The development of neuromotor skills and hand preference during infancy

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Abstract:

Assessing infant handedness has been controversial. Different assessment techniques and theoretical approaches produce different results. Evidence from a dynamic systems perspective showed that the development of postural control during infancy affects the expression of an infant's handedness. However, others found that developmental changes in postural control influenced the amount of symmetrical(bimanual) reaching during infancy, but not hand preference. Since most studies of infant handedness use age to assess development, perhaps measures of an infant's developing neuromotor control, irrespective of age, would better predict changes in an infant's hand preference. To assess neuromotor development, items from [Touwen's (1976) Neurological development in infancy. Lavenham, Suffolk: The Lavenham Press, LTD]. "Group III" indices were used. These items assess developmental changes in neuromotor abilities throughout the 6–14-month age period. Hand preference for acquiring objects was measured during these same months. Group Based Trajectory Models (GBTM) of 380 infants identified four different groups of infants according to the trajectory of the development of their hand preferences (32% Early Right, 12%Early Left, 25% Late Right, 30% No Preference). A multilevel model was used to compare these four developmental trajectories according to age and neuromotor development. Age, not neuromotor development, is a better predictor of differences in developmental trajectories of the four hand preference groups. However, Late Right infants are significantly less developed at 6 months than No Preference, Early Right and Left infants and both Early Right and Left infants are most advanced at 6 months. All groups exhibit similar rates of neuromotor development indicating no "catch-up" by the Late Right infants. Thus, any assessment of infant handedness will incorporate necessarily four groups of infants with differently developing hand preferences and neuromotor abilities.

Keywords: infant hand preference | lateralization | locomotion | longitudinal | neuromotor ability

Article:

Introduction

The primary purpose of this study was to examine neuromotor development, in contrast to age, as a predictor of the development of infant hand preferences. There are several reasons to examine the relation of neuromotor development to the development of hand preferences during infancy: (i) Infancy is a period of rapid neuromotor development and hand preferences are an aspect of neuromotor development (Michel, 1991); therefore, neuromotor development and the development of hand preferences are likely to be related; (ii) Dynamical systems theory proposes, and several studies have shown (e.g., Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996, 2002; Fagard & Lockman, 2005), that infant hand preferences reflect or at least are perturbed by typical developmental transitions in infant locomotor control; (iii) Since age is recognized as a relatively weak marker for development (cf., Wohlwill, 1970), perhaps another marker of development such as neuromotor abilities might better predict the development of hand preferences during infancy; (iv) Handedness is an aspect of hemispheric specialization of function and its early development may be tied closely to the development of other neural systems. Michel, Nelson, Babik, Campbell and Marcinowski (2013) argued that the development of infant hand preferences contributes to the development of hemispheric specialization for language. In contrast, several recent studies (e.g., Cochet, 2016; Esseily, Jacquet, & Fagard, 2011; Häberling, Corballis, & Corballis, 2016) have proposed that handedness is an independent aspect of hemispheric specialization and its development is unrelated to specialization for communication, language, and praxis functions.

Most studies examining the development of handedness and its relation to other aspects of hemispheric specialization such as language functions have used statistically indefensible measures to characterize individual handedness (Michel et al., 2013). Therefore, it is difficult to draw definitive conclusions about the relation of hemispheric specialization for language, praxis (skills using the hands), and other functions to a measure of handedness that is poorly identified. Since the lateralization of neural networks is sensitive to experiential factors (cf., Park, Chiang, Brannon, & Woldorff, 2014), the relations among lateralized functions and handedness for adults and even children may be confounded by such experiential influences. Therefore, investigation of the development of infant hand preferences can provide a foundation for the investigation of handedness and hemispheric specialization early in development.

Unfortunately, assessing the development of hand preferences during infancy is fraught with controversy. Groen, Whitehouse, Badcock, and Bishop (2013) correctly report that hand preference has been assessed in an over-simplified manner, that designations for hand preferences groupings are often arbitrary, and grouping agreement is non-existent among researchers. Several investigators have argued that infants do not exhibit stable, consistent hand preferences when reaching for or manipulating objects (e.g., Dubois et al., 2009). In contrast, others have reported consistent preferences for a large proportion of infants but not for all (e.g., Michel et al., 2013). However, different assessment procedures produce different results (e.g., Bishop, Ross, Daniels, & Bright, 1996; Campbell, Marcinowski, Latta, & Michel, 2015; Fagard, Margules, Lopez, Granjon, & Huet, 2017). Also, most studies of infant hand preference define the preference using an insufficient number of trials to generate any statistically reliable estimate of hand preference; hence, the handedness categories likely reflect haphazard distributions (Campbell, Marcinowski, Latta, et al., 2015). And many studies lack an adequate number of assessment periods to identify developmental trajectories for hand preference (Ferre, Babik, & Michel, 2010). We would argue that infant hand preferences should be identified only from longitudinal studies involving large samples assessed at least monthly for 6 months or more so that the characterization of the trajectories of hand preference development are statistically rigorous (e.g., Ferre et al., 2010; Michel, Babik, Sheu, & Campbell, 2014; Nelson, Campbell, & Michel, 2013).

Proponents of the dynamic systems theory have used several weekly and daily assessment periods organized around expected transitions in locomotion or posture (onset of sitting, crawling, walking) and have shown that control of the hands becomes recruited into the control of these locomotion and posture transitions (see, Michel et al., 2013). Thus, when reaching for and acquiring objects, the use of one or both hands will depend upon the locomotor/postural skill concurrently being mastered. For example, when the infant begins walking, the arms must be controlled in a symmetric manner to maintain balance. This recruitment is proposed to result in a facilitation of symmetric reaching for objects, even when seated, and a loss of any hand preference. Corbetta and Bojyck (2002) observed that infants increased bimanual reaching at the onset of walking; however, as infants gain better balance control, bimanual reaching declines (see also, Berger, Friedman, & Polis, 2011).

Unfortunately, the assumption that the expression of a hand preference when reaching for and acquiring objects is tied to the developmental transitions of locomotor pattern, was not supported in a large sample (275 infants), longitudinal (monthly assessments from 6 to 14 months) study (Babik, Campbell, & Michel, 2013). Babik et al. (2013) reported no relation of the onset of infant locomotor or posture control (sitting, crawling, walking) to lateralized hand use for acquiring objects. They did observe a rather complicated relation between symmetrical hand use for object acquisition and postural development; that is, there were complex interactions among the infant's sex, handedness status (left, right, or no preference) and the onset of sitting and crawling, but no relation to the onset of walking. Babik et al. also found that early sitters change their symmetric hand use reaching trajectory about 2 months sooner than do late sitters and early walkers change their trajectory of symmetric reaching about 1 month sooner than late walkers. Thus, this large sample, long-term longitudinal study observed no relation of the development of hand preference to developmental changes in sitting, crawling, and walking, but did observe some relation of symmetrical hand use to the onset of sitting and walking.

The present study is designed to examine the relation of general neuromotor development, rather than the developmental onset of the specific locomotor and postural control skills of sitting, crawling, and walking, to the development of handedness for a large sample assessed monthly from 6 to 14 months of age. This represents an expansion of the study by Babik, Campbell, and Michel (2014) with a larger sample size and the use of measures of neuromotor development from Group III items from Touwen's (1976) neurological assessment scale. Although the scale includes the identification of the onset of sitting, crawling, and walking, Touwen's procedure allows the recording of more developmental changes in these skills that lead up to onsets. Therefore, unlike assessments of motor “milestones,” Touwen's procedure tracks developmental changes in a variety of limb movements and postural/locomotor patterns and their resistance to perturbation. Touwen's procedure was based upon careful longitudinal assessment (every 4 weeks) of 51 infants (28 males) from 4 weeks up to 22 months of age. Assessment items were divided into four groups according to their age of developmental transitions. Items from Touwen's Group III exhibit the greatest pattern of change during the 6–14 month period and were used for this study.

In addition, the present study expands on the previous study (Michel et al., 2013) which used a Group Based Trajectory Model (GBTM, Nagin, 2005) that identified three latent classes in the developmental trajectories of infant hand preference during the 6–14-month period. Of 328 infants (182 males), 38% had an identifiable right hand preference when reaching for and acquiring objects; 14% had an identifiable left hand preference but 48% had no identifiable hand preference. Thus, nearly half of the sample did not exhibit a consistent pattern in their hand preference and would seem to support the notion that: (i) a large proportion of infants do not manifest a hand use preference during infancy and (ii) developmental changes in neuromotor development likely affect the expression of hand preferences. However, the GBTM analysis relies upon the BIC for identifying the number of latent classes within a sample. Although only the model with three latent groups met that criterion in the Michel et al. (2013) study, the model with four latent groups came close to meeting the criterion. Therefore, it is possible that within the large group of infants with no distinct hand preference trajectory, there were infants with a trajectory that failed to reach the criterion. This current study, with its larger sample size, reexamined the number of latent groups in the trajectories of infant hand-use preference.

By using a large sample size and examining both neuromotor development and the development of hand preference, we could untangle the relation of age and neuromotor ability to the development of hand preference. Also, it is possible to determine whether age or neuromotor development has a stronger predictive relation to the development of hand preference for any particular hand preference group. That is, perhaps neuromotor development or age predicts hand preference only for infants who prefer to use their right hand. Thus, in the current paper, we address two main issues. First, we examine the classification of infants into hand preference groups using the methods outlined in Michel et al. (2013) but with a larger sample of infants. We predict that with the larger sample size, the no preference group will shrink as those infants become absorbed into a hand preference classification. Second, using the revised classification of infant hand preferences, we address the question of whether age or neuromotor development is a better predictor of the trajectories of infant hand preference development. We predict that neuromotor development will be a better predictor of the development of hand preferences than age.

From these two issues, we examined four questions: (i) Does Touwen's neuromotor assessment identify changes with age? (ii) Are there differences among groups of infants according to the trajectory of their hand preference development? (iii) Does age or neuromotor developmental score or BOTH predict the trajectories of hand preference development? and (iv) Does age and/or handedness predict neuromotor development?

Method

2.1 Participants

The sample consisted of 328 infants (182 males) from a previous publication (Michel et al., 2013) plus an additional 60 (29 males) from a study of the relation of infant handedness to handedness assessed at 5 years of age. The 388 infants were tested in the Infant Development Center at the University of North Carolina Greensboro. Eight of the additional 60 infants did not provide sufficient data for analysis (missed more than two visits) so the total sample for statistical analysis was 380 (209 males). Enrollment of participants, informed consent, data collection, and storage were completed in compliance with IRB regulations for the protection of human subjects. At each monthly visit, parents received a $10 gift card. All infants had a normal gestation period and birth weight, and came from uncomplicated single births. The current sample was ethnically diverse: 61% Caucasian, 23% African American, 3% Hispanic or Latino, 1% Asian, 1% Pacific, 4% other, and 7% mixed ethnicity (plus one family did not provide ethnicity information). All subjects were tested monthly, within ±7 days of the infants' monthly birthdays, from 6 to 14 months (total 9 visits) on object acquisition and their hand preference was analyzed with the GBTM (Nagin, 2005) technique for identifying potential latent class differences in their trajectories of hand preference development. A subsample (303 infants, 169 males) of the group of 380 infants were assessed at each monthly visit on a set of Group III items from Touwen's (1976) assessment of neuromotor development.

Information on maternal hand preference was also collected in order to compare the hand preference of the infant to that of the mother. We used the Briggs and Nebes (1975) version of the Annett (1970) hand preference questionnaire to obtain hand preference information from 274 mothers.

2.2 Procedure

2.2.1 Object acquisition

Infant hand preference for object acquisition was observed monthly from 6 to 14 months. Acquisition was defined as an action that included grasping an object and lifting it off the table or changing its location in space. Behavioral coders marked whether the infant used the left, right, or both hand(s) to acquire each object. Both hands had to acquire the object simultaneously for a "both" hand acquisition to be coded, otherwise the first hand to acquire the object was marked. Simultaneous acquisitions were decided upon when a coder viewed an action three times and was still unable to determine whether the right or left hand was used to acquire the object. Although each item may have been acquired several times during each trial, only the initial acquisition was recorded.

Two synchronized cameras which provided both an overhead and a side view of the infant's hands were used to record 34 presentations of 32 infant toys to each infant (see, Michel et al., 2013 for more details). Infants were seated on their parents' lap, and parents were asked to hold the infant around the waist area in order to provide support for the infant's posture during the procedure. A large, crescent shaped table was positioned in the center of the room. On the concave side of the table, the infant was seated on the parent's lap. On the convex side of the table, a research assistant was seated and presented each of the items on the table either directly to the infant's midline on the table surface (17 items), suspended in the air (5), 7 pairs of identical items were presented on the table surface separated from each other by a width roughly equivalent to the distance between the infant's shoulders, and three pairs were presented suspended in the air in line with the shoulders. The entire object acquisition procedure lasted 20–25 min. Infants were allowed to pick up the toys and explore the objects for up to 25 s before the research assistant removed the item and presented the next item.

The software program Observer® XT (Noldus Information Technology, Wageningen, Netherlands) was used to code all videos. This program provides the ability to view the video in milliseconds which allowed us to accurately identify the hand used to acquire each object. Inter-rater reliability was calculated from 20% of the videos which were coded by two coders (Cohen's Kappa M = 0.91, Mdn = 0.91, range = 0.82–0.99). Intra-rater reliability was calculated from a different 20% of the videos which were re-coded by the same coder (Cohen's Kappa M = 0.94, Mdn = 0.94, range = 0.88–0.99). All coders were blind to infants' hand preferences since these were determined subsequently by the coded data. The infant's monthly hand preference scores for object acquisition were converted into Handedness Index (HI) scores: R/(R + L), where R and

L correspond to the total number of acquisitions performed by the right and left hand. In order to derive hand-preference latent classes from the 380 infants' monthly assessments, the GBTM, (Nagin, 2005) and the SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001) were used with these HI scores.

2.2.2 Neuromotor score

At each monthly visit from 6 to 14 months, infants were tested using items from Group III of Touwen's neurological assessment (Touwen, 1976) to specify the infant's development of motor and postural control. Touwen's items measure developmental changes in the manifestation of postural control and motility of the limbs, patterns of locomotion, duration of sitting and resistance to perturbation, standing, and walking. Scores for each of the 11 measurements range from 0 to 3 or 0 to 5 with each score marking a developmental change in apparent neuromotor control. Thus, "milestones" are not represented as present or absent but rather emerge from the developmental progress of the behaviors. These scores were summed at each month to measure neuromotor development.

Upon entering the lab, the infant was seated on a rubber mat on the floor with a research assistant who then tested the eleven neuromotor tasks. The ability level of the infant was recorded on a paper, and 10% of the observations were conducted with two research assistants in the room in order to assess reliability on this measure. The scores of all eleven tasks were summed each month to create a monthly score of neuromotor development.

Maternal hand preference was assessed using the Briggs and Nebes (1975) hand preference questionnaire. Mother hand preference was collected because too few fathers were available to provide hand preference information. Annett (1973, 1978) reported that mother's hand preference was a reliable predictor of offspring hand preference. The Briggs and Nebes (1975) questionnaire assesses 12 common tasks with responses to each task ranging in five steps from −2 (always use my left hand) to +2 (always use my right hand). Mothers were considered to be right handed if total score was greater than or equal to +9, and left handed if total score was less than or equal to −9. Mothers with scores between −8 and +8 were classified as "non preferent" (Raczkowski, Kalat, & Nebes, 1974).

2.3 Analytic plan

There are four main lines of inquiry that require analysis as we describe the relation between age, neuromotor development, and hand preference. First, we describe how neuromotor scores change across age using a multilevel model to ensure that neuromotor scores significantly change during this age period. Second, using GBTM, we classify infants into hand preference groups according to differences in their latent trajectories and then describe the pattern of these trajectories according to the multilevel model. Third, we analyze whether age and/or neuromotor development predicts hand preference using a multilevel model. Fourth, we modeled how hand preference predicts neuromotor development using a multilevel model in order to investigate further the relation between neuromotor development and the development of hand preferences. All models were analyzed using the software program, Hierarchical Linear Modeling (HLM v. 7) or using the SAS (v. 9.2) Proc Traj procedure (Jones et al., 2001).

The GBTM was performed on a monthly HI which was $HI = R/(R + L)$. GBTM clusters similar patterns of trajectories together and identifies sub-groups whose members follow a similar developmental trend (Haviland, Nagin, Rosenbaum, & Tremblay, 2008). Although individuals can differ from a whole population qualitatively, they may remain relatively homogeneous within the sub-group. GBTM assumes that individuals are drawn from a population with distinct sub-groups (Michel et al., 2014; Michel, Sheu & Brumley, 2002). When the analysis finds sub-groups, each individual is assigned a probability of group membership for each sub-group (i.e., a posterior probability) and the infant is assigned to the group where the posterior probability is the highest. We used the SAS TRAJ procedure (Jones et al., 2001) and the Bayesian Information Criterion (BIC) was used to identify the most parsimonious model (Schwarz, 1978). We calculated the difference between the BIC for the full model (the model with the larger number of groups) and the BIC for the reduced model (the model with the smaller number of groups), and multiplied this difference by 2. The model that has a value greater than 10 is considered the best fitting model. This interpretation is justified because 2ΔBIC is approximately 2lnB10, where B10 is the Bayes factor (Kass & Raftery, 1995).

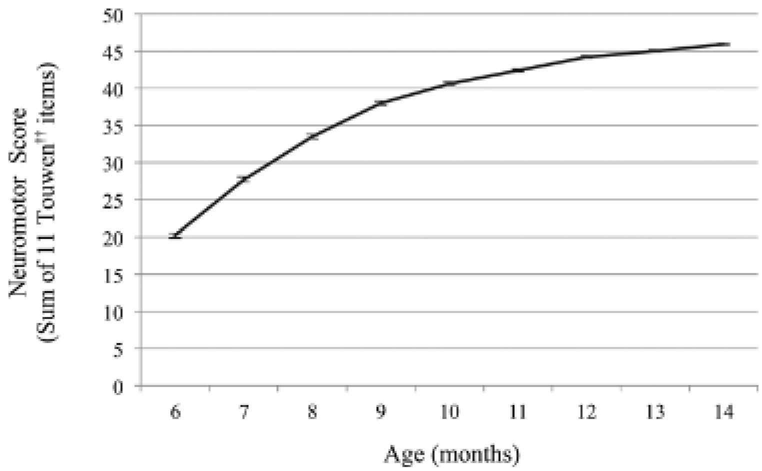
The hand preference groups that were identified by the GBTM were then used in four separate multilevel models in order to examine the prediction of: (i) age to hand preference (model 1); (ii) neuromotor development to hand preference (model 2); (iii) age and neuromotor development to hand preference; and (iv) hand preference to neuromotor development. The multilevel model building and reduction strategies recommended by Raudenbush, Bryk, Cheong, Congdon, and du Toit (2004) and Singer and Willett (2003) were employed. This involves creating two models: the unconditional and the conditional growth model. The unconditional growth model represents the "structure" of change for a variable and only includes variables that change with time and their variance components, including Age, Age2, Neuromotor, and Neuromotor2. The change found in the unconditional growth model, then becomes the structure of examining change for the conditional growth model. This conditional growth model maps change while taking into account variables that are not sensitive to change; in this case our four handedness groups.

Results

3.1 Does Touwen's neuromotor assessment identify changes with age?

A multilevel model was used to analyze how age predicts infant neuromotor development. The level-1 variables were Age and Age2, centered on 6 months. Also, variance components for the intercept, Age and Age2 were included to test for significant individual variability at the intercept and change over time. The outcome variable, neuromotor development, was calculated as a sum score of all 11 items at each age (possible range: 0–50); each infant had nine neuromotor scores, one score for each age. The neuromotor mean scores were 20.21 for 6 (se = 5.93, range: 8–38), 27.70 for 7 (se = 6.20, range: 10–43), 33.50 for 8 (se = 5.58, 19–47), 38.01 for 9 (se = 4.49, range: 19–47), 40.62 for 10 (se = 3.79, range: 27–48), 42.43 for 11 (se = 3.49, range: 30–50), 44.22 for 12 (se = 2.72, range: 30–49), 45.04 for 13 (se = 2.72, range: 30–49), and 45.96 for 14 (se = 45.96, range: 36–49) months (see Figure 1).

Age, Age2, and variance components for Age, Age2 were significant for neuromotor score. On average, neuromotor had an intercept significantly higher than a score of 0 ($\beta 0 = 8.78$, $t(302) = 28.09$, $p < 0.001$) and increased quadratically ($\beta 2 = -0.48$, $t(302) = -38.14$, $p < 0.001$) and linearly ($\beta 1 = 3.00$, $t(302) = 74.12$, $p < 0.001$). Thus, infants initially increased their neuromotor score at a constant rate (i.e., linear), but this increase slowed significantly (i.e., quadratic).



Mean neuromotor scores across age (†). †, Bars are standard errors, which are very small; ††, Touwen, 1976

3.2 Are there differences among groups of infants according to the trajectory of their hand preference development?

A group-based trajectory model (GBTM) analysis was conducted on the pattern of hand preference development across the nine monthly assessments for the larger sample (n = 380) of infants. The BIC was used to decide the best fitting model. After the appropriate model was identified, each individual is assigned a probability of group membership for each identified latent class, "posterior probability." The infant is then assigned to that latent class where his/her posterior probability is the highest. These posterior probabilities can be interpreted as the probability of an infant actually belonging to that latent class and were used to test the effect of hand preference in all further analyses that include hand preference. Although categorical assignment is used in figures, the posterior probability, rather than the categorical assignment, was chosen for all subsequent analysis in order to account for infants' differing levels of likelihood of belonging to the group and similarities to that group.

Four groups were identified as the most likely classification of hand preference within the sample of 380 infants (See Figure 2). The grouping distribution among infants was: 32% (123) were in Early Right preference group, 25% (96) were in Late Right preference, 12% were in the Early Left preference group, and 30% (114) were in the No preference group. The names of these latent classes were derived from the trajectories revealed by their multilevel model analysis. The mean posterior probabilities by group were 0.849 for Early Left (se = 0.16), 0.753 for Late Right (se = 0.17), 0.821 for Early Right (se = 0.17), and 0.798 for infants with No preference (se = 0.16).

After the assigning infants to the four groups, we used a multilevel model to identify whether the four groups exhibited significant differences in the trajectories of their HI scores (R/(R + L)) for acquisition across the nine age periods. The level-1 variables were Age, Age2, and variance components for the intercept, Age and Age2. The level-2 variables were hand preference groups, modeled as the posterior probabilities of the infant's assigned group from the GBTM analysis (Early right, Late right, Left). No preference served as the reference group.

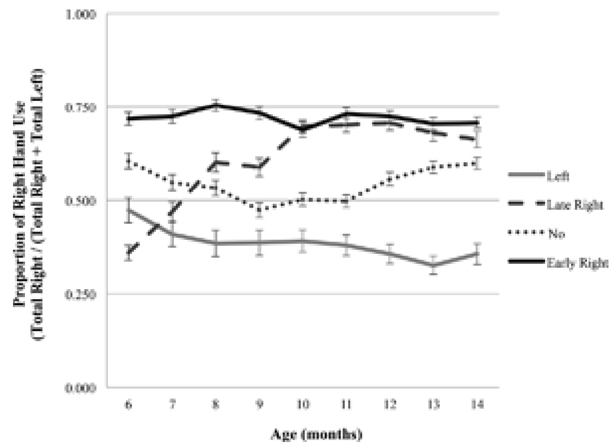


Figure 2. Mean proportion of right hand use across age (n = 303) (†). †, Bars are standard errors

The outcome variable was the HI or the proportion of right hand use. The mean scores for the HI across groups were 0.56 for 6 (se = 0.23, range: 0–1), 0.57 for 7 (se = 0.23, range: 0–1), 0.60 for 8 (se = 0.23, range: 0–1), 0.57 for 9 (se = 0.23, range: 0–1), 0.59 for 10 (se = 0.21, range: 0.06–1), 0.61 for 11 (se = 0.21, range: 0.07–1), 0.62 for 12 (se = 0.21, range: 0–1), 0.61 for 13 (se = 0.21, range: 0–1), and 0.62 for 14 (se = 0.20, range: 0–1) months. With 34 presentations (mean single hand acquisitions = 27, sd = 1.87), a right hand proportion of 0.6 or larger and 0.4 and smaller is unlikely to occur by chance (Binomial test, $p < 0.05$). So, for six of the nine visits, the mean hand preference scores of the group of 380 infants was significantly shifted to the right, consistent with child and adult measures of handedness.

The unconditional growth model revealed that the intercept ($\beta_0 = 0.57$, $t(302) = 54.92$, $p < 0.001$), Age ($\beta_1 = 0.007$, $t(302) = 4.16$, $p < 0.001$) and the variance components for the intercept ($\delta_0 = 0.016$, $\chi^2 = 580.30$, $p < 0.001$), Age ($\delta_1 = 0.0004$, $\chi^2 = 510.36$, $p < 0.001$), and Age2 ($\delta_2 = 0.00004$, $\chi^2 = 420.83$, $p < 0.001$) were significant for HI; however the Age2 slope was not ($\beta_2 < -0.001$, $t(302) = -0.62$, $p < 0.001$). On average, infants increased their right-hand use linearly, but showed significant variability in quadratic change. The reason for why the variance component for Age2 is significant while Age2 itself not significant, is likely because there are quadratic trajectories of infants changing their hand use in different directions—some infants increasing their right-hand use (i.e., Early and Late Right) and others are decreasing their right hand use (i.e., Left). Therefore, the Age2 slope and its variance component were retained for the conditional growth model, despite Age2 not being significant.

Next, the conditional growth model (i.e., models with handedness at level-2) was built using the structure of change found in the unconditional growth model. The Left ($\beta_{21} = -0.013$, $t(299) = -5.60$, $p < 0.001$), Late Right ($\beta_{22} = -0.031$, $t(299) = -14.96$, $p < 0.001$), Early Right ($\beta_{23} = -0.13$, $t(299) = -7.98$, $p < 0.001$), and No preference ($\beta_{20} = 0.013$, $t(299) = 11.25$, $p < 0.001$) groups all exhibited significant quadratic change for proportion of right hand use (see Table 1 and Figure 2). Early Right preference infants had a higher proportion of right-hand use than infants with No preference at 6 months ($\beta_{03} = 0.35$, $t(299) = 15.27$, $p < 0.001$), but Left

($\beta 01 = -0.039$, $t(299) = -1.14$, $p = 0.258$) and Late Right infants ($\beta 02 = 0.033$, $t(299) = 1.16$, $p = 0.245$) did not. Additionally, Late Right preference infants had a higher initial rate of change (i.e., linear slope: $\beta 12 = 0.061$, $t(299) = 13.279$, $p < 0.001$) of right hand use, than Early Left preference infants ($\beta 11 = -0.01$, $t(299) = -1.93$, $p = 0.054$) and Early Right preference infants ($\beta 13 = -0.01$, $t(299) = -1.87$, $p = 0.062$). It is this rate of change that helps distinguish the early hand preference groups (Right and Left) from the Late Right hand preference group. It should be noted that none of the variance components were significant ($\delta s < 0.003$, $\chi 2s$ 277.32–315.69, $ps > 0.24$), in the conditional growth model. The likely reason is that we may have explained some of this individual variability with our handedness groups (i.e., quadratic change in different directions).

	Proportion of right hand use	
	Coefficient	
	Unconditional growth	Conditional growth
Fixed effects		
Intercept	0.569***	0.458***
Age	0.008 ***	−0.004
Age^2	−0.0004	0.013***
Left	–	−0.039
Left* age	–	−0.013
Left* age^2	–	−0.013***
Early right	–	0.033
Early right* Age	–	0.061***
Early right* age^2	–	−0.031***
Late right	–	0.346***
Late right* age	–	−0.008
Late right* age^2	–	−0.013***
	Variance component	
Random effects		
Intercept	0.016***	0.003
Linear	0.0004***	0.0001
Quadratic	0.00004***	0.00001
Level-1 error	0.031	0.027

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 1 Final models of age and hand preference group predicting proportion of right hand use

3.3 Does age or neuromotor developmental score or BOTH predict the trajectories of hand preference development?

Again, we used a multilevel model to analyze how age and neuromotor development predicts infant hand preference development. The level-1 variables were Age, Age2, Neuromotor, and Neuromotor2. Variance components for the intercept, Age, Age2, Neuromotor, and Neuromotor2 slopes were also included in the same model to test for significant individual variability at the intercept and change over time. The level-2 variable was hand preference, modeled as the posterior probabilities of the infant's assigned group in the GBTM analysis (Early Right, Late right, Left), and, again, No preference infants served as the reference group.

Age ($\beta1 = 0.01$, $t(302) = 2.95$, $p = 0.004$), Age's variance component ($\delta1 = 0001$, $\chi2 = 390.34$, $p = 0.001$), and Age2's variance component ($\delta2 = 007$, $\chi2 = 379.43$, $p = 0.002$) were all significant predictors of the proportion of right hand preference, although Age2 was not ($\beta2 = -0.113$, $t(302) = -1.25$, $p = 0.21$). Neuromotor ($\beta3 = -0.001$, $t(302) = -1.26$, $p = 0.21$), Neuromotor2 ($\beta4 < -0.001$, $t(302) = -1.07$, $p = 0.29$), and Neuromotor2's variance component ($\delta4 < 0.001$, $\chi2 = 188.02$, $p = 0.11$) did not predict proportion of right hand preference, but, interestingly, the variance component for Neuromotor did ($\delta3 = 0.007$, $\chi2 = 368.50$, $p = 0.005$).

In the conditional growth model, Left- ($\beta21 = -0.013$, $t(299) = -5.60$, $p < 0.001$), Late Right ($\beta22 = -0.031$, $t(299) = -5.60$, $p< 0.001$), Early Right ($\beta23 = -0.013$, $t(299) = -14.94$, $p < 0.001$), and No preference ($\beta20 = 0.013$, $t(299) = 10.57$, $p < 0.001$) all exhibited quadratic change across age. This is similar to that reported above when hand preference group was not a part of the model. Again, Early right-handers had a higher proportion of right hand use initially ($\beta03 = 0.35$, $t(299) = 15.28$, $p < 0.001$), but late Right hand preference had a higher initial rate of change than early right ($\chi2 = 274.49$, $p < 0.001$), left ($\chi2 = 251.06$, $p < 0.001$), and infants with no preference ($\beta23 = -0.013$, $t(299) = -14.94$, $p < 0.001$). In contrast to age, no handedness effects were found for Neuromotor (βs < 0.001, ts (299) <0.11, ps > 0.52) development (Table 2).

These analyses reveal that age is a better predictor, than neuromotor development of the trajectory differences in the development of the infant's hand preference for acquiring objects. When both variables were included in the model, neuromotor scores reduced out of the model (except for the linear variance component); yet Age, Age2 and their variance components remained significant predictors. In addition, infants change differently on hand preference according to age and preference group, but not according to neuromotor score and preference group.

3.4 Does age and/or handedness predict neuromotor development?

Since neuromotor scores varied significantly in relation to the HI (proportion of right hand use) but did not predict it, we tested whether the different trajectories of the hand preference groups could predict differences in neuromotor development. Again, a multilevel model was constructed in which Age, Age2, and hand preference group predicted neuromotor score. Hand preference group did not predict the linear (βs −0.01–0.10, ts (299) = −0.05–0.62, ps > 0.53) and quadratic slopes (βs −0.002–0.06, ts (299) = −0.03–0.83, ps > 0.25) of the neuromotor development. However, Late Right preference infants do have a lower initial neuromotor score than all other hand preference groups ($\beta01 = -0.93$, $t(301) = -2.04$, $p = 0.04$) and they seem to maintain this lower level of neuromotor development throughout this age period (Figure 3 and Table 3).

	Proportion of right hand use	
	Coefficient	
	Unconditional growth	Conditional growth
Fixed effects		
Intercept	0.579***	0.464***
Age	0.011**	−0.001
Age^2	−0.001	0.013***
Left	–	−0.038
Left* age	–	−0.013
Left* age^2	–	−0.013***
Early right	–	0.347***
Early right* age	–	−0.008
Early right* age^2	–	−0.013***
Late right	–	0.033
Late right* age	–	0.061***
Late right* age^2	–	−0.031***
Neuromotor score	−0.001	−0.001
	Variance component	
Random effects		
Age–Intercept	0.014***	0.002*
Age–Linear	0.001**	0.0002***
Age–Quadratic	0.00001**	0.00001
Neuromotor–Quadratic	0.0001**	<0.00001***
Level-1 error	0.031	0.027

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 2. Final models of age, neuromotor score and handedness predicting proportion of right hand preference

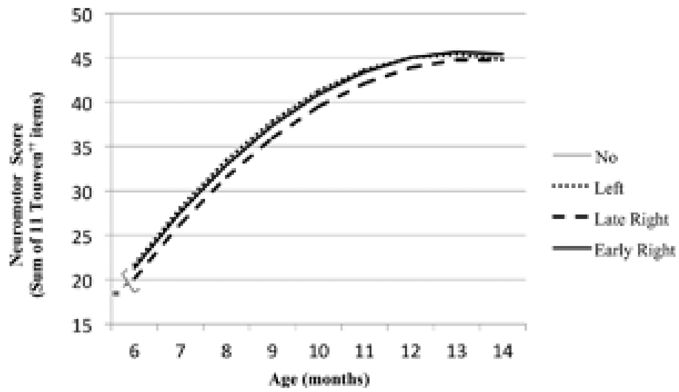


Figure 2. Model of neuromotor scores across age.*p < 0.05; ††, Touwen (1976)

	Neuromotor score	
	Coefficient	
	Unconditional growth	Conditional growth
Fixed effects		
Intercept	8.48***	8.71***
Age	3.00***	3.00***
Age^2	−0.48***	−0.48***
Late right	–	-0.93*
	Variance component	
Random effects		
Intercept	23.87***	23.60***
Linear	0.37***	0.37***
Quadratic	0.02***	0.02***
Level-1 error	8.11	8.11

*$p < 0.05$, ***$p < 0.001$.

Table 3. Final models of age and hand preference group predicting neuromotor score

Since age is the best predictor of the differences in the trajectories of the four hand preference groups, Table 4 shows the relation of the infant's group assignment to the four hand preference groups as determined by GBTM to their proportion right hand use at each age. At each month, the infant's HI was classified into Right, Left, or No preference according to the binomial test of the significance of the proportion ($p < 0.05$). These classes were compared to the classification identified by the GBTM. Since there was no way of statistically determining a "Late Right" infant at each age, the Late Right and Early Right infants were combined into one "Right" group. Thus, at each month, the three binomially defined classes of HI (Right, Left, No preference) were compared to three GBTM defined classes of HI (Early Right + Late Right, Early Left, No preference). This comparison would allow identification of the number of infants misclassified by the single month classification compared to the classification derived from the trajectories of their nine monthly assessments.

	Age (months)								
	6	7	8	9	10	11	12	13	14
Kappa									
Test of agreement	0.11[c]	0.13[c]	0.26[b]	0.24[b]	0.29[b]	0.32[b]	0.28[b]	0.25[b]	0.23[b]
Identified correctly	42.9	44.7	54.2	51.8	56.3	58.7	56.3	53.9	53.2
Right HI→ Left GBTM	13.3	8.9	11.1	4.4	6.7	2.2	0	4.4	2.2
Right HI→ No pref GBTM	8.2	26.5	15.9	15.0	12.4	15.0	15.0	22.1	24.8
Left HI→ Right GBTM‡	10.8	10.4	3.2	4.5	2.3	0.45	0.45	1.4	0.90
Left HI→ No pref GBTM	5.3	4.5	12.4	16.8	11.5	9.7	8.0	1.8	3.5
No pref HI→ Right GBTM[a]	55.4	50.9	48.6	48.2	46.4	43.2	47.2	52.7	51.8
No pref HI→ Left GBTM	60	66.6	48.9	62.2	62.2	68.9	75.5	57.8	62.2

[a]"Right" GBTM includes both late and early right groups.
[b]Fair agreement.
[c]Slight agreement.

Table 4. Correspondence (%) between handedness group assignments using GBTM (Early plus late right, Early left, No preference) and monthly classification using binomial test of HI scores (Right, Left, No preference)

Although we advocate for a longitudinal approach to studying handedness, we understand that such rigorous methods are not always possible. Table 4 shows that 10, 11, or 12 months show the greatest percentage of binomially tested HI as correctly classified (as determined by the GBTM; 56.3, 58.7, 56.3, respectively). Nevertheless, at each month more than 42% of infants are misclassified. Only at 12 months are the smallest percentage of infants (<3%) misclassified according to the direction of their hand preference (0% Right HI à Left GBTM and 0.45% Left HI à Right GBTM). The remaining misclassifications involve the No preference category. Kappa test of agreement was based on criterion proposed by Viera and Garrett (2005).

The Briggs and Nebes (1975) questionnaire revealed that of 274 mothers, 240 had a right-hand preference, 23 a left preference, and 11 no preference. Amongst 96 infants identified as having an early right preference, the majority (n = 86) have right hand mothers. For the late right preference infants, 58 of 67 mothers are right-handed, whereas, for the no preference infants, 71 of 83 mothers are right-handed. For the left preference infants, 25 of 28 mothers are right-handed. Only two mothers of the left-handed infants were left-handed (see Figure 4).

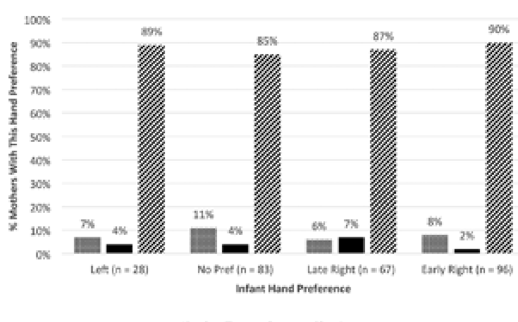


Figure 4. Maternal hand preference percentage across infant preference group (n = 274) (†)

4. Discussion

The primary objective of the current study was to examine whether an infant's neuromotor development would predict differences in the developmental trajectories of infant hand preferences, irrespective of age. As the data revealed, infants exhibit both significant linear and quadratic developmental trends in their Touwen scores, meaning that the Touwen assessment does capture developmental changes in neuromotor control during the period from 6 to 14 months of age. The latent class analysis also showed that the development of infant hand preferences when reaching for and acquiring objects reflects four different patterns of development best described as groups with early right- and left-hand preferences, another group with a late developing right-hand preference and a fourth group with no consistent hand preference during this period. Thus, most infants (70%) do manifest hand preferences when reaching for and acquiring objects. Finally, the data demonstrated that the developmental trajectory of the infant's hand preference was best predicted by the infant's age and not by the status of his/her neuromotor development.

This last result means that the neuromotor developmental patterns revealed by Touwen's Group III items (which undergo extensive development during the age period investigated in this study) are relatively unrelated to hand preference development. This is consistent with other studies that failed to find an effect of developmental transitions in locomotor and postural control (onset sitting, crawling, walking) on hand preference (Babik et al., 2013) and inconsistent with those that did (e.g., Berger et al., 2011; Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996, 2002; Fagard & Lockman, 2005). Perhaps, transitions in locomotor and postural control transiently disrupt the manifestation of a hand preference during tests of acquisition of objects but this transitory influence is very short-lived and does not affect the longitudinally identified preference. Or, perhaps the neural circuits involved with the development of hand preferences are independent of those involved with the control of limbs, posture, and locomotion as assessed by the Touwen procedure. This latter explanation would be consistent with those who have proposed that the lateralized neural control of hand preference is independent of lateralized neural circuits controlling language and praxis skills (e.g., Cochet, 2016; Esseily et al., 2011; Häberling et al., 2016).

It may be that there are several, relatively independent, lateralized networks of hemispheric specialization, of which handedness may only be one. However, we (Michel et al., 2013) and others (e.g., Arbib, 2011; Willems & Hagoort, 2007) have proposed ways by which neural circuits involved with hand preferences could affect those involved with other lateralized functions (however, see Groen et al., 2013, for an alternative argument). Another possibility is that the experiences that infants have during development may be more important to the development of handedness than previously believed. Because our results show that age is more related to hand preference development than neuromotor skills, one might examine the differences in an infant's experiences to account for the variability in hand preference development. Future studies should explore the influence of experience on hand preference development.

By identifying reliable longitudinal consistencies in the development of infant hand preferences, our results permit further examination of the relations among various neural circuits underlying lateralized cognitive systems (i.e., language) during early infancy when many of these circuits are developing rapidly and likely can engage in more extensive cross-talk than in later periods of development. However, all such future studies that examine the relation of infant hand preferences to other cognitive functions need to adjust for the four patterns of hand preference development underlying any non-longitudinal assessment of hand preference during infancy. As our comparison with monthly assessments (with three categories of hand preference—right, left, and not significant, as determined by binomial test) revealed, many infants without a longitudinally identified preference are misclassified as having a preference and many with a longitudinally identified preference are misclassified as not having a preference. Moreover, when a right-hand preference is identified, it likely consists of two groups representing those infants who had established their preference by 6 months of age and those who establish their preference only toward the end of their first year.

These results prompt our recommendation that large samples with frequent (more than 6) longitudinal assessments be employed when investigating infant hand preference development, especially if we are ever going to discover the relation between the development of hand preferences and the development of other lateralized functions and/or the development of cognitive and social/emotional abilities. Too often we employ too few assessment periods with small samples and only identify three groups of infants (right-, left-, and no preference), which are often based on statistically indefensible categorization processes. Such procedures not only fail to allow real developmental analysis, but also increase the probability of both Type I and II errors and create confusion in the research literature.

Why did the analysis not reveal a “late left-hand” preference group? It is possible that a “late left” group is hidden within the “no preference” group. A larger sample size may reveal this additional group. It is also possible that a late left group may not become apparent until after 14 months. Our data reveals that those with a right preference use their right hand at 8 months as much, or more than, infants with a left-hand preference use their left hand at 13 months (the peak of left hand use for this group). This is a five-month gap in the peak of preferred hand use for each of these groups. Also, our analysis of the relation of mother handedness to infant hand preference group revealed that all groups had a predominance of right-handed mothers. Michel (1992) observed that mothers interact with their infants in ways that reflect their own hand preference and not the preference of their infant. Since maternal handedness can influence the development of infant handedness (Michel, 1992), perhaps a late developing left handedness during early development will be stifled by the handedness of the mother. Clearly, this should be examined in infancy using a large sample of left-handed mothers. The current analyses revealed a percentage of infants with a left-hand preference (12%) that is consistent with estimates of left-handedness in most human populations (particularly those that do not have highly restrictive cultural proscriptions against left-handedness, Annett, 2002; McManus, 2004). As in the adult literature (Annett, 2002), those infants who manifest a left-hand preference do not exhibit as strong a preference (although still significant) as the right-hand preference of those with an early right-hand preference. However, it is likely that many of left preference infants typically have parents with a right-hand preference. Therefore, parent-infant social interactions over objects are likely to weaken the left-hand use and strengthen right hand use for these left-hand preferring infants (Michel, 1992; Mundale, 1992).

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