes in many forms that are equivalent in their arithmetic character. One form, the HI (the ratio of right-hand acquisitions over the sum of right- and left-hand acquisitions across the 32 toy presentations: HI = R/[R + L]) was calculated for each infant at each monthly visit in this study. The range of possible scores for HI was from 0 to 1. Note that another form of the Handedness Index is HI* = (R–L)/(R + L). HI* is equivalent to HI, since in HI* the negative scores signify more left- than right-hand use, whereas in HI scores smaller than 0.5 signify more left- than right-hand use. In HI* right-handedness is sometimes defined as HI* > +0.5 (equivalent to HI = 0.75), and left-handedness is defined as HI* < −0.5 (equivalent to HI = 0.25). "No preference" HI* scores are those between 0.5 and −0.5. However, there is no statistical justification for such a classification criterion. A third form (LAQ) might be used if there are many actions that involve simultaneous

use of both hands (“B” in the formula). The LAQ is defined as {[R + (B/2)] − [L + (B/2)]}/{[R + (B/2)] + [L + (B/2)]}, which is equivalent to (R − L)/(R + L + B).

The various forms of the Handedness Index provide a measure of the magnitude of the difference in use between the hands. Calculation of 95% confidence interval (CI) for the mean HI across the nine monthly assessments for each infant permitted the classification of infants into three handedness categories. Infants with their 95% CI located completely above the 0.5 threshold of “no difference” in use between the hands were assigned to the “right-hand preference” group, whereas infants with 95% CIs completely below 0.5 were assigned to the “left-hand preference” group. Infants whose 95% CIs overlapped the 0.5 threshold were assigned to the “no preference” group.

Note that this HI-CI classification technique treats any variation in the HI across months as simply sampling error. These categories ignore any trajectory information in the variable distribution of the HI across visits. If infant handedness simply reflects underlying cerebral asymmetry, then the HI-CI classification should exhibit a predominant right-hand preference with strikingly smaller left-hand and no preference groups. If infant handedness is merely a reflection of other factors such as an infant’s state, then the distributions across the three categories should be more symmetrical with most infants exhibiting no preference and relatively equal proportions exhibiting right- and left-handedness. Also, if there was no reliable developmental trajectory in the manifestation of a hand-use preference for acquiring objects, then the HIs would not be correlated across visits and the HI-CIs might provide a statistically reliable measure for categorizing infants according to their hand-use preference.

2. A z-score (the difference between the number of right-hand and left-hand acquisitions divided by the square root of the sum of the right- and left-hand acquisitions across all toy presentations: z = [R − L]/[R + L]1/2) was calculated for each infant at each monthly visit. Unlike the monthly HI, which treats all differences in proportions as equally probable, the z-scores provide an estimate of the relative probability of each infant’s right or left hand-use preference for that month. This permits classification of infants into those with “statistically reliable” preferences ($z > 1.96$ or $z < 1.96$) and those without reliable preferences. A z-score of 1.96 closely approximates t-scores (2.0–2.1) for df = 14–20 with $p = .05$. Whereas the magnitude of the HI is a measure of the relative degree of the difference in use between the two hands, the magnitude of the z-scores indicates the probability that the difference between the two hands occurred by chance (Michel et al., 2002). Although both the monthly HI and the z-score are equivalent for assessing the trajectory of handedness across the nine visits, the z-scores are an effective means for classifying the infant’s monthly handedness preference (Michel et al., 2002). Hence, the infant’s monthly handedness classification can be compared with his or her classification according to the developmental trajectory of his or her hand-use preference. Since we discovered a somewhat higher frequency of infants using both hands to acquire objects than we had in previous research (Figure 1), we also calculated z-scores including bimanual acquisitions in the denominator: zb = (R–L)/(R + L + B)1/2. Addition of bimanual acquisitions would reduce the probability of obtaining a significant ($p < .05$) z-score for any particular visit but would not affect trajectory analyses since the numerator in the z-score definition is unchanged.

Data Analysis Plan

To calculate the latent groups in the infants' developmental trajectories, the infant's monthly z-score conversion of their right and left-hand use was used. Group-based trajectory modeling (GBTM) is a statistical method that is designed to discover distinctive patterns in the distribution of a sample's trajectories (Nagin, 2005) and is particularly useful in identifying heterogeneous subpopulations (see the online supplemental materials for further description of the model).

The model assumed that there are unobserved latent groups in the population of infants and that these latent groups have distinct developmental trajectories of hand-use preference. The SAS TRAJ procedure (B. L. Jones, Nagin, & Roeder, 2001) was used to fit a series of mixture models to the data. The Bayesian information criterion (BIC) was used to identify the number of groups in the model (Schwarz, 1978). Specifically, $2\Delta BIC$, twice the difference between the BIC for the full model (larger number of groups) and that for the reduced model (smaller number of groups), is interpreted as the degree of evidence for the full model. This interpretation is justified because $2\Delta BIC$ is approximately $2\ln B10$, where B10 is the Bayes factor (Kass & Raftery, 1995). A value of $2\ln B10$ greater than 10 is interpreted as very strong evidence against the reduced model, which can be replaced in favor of the more complicated model (Kass & Wasserman, 1995). The GBTM assigns infants to latent classes according to the highest associated classification probabilities.

Results

Exploratory and Latent Class Analyses

The distribution of mean HI approximated normal with slight negative skew toward right hand-use ($M = 0.60$, $Mdn = 0.61$, range = 0.20 to 0.87, skewness = 0.71, kurtosis = 0.75). Although there is a right bias in the distribution of infant HI means, the distribution is not as strongly right shifted as adult handedness. Table S1 in the online supplemental materials shows that monthly HIs correlate across visits. Mean HIs show a distinct right-hand predominance in the sample that seems to increase with age, indicating that acquisition handedness is developing during infancy. According to the 95% CI for each infant's mean HI our sample represents three handedness groups: 53.66% likely right-handed, 4.88% likely left-handed and 41.46% appear to have no distinct hand-use preference. The extremely small percentage of "left-handers" in our sample suggests that 95% confidence interval of mean HI is a very stringent criterion for handedness group assignment that may overestimate the percentage of infants without a stable hand-use preference.

A mixed-effect linear regression of infants' z-scores on age (in months) was performed using SAS PROC MIXED procedure. The results showed that the trajectory of hand-use has a significant linear, $\beta = 0.393$; $t(327) = 3.45$, $p = .001$, as well as quadratic trend, $\beta = -0.016$; $t(2895) = -2.876$, $p = .005$, illustrated in Figure 2, whereas the cubic trend was not significant, $t(2894) = -0.177$, $p = .860$. Sex differences in hand-use were not significant, $t(326) = -0.359$, $p = .719$.

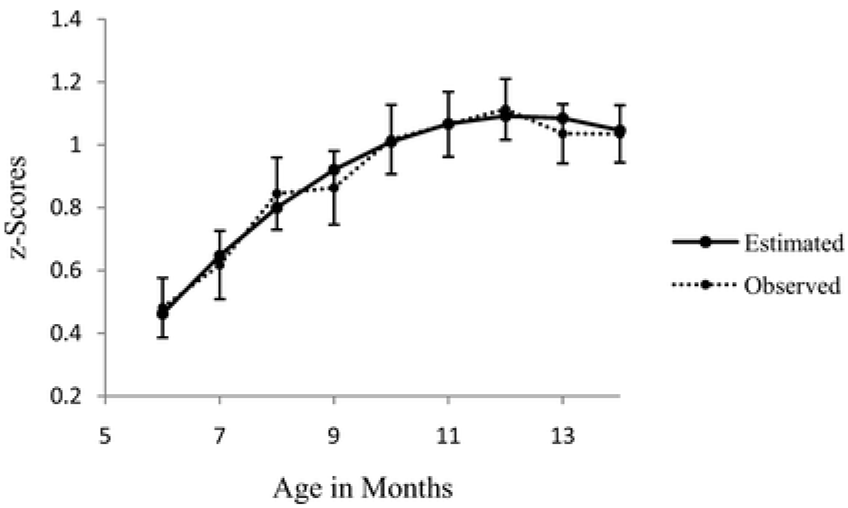

Figure 2. Estimated and observed (with standard errors) trajectories of handedness using z-scores.

The variability in trajectories across a semi-random sample of nine infants (Figure S1) from simple linear relations (ID 6) to complex quadratic trends (ID 1). Some seem to remain consistently right-handed (ID 1) or left-handed (ID 9); some seem to trend toward right-handedness (ID 2) or left-handedness (ID 3). Clearly, it is this individual variability that supports the conventional notion that infant handedness is either not identifiable or not consistent. It is this variability in our 328 trajectories of handedness that the GBTM will examine for latent classes.

The SAS TRAJ procedure (B. L. Jones et al., 2001) was used to identify the number of latent classes in the trajectories of handedness in the period from 6 to 14 months. Since exploratory multilevel analysis suggested a significant quadratic, but not cubic, trend of change in handedness z-scores with age, the mixture model trajectories were assumed to follow a second-order polynomial function. 2ΔBIC criterion suggested that the best fitting model has three latent groups underlying infant handedness (Table 1—Complete Sample). Since our model is a mixture of censured normals, after defining the latent classes, we ensured that z-scores for each of the three latent classes do not show any considerable departure from normality. We examined monthly q-q plots and conducted Kolmogorov-Smirnov test of normality for each of the months (6–14) by each of the three latent classes and concluded that data are normally distributed.

	Complete sample (n = 328)		Subsample 1 (n = 164)		Subsample 2 (n = 164)	
No. of groups	BIC	2ΔBIC	BIC	2ΔBIC	BIC	2ΔBIC
1	−5,929.16	—	−2,989.23	—	−2,910.54	—
2	−5,795.82	266.68	−2,911.53	155.4	−2,901.36	18.36
3	−5,780.39	**30.86**	−2,902.47	**18.12**	−2,893.60	**15.52**
4	−5,788.00	−15.22	−2,910.01	−15.08	−2,894.65	−2.1
5	−5,792.12	−8.24	−2,913.38	−6.74	−2,940.69	−92.08

Note. Dashes indicate that the value cannot be calculated. The boldface values indicate the last occasion when 2ΔBIC is larger than 10, which is the criterion for the best fitting model. In this case, the boldface number for 2ΔBIC would appear in the row with the best fitting number of groups (latent classes). BIC = Bayesian information criterion.

Table 1. Tabulated BIC and 2ΔBIC for the Complete Sample and Two Random Subsamples From the Latent Class Analysis

According to Figure 3, we can assume that those classes represent “right-handed” infants (37.58%, SE = 6.18), “left-handers”(13.70%, SE = 3.66), and infants initially without an identifiable hand-use preference (48.72%, SE = 5.59).

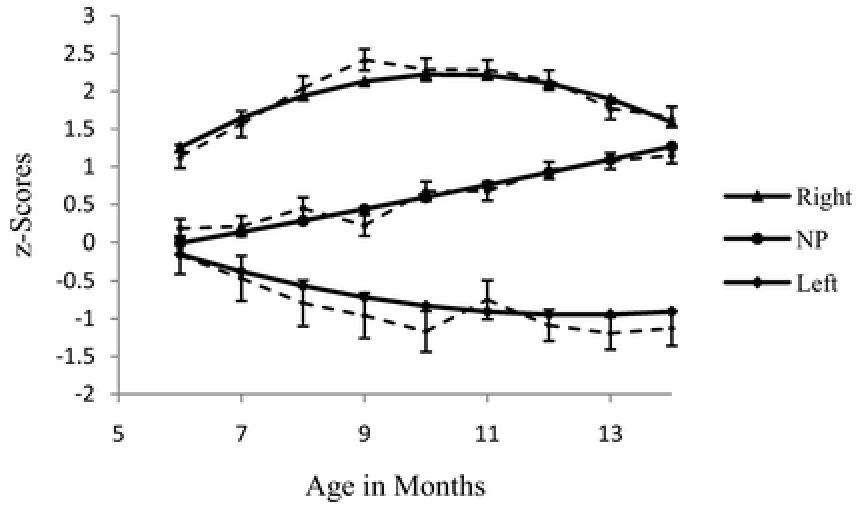

Figure 3. Estimated trajectories of handedness for the three groups defined by the latent class analysis (dashed lines show observed mean z-scores with standard errors). NP = no preference.

The latent class analysis revealed significant quadratic trends of change for all three handedness groups (Table S2—Full sample) with “right-handers” seeming to increase their right-handedness from 6 to 10 months and then decrease thereafter; “left-handers” seem to increase their left-handedness; infants without a statistically identifiable hand-use preference exhibit increasing right-hand use for the entire 6- to 14-month age interval (Figure 3). The random effects were not significant and were dropped from the model (Table S2). Additional analysis (SAS PROC MIXED) of the handedness trajectories from 10 to 14 months for the three latent handedness groups confirmed significant negative linear trends for both the “right-” and “left-handed” infants and a significant positive linear trend for the infants without an identifiable hand-use preference: AGE $\beta = -0.138$, $t(326) = -3.26$, $p = .002$; AGE*LC2 $\beta = 0.272$, $t(326) = 4.89$, $p < .0001$. Hence, a decrease in right-handedness after 10 months among the identified right-handers (Figure 3) is not an artifact of the quadratic trajectory.

Is the Developmental Trajectory of Infants Identified as “Left-Handers” the Mirror Image of the Trajectory of Infants Identified as “Right-Handers”?

In order to test this question, we multiplied the monthly z-scores of the infants associated with the left-handed latent group by (–1) so as to place the scores of both “lateralized” groups on the same scale. These two latent groups were significantly different for both their linear and quadratic trends (Table S3 and Figure 4). Although developmental trajectories of “right-handers” and mirrored “left-handers” are similar in the pattern of increasing lateralization, the two groups seem to be developing on different time-lines: whereas “right-handers” start decreasing their right-handedness at about 10–11 months, “left-handers” do not reach the peak even at 14 months. Thus, “left-handers” have a pattern of handedness development that is distinct from that of “right-handers,” and we conclude that the two groups are not mirror images of each other.

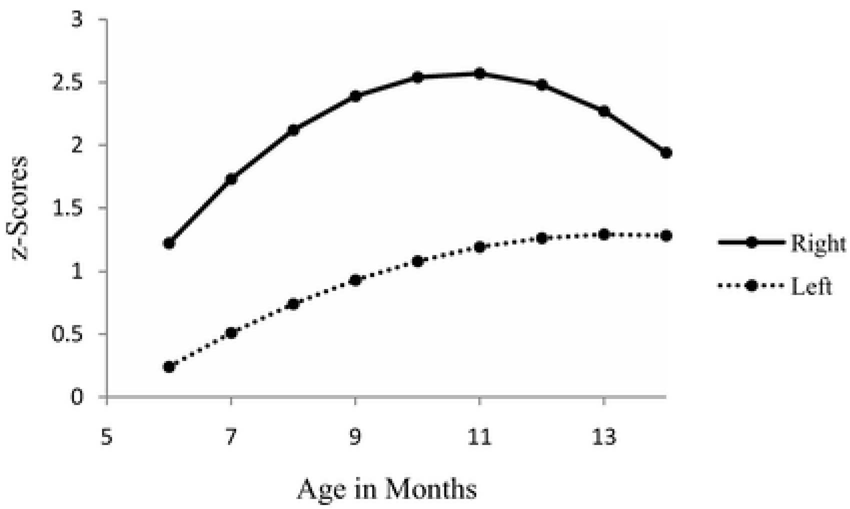

Figure 4. Estimated developmental trajectories of handedness for latent groups of "right-handers" and mirrored "left-handers."

Is There a Sex Difference in Distribution Across the Three Latent Handedness Groups?

Differences in sex distribution across different latent hand-use groups for the sample of 328 infants are not statistically significant, $\chi2(2, N = 328) = 0.768$, $p = .681$. Thus, the distributions of males and females across all three latent classes are similar (proportion of males in the left hand-use group = 59.5%, no hand-use preference group = 53.3%, and in the right hand-use group = 57.3%). Either sex difference in handedness appear later in development or a different measure of handedness is required for detecting it.

How Stable Are the Results Obtained by the Latent Class Model?

In order to evaluate further how well the latent class analysis identified groups in the complete sample, we randomly separated our sample into two subsamples of 164 infants each controlling for gender (91 males and 73 females in each group) and performed the latent class analysis on both random samples. Both latent class analyses suggested that three latent classes produce the best fit of the model to the data (Table 1—Subsamples 1 and 2).

In the first subsample, we observed the following distribution of infants across the three latent groups: 15.72% (SE = 4.26) with a left hand-use preference, 53.06% (SE = 6.73) with no preference, and 31.23% (SE = 7.21) with a right hand-use preference. The second random sample had the following distribution of latent groups: 16.50% (SE = 5.73) left-handed, 35.47% (SE = 10.01) no preference, 48.03% (SE = 8.68) right-handed. Although the two random samples produced slightly different distribution among the three latent groups, the comparison of the latent class assignment for the same infants done using the complete sample and then using two separate subsamples showed very good strength of agreement ($k = 0.86$) with 91.8% infants assigned into the same latent class according to both latent class analyses and no infant with an opposite handedness assignment. Therefore, we feel confident that the latent class analysis identified three groups of infants with differences in their developmental trajectories as revealed by their developing handedness for acquiring objects.

Should We Account for Bimanual Acquisitions When Estimating Infant Handedness?

In all previous analyses we ignored the role of bimanual acquisitions. However, one might argue that bimanual acquisitions are an important part of manual repertoire of an infant and have to be appropriately accounted for in careful data analysis. Thus, we explored how the latent class assignment would change with the inclusion of bimanual actions by performing the latent class analysis using recalculated z-scores [zb = (R–L)/(R + L + B)1/2] that adjust for bimanual pick-ups (B in denominator) and another analysis using the lateral asymmetry quotient [LAQ = (R–L)/(R + L + B)], which, as we noted above, some researchers have used to incorporate bimanual actions in the analysis of lateral hand-use. The results revealed three latent classes representing right- and left-handers, as well as infants without distinct hand-use preference for both analyses (Table 2).

Tabulated BIC and 2ΔBIC for z-Scores Corrected for Bimanual Acquisitions and the LAQ From the Latent Class Analysis

	zb		LAQ	
No. of groups	BIC	2ΔBIC	BIC	2ΔBIC
1	−5,583.71	—	−865.87	—
2	−5,453.47	260.48	−749.02	233.7
3	−5,434.15	**38.64**	−732.02	**34**
4	−5,439.01	−9.72	−736.05	−8.06
5	−5,441.38	−4.74	737.18	−2.26

Note. Dashes indicate that the value cannot be calculated. The boldface values indicate the last occasion when 2ΔBIC is larger than 10, which is the criterion for the best fitting model. In this case, the boldface number for 2ΔBIC would appear in the row with the best fitting number of groups (latent classes). BIC = Bayesian information criterion; LAQ = lateral asymmetry quotient.

Table 2 Tabulated BIC and 2ΔBIC for z-Scores Corrected for Bimanual Acquisitions and the LAQ From the Latent Class Analysis

Comparison of the latent group assignments for the same infants done by using regular z-scores and zb-scores shows very good strength of association (Cohen's κ = 0.87) with 92.7% of infants being correctly classified. Comparison of handedness assignments between regular z-scores and the Lateral Asymmetry Quotient revealed somewhat weaker, but still very good strength of association (Cohen's κ = 0.82) with 89.6% of infants being correctly classified. Thus, we conclude that adjustment for bimanual acquisitions does not significantly change handedness group assignment.

Is it Possible to Predict the Latent Class Assignment Without the Latent Class Analysis?

In order to determine whether there might be some smaller number of monthly assessments that would adequately capture the infant's handedness trajectory for acquiring objects, we performed the latent class analysis on our total sample (N = 328) using only information obtained during odd months (7, 9, 11, and 13 months) and again using only information obtained during even months (8, 10, 12, and 14 months). When only four monthly visits (odd or even months) are used for latent class analysis, the results reveal only two latent groups (Table 3), in contrast to three groups found by the analysis of all nine monthly visits. This is not too surprising since the latent class analysis that we are using is sensitive to patterns in the trajectories of the infants' performance. Nine longitudinal data points provide more opportunities either to detect more complicated trajectories or to be more confident in the simple trajectories that might be detected.

	Odd months		Even months	
No. of groups	BIC	2ΔBIC	BIC	2ΔBIC
1	−2,678.84	—	−2,646.49	—
2	−2,653.52	**50.64**	−2,606.71	**79.56**
3	−2,658.95	−10.86	−2,606.85	−0.28
4	−2,663.03	−8.16	−2,612.02	−10.34
5	−2,674.62	−23.18	−2,620.30	−16.56

Note. Dashes indicate that the value cannot be calculated. The boldface values indicate the last occasion when 2ΔBIC is larger than 10, which is the criterion for the best fitting model. In this case, the boldface number for 2ΔBIC would appear in the row with the best fitting number of groups (latent classes). BIC = Bayesian information criterion.

Table 3. Tabulated BIC and 2ΔBIC for the Complete Sample Including Only Odd or Even Months From the Latent Class Analysis

Interestingly, we detected significant differences in the trajectories of the two latent groups identified from odd and even month data. The latent class analysis performed on odd month combination suggested that the sample is almost equally divided into right-handers (49.45%, SE = 9.16) and infants without a distinct hand-use preference (50.55%, SE = 9.16), with a quadratic trend of change in handedness being significant in both groups (Figure S2). In contrast, analysis of even months resulted in sharply unbalanced latent groups of right-handers (75.19%, SE = 4.8) and left-handers (24.80%, SE = 4.8) with change in handedness adequately described by the linear tend (Figure S3). Since the composition of latent groups and their trajectories differ significantly when we switch from latent class analysis done on all monthly data to bimonthly data only, we conclude that the four bimonthly data points representing the period from 6 to 14 months of age provide misleading information about the trajectories of handedness development when compared to the nine monthly data points.

Next we evaluated the strength of association and correspondence between handedness assignments done using HI-CIs of some combination of monthly visits with handedness according to the latent class analysis. We started with the combination of all nine monthly visits. The results showed moderate strength of agreement between HI-CI for 9 months and latent class assignment (Cohen's κ = 0.53), with 72.3% of infants being classified correctly (Table 4). The rest of the infants were either identified as having a hand-use preference by HI-CI, while the latent class analysis suggested no preference, or HI-CI assigned infants to the no preference group, whereas latent class identified them as being distinctly right- or left-handed.

	Combined months						
	All	6, 7, 8, 9	7, 8, 9, 10	**8, 9, 10, 11**	**9, 10, 11, 12**	10, 11, 12, 13	11, 12, 13, 14
Kappa, test of agreement	0.53**	0.33*	0.51**	0.55**	0.55**	0.45**	0.37*
Identified correctly	72.3	62.5	72.0	74.1	74.1	67.7	62.5
Right HI-CI identified as left LC	0	1.0	0	0	0.7	0	0
Right HI-CI identified as no pref. LC	35.2	28.4	25.0	24.4	30.5	40.2	45.9
Left HI-CI identified as right LC	0	0	0	0	0	0	0
Left HI-CI identified as no pref. LC	0	64.0	30.4	28.6	10.0	4.3	4.2
No pref. HI-CI identified as right LC	2.2	22.4	15.9	11.7	8.3	13.5	18.7
No pref. HI-CI identified as left LC	19.1	15.9	13.8	15.0	14.6	14.2	14.2

Note. The boldface values indicate comparatively better models (combinations of months that result in a milder misfit when compared to the classification according to the latent class analysis). HI-CI = handedness index confidence interval; LC = latent class; pref. = preference.
* fair strength of agreement. ** moderate strength of agreement.

Table 4. Correspondence (in Percentage) Between Handedness Group Assignment According to the HI-Cis and Latent Class Analysis for All Monthly Visits and Rolling Combinations of Four Monthly Assessments

It was important to test whether some combinations of months would predict latent class assignment better than all nine monthly data. Thus, we examined HI-CIs for six rolling combinations of four contiguous months and found that the handedness groups identified by the HI-CIs derived from the 8, 9, 10, 11 months and the 9, 10, 11, 12 months age-periods seem to provide the least inaccurate estimate of the infant's latent class group (Table 4). Absolutely no infant's left- or right-handedness trajectory is reversed by the 8–11 HI-CI measurements and only one in the 9–12 HI-CI measurements. Note that in the 8–11 age period, 24.4% of those with a right HI-CI measurement and 28.6% of those with a left HI-CI measurement are in the no preference latent class developmental trajectory. The latter is reduced to 10% in the 9- to 12-month age period. Although none of the other HI-CIs from the 4-month age periods appears to provide as accurate an estimate of the latent classes, these HI-CIs are likely to misrepresent only those infants with a right- and left-handed developmental trajectory as having no hand use preference and those infants with a trajectory of no preference as being right- or left-handed. This does make this technique of classifying infant handedness somewhat problematic for investigating the role of handedness status in infant neuropsychological, social, cognitive, and emotional development.

The classification of handedness based on the HI-CIs for the 3-month age periods of 8–10, 9–11, and 10–12 provide the most reliable estimate of the infant's latent class (Table 5). Again, the HI-CIs from these 3-month age periods are likely to misrepresent infants with a right- and left-handed developmental trajectory as having no hand use preference and infants with a trajectory of no preference as being right- or left-handed.

	Combined months					
	7, 8, 9	**8, 9, 10**	**9, 10, 11**	**10, 11, 12**	11, 12, 13	12, 13, 14
Kappa, test of agreement	0.37*	0.47**	0.47**	0.47**	0.39*	0.27*
Identified correctly	64.3	69.5	69.2	68.9	64.6	56.7
Right HI-CI identified as left LC	0	0	0.7	0.7	0	0
Right HI-CI identified as no pref. LC	28.7	29.2	30.9	37.1	41.7	50.9
Left HI-CI identified as right LC	3.7	0	0	0	5.0	0
Left HI-CI identified as no pref. LC	55.6	39.1	39.3	12.0	5.0	4.5
No pref. HI-CI identified as right LC	20.2	14.3	13.7	15.1	16.4	25.5
No pref. HI-CI identified as left LC	16.1	16.0	14.9	12.5	15.8	14.9

Note. The boldface values indicate comparatively better models (combinations of months that result in a milder misfit when compared to the classification according to the latent class analysis). HI-CI = handedness index confidence interval; LC = latent class; pref. = preference.
* fair strength of agreement. ** moderate strength of agreement.

Table 5. Correspondence (in Percentage) Between Handedness Group Assignment According to the HI-Cis and Latent Class Analysis for Rolling Combinations for Three Monthly Assessments

Inspection of the HI-CIs for the combination of 2-month assessments suggests that none of 2-month combinations provide even moderate strength of agreement with latent class assignment (Table 6). For some purposes, such levels of handedness misclassification may be acceptable, but it may not be acceptable for research designed to determine the relation of infant handedness to other aspects of neuropsychological, cognitive, and social/emotional functioning.

	Combined months					
	7, 8	8, 9	9, 10	10, 11	11, 12	12, 13
Kappa, test of agreement	0.27*	0.32*	0.37*	0.32*	0.34*	0.26*
Identified correctly	58.0	60.2	62.4	58.8	60.6	55.8
Right HI-CI identified as left LC	2.0	2.5	1.4	2.7	1.4	0
Right HI-CI identified as no pref. LC	34.7	35.2	36.7	40.7	42.2	50.6
Left HI-CI identified as right LC	6.1	3.4	3.1	0	3.6	6.5
Left HI-CI identified as no pref. LC	60.6	58.6	46.9	48.6	32.1	22.6
No pref. HI-CI identified as right LC	25.3	20.9	17.5	22.2	20.4	25.4
No pref. HI-CI identified as left LC	15.2	16.6	16.8	14.8	15.5	14.6

Note. HI-CI = handedness index confidence interval; LC = latent class; pref. = preference.
* fair strength of agreement. ** moderate strength of agreement.

Table 6. Correspondence (in Percentage) Between Handedness Group Assignment According to the HI-Cis and Latent Class Analysis for Rolling Combinations for Two Monthly Assessments

Since the majority of research relating handedness to some aspects of cognitive, neuropsychological, social, and emotional development usually assesses handedness only once, we compared handedness status based on classification by monthly z-scores with the latent class assignment (Table 7). Our 17–32 ($M = 27.1$, $SD = 4.1$) object presentations permit the z-score to approximate a normal distribution in which a left hand-use preference can be identified by a $z < -1.96$ ($p < .05$) and a right hand-use preference can be identified by $z > 1.96$. No hand-use preference was identified when z-scores are between −1.96 and +1.96. However, since the number of scored presentations varied between individuals, we corrected each individual's score at each month to reflect a t-distribution with the degrees of freedom being the number of scored presentations minus 1.

	Infant's age in months								
	6	7	8	9	10	11	**12**	13	14
Kappa, test of agreement	0.20†	0.23*	0.29*	0.33*	0.34*	0.36*	0.30*	0.23*	0.22*
Identified correctly	54.6	55.6	58.5	60.8	61.7	63.0	60.4	56.8	55.9
Right *z*-score identified as left LC	7.0	6.3	4.2	2.6	2.4	2.4	0.8	0.9	1.7
Right *z*-score identified as no pref. LC	32.4	33.3	36.4	30.4	35.0	33.9	38.7	46.2	47.9
Left *z*-score identified as right LC	19.4	16.2	6.1	2.6	9.1	4.3	0	10.0	10.5
Left *z*-score identified as no pref. LC	51.6	56.8	57.6	61.5	45.5	47.8	42.9	25.0	15.8
No pref. *z*-score identified as right LC	30.5	28.0	23.4	22.9	21.8	19.2	23.5	27.3	28.7
No pref. *z*-score identified as left LC	13.1	13.2	14.4	14.7	14.1	16.3	15.8	14.4	13.8

Note. Boldface indicates a comparatively better model (a month that results in a milder misfit when compared to the classification according to the latent class analysis). LC = latent class; pref. = preference.
† poor strength of agreement. * fair strength of agreement.

Table 7. Correspondence (in Percentage) Between Handedness Group Assignment According to the Monthly z-Score and Latent Class Analysis

Inspection of Table 7 reveals that months 7 to 14 provide only fair strength of agreement between the z-scores and the latent class assignment. If there is only 1 month when handedness can be assessed, the 12-month age may be useful because left- and right-handed infants (as identified by the z-score) are least likely to be identified as having the opposite handedness by the latent class analysis of the developmental trajectories. However, even with the lowest likelihood of opposite classification, we risk misclassifying about 40% of infants. These results suggest that testing infant handedness on one or only a few occasions, each treated as an independent assessment, is unlikely to provide statistically reliable information about an infant's developmental trajectory of handedness.

Discussion

We have shown that the extensive individual variability in the trajectories of the development of handedness for acquiring objects during the period from 6 to 14 months can be reduced effectively to three latent groups, each with its own pattern of development, representing "identifiable right-handers" (38%), "identifiable left-handers" (14%), and a relatively large group of infants without an identifiable hand-use preference (48%) trending toward right-handedness. We are quite confident in the results because each of two quasi-randomly divided subsamples (retaining the same proportion of males as the complete sample) revealed the same three latent classes in proportions roughly similar to those observed in the complete sample.

Examination of both the mean handedness indices (HIs) and the z-scores revealed a continuous distribution for infant handedness with a right shift similar to that observed for adults (Annett, 2002). Such similarity suggests that infant hand-use preferences for acquiring objects might be an early developmental precursor of subsequent handedness in adults. In contrast, it is possible that infant handedness for acquiring objects may be simply a marker of the processes that will eventuate in adult handedness. Either way, mathematical similarity between the handedness distributions of infants and adults is not evidence for stability of individual differences in development. Only a coherent and convincing procedure for studying the development of handedness from infancy to adulthood would allow future research to address these alternatives empirically. We believe that our study is a step forward for the construction of such a procedure.

Each of the three latent trajectory groups exhibited a significant quadratic trend in their developmental pattern. The right-handers showed a rise from 6 months to an asymptote at 10 months and then a significant decline thereafter. Left-handers became more left-handed with age. Those without an identifiable preference exhibited a significant drift toward increasing right hand-use (as might be expected from the extensive right bias in adult handedness). Since almost half of our sample did not manifest an identifiable hand-use preference for acquiring objects during 6- to 14-month age period, it is important to know when and how their handedness becomes established and how it relates to their handedness in other manual skills (e.g., RDBM). Currently, we are examining this issue.

To help account for the "quadratic" trend observed in our trajectories of handedness development for object acquisition, we propose that early handedness development reflects a complex cascade of developmental contingencies (e.g., Ferre et al., 2010; Michel, 2002; Michel et al., 2006). The cascade begins with prenatally influenced (Fong, Savelsbergh, van Geijn, & de Vries, 2005; Michel & Goodwin, 1979) congenital postural asymmetries affecting the direction of orientation of the neonate's head while supine or upright (Kurjak et al., 2004; Michel, 1981; Schaafsma et al., 2009). These postural asymmetries feed into the establishment of sensorimotor asymmetries of the action systems controlling the use of the arms and hands in early infancy (Michel & Harkins, 1986). Initially, hand-use preferences are observed in reaching for and acquiring objects (Ferre et al., 2010; Michel & Harkins, 1986), subsequently in unimanual manipulation (Hinojosa, Sheu, Michel, 2003), and finally in the establishment of handedness preferences for role-differentiated bimanual manipulation (RDBM) and tool-use (Michel et al., 1985). As each new manual skill develops, the right bias spreads because each new skill is influenced by the previous skill and, in turn, influences the development of subsequent skills.

Thus, the "quadratic" trend we observed in our trajectories of handedness development likely reflects an increase in handedness lateralization as the skill of object acquisition gets mastered (6–11 months), and a decrease in handedness for acquisition (11–14 months) as the skill of unimanual manipulation becomes dominant and the skill of RDBM begins to develop more extensively. That is, at 10–11 months, infants may start using their nonpreferred hand for reaching and acquiring certain objects in order to engage in immediate manipulation with the preferred hand. We are investigating this specific aspect of the developmental cascade in infant handedness in an attempt to understand why "left-handers" do not seem to exhibit the decline in use of their preferred hand for acquisition (this may appear at a later age).

Although our three latent groups are identified by the pattern of the development of their hand-use preferences for acquiring objects, it is likely that these three groups represent quite different patterns in the development of their neurobehavioral organization. As such, we believe that it is likely, also, that these three groups may respond differently in various tasks that are used to assess the cognitive, social, and emotional abilities of infants during this period. Since handedness interacts with performance on many of these psychological tasks in adults, it is reasonable to consider that there might be some effect of the infant's pattern of handedness development (if this represents the infant's neurobehavioral development) on assessments of these abilities during this age period.

It is important to remember that in adults, it is not handedness that is thought to interact with their cognitive, social and emotional functioning but rather it is the pattern of hemispheric specialization that is represented by their handedness that is believed to affect these other psychological functions. Since we have shown that the developmental trajectory of left-handers is not the mirror image of that of right-handers (also cf. Michel, 1998) but, rather, represents its own pattern of neurobehavioral organization (G. V. Jones & Martin, 2010; Knecht et al., 2000), one possible explanation for that difference is that all infants are more likely to be interacting with mothers and other adults who are right-handed. Mundale (1992, cf. Michel, 1992) found that left-handed mothers influence their infants' hand-use when playing with objects quite differently from right-handed mothers, and that influence is not a mirror image of the right-handers' influence. Moreover, left-hand preferring infants with right-handed mothers become less lateralized in their hand use during their first year than do right-hand preferring infants

(Michel, 1992). Thus interaction with adults may affect the developing hand-use skills of "right-handers" differently from that of "left-handers." Currently, we are examining the relation of parental handedness to the handedness trajectories of these infants.

If the neurobehavioral development of infants differs in relation to the trajectories of their handedness development, then future research on infant psychological development might want to have some estimate of the infants' patterns of handedness development. It is troubling that patterns of handedness development during infancy that we discovered may not be reliably identified by one to four assessments of handedness. The data from bimonthly handedness assessments (four odd or even months) were not sufficient to reveal the three latent trajectories initially identified by using all nine monthly assessments. Indeed, the odd and even months revealed strikingly different latent classes, perhaps because of the quadratic trends revealed in the developmental trajectories. Also, comparison of the infant handedness status, as determined by the confidence interval of handedness index (HI-CIs), with their latent class membership revealed that infant handedness cannot be reliably identified by nine or fewer assessments when each assessment is treated as an independent measurement. At least 28% of the infants will be misclassified when compared to their latent class membership. Moreover, handedness of up to 45% of infants may be misclassified when the classification is based on a handedness assessment (z-score) obtained at only 1 month during this age period. Therefore, the infant's handedness may be best characterized by monthly assessments that are used as measures of developmental trajectories, rather than as multiple measures of a trait. This means that investigating the role of handedness in other aspects of infant development will require comparisons of their trajectories of development, rather than simply differences between handedness groups.

For those studies that are not focused on the development of handedness but want to have some indication of the infant's handedness status, a single measure of hand-use preference (identified by z-score) at 12 months of age was the least likely to cross-classify right- and left-handedness. This measure would roughly identify the infant's right- or left-handedness. Unfortunately, this measure will misclassify some potentially left- or right-handed infants as no preference infants and will misclassify some no preference infants as left- or right-handers. These types of misclassification may or may not be an important issue.Previous research has reported that males and females may differ in their hemispheric specialization and handedness patterns (Papadatou-Pastou, Martin, Munafò, & Jones, 2008). Since differences in the distribution of males and females in the three groups of handedness development identified by the GBTM analysis were not significant, it may be that the sex difference in handedness appears later in development or with a different measure of handedness. This issue should be pursued in more detail in future research.

So what does it mean for the infant's development that he or she is identified as right- or left-handed for acquiring objects? According to Casasanto's work on children and adults (Casasanto, 2009; Casasanto & Henetz, 2012), the left- and right-handed infant may be developing abstract concepts differently. What, then, does that mean for the large proportion of infants who, during this age period, exhibit no identifiable hand-use preference for acquiring objects? Currently, we are examining the relation of the infant's developing handedness status to his or her development of object construction skills, tool-use, and language. We expect that the three patterns of developing handedness (as revealed by the three latent groups) are associated with differences in the development of these abilities (cf. Kotwica, Ferre, & Michel, 2008). If they are, then it is likely that future studies of the infant's cognitive, social, and emotional development may want to include information about the participant's pattern of handedness development.

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