Received: 1 May 2017 | Accepted: 24 July 2017
DOI: 10.1002/dev.21560

RESEARCH ARTICLE

WILEY Developmental Psychobiology

Toddler hand preference trajectories predict 3-year language outcome

Eliza L. Nelson[1] | Sandy L. Gonzalez[1] | Stefany Coxe[1] | Julie M. Campbell[2] | Emily C. Marcinowski[3] | George F. Michel[4]

[1] Department of Psychology, Florida International University, Miami, Florida

[2] Department of Psychology, Illinois State University, Normal, Illinois

[3] Department of Physical Therapy, Virginia Commonwealth University, Richmond, Virginia

[4] Department of Psychology, University of North Carolina at Greensboro, Greensboro, North Carolina

Correspondence
Eliza L. Nelson, Department of Psychology, Florida International University, 11200 SW 8th Street DM 256, Miami, FL 33199.
Email: elnelson@fiu.edu

Funding information
National Science Foundation, Grant number: DLS 0718045; Eunice Kennedy Shriver National Institute of Child Health and Human Development, Grant number: T32-HD007376; National Institute of General Medical Sciences, Grant number: R25GM061347

Abstract

A growing body of work suggests that early motor experience affects development in unexpected domains. In the current study, children's hand preference for role-differentiated bimanual manipulation (RDBM) was measured at monthly intervals from 18 to 24 months of age ($N = 90$). At 3 years of age, children's language ability was assessed using the Preschool Language Scales 5th edition (PLS™-5). Three distinct RDBM hand preference trajectories were identified using latent class growth analysis: (1) children with a left hand preference but a moderate amount of right hand use; (2) children with a right hand preference but a moderate amount of left hand use; and (3) children with a right hand preference and only a mild amount of left hand use. Stability over time within all three trajectories indicated that children did not change hand use patterns from 18 to 24 months. Children with the greatest amount of preferred (i.e., right) hand use demonstrated higher expressive language scores compared to children in both trajectories with moderate levels of non-preferred hand use. Children with the greatest amount of right hand use also had higher scores for receptive language compared to children with a right hand preference but moderate left hand use. Results support that consistency in handedness as measured by the amount of preferred hand use is related to distal language outcomes in development.

KEYWORDS
hand preference, handedness, hemispheric specialization, language, laterality

1 | INTRODUCTION

Motor development changes rapidly during the first years of life. Gains in posture, such as the ability to sit and stand independently, as well as changes in arm and leg control that contribute to an infant's ability to grasp objects and move around, fundamentally alters how infants engage in their social and physical world. A growing body of work suggests that early motor experience affects development in unexpected domains. The idea that cumulative change in one domain can spread across to other domains over time to influence an outcome is a concept known as *developmental cascades* (Masten & Cicchetti, 2010). For example, allowing infants to engage in simulated reaching and grasping prior to its typical onset changes infant attention to social stimuli and events (Libertus & Needham, 2010, 2011, 2014a, 2014b; Needham, Barrett, & Peterman, 2002; Sommerville, Woodward, & Needham, 2005). The later shift from crawling to walking has been linked to cascading shifts in how infants interact with caregivers, as well as changes in how caregivers in turn respond to their infants (Campos et al., 2000; Clearfield, 2011; Karasik, Tamis-LeMonda, & Adolph, 2011, 2014, 2005). Finally, it has been shown that infants and toddlers who demonstrate proficiency in a motor skill (i.e., attainment of independent sitting or walking; greater motor control) are more likely to exhibit advanced language skills (Alcock & Krawczyk, 2010; He, Walle, & Campos, 2015; Libertus & Violi, 2016; Oudgenoeg-Paz, Leseman, & Volman, 2015; Oudgenoeg-Paz, Volman, & Leseman, 2012; Walle, 2016; Walle & Campos, 2014; Walle & Warlaumont, 2015; Wang, Lekhal, Aaro, & Schjolberg, 2014).

One limitation of prior work examining motor-social and motor-cognitive cascades is that most studies have focused on the presence/absence of a given motor skill, which provides a static and dichotomous assessment of the child at just one point in time. This kind of approach does not adequately do service to the systems theories that encompass developmental cascades, and have guided much of such work. Motor development is not a series of prescribed milestones. Rather, motor development is best characterized as *learning to learn* (Adolph, 2005; Adolph & Robinson, 2015). Infants must continually solve difficult problems in controlling their movement, and these solutions lead to changes in how they explore and subsequently learn about their environment, thereby influencing the development of other psychological domains (Gibson, 1988). *Dynamic systems theory* (DST; Spencer et al., 2006; Thelen & Smith, 2006; Thelen, Ulrich, & Wolff, 1991) emphasizes this embodiment of perception, action, and cognition in which behavior is softly assembled from the continuous interactions between levels over many timescales. Time is central within DST because changes build upon one another and accumulate; each change lays the groundwork for future change. Moreover, because children have different experiences, they solve problems in different ways. These different solutions can be expected to shape different trajectories in development, even though the outcome may be similar. An elegant example is the development of handedness.

1.1 | The development of handedness

The hands are essential to learning about objects and their parts, transporting objects to new locations, and sharing objects with caregivers. Infants must learn not only how to control each hand, but also to solve the problem of how to use the hands together, which requires coordination between brain hemispheres (Serrien, Ivry, & Swinnen, 2006). At least 85% of adults are right handed (Annett, 2002). How such a bias develops has been widely discussed (for an overview, see Michel, Babik, Nelson, Campbell, & Marcinowski, 2013). The *cascade theory of handedness* has emerged from the developmental literature as a guiding framework and posits that handedness emerges over infancy in a series of cascades stemming from continuous individual–environment interactions (Michel, 2002, 2013). According to this framework, an early bias observed in neonatal head orientation results in differential visual regard of one hand over the other, which in turn leads to differential haptic stimulation and use of the observed hand for reaching (Coryell & Michel, 1978; Michel, 1981). The hand bias for reaching then concatenates into greater use of one hand for acquiring objects (Michel & Harkins, 1986), which cascades into a hand preference for unimanual manipulation (Campbell, Marcinowski, Babik, & Michel, 2015; Hinojosa, Sheu, & Michel, 2003). Ultimately, hand preference for unimanual manipulation leads to a hand preference for role-differentiated bimanual manipulation (RDBM), where the hands work together in an asymmetric fashion (Babik & Michel, 2016a; Nelson, Campbell, & Michel, 2013). A large body of work over multiple decades has built support for the cascade theory of hand preference development (Michel, 1983, 1988, 1998, 2002; Michel, Campbell, Marcinowski, Nelson, & Babik, 2016). Although all typically developing infants will exhibit reaching and manipulation skills in this order, the patterning with which they use each hand across these manual skills varies. Michel, Babik, Sheu, and Campbell (2014) recently captured this variability in a large longitudinal study involving 328 infants examined at 9 time points from 6 to 14 months of age. Three distinct patterns, or handedness trajectories, were identified for acquiring objects: (1) infants with a left hand preference; (2) infants with a right hand preference; and (3) infants with no identifiable preference but trending toward a right hand preference. Thus, infants solve the problem of hand use in different ways, which can be measured as hand trajectories for a particular manual skill.

Given the concept of developmental cascades and DST, it is no surprise then that hand use patterns across development matter for outcomes in other domains. In particular, handedness trajectories have been linked to language outcomes. An overt behavioral bias like handedness is thought to reflect underlying *hemispheric specialization*, or asymmetric brain function. Right handedness and language are left hemispheric functions in most adults (Knecht et al., 2000). It has been argued that an advantage of having specialized hemispheres for demanding skills like fine motor control and language is streamlined neural processing (Rogers & Vallortigara, 2015; Rogers, Vallortigara, & Andrew, 2013; Vallortigara & Rogers, 2005). Furthermore, manual activity shapes structure and function in the contralateral primary motor hand area in adults (Granert et al., 2011). Thus, laterality is a critical property of brain organization, but the brain is also flexible to experience. We suggest that the experiences children have using their hands early in development may shape their later language abilities through cascading brain-behavior relations. In other words, the programming of manual actions is driven by experience, particularly with the preferred hand, and language programming may be in turn influenced in part by such early manual programming (Michel et al., 2013). For additional discussion and alternative hypotheses, see Cochet (2016).

1.2 | Handedness trajectories and language

Research that has focused on differences in children's handedness trajectories has found that consistency in hand use preference early in development is related to language outcomes (Gottfried & Bathurst, 1983; Kee, Gottfried, & Bathurst, 1991; Kee, Gottfried, Bathurst, & Brown, 1987; Nelson, Campbell, & Michel, 2014; Wilbourn, Gottfried, & Kee, 2011). The Fullerton Longitudinal Study (FLS) is the longest running study to assess early hand preference and later cognitive development in children, spanning 18 months until 17 years of age (Gottfried & Bathurst, 1983; Kee et al., 1987, 1991; Wilbourn et al., 2011). Children were classified as having a consistent or inconsistent hand preference for drawing across five hand preference assessment points: 18, 24, 30, 36, and 42 months (Gottfried & Bathurst, 1983). Following the FLS sample into middle childhood (5–9 years old), females with a consistent hand preference scored significantly higher on assessments of verbal intelligence and reading achievement in school compared to females with an inconsistent hand preference, although no effect was found in males (Kee et al., 1991). A more recent follow-up study identified continued differences in females, with children in the consistent hand preference group scoring higher on verbal intelligence and reading achievement measures at 12, 15, and 17 years old compared to children with an inconsistent hand preference (Wilbourn et al., 2011). Overall, the findings of the FLS cohort support a continued relation between hand use and later language-related outcomes using a trajectory-based approach to handedness.

In another longitudinal study focused on handedness patterns and their relation to language, Nelson et al. (2014) measured hand use preference across infancy (6–14 months) and toddlerhood (18–24 months) using age appropriate manual tasks (infants: unimanual object acquisition; toddlers: RDBM). Children were categorized into three trajectories: early right handed (right-preferent for both manual skills), late right handed (no hand preference as infant, but right preference as toddler), and late left handed (no hand preference as infant, but left preference as toddler). At 24 months of age, children completed the Bayley Scales of Infant and Toddler Development, third edition (Bayley-III; Bayley & Reuner, 2006). Handedness trajectories accounted for 25% of the variability in language scores on the Bayley-III, with children in the early right handed trajectory exhibiting advanced language skills compared to late right handers and late left handers (Nelson et al., 2014). There were no differences between trajectories on the cognitive or motor subscales. Taken together, these studies illustrate (1) that children can be classified into hand use trajectories for different manual skills and (2) handedness trajectories differentially predict language outcomes at different points in development.

A crucial factor in understanding how variability in hand use experience shapes language development is the implementation of longitudinal designs using a trajectory-based approach. However, a large portion of research examining the relations between early handedness and language has used cross-sectional designs or longitudinal designs with too few time points (Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; Cochet, Jover, & Vauclair, 2011; Esseily, Jacquet, & Fagard, 2011; Ramsay, 1980, 1984, 1985; Vauclair & Cochet, 2013). Such work has found a variety of shifts in hand use around times of significant change in language like the onset of duplicated syllable babbling, after the word spurt, or around the initial use of word combinations (e.g., Bates et al., 1986; Cochet et al., 2011; Ramsay, 1984). Critically, such designs have often focused on monthly fluctuations in hand use where handedness is treated as a trait, rather than a developmental phenomenon; the result has been the use of cross-sectional analyses of longitudinal data. However, as many as 45% of infants may be misclassified when handedness is based on one monthly assessment, as opposed to a trajectory (Michel et al., 2014). Moreover, cross-sectional analyses treat all of the individuals in the group as the same, and do not allow for variability to be interpreted as individual differences. Here, we argue that a trajectory-based approach is a more powerful and appropriate tool for understanding the relationship between hand use across development and language ability.

1.3 | Current study

Infants' experience with motor skills has been hypothesized to lay the groundwork for language skills with similar action components; an example from early in development is rhythmic arm movements and reduplicated babble (Iverson, 2010). In other words, acquiring motor skills offers children the chance to practice skills that will be used later in language. In this vein, we were interested in extending the work of Nelson et al. (2014) to further characterize how toddlers perform the motor skill RDBM where one hand holds an object for the other hand's manipulation (Babik & Michel, 2016b; Birtles et al., 2011; Fagard, 1998; Fagard & Jacquet, 1989; Fagard & Lockman, 2005; Fagard & Pezé, 1997; Kimmerle, Ferre, Kotwica, & Michel, 2010; Kimmerle, Mick, & Michel, 1995; Ramsay, Campos, & Fenson, 1979). Hand preference for RDBM was measured at 7 monthly visits from 18 to 24 months of age, and language ability was measured at 3 years of age using the Preschool Language Scales, 5th edition (PLS™-5; Zimmerman, Steiner, & Pond, 2011). The current study follows the original cohort from Nelson et al. (2014) in addition to two new cohorts, increasing the sample size from 38 to 90. The larger sample size allows for the use of latent class growth analysis (LCGA) to determine RDBM hand preference trajectory groups; RDBM trajectories were then used to predict language outcome at 3 years of age (see Figure 1a for a

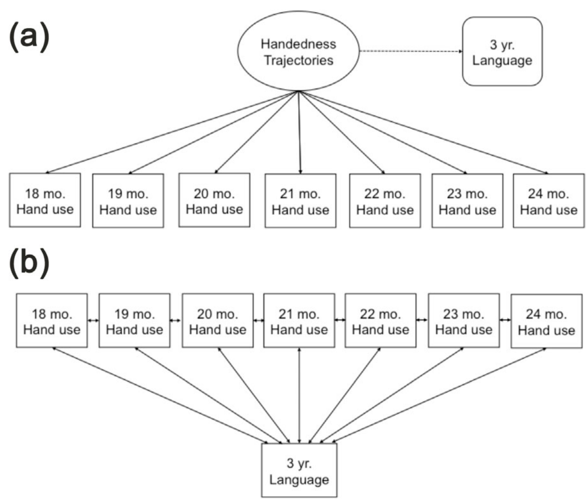

FIGURE 1 (a) Conceptual figure for the proposed latent class growth analysis. Squares denote observed variables, the circle represents the latent class variable, and the rounded box is the distal outcome variable. (b) Conceptual figure for traditional correlational analyses

conceptual overview of the current study). We hypothesized that there is a continued relationship between hand use experience and language outcome, and we predicted that we would identify multiple trajectories for RDBM in toddlers. A priori predictions regarding differences in language scores between hand preference trajectories was not possible, as the nature and number of hand preference trajectories for RDBM in our sample were unknown prior to statistical analysis. Planned analyses examined 2, 3, and 4 latent classes for toddler RDBM hand preference. For comparison, we also performed traditional analyses of examining correlations between hand preference for each month and language scores (Figure 1b).

2 | METHODS

2.1 | Participants

Ninety children participated in the study. Families were recruited for the project using Guilford County public birth records from a midsized metropolitan city in the Southeastern United States (Greensboro, NC). All children included in the study were delivered without complications following full-term pregnancy of at least 37 weeks gestation. Parents reported the sex of their infant. There were 46 boys and 44 girls in the study. The racial and ethnic distribution of the sample was 75% White, 18% Black or African American, 3% More than One Race (not Hispanic or Latino), 2% More than One Race (Hispanic or Latino), 1% White Hispanic or Latino, and 1% Other Race. Families provided information regarding yearly household income and parent education by paper or electronic questionnaire. Eighteen families did not wish to report income, 17 families did not report mother's education level, and 19 families did not report father's education level. Yearly family incomes ranged from $10,000–$19,999 to $150,000 or more with a median income of $60,000–$69,999. Mothers' education level ranged from a high school diploma or GED equivalent to a professional degree. Fathers' education level ranged from 1 or more years of high school/no diploma to a doctorate degree. The median educational level for both parents was a bachelor's degree.

Seventy-nine of the children provided complete data for RDBM hand preference at 7 monthly time points from 18 to 24 months of age. Ten additional children missed 1 monthly visit and had hand preference data for 6 time points. One child missed two monthly visits and had hand preference data for 5 time points. At 3 years, 12 children were not tested on the PLS™-5 because the family moved, declined participation, or could not be reached. An additional 18 children could not be assessed on the PLS™-5 at 3 years of age due to a gap in funding and staff. In total, of the 90 children for whom we had hand preference data for analyses, 60 children (31 girls) were tested for language abilities on the PLS™-5 at 3 years of age.

2.2 | Design and procedure

The University of North Carolina at Greensboro Institutional Review Board approved the following procedures, and parents gave written consent for their child to participate in this study. Parents received a $10 Target gift card for each visit to the lab, and children additionally received a small toy prize at the 3-year visit. Hand preference for RDBM was assessed from 7 monthly visits from 18 to 24 months. RDBM was chosen as the target skill for evaluating hand preference because it is developmentally appropriate for this age group (for discussion, see Nelson et al., 2013). Each hand preference assessment occurred within ±7 days of the child's monthly birthday. The details of the RDBM measure have been published elsewhere (Nelson et al., 2013). Briefly, the child was seated at a table on a parent's lap. Twenty-nine objects that afford RDBM where one hand stabilizes the object (non-preferred hand) for the other hand's manipulation (preferred hand) were presented at the child's midline one at a time. The child was allowed to manipulate each object for approximately 20 s and the entire procedure took about 10 min. Examples of target RDBM actions performed included removing a toy from inside of another toy, removing a lid, unlatching a container, unzipping a bag, and peeling a sticker from its backing. The RDBM test battery has been previously shown to discriminate both degree and direction of preference in toddlers and adults (Nelson et al., 2013). Video data were scored offline by trained coders with the Observer XT software program (Noldus Information Technology, v.10.5). The hand that performed the active manipulation was scored as the preferred hand. Interrater reliability was calculated using percent agreement between coder pairs for each presentation. Coders scored 124 videos that were representative of each month tested, which is equivalent to 20% of the data. Interrater reliability for RDBM hand preference using percent agreement was 96%. Disagreements included miscoding the active hand or not coding a presentation. Trained observers administered the PLS™-5 to assess receptive and expressive language skills when children were 36.13–39.93 months of age ($M \pm SD = 36.97 \pm 0.80$ months). The PLS™-5 consists of two standardized scales, Auditory Comprehension (PLSAC) and Expression Communication (PLSEC). PLSAC and PLSEC standard scores were used in analyses. Standard scores are normed at 100 with a standard deviation of 15 (typical range = 85–115). The PLS™-5 took approximately 1 to 2 hr to administer depending on the child.

2.3 | Statistical analysis

A Handedness Index (HI) was first calculated for each toddler at each monthly visit using the formula $HI = (R - L)/(R + L)$, where R is the number of active right hand RDBMs and L is the number of active left hand RDBMS. Using this formula allows hand use to vary on a continuum from −1.00 (exclusively left hand RDBMs) to 1.00 (exclusively right hand RDBMs). The seven monthly HI scores (18, 19, 20, 21, 22, 23, and 24 months) were then used to calculate latent groups in the toddlers' developmental trajectories for RDBM hand preference using latent class growth analysis (LCGA; Jung & Wickrama, 2008). LCGA is an extension of latent growth modeling that allows researchers to identify homogenous sub-groups ("classes") of individuals based on their trajectories over time (Nagin & Land, 1993). LCGA is similar to the more general growth mixture model (GMM). However, LCGA is a more constrained model because it additionally assumes that the intercept variance and slope variance (i.e., variability of initial status and change over time) within each class is 0. LCGA has previously been used to examine latent trajectories of hand preference for acquiring objects in 6- to 14-month-old infants (Michel et al., 2014).

LCGA models with 2, 3, and 4 latent classes were assessed, with parameter estimates from each model serving as start values for the model with one additional class. Both linear and quadratic trajectories (indicating curvilinear change over time) were assessed to determine the best overall model. Sex and language outcomes (PLSAC and PLSEC at 36 months) were included in the model to assess latent class differences on these variables. The means and variances of the PLSAC and PLSEC scores were allowed to vary across class. The best model was selected using the Lo–Mendell–Rubin (LMR) likelihood ratio test and sample-size adjusted BIC (saBIC), according to best practices (Nylund, Asparouhov, & Muthén, 2007; Tein, Coxe, & Cham, 2013).

LCGA is relatively robust to missingness in trajectory variables (i.e., hand preference measure) and uses all available observations to estimate model parameters. Missing values for RDBM were minimal (1–5% at any single time point; see section 2.1). Missing values for RDBM hand preference were unrelated to demographic variables (i.e., sex, mother's education, father's education, family income) or language outcomes (i.e., PLSAC and PLSEC scores), indicating a missing at random mechanism (MAR; Rubin, 1976). Full information maximum likelihood estimation was used to further reduce bias due to missing values (Enders & Bandalos, 2001).

Additionally, correlations between HI at each month, PLSAC, and PLSEC scores were conducted. These separate analyses were performed in an effort to objectively compare the results obtained from the LCGA to the results obtained when using statistical methods similar to prior literature. By performing these additional analyses on our data set, we will highlight how the choice of data analysis in past studies could have contributed to the mixed characterization of the relations between hand preference and language acquisition in development.

3 | RESULTS

The LCGA model with three latent classes and linear trajectories was selected based on the saBIC and the LMR LR test. Classification for the model was excellent, with entropy = 0.975 and individual classification percentages ranging from 0.976 to 1.000; values of 1.000 indicate perfect classification of individuals into classes. Values for latent class intercepts, slopes, and membership percentages are shown in Table 1. All classes had intercept values that were significantly different from zero, indicating that all classes show some hand preference for RDBM at 18 months. All classes had slope values that were not significantly different from zero, indicating that children are not changing in their RDBM hand preference during the 18–24 month period (Figure 2). The three classes were named following the framework of Annett (2002).

Approximately 24% of the sample was characterized by greater left hand use with moderate right hand use (L-Mod R) and an estimated mean HI of −.40. A larger proportion or roughly 36% of the sample was characterized by greater right hand use with moderate left hand use (R-Mod L) and an estimated mean HI of 0.40. The largest proportion at 40% of the sample was characterized as predominantly right hand use with mild left hand use (R-Mild L) and had an estimated mean HI of 0.80. Analysis of variances on demographic data showed that the three hand preference classes were not significantly different in terms of sex, $F(2, 87) = 0.18$, $p > .05$, mother's education, $F(2, 87) = 2.56$, $p > .05$, or father's education, $F(2, 87) = 1.88$, $p > .05$. There was a significant difference between classes for family income, $F(2, 87) = 3.74$, $p < .05$. The L-Mod R class had a lower income than the R-Mod L class (95%CI = .04 to 3.53, $p < .05$), and a lower income than the R-Mild L class (95%CI = .05 to 3.62, $p < .05$). The R-Mod L and R-Mild L classes did not differ on income (95%CI = −1.52 to 1.62, $p > .05$).

Language scores for the R-Mild L class ranged from 74 to 150 for PLSAC ($M = 113.88 \pm 19.20$) and from 75 to 150 for PLSEC ($M = 111.23 \pm 19.67$). Language scores for the R-Mod L class ranged from 81 to 132 for PLSAC ($M = 103.64 \pm 10.83$) and from 79 to 188 for PLSEC ($M = 98.06 \pm 10.93$). Finally, language scores for the L-Mod R class ranged from 81 to 132 for PLSAC ($M = 105.19 \pm 13.99$) and from 81 to 132 for PLSEC ($M = 99.07 \pm 12.50$). Analysis of variances based on the summary language data found a significant difference between the three classes on auditory comprehension (PLSAC), $F(2, 87) = 4.27$, $p < .05$. Using Tukey's HSD, the R-Mild L class had significantly higher scores than the R-Mod L class (95%CI = −19.16, −1.32, $p < .05$) on PLSAC. The R-Mild L class was not different from the L-Mod R class

TABLE 1 Latent class membership percentages, intercepts, and slopes for the selected model

Class	N	Intercept	Slope
L-Mod R	22	−.412***	.007
R-Mod L	32	.422***	−.010
R-Mild L	36	.791***	.002

***$p < .001$.

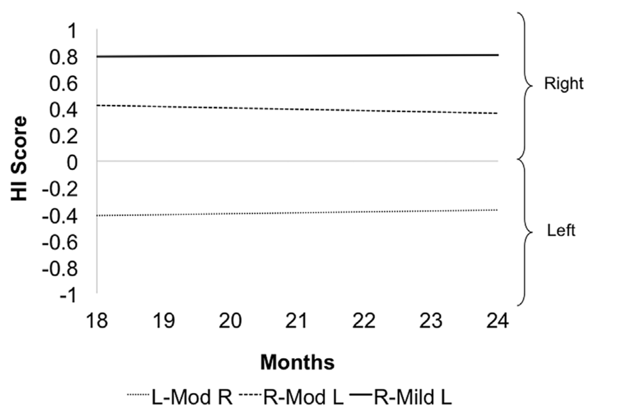

FIGURE 2 Predicted RDBM handedness trajectories from 18 to 24 months. HI, handedness index; L-Mod R, left hand preference with a moderate amount of right hand use; R-Mod L, right hand preference with a moderate amount of left hand use; R-Mild L, right hand preference with a mild amount of left hand use

(95%CI = −18.63, 1.25, $p > .05$) and the R-Mod L class was not different from the L-Mod R class (95%CI = −8.62, 11.72, $p > .05$) on PLSAC. Figure 3a shows the mean PLSAC score (and standard error) as a function of RDBM hand preference class. There was also a significant effect of hand preference class on expressive communication (PLSEC), $F(2, 87) = 7.49$, $p < .01$. The R-Mild L class had significantly higher scores than the R-Mod L class (95%CI = −22.08, −4.28, $p < .01$), and significantly higher scores than the L-Mod R class (95%CI = −22.07, −2.25, $p < .05$) on PLSEC. The L-Mod R class was not different from the R-Mod L class on PLSEC (95%CI = −11.16, 9.13, $p > .05$). Figure 3b shows the mean PLSEC score (and standard error) as a function of RDBM hand preference class.

Finally, correlations between RDBM hand preference at each time point (HI: 18, 19, 20, 21, 22, 23, and 24 months), expressive communication at 3 years (PLSEC), and auditory comprehension at 3 years (PLSAC) were conducted (Table 2). Briefly, HI at 18, 19, 20, and 23 months was significantly correlated with PLSEC at 3 years (all $ps < .05$). Correlations between HI scores at 21, 22, and 24 months and PLSEC did not reach significance. PLSAC was not significantly correlated with HI at any time point from 18 to 24 months. HI scores were strongly positively correlated at all months (all $ps < .01$). PLSEC and PLSAC were also strongly positively correlated ($p < .01$).

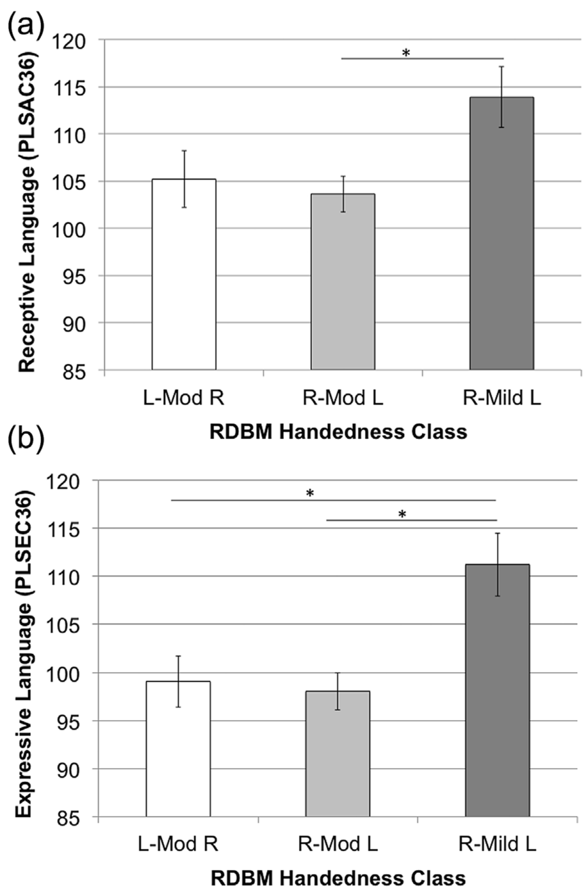

FIGURE 3 Receptive language skill (a) and expressive language skill (b) as a function of RDBM handedness class. Error bars denote standard error. The PLS-5 is normed at 100 with a standard deviation of 15. L-Mod R, left hand preference with a moderate amount of right hand use; R-Mod L, right hand preference with a moderate amount of left hand use, R-Mild L, right hand preference with a mild amount of left hand use. *Denotes $p < .05$

4 | DISCUSSION

The goals of the current study were (1) to determine the number of hand preference trajectory groups for the manual skill RDBM over the period from 18 to 24 months of age and (2) to examine whether RDBM trajectories predict distal language outcomes at 3 years of age. The LCGA identified three distinct hand preference trajectories for toddler RDBM independent of sex or parent education level: L-Mod R (left hand preference but a moderate amount of right hand use), R-Mod L (right hand preference but a moderate amount of left hand use), and R-Mild L (right hand preference with a mild amount of left hand use). In terms of 3-year language outcomes, children in the R-Mild L group had significantly higher scores on receptive and expressive language than children in the R-Mod L trajectory group. Children in the R-Mild L trajectory also scored significantly higher on expressive language than children in the L-Mod R group. However, there was no difference between the L-Mod R trajectory and the R-Mod L trajectory on receptive or expressive language. There was also no significant difference between the L-Mod R trajectory and the R-Mild L trajectory on receptive language. Although we observed an income difference between L-Mod R and the two right preference groups, there was no negative effect on language outcome. The mean language scores for all classes were within the normative range for the PLS-5. When using statistical methods similar to prior literature, hand preference (as indicated by monthly HI scores) was correlated to 3-year expressive language at 18, 19, 20, and 23 months only. There were no significant correlations between HI at any month from 18 to 24 months and receptive language. Overall, these data demonstrate that differences in hand preference patterns over time can have cascading effects on language development, and that these patterns are not discernable by traditional correlation analyses.

4.1 | Developmental trajectories for RDBM hand preference

In the study presented here, three RDBM hand preference trajectories from 18 to 24 months were identified for the first time. The R-Mild L trajectory described the majority of children in the sample, with 40% demonstrating a highly consistent preference for the right hand when preforming RDBM across 18–24 months, with infrequent use of the left hand as the manipulating hand when performing RDBM. About 36% of children were classified as R-Mod L, meaning they demonstrated a consistent right hand preference, but would frequently use the left (non-preferred) hand as the manipulating hand when performing RDBM. The third trajectory group, L-Mod R, comprised the remaining 24% of the sample. Children classified as L-Mod R had a consistent left hand preference, but would frequently use the right (non-preferred) hand as the manipulating hand when

TABLE 2 Correlations between monthly HI scores and PLS-5 scores

	1	2	3	4	5	6	7	8	9
1. 18 mo. HI	–	.756**	.783**	.796**	.728**	.756**	.725**	.132	.266*
2. 19 mo. HI		–	.825**	.777**	.770**	.712**	.762**	.150	.263*
3. 20 mo. HI			–	.843**	.802**	.783**	.704**	.209	.326*
4. 21 mo. HI				–	.818**	.786**	.721**	.151	.171
5. 22 mo. HI					–	.856**	.745**	.192	.229
6. 23 mo. HI						–	.817**	.251	.270*
7. 24 mo. HI							–	.161	.187
8. PLSAC36								–	.744**
9. PLSEC36									–

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

performing RDBM. Other investigators have similarly reported a higher incidence of left hand preference in toddlers and preschoolers compared to adults (Annett, 1985; Marschik et al., 2008; Ramsay et al., 1979; Tirosh, Stein, Harel, & Scher, 1999). These data cannot address when in development the proportion of left handers matches adult levels. More notably, however, the slopes of all three trajectories were not significantly different from zero, indicating that within each trajectory the specific pattern of RDBM hand use remained stable across the toddler period examined in the current study.

These flat trajectory patterns differ from prior research that also used LCGA to examine the development of hand preference, albeit in younger children (Babik & Michel, 2016b; Michel et al., 2014). Infants in the Michel et al. (2014) sample exhibited significant quadratic trends for acquiring objects with one hand, with those in the right and left groups increasing in hand preference until 10 and 11 months, respectively, and then decreasing thereafter. Infants with no preference continued to increase in right hand use over time. Studying RDBM specifically, Babik and Michel (2016b) recently identified three trajectories for RDBM hand preference longitudinally from 9 to 14 months using LCGA: right hand preference (22.2%), left hand preference (21.1%), and no preference but trending toward right hand use (56.7%). All three trajectories exhibited significant quadratic trends, with infants in the right hand or no preference trajectories showing increased right hand use over time for RDBM, while infants in the left hand preference trajectory showed increased left hand use over time for RDBM. It is important to note that while Babik and Michel (2016b) did study the development of RDBM using latent class, their study focused on the early development of RDBM (i.e., 9–14 months), and included simple variations of RDBM that differed from the more advanced fully differentiated actions analyzed in the current study. Interestingly, Babik and Michel (2016b) found that most infants in their sample were categorized in the no preference group from 9 to 14 months. Additional work examining RDBM at specific ages has provided some support for 13 months as the shift when infants begin to exhibit a hand preference for RDBM, with a significant increase in the number of lateralized infants for RDBM at this time point (Babik & Michel, 2016b; Kimmerle et al., 2010). The period between 14 and 17 months is likely a transition time for RDBM hand preference, given that all children in our sample demonstrated a stable hand preference pattern for RDBM from 18 months on. In general, longitudinal research on RDBM hand preference covering the 14–17 month period, as well as the early infancy and later toddler periods, is not available (Gonzalez & Nelson, 2015), and closing this gap remains a goal for future work.

4.2 | Hand preference trajectories and language outcomes

Although all handedness trajectories were flat in the current study, there was clear variability in hand use between trajectories. When taken as a whole, the three trajectories reveal two overall patterns of hand use: consistent (R-Mild L) and inconsistent (R-Mod L and L-Mod-R). Thus, children were stable from 18 to 24 months in the frequency of using their preferred hand, but the amount of preferred hand use differed between the trajectories, and this difference mattered for predicting language outcomes. Children in the R-Mild L trajectory had the highest level of consistent hand use, and also demonstrated significantly higher receptive language scores than the R-Mod L trajectory, and higher expressive language scores than the R-Mod L and the L-Mod R trajectories. Conceptualizing our results as consistent versus inconsistent groups, these data presented here are comparable to previous FLS findings, where consistency in hand use early in development was related to later outcomes in verbal intelligence and reading achievement in childhood and adolescence (Gottfried & Bathurst, 1983; Kee et al., 1987, 1991; Nelson et al., 2014; Wilbourn et al., 2011). Similarly, Nelson et al. (2014) also found that consistency in hand preference for acquiring objects and then cascading into RDBM accounted for 25% of the variability in language scores at 24 months. In the FLS studies and Nelson et al.'s (2014) study, it was the consistent group that scored higher on language outcomes, which is in line with the findings presented here. What is critical for the data in the current study is that for the first time consistency was determined through LCGA, providing a robust statistical measure to support the concept of individual differences in hand preference in toddlerhood influencing later language abilities. A caveat is that we did not find any sex effects related to hand use consistency in our data, which is counter to the FLS findings. Michel et al. (2014) similarly did not report sex effects in a latent class analysis of infant hand use preferences. In adults, however, a greater incidence of left handedness has been reported in males (Papadatou-Pastou, Martin, Munafo, & Jones, 2008). Future studies measuring more nuanced language subskills at different ages are needed to clarify the potential relations between hand use, language, and sex across development.

Our prior work was limited in that we were only able to examine total language at 2 years of age (Nelson et al., 2014). Here, we want to emphasize that different patterns were observed when receptive and expressive language were analyzed separately, and at a distal timepoint that did not overlap the hand use assessments. It is important to note that differences in receptive versus expressive language skills at 3 years (where the R-Mild L group scored higher on expressive language than both R-Mod L and L-Mod R, but only higher than the R-Mod L group on receptive language) may be a feature of the longevity of motor-language cascades (e.g., Oudgenoeg-Paz, Volman, & Leseman, 2016). The development of language comprehension typically precedes language production in infancy (Benedict, 1979; Caselli et al., 1995; Fenson et al., 1994; Jackson-Maldonado, Thal, Marchman, Bates, & Gutiérrez-Clellen, 1993; Sansavini et al., 2010). Specifically, language comprehension accelerates at an earlier age, usually between 11 and 16 months, while similar growth in language production is more typical around 18 months or older. It is possible that by 3 years of age, any lasting effect of hand preference on language comprehension is not as strong as the relation between production and hand preference, given the later onset of expressive language capabilities. While speculative, the L-Mod R group may have caught up to the R-Mild L group on auditory comprehension over that period of time. Additionally, it is possible that because hand preference was measured after the typical spurt in comprehension, the study did not capture the full cascade between hand preference and language comprehension. Conversely, because hand preference was measured within the typical period where children demonstrate a language production spurt (18-24 months), the design may have been ideal for teasing apart the cascade between hand preference and expressive communication specifically. It is already well documented within the handedness and language literature that periods of fluctuations in language development are tied to concurrent shifts in hand preference (e.g., Bates et al., 1986; Cochet et al., 2011; Ramsay, 1984). The results here may imply something subtly but critically different: hand preference trajectories measured during times when a particular aspect of language is changing rapidly may be the best predictors of related distal language ability.

An alternative but not mutually exclusive explanation for the links observed in our data between consistent right hand preference and language may be increased lateralization. Our data cannot address whether the increased hand use asymmetry in this group is matched by increased structural or functional asymmetries in manual control or language at the neural level. It is also possible that consistent hand use may be a marker of maturity or an inherited pattern of brain organization, which would be inconsistent with our dynamic systems framework. It may also be the case that hand preference and language involve separate neural circuits (Häberling, Corballis, & Corballis, 2016). Studies of hemispheric specialization for hand use and language across development using a brain measure are needed to evaluate the behavioral evidence for dynamic systems and developmental cascades, and to address some of the alternative explanations presented here.

Results implementing more traditional analyses of using correlations between hand preference and language found a similar pattern to previous longitudinal and cross-sectional research where monthly hand preference scores show tremendous fluctuation with respect to language (Bates et al., 1986; Cochet et al., 2011; Esseily et al., 2011; Ramsay, 1980, 1984, 1985; Vauclair & Cochet, 2013). Results indicate that 18, 19, 20, and 23-month RDBM hand preference were positively correlated with expressive skills at 3 years. Receptive skills were not significantly correlated with RDBM hand preference at any time point. In comparing the results of LCGA and the individual correlations, it is important to note that the correlational method can only indicate how hand preference at a single time point relates to language outcomes at 3 years. Thus, the correlational approach does not capture change over time, nor does it convey any information about individuals. By contrast, LCGA is a person-center approach that focuses on the trajectory for each person, and therefore captures a more complete picture of hand preference development: how individual monthly fluctuations in hand preference coalesce to comprise a discernable pattern of hand preference over time. It is these individual stable patterns that likely canalize motor experiences leading to a cascade effect within language development (Spencer et al., 2006; Thelen & Smith, 2006).

5 | LIMITATIONS

Ultimately, we caution against interpreting these results as indicative that the R-Mild L pattern of hand use is the “best” trajectory for language development. The mean language scores regardless of class were all in the typical range. As was the case with previous work looking at the effect of long-term trajectories for hand preference on language (e.g., Nelson et al., 2014), a lack of children with a L-Mild R pattern limits our conclusions on directionality. Instead, the results seem to more generally support previous evidence that greater consistency in using a specific hand is an important feature linking hand preference and language. However, the current study measured language ability as an outcome variable at a single time point. A more powerful design should measure the development of hand preference and language concurrently. A study using such a design would further disentangle the complex relationship between hand preference and language over development.

6 | CONCLUSION

Overall, the current study lends additional support to the concept of developmental cascades between handedness and language. As evidenced here, the system can coalesce in different ways to solve the same problem, with solutions then shaping changes across domains. These data bolster the notion that motor development is not comprised of predetermined milestones that a child achieves, but rather it is due to the variability within motor behaviors themselves that individual differences in other areas, like language, emerge. In the case of hand preference, evidence increasingly seems to identify consistency as an important factor for future language outcomes (Gottfried & Bathurst, 1983; Kee et al., 1987, 1991; Nelson et al., 2014; Wilbourn et al., 2011). Infants with a stable hand preference are likely to have better multi-object management skills, showing greater sophistication in how they store and manipulate multiple objects concurrently (Kotwica, Ferre, & Michel, 2008). Opportunities for handling objects allow infants to further learn about object affordances via multimodal exploration (Gibson, 1988). Such exploration can provide infants with increased and richer interactions with caregivers that may foster language growth. Importantly, because most work on motor-social and motor-cognitive cascades has framed motor behaviors as present or absent, and because handedness can and should be measured as a continuous variable, handedness is the ideal motor skill for understanding individual differences over time and for further testing cascade models.

Moreover, a growing body of work suggests that fine motor skill measured in object manipulation as well as writing ability in early childhood is associated with later academic achievement in typically developing children (Cameron, Cottone, Murrah, & Grissmer, 2016; Cameron et al., 2012; Carlton & Winsler, 1999; Dinehart & Manfra, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Luo, Jose, Huntsinger, & Pigott, 2007; Sortor & Kulp, 2003). Fine motor abilities are often the basis of hand preference measures in older children and adults, and there is evidence supporting differences in motor skill proficiency according to hand preference in young children and adults (Connolly, 1973; Provins, 1956; Steenhuis & Bryden, 1999; Todor & Doane, 1977). More recent work shows evidence of differences in motor skill proficiency according to hand preference during infancy. Marcinowski, Campbell, Faldowski, and Michel (2016) assessed stacking skills of infants from 10 to 14 months of age and found that infants with a hand preference were more proficient stackers by 14 months of age than infants who did not have a hand preference. Marcinowski and Campbell (2017) then linked object manipulation and language by examining construction tasks from 10 to 14 months and language outcomes at 2 and 3 years of age. Results found that infants who performed well on the construction task showed higher knowledge of spatial relation words as compared to the infants who did not perform as well on the construction task. Taken together, these studies provide evidence that the development of handedness and object manipulation proficiency are related, and that the development of object manipulation proficiency and language skills are related. Ongoing work in our group is quantifying RDBM proficiency in early development within our sample of children, which may further our understanding of the connections between fine motor skill, hand preference, and later language proficiency.

There is also compelling behavioral evidence for developmental motor-language cascades in atypical populations. Children at risk for developing autism spectrum disorder (ASD) have poor fine motor skills at 6 months of age (Libertus & Landa, 2014), and motor delays observed in these children in the first 2 years are thought to be linked to later emerging problems in social development, including language (Bhat, Landa, & Galloway, 2011). In children at risk for ASD, fine motor skills at 12–18 months and at 24 months was predictive of expressive language ability at 36 months (LeBarton & Iverson, 2013). Specific Language Impairment is also characterized by early motor delays (Hill, 2001; Leonard & Hill, 2014). In conclusion, there is a need to utilize trajectory-based approaches in measuring early motor skills, and hand use patterns for those skills, to predict typical and atypical language outcomes. The approach we have described here is person centered, rich in developmental theory, and has important implications for guiding future research.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the families that participated in this project, and the many research assistants at the UNCG Infant Developmental Center and the HANDS Lab at FIU for collecting and coding these data. The research described in this report was supported by National Science Foundation Grant DLS 0718045 (GFM) and NIH/NICHD Grant T32-HD007376 (ELN and JMC). SLG was supported by NIH/NIGMS R25GM061347. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

ORCID

Eliza L. Nelson http://orcid.org/0000-0003-0058-8409
Sandy L. Gonzalez http://orcid.org/0000-0003-3498-0943
Stefany Coxe http://orcid.org/0000-0002-2203-0775
Julie M. Campbell http://orcid.org/0000-0002-0843-6445
Emily C. Marcinowski http://orcid.org/0000-0003-2010-3827
George F. Michel http://orcid.org/0000-0003-3415-8925

REFERENCES

Adolph, K. E. (2005). Learning to learn in the development of action. In J. Lockman, J. Reiser, & C. A. Nelson (Eds.), *Action as an organizer of perception and cognition during learning and development: Minnesota Symposium on Child Development* (Vol. *33*, pp. 91–122). Hillsdale, NJ: Erlbaum.

Adolph, K. E., & Robinson, S. R. (2015). Motor development. In L. Liben & U. Muller (Eds.), *Handbook of child psychology and developmental science* (pp. 114–157). New York: Wiley.

Alcock, K. J., & Krawczyk, K. (2010). Individual differences in language development: Relationship with motor skill at 21 months. *Developmental Science*, *13*(5), 677–691. https://doi.org/10.1111/j.1467-7687.2009.00924.x

Annett, M. (1985). *Left, right, hand and brain: The right shift theory*. New York: Psychology Press.

Annett, M. (2002). *Handedness and brain asymmetry: The right shift theory*. London, England: Erlbaum.

Babik, I., & Michel, G. F. (2016a). Development of role-differentiated bimanual manipulation in infancy: Part 2. Hand preferences for object acquisition and RDBM-continuity or discontinuity? *Developmental Psychobiology*, *58*(2), 257–267. https://doi.org/10.1002/dev.21378

Babik, I., & Michel, G. F. (2016b). Development of role-differentiated bimanual manipulation in infancy: Part 1. The emergence of the skill. *Developmental Psychobiology*, *58*(2), 243–256.

Bates, E., O'Connell, B., Vaid, J., Sledge, P., & Oakes, L. (1986). Language and hand preference in early development. *Developmental Neuropsychology*, *2*(1), 1–15. https://doi.org/10.1080/87565648609540323

Bayley, N., & Reuner, G. (2006). *Bayley scales of infant and toddler development: Bayley-III* (Vol. *7*). San Antonio, TX: Harcourt Assessment, Psych. Corporation.

Benedict, H. (1979). Early lexical development: Comprehension and production. *Journal of Child Language*, *6*(02), 183–200.

Bhat, A. N., Landa, R. J., & Galloway, J. C. (2011). Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. *Physical Therapy*, *91*(7), 1116–1129.

Birtles, D., Anker, S., Atkinson, J., Shellens, R., Briscoe, A., Mahoney, M., & Braddick, O. (2011). Bimanual strategies for object retrieval in infants and young children. *Experimental Brain Research*, *211*(2), 207–218.

Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development*, *83*(4), 1229–1244.

Cameron, C. E., Cottone, E. A., Murrah, W. M., & Grissmer, D. W. (2016). How are motor skills linked to children's school performance and academic achievement? *Child Development Perspectives*, *10*(2), 93–98.

Campbell, J. M., Marcinowski, E. C., Babik, I., & Michel, G. F. (2015). The influence of a hand preference for acquiring objects on the development of a hand preference for unimanual manipulation from 6 to 14 months. *Infant Behavior and Development*, *39*, 107–117. https://doi.org/10.1016/j.infbeh.2015.02.013

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy*, *1*(2), 149–219.

Carlton, M. P., & Winsler, A. (1999). School readiness: The need for a paradigm shift. *School Psychology Review*, *28*(3), 338.

Caselli, M. C., Bates, E., Casadio, P., Fenson, J., Fenson, L., Sanderl, L., & Weir, J. (1995). A cross-linguistic study of early lexical development. *Cognitive Development*, *10*(2), 159–199.

Clearfield, M. W. (2011). Learning to walk changes infants' social interactions. *Infant Behavior and Development*, *34*(1), 15–25. https://doi.org/10.1016/j.infbeh.2010.04.008

Cochet, H. (2016). Manual asymmetries and hemispheric specialization: Insight from developmental studies. *Neuropsychologia*, *93*, 335–341.

Cochet, H., Jover, M., & Vauclair, J. (2011). Hand preference for pointing gestures and bimanual manipulation around the vocabulary spurt period. *Journal of Experimental Child Psychology*, *110*(3), 393–407. https://doi.org/10.1016/j.jecp.2011.04.009

Connolly, K. (1973). Factors influencing the learning of manual skills by young children. In R. A. Hinde & J. S. Hinde (Eds.), *Constraints on learning* (pp. 337–365). London: Academic Press.

Coryell, J. F., & Michel, G. F. (1978). How supine postural preferences of infants can contribute toward the development of handedness. *Infant Behavior and Development*, *1*, 245–257.

Dinehart, L., & Manfra, L. (2013). Associations between low-income children's fine motor skills in preschool and academic performance in second grade. *Early Education & Development*, *24*(2), 138–161. https://doi.org/10.1080/10409289.2011.636729

Enders, C. K., & Bandalos, D. L. (2001). The relative performance of full information maximum likelihood estimation for missing data in structural equation models. *Structural Equation Modeling*, *8*(3), 430–457.

Esseily, R., Jacquet, A.-Y., & Fagard, J. (2011). Handedness for grasping objects and pointing and the development of language in 14-month-old infants. *Laterality: Asymmetries of Body*, *Brain and Cognition*, *16*(5), 565–585.

Fagard, J. (1998). Changes in grasping skills and the emergence of bimanual coordination during the first year of life. In K. J. Connolly (Ed.), *The psychobiology of the hand* (pp. 123–143). London: Mac Keith Press.

Fagard, J., & Jacquet, A.-Y. (1989). Onset of bimanual coordination and symmetry versus asymmetry of movement. *Infant Behavior and Development*, *12*(2), 229–235.

Fagard, J., & Lockman, J. J. (2005). The effect of task constraints on infants'(bi) manual strategy for grasping and exploring objects. *Infant Behavior and Development*, *28*(3), 305–315.

Fagard, J., & Pezé, A. (1997). Age changes in interlimb coupling and the development of bimanual coordination. *Journal of Motor Behavior*, *29*(3), 199–208.

Fenson, L., Dale, P., Reznick, J., Bates, E., Thal, D., & Pethick, S. (1994). *Variability in early communicative development* (Monographs Nos. 242, 59, 5). Ann Arbor, MI: Society for Research in Child Development.

Gibson, E. J. (1988). Exploratory-behavior in the development of perceiving, acting, and the acquiring of knowledge.9. *Annual Review of Psychology*, *39*, 1–41. https://doi.org/10.1146/annurev.ps.39.020188.000245

Gonzalez, S. L., & Nelson, E. L. (2015). Addressing the gap: A blueprint for studying bimanual hand preference in infants. *Frontiers in Psychology*, *6*, 560. https://doi.org/10.3389/fpsyg.2015.00560

Gottfried, A. W., & Bathurst, K. (1983). Hand preference across time is related to intelligence in young girls, not boys. *Science*, *221*(4615), 1074–1076.

Granert, O., Peller, M., Gaser, C., Groppa, S., Hallett, M., Knutzen, A., … Siebner, H. R. (2011). Manual activity shapes structure and function in contralateral human motor hand area. *Neuroimage*, *54*(1), 32–41.

Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology*, *46*(5), 1008.

Häberling, I. S., Corballis, P. M., & Corballis, M. C. (2016). Language, gesture, and handedness: Evidence for independent lateralized networks. *Cortex*, *82*, 72–85.

He, M., Walle, E. A., & Campos, J. J. (2015). A cross-national investigation of the relationship between infant walking and language development. *Infancy*, *20*(3), 283–305.

Hill, E. L. (2001). Non-specific nature of specific language impairment: A review of the literature with regard to concomitant motor impairments. *International Journal of Language & Communication Disorders*, *36*(2), 149–171.

Hinojosa, T., Sheu, C. F., & Michel, G. F. (2003). Infant hand-use preferences for grasping objects contributes to the development of a hand-use preference for manipulating objects. *Developmental Psychobiology*, *43*(4), 328–334. https://doi.org/10.1002/dev.10142

Iverson, J. M. (2010). Developing language in a developing body: The relationship between motor development and language development. *Journal of Child Language*, *37*(2), 229–261. https://doi.org/10.1017/S0305000909990432

Jackson-Maldonado, D., Thal, D., Marchman, V., Bates, E., & Gutiérrez-Clellen, V. (1993). Early lexical development in Spanish-speaking infants and toddlers. *Journal of Child Language*, *20*(03), 523–549.

Jung, T., & Wickrama, K. (2008). An introduction to latent class growth analysis and growth mixture modeling. *Social and Personality Psychology Compass*, *2*(1), 302–317.

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2011). Transition from crawling to walking and infants' actions with objects and people. *Child*

Development, *82*(4), 1199–1209. https://doi.org/10.1111/j.1467-8624. 2011.01595.x

Karasik, L. B., Tamis-Lemonda, C. S., & Adolph, K. E. (2014). Crawling and walking infants elicit different verbal responses from mothers. *Developmental Science*, *17*(3), 388–395. https://doi.org/10.1111/desc.12129

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2005). Decisions at the brink: Locomotor experience affects infants' use of social information on an adjustable drop-off. *Frontiers in Psychology*, *7*, 797. https://doi.org/10.3389/fpsyg.2016.00797

Kee, D. W., Gottfried, A., & Bathurst, K. (1991). Consistency of hand preference: Predictions to intelligence and school achievement. *Brain and Cognition*, *16*(1), 1–10.

Kee, D. W., Gottfried, A. W., Bathurst, K., & Brown, K. (1987). Left-hemisphere language specialization: Consistency in hand preference and sex differences. *Child Development*, *58*(3), 718–724.

Kimmerle, M., Ferre, C. L., Kotwica, K. A., & Michel, G. F. (2010). Development of role-differentiated bimanual manipulation during the infant's first year. *Developmental Psychobiology*, *52*(2), 168–180.

Kimmerle, M., Mick, L. A., & Michel, G. F. (1995). Bimanual role-differentiated toy play during infancy. *Infant Behavior and Development*, *18*(3), 299–307.

Knecht, S., Dräger, B., Deppe, M., Bobe, L., Lohmann, H., Flöel, A., … Henningsen, H. (2000). Handedness and hemispheric language dominance in healthy humans. *Brain*, *123*(12), 2512–2518.

Kotwica, K. A., Ferre, C. L., & Michel, G. F. (2008). Relation of stable hand-use preferences to the development of skill for managing multiple objects from 7 to 13 months of age. *Developmental Psychobiology*, *50*(5), 519–529. https://doi.org/10.1002/dev.20311

LeBarton, E. S., & Iverson, J. M. (2013). Fine motor skill predicts expressive language in infant siblings of children with autism. *Developmental Science*, *16*(6), 815–827.

Leonard, H. C., & Hill, E. L. (2014). The impact of motor development on typical and atypical social cognition and language: A systematic review. *Child and Adolescent Mental Health*, *19*(3), 163–170.

Libertus, K., & Landa, R. J. (2014). Scaffolded reaching experiences encourage grasping activity in infants at high risk for autism. *Frontiers in Psychology*, *5*, 1071. https://doi.org/10.3389/fpsyg.2014.01071

Libertus, K., & Needham, A. (2010). Teach to reach: The effects of active vs. passive reaching experiences on action and perception. *Vision Research*, *50*(24), 2750–2757. https://doi.org/10.1016/j.visres.2010.09.001

Libertus, K., & Needham, A. (2011). Reaching experience increases face preference in 3-month-old infants. *Developmental Science*, *14*(6), 1355–1364. https://doi.org/10.1111/j.1467-7687.2011.01084.x

Libertus, K., & Needham, A. (2014a). Encouragement is nothing without control: Factors influencing the development of reaching and face preference. *Journal of Motor Learning and Development*, *2*(1), 16–27. https://doi.org/10.1123/jmld.2013-0019

Libertus, K., & Needham, A. (2014b). Face preference in infancy and its relation to motor activity. *International Journal of Behavioral Development*, *38*(6), 529–538. https://doi.org/10.1177/0165025414535122

Libertus, K., & Violi, D. A. (2016). Sit to talk: Relation between motor skills and language development in infancy. *Frontiers in Psychology*, *7*, 475. https://doi.org/10.3389/fpsyg.2016.00475

Luo, Z., Jose, P. E., Huntsinger, C. S., & Pigott, T. D. (2007). Fine motor skills and mathematics achievement in East Asian American and European American kindergartners and first graders. *British Journal of Developmental Psychology*, *25*(4), 595–614.

Marcinowski, E. C., & Campbell, J. M. (2017). Building on what you have learned: Object construction skill during infancy predicts the comprehension of spatial relations words. *International Journal of Behavioral Development*, *41*(3), 341–349.

Marcinowski, E. C., Campbell, J. M., Faldowski, R. A., & Michel, G. F. (2016). Do hand preferences predict stacking skill during infancy? *Developmental Psychobiology*, *58*(8), 958–967.

Marschik, P. B., Einspieler, C., Strohmeier, A., Plienegger, J., Garzarolli, B., & Prechtl, H. F. (2008). From the reaching behavior at 5 months of age to hand preference at preschool age. *Developmental Psychobiology*, *50*(5), 511–518. https://doi.org/10.1002/dev.20307

Masten, A. S., & Cicchetti, D. (2010). Developmental cascades. *Development and Psychopathology*, *22*(03), 491–495.

Michel, G. F. (1981). Right-handedness: A consequence of infant supine head-orientation preference. *Science*, *212*(4495), 685–687.

Michel, G. F. (1983). Development of hand-use preference during infancy. In G. Young, S. Segalowitz, C. Corter, & S. Trehub (Eds.), *Manual specialization and the developing brain* (pp. 33–70). New York: Academic Press.

Michel, G. F. (1988). A neuropsychological perspective on infant sensorimotor development. In L. P. Lipsitt & C. K. Rovee-Collier (Eds.), *Advances in infancy research*. (Vol. 5, pp. 1–37). Norwood, NJ: Ablex Publishing Corporation.

Michel, G. F. (1998). A lateral bias in the neuropsychological functioning of human infants. *Developmental Neuropsychology*, *14*(4), 445–469. https://doi.org/10.1080/87565649809540723

Michel, G. F. (2002). Development of infant handedness. In D. J. Lewkowicz & R. Lickliter (Eds.), *Conceptions of development: Lessons from the laboratory* (pp. 165–186). New York: Psychology Press.

Michel, G. F. (2013). The concept of homology in the development of handedness. *Developmental Psychobiology*, *55*(1), 84–91. https://doi.org/10.1002/dev.21038

Michel, G. F., Babik, I., Nelson, E. L., Campbell, J. M., & Marcinowski, E. C. (2013). How the development of handedness could contribute to the development of language. *Developmental Psychobiology*, *55*(6), 608–620. https://doi.org/10.1002/dev.21121

Michel, G. F., Babik, I., Sheu, C. F., & Campbell, J. M. (2014). Latent classes in the developmental trajectories of infant handedness. *Developmental Psychology*, *50*(2), 349–359. https://doi.org/10.1037/a0033312

Michel, G. F., Campbell, J. M., Marcinowski, E. C., Nelson, E. L., & Babik, I. (2016). Infant hand preference and the development of cognitive abilities. *Frontiers in Psychology*, *7*, 410. https://doi.org/10.3389/fpsyg.2016.00410

Michel, G. F., & Harkins, D. A. (1986). Postural and lateral asymmetries in the ontogeny of handedness during infancy. *Developmental Psychobiology*, *19*(3), 247–258.

Nagin, D. S., & Land, K. C. (1993). Age, criminal careers, and population heterogeneity: Specification and estimation of a nonparametric, mixed Poisson model*. *Criminology*, *31*(3), 327–362.

Needham, A., Barrett, T., & Peterman, K. (2002). A pick-me-up for infants' exploratory skills: Early simulated experiences reaching for objects using 'sticky mittens' enhances young infants' object exploration skills. *Infant Behavior and Development*, *25*(3), 279–295.

Nelson, E. L., Campbell, J. M., & Michel, G. F. (2013). Unimanual to bimanual: Tracking the development of handedness from 6 to 24 months. *Infant Behavior and Development*, *36*(2), 181–188. https://doi.org/10.1016/j.infbeh.2013.01.009

Nelson, E. L., Campbell, J. M., & Michel, G. F. (2014). Early handedness in infancy predicts language ability in toddlers. *Developmental Psychology*, *50*(3), 809–814. https://doi.org/10.1037/a0033803

Nylund, K. L., Asparouhov, T., & Muthén, B. O. (2007). Deciding on the number of classes in latent class analysis and growth mixture modeling: A Monte Carlo simulation study. *Structural Equation Modeling*, *14*(4), 535–569.

Oudgenoeg-Paz, O., Leseman, P. P., & Volman, M. C. (2015). Exploration as a mediator of the relation between the attainment of motor milestones and the development of spatial cognition and spatial language. *Developmental Psychology*, *51*(9), 1241–1253. https://doi.org/10.1037/a0039572

Oudgenoeg-Paz, O., Volman, M. C., & Leseman, P. P. (2016). First steps into language? Examining the specific longitudinal relations between walking, exploration and linguistic skills. *Frontiers in Psychology*, *7*, 1458.

Oudgenoeg-Paz, O., Volman, M. C. J., & Leseman, P. P. (2012). Attainment of sitting and walking predicts development of productive vocabulary between ages 16 and 28 months. *Infant Behavior and Development*, *35*(4), 733–736.

Papadatou-Pastou, M., Martin, M., Munafo, M. R., & Jones, G. V. (2008). Sex differences in left-handedness: A meta-analysis of 144 studies. *Psychological Bulletin*, *134*(5), 677–699. https://doi.org/10.1037/a0012814

Provins, K. (1956). Handedness" and skill. *Quarterly Journal of Experimental Psychology*, *8*(2), 79–95.

Ramsay, D. S. (1980). Onset of unimanual handedness in infants. *Infant Behavior and Development*, *3*(4), 377–385. https://doi.org/10.1016/s0163-6383(80)80045-2

Ramsay, D. S. (1984). Onset of duplicated syllable babbling and unimanual handedness in infancy: Evidence for developmental change in hemispheric specialization? *Developmental Psychology*, *20*(1), 64.

Ramsay, D. S. (1985). Fluctuations in unimanual hand preference in infants following the onset of duplicated syllable babbling. *Developmental Psychology*, *21*(2), 318–324. https://doi.org/10.1037/ 0012-1649.21.2.318

Ramsay, D. S., Campos, J. J., & Fenson, L. (1979). Onset of bimanual handedness in infants. *Infant Behavior and Development*, *2*, 69–76.

Rogers, L. J., & Vallortigara, G. (2015). When and why did brains Break symmetry? *Symmetry*, *7*(4), 2181–2194.

Rogers, L. J., Vallortigara, G., & Andrew, R. J. (2013). *Divided brains: The biology and behaviour of brain asymmetries*. New York: Cambridge University Press.

Rubin, D. (1976). Inference and missing data. *Biometrika*, *63*(3), 584–592.

Sansavini, A., Bello, A., Guarini, A., Savini, S., Stefanini, S., & Caselli, M. C. (2010). Early development of gestures, object-related-actions, word comprehension and word production, and their relationships in Italian infants A longitudinal study. *Gesture*, *10*(1), 52–85.

Serrien, D. J., Ivry, R. B., & Swinnen, S. P. (2006). Dynamics of hemispheric specialization and integration in the context of motor control. *Nature Reviews Neuroscience*, *7*(2), 160–166.

Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition*, *96*(1), B1–11. https://doi.org/10.1016/j.cognition.2004.07.004

Sortor, J., & Kulp, M. (2003). Are the results of the Beery-Buktenica developmental test of visual-motor integration and its subtests related to achievement test scores? *Optometry and Vision Science*, *80*(11), 758.

Spencer, J. P., Clearfield, M., Corbetta, D., Ulrich, B., Buchanan, P., & Schöner, G. (2006). Moving toward a grand theory of development: In memory of Esther Thelen. *Child Development*, *77*(6), 1521–1538.

Steenhuis, R. E., & Bryden, M. P. (1999). The relation between hand preference and hand performance: What you get depends on what you measure. *Laterality: Asymmetries of Body, Brain and Cognition*, *4*(1), 3–26.

Tein, J.-Y., Coxe, S., & Cham, H. (2013). Statistical power to detect the correct number of classes in latent profile analysis. *Structural Equation Modeling:A Multidisciplinary Journal*, *20*(4), 640–657.

Thelen, E., & Smith, L. B. (2006). Dynamic systems theories. In W. Damon & R. M. Lerner (Eds.), *Hand book of child psychology* (6 ed.,Vol. *1*, pp. 258–312). New York: Wiley.

Thelen, E., Ulrich, B. D., & Wolff, P. H. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development*, 56(Serial No. 223), i-103. https://doi.org/10.2307/1166099

Tirosh, E., Stein, M., Harel, J., & Scher, A. (1999). Hand preference as related to development and behavior in infancy. *Perceptual and Motor Skills*, *89*(2), 371–380.

Todor, J. I., & Doane, T. (1977). Handedness classification: Preference versus proficiency. *Perceptual and Motor Skills*, *45*(3 suppl), 1041–1042.

Vallortigara, G., & Rogers, L. J. (2005). Survival with an asymmetrical brain: Advantages and disadvantages of cerebral lateralization. *Behavioral and Brain Sciences*, *28*(4), 575–588.

Vauclair, J., & Cochet, H. (2013). Hand preference for pointing and language development in toddlers. *Developmental Psychobiology*, *55*(7), 757–765. https://doi.org/10.1002/dev.21073

Walle, E. A. (2016). Infant social development across the transition from crawling to walking. *Frontiers in Psychology*, *7*, 960. https://doi.org/10.3389/fpsyg.2016.00960

Walle, E. A., & Campos, J. J. (2014). Infant language development is related to the acquisition of walking. *Developmental Psychology*, *50*(2), 336–348. https://doi.org/10.1037/a0033238

Walle, E. A., & Warlaumont, A. S. (2015). "Infant locomotion, the language environment, and language development: a home observation study," in Proceedings of the 37th Annual Meeting of the Cognitive Science Society (Santa Barbara, CA: Cognitive Science Society), 2577–2582.

Wang, M. V., Lekhal, R., Aaro, L. E, & Schjolberg, S. (2014). Co-occurring development of early childhood communication and motor skills: Results from a population-based longitudinal study. *Child: Care, Health and Development*, *40*(1), 77–84. https://doi.org/10.1111/cch.12003

Wilbourn, M. P., Gottfried, A. W., & Kee, D. W. (2011). Consistency of hand-preference across the early years: Long-term relationship to verbal intelligence and reading achievement in girls. *Developmental Psychology*, *47*(4), 931–942. https://doi.org/10.1037/a0023834

Zimmerman, I., Steiner, V., & Pond, R. (2011). *PLS-5: Preschool language scale-5 [measurement instrument]*. San Antonio, TX: Psychological Corporation.

How to cite this article: Nelson EL, Gonzalez SL, Coxe S, Campbell JM, Marcinowski EC, Michel GF. Toddler hand preference trajectories predict 3-year language outcome. *Developmental Psychobiology*. 2017;1–12. https://doi.org/10.1002/dev.21560