









REPORT

# Hand preference trajectories as predictors of language outcomes above and beyond SES: Infant patterns explain more variance than toddler patterns at 5 years of age

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## Abstract

Prior studies found that hand preference trajectories predict preschool language outcomes. However, this approach has been limited to examining bimanual manipulation in toddlers. It is not known whether hand preference during infancy for acquiring objects (i.e., reach-to-grasp) similarly predicts childhood language ability. The current study explored this motor-language developmental cascade in 90 children. Hand preference for acquiring objects was assessed monthly from 6 to 14 months, and language skill was assessed at 5 years. Latent class growth analysis identified three infant hand preference classes: left, early right and late right. Infant hand preference classes predicted 5-year language skills. Children in the left and early right classes, who were categorized as having a consistent hand preference, had higher expressive and receptive language scores relative to children in the inconsistent late right class. Consistent classes did not differ from each other on language outcomes. Infant hand preference patterns explained more variance for expressive and receptive language relative to previously reported toddler hand preference patterns, above and beyond socio-economic status. Results suggest that hand preference, measured at different

time points across development using a trajectory approach, is reliably linked to later language.

#### Highlights

- Hand preference trajectories reliably predict preschool language above and beyond SES.
- Infants with a consistent hand preference for reaching had greater language skills at 5 years.
- Infant hand preference explained more variance in language than toddler hand preference.

#### KEYWORDS

developmental cascades, hand preference, infant, language, preschool, reach-to-grasp

## 1 | INTRODUCTION

The achievement of motor skill benchmarks like reaching for objects, sitting unsupported, crawling and walking independently has commanded the attention of paediatricians and parents. In fact, there are individual differences in the developmental trajectories of these motor skills (e.g., shifts in manual action, posture and locomotion) that shape how infants engage with their world (Adolph & Franchak, 2017). This rich individual variability has developmental implications because each advance in motor skill offers new opportunities for infant learning—a concept known as *developmental cascades*. Developmental cascades refer to a process, whereby advances in one domain can have widespread and seemingly disparate effects in other domains within a developing system (Iverson, 2021; Masten & Cicchetti, 2010). In one of the most powerful demonstrations of a developmental cascade, Bornstein et al. (2013) reported that infants who explored objects more actively at 5 months had greater academic achievement at 14 years old.

Further examining how children manipulate objects with their hands has revealed that toddler hand preference trajectories consistently predict preschool language skills (Gonzalez et al., 2020; Nelson et al., 2017). While prior work has established there are multiple hand preference trajectories in infancy (Campbell et al., 2018; Michel et al., 2014), it is not known whether hand use patterns measured at *different* time points earlier in development for a *different* motor skill (i.e., reach-to-grasp) are also tied to later language. The current study fills this gap by examining whether infant hand preference trajectories for acquiring objects, measured from 6 to 14 months, predict expressive and receptive language at 5 years old. Using a unique rich longitudinal dataset spanning infancy, toddlerhood and the preschool years, we also compared how much variance in 5-year receptive and expressive language scores infant hand preference patterns explain relative to toddler hand preference patterns previously reported by Gonzalez et al. (2020), above and beyond the expected contributions of socio-economic status (SES). We report the utility of using different hand preference patterns as a predictor for distal language outcomes for the first time using a statistical technique that was not available in earlier analyses (Hayes, 2021).

### 1.1 | The onset of new motor skills has a cascading effect on the development of language

Changing relations between motor skills, object knowledge and social interactions sets the stage for motor-language cascades. Motor-language cascades assess the development of language skills through cascading changes in infants'

motor achievements (Iverson, 2010, 2021, 2022). A review by Gonzalez et al. (2019) found that both gross and fine motor skills predict language outcomes across early childhood; yet, studies have largely focused on the gross motor links. Gross motor skills refer to actions that involve large muscle movements such as sitting, crawling and walking. By comparison, fine motor skills are actions that involve small muscle movements such as reaching to and manipulating objects. Only one prior study has examined reach-to-grasp actions (i.e., object acquisition) as a predictor for later language outcomes. Libertus and Violi (2016) examined the rate of skill development for grasping objects and sitting from 3 to 5 months and language at 10 and 14 months. Motor behaviours were indexed as the proportion of time spent either grasping an object or in a sitting posture during 1-minute observations. Growth in sitting, but not grasping, was correlated with receptive vocabulary at both of the later time points in the study. Potential links to expressive vocabulary were not measured.

Grasping and receptive language may not have been related in the Libertus and Violi (2016) study because grasping was assessed before meaningful hand use patterns for this skill are established. Reaching for objects is the most popular measure of hand preference in infants, and almost all of the research in this field has been with infants 6 months or older (for a review, see Nelson & Gonzalez, 2020). Moreover, reaching for objects is one of many asymmetries in a cascade for the development of handedness (Michel, 2021). In the next section, we describe how reaching fits into this cascade and show why a hand preference trajectory approach is needed to evaluate reach-to-grasp as a potential predictor for developmental outcomes like language. Notably, our approach contrasts with other investigators who have measured hand preference for language-related paradigms such as pointing relative to hand preferences for other manual tasks where reporting focused on age differences (e.g., Bates et al., 1986; Vauclair & Imbault, 2009).

## 1.2 | Infant reaching is a component of a developmental cascade for handedness

Infant handedness results from cascading asymmetries across a variety of developmental experiences. This theoretical framing is known as the *cascade theory of handedness* (Michel, 2002, 2021; Michel et al., 2013). According to this developmental framework, the intrauterine environment (measured by the vertex position in utero) induces an asymmetry where typically the left hand is constrained, and the right hand is freed in most fetuses. The intrauterine orientation of the foetus (measured as birth position) is a reliable predictor for neonatal supine head orientation preference, which is a newborn's preference to lie on their back with their head turned to the right (Michel & Goodwin, 1979). Head orientation directly influences an infant's visual environment such that right-oriented infants view their right hand more often than their left hand and vice versa, and the hand that is viewed more is more active (Coryell & Michel, 1978; Michel & Harkins, 1986; van der Meer et al., 1995). A right supine head orientation preference in turn predicts a right-hand preference for reaching to and acquiring objects (Michel, 1981). Furthermore, a right-hand preference for acquiring objects predicts a right-hand preference when infants begin manipulating objects with one hand (Campbell, Marcinowski, Babik, & Michel, 2015; Hinojosa et al., 2003). Finally, a right-hand unimanual preference cascades to a right-hand preference for the manipulating hand in the skill role-differentiated bimanual manipulation (RDBM; Babik & Michel, 2016; Nelson et al., 2013). RDBM requires distinct differentiation between the actions of both hands (Kimmerle et al., 1995). Although the cascade was illustrated here for right-handed infants, who constitute most infants, similar leftward cascading preferences are also observed for left-handed infants.

The nature of cascading hand preferences across different manual skills means that handedness cannot be measured from static individual time points in development—rather, measuring infant handedness requires trajectory modelling nested in a longitudinal design. Only two studies have examined the development of handedness by extracting latent classes of hand preference trajectories during reach-to-grasp in infancy (Campbell et al., 2018; Michel et al., 2014). Michel et al. (2014) assessed the development of a hand preference for object acquisition at nine time points from 6 to 14 months in a sample of 328 infants and identified three classes or group patterns. These patterns were described as identifiable right preference (38% of the sample), identifiable left preference (14%) and no

statistically identifiable preference but trending right preference (48%). Campbell et al. (2018) extended these findings in a larger sample using the same design, identifying four trajectories of hand preference in 380 infants. The breakdown by trajectory class in this larger sample was 32% early right, 12% early left, 30% late right and 25% no preference. The difference between the two distributions of infant hand preference classes is likely sample size, as increasing the N can lead to identifying more classes (Jung & Wickrama, 2008).

The first important takeaway from the prior two studies that extracted latent classes of infant hand preference is that trajectories for object acquisition could not be identified from a smaller number of monthly observations. Characterizing the development of handedness requires a longitudinal design with hand preferences assessed at many time points. The second key takeaway is that there is no one-size-fits-all pattern for the development of infant hand preference. Data are usefully summarized by multiple patterns (termed 'classes'), and we will show in the next section that differences across hand preference classes are meaningful in developmental science because they have cascading effects on other skills.

### 1.3 | Consistent handedness has cascading effects across developmental domains

Trajectory analyses parse the variability in early hand use into different developmental patterns, and these different patterns seemingly have cascading effects on skills in other domains. Specifically, toddler hand preference trajectories that were characterized as consistent have been positively related to later school readiness and academic achievement (Gonzalez et al., 2020; Gottfried & Bathurst, 1983; Nelson et al., 2014; Nelson et al., 2017; Wilbourn et al., 2011). In the Fullerton Longitudinal Study, the relationship between hand preference consistency and later cognitive ability was assessed from 18 months to 17 years (Gottfried & Bathurst, 1983; Kee et al., 1987; Kee et al., 1991; Wilbourn et al., 2011). Children's hand preference was measured by observing which hand the child chose to draw with at 18, 24, 30, 36 and 42 months. Children who used the same hand to draw in all five visits were identified as having a consistent hand preference. Children who did not use the same hand to draw in all five visits were identified as having an inconsistent hand preference (Gottfried & Bathurst, 1983). From 5 to 9 years old, scores for children's verbal intelligence and reading achievement were obtained (Kee et al., 1991). Girls with a consistent hand preference from 10 to 42 months had higher verbal intelligence and reading achievement than those with an inconsistent hand preference. Wilbourn et al. (2011) extended this pattern in girls with a consistent early hand preference, finding that this group also had enhanced verbal intelligence and reading achievement as adolescents at 12, 15 and 17 years.

Individual differences in hand preference trajectories from infancy to toddlerhood have been linked to language achievement at 2 years old (Nelson et al., 2014). In this study spanning the first 2 years of life, children performed age-appropriate manual skills with respect to the cascade theory of handedness. In infancy, hand preference for object acquisition was assessed in monthly intervals from 6 to 14 months. As toddlers, hand preference for RDBM was assessed in monthly intervals from 18 to 24 months. Three groups of handedness trajectories were identified: early right-handed (children with a consistent right-hand preference from infant acquisition to toddler RDBM); late right-handed (children who did not have a hand preference for acquisition as infants but developed a right-hand preference as toddlers); and late left-handed (children who did not have a hand preference for acquisition as infants but developed a left-hand preference as toddlers). There was a large effect of infant hand preference status on 2-year language outcome. Children who were consistent as infants (early right-handed) had higher scores than children who were inconsistent as infants (late right-handed and late left-handed). Moreover, there were no differences among the three trajectories in general motor or cognitive skills, suggesting that hand preference patterns may uniquely contribute to later language variance (Nelson et al., 2014).

Similarly, individual differences in hand preference trajectories in toddlerhood have predicted preschool language ability (Gonzalez et al., 2020; Nelson et al., 2017). In a study by Nelson et al. (2017), hand preference for RDBM was assessed monthly from 18 to 24 months, and receptive and expressive language was measured at

3 years. Latent class growth analysis (LCGA) identified three toddler RDBM trajectories: right-mild left (right-hand preference with little left-hand use), right-moderate left (right-hand preference with a moderate amount of left-hand use) and left-moderate right (left-hand preference with a moderate amount of right-hand use). Consistency was defined in this study by the amount of use of the non-preferred hand. Children in the right-mild left group were classified as consistent right, and children in the two moderate groups were classified as inconsistent right and inconsistent left. Hand preference consistency predicted 3-year language outcomes. Consistent right toddlers had higher expressive and receptive language scores than inconsistent right toddlers, as well as higher expressive language scores than inconsistent left toddlers.

Gonzalez et al. (2020) extended these findings by assessing the relation between toddler RDBM trajectories and 5-year language outcomes. Again, there was an effect of hand preference trajectory consistency on later language. Children in the consistent right group had higher expressive and receptive scores than children classified as inconsistent left. Additionally, the consistent right group had higher receptive language scores than children in the inconsistent right group. Across both prior studies, consistency was the key attribute of hand preference trajectory as a predictor for language. Robust links between individual monthly hand preference scores and yearly language scores were not found using traditional correlational methods. Taken together, these studies show that hand preference consistency is a meaningful predictor for many later developmental outcomes, including language, which is the distal outcome measure in the current study (Gonzalez et al., 2020; Gottfried & Bathurst, 1983; Nelson et al., 2014; Nelson et al., 2017; Wilbourn et al., 2011). However, neither of these toddler hand preference studies examined how much variance in language outcomes the hand preference classes explain.

#### 1.4 | Current study

The current study assessed the relation between infant hand preference for acquiring objects (i.e., reach-to-grasp) and language ability at 5 years of age using LCGA. Acquisition was selected as the observed motor skill for three reasons: (1) acquisition hand preference occurs earlier in the cascade for the development of handedness (Michel, 2021); (2) acquisition hand preference has previously been characterized by multiple trajectories (Campbell et al., 2018; Michel et al., 2014); and (3) little is known about reaching to acquire objects as a predictor in motor-language cascades (Libertus & Violi, 2016). The current study extends prior work on toddler hand preference trajectories for RDBM predicting language by utilizing the same sample from Nelson et al. (2017) and Gonzalez et al. (2020). The current study had three goals. The first goal was to identify the number of latent classes for infant object acquisition hand preference. Trajectories were computed from nine observations of object acquisition taken at monthly laboratory visits from 6 to 14 months. Models with 2, 3 and 4 latent classes were examined with LCGA. We expected to identify multiple trajectories or patterns in infant hand preference for acquiring objects. The second goal was to determine whether infant trajectories predict 5-year language outcomes. We hypothesized that there is a link between infant object acquisition preference patterns and later expressive and receptive language abilities; however, we did not make specific predictions about the nature of these links since the number of latent classes for infant object acquisition hand preference was not known a priori. Correlations between monthly hand preference scores and language outcomes were also run for comparison to LCGA models and to prior studies that have used this type of analytic approach. The third and final goal was to determine whether infant hand preference or toddler hand preference is the stronger predictor of later language based on the proportion of variance that each explained. Alternatively, infant and toddler hand preference may be equally as good at predicting receptive and expressive language. With this last goal, our intent was to establish where effort should go in future research that can directly test potential mechanisms underlying motor-language cascades.

Because hand preference classes are an emerging predictor of later language, we also examined what portion of the variance was unique to hand preference classes above and beyond what could be explained by an established predictor: SES, measured as maternal education and family income. SES is a well-known predictor of language

outcomes in infancy and early childhood with children from low SES families showing lower levels of language skills than children from high-SES families (e.g., Hart & Risley, 2003; Hoff, 2003; Hoff, 2013). Drawing from a recent paper relative to the current study that parcelled out variance for a novel predictor of language outcomes relative to SES (intersensory matching; Edgar et al., 2022), we expected SES to explain a small amount of variance in 5-year language scores. We did not have a priori predictions for the amount of unique variance in language outcomes explained by hand preference classes.

## 2 | METHOD

### 2.1 | Openness and transparency

We report how we determined our sample size, all data exclusions, all manipulations and all measures in the study. Processed data and scripts are available at the following link: <https://osf.io/v7r9g/>. Analyses drew from a rich longitudinal dataset ( $N = 368$ ). The purpose of the original study was to examine the development of handedness from 6 to 14 months of age. Enrolment criteria in the original study included the following: the infant born to term at 37 or more weeks with no birth complications and no known developmental disorders or serious medical conditions as reported by one of their parents. The sample was recruited from a midsized city in the Southeastern United States (Greensboro, NC) via public birth records using a rolling cohort design with eight waves. All families in the final three waves were contacted to return for toddler and preschool follow-ups where language assessments were conducted. Families were invited by mail for initial enrolment into the study. Appointments were scheduled within  $\pm 7$  days of the child's monthly birthdate. Prior related publications from this dataset have reported on the connection between toddler hand preference trajectories, measured from the manual skill RDBM, and language outcomes (Gonzalez et al., 2020; Nelson et al., 2017). This paper adds new knowledge by testing infant hand preference, measured from acquiring objects, as a potential predictor of later language, and directly compares how much variance in receptive and expressive language at 5 years is explained by infant hand preference versus toddler hand preference in the same children, above and beyond SES. Gonzalez et al. (2020) provided the toddler hand preference data that were used in the variance-explained analyses.

### 2.2 | Participants

Ninety typically developing infants (47 males) participated in the current study. The  $N$  reflects the number of participants from the final three waves of the larger study where language was assessed. The language spoken in the home was English. The racial and ethnic makeup of the sample as reported by one parent 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. Family income ranged from \$10,000 to \$19,000 to \$150,000 or more, and the median income level was \$60,000–\$69,999. Eighteen families did not report income level. Mother's education ranged from high school diploma or general education development test equivalent to a professional degree. Seventeen families did not report mother's education. Father's education ranged from 1 or more years of high school with no degree to a doctorate degree. Nineteen families did not report father's education level. The median education level for both parents was a bachelor's degree.

A total of 80 infants had complete hand preference data across the nine visits from 6 to 14 months. Nine infants had missing data for one hand preference time point, and one infant was missing data for two hand preference time points. No infants were missing data for more than two hand preference visits between 6 and 14 months. All 90 infants were included in the reported analyses on hand preference. At 5 years old, 64 children (37 males) returned to the laboratory for language testing.

## 2.3 | Procedure

The following procedures were approved by the University of North Carolina Greensboro Institutional Review Board (project title: "Development of Infant Handedness"; research protocol number IRB 05-0071). Informed consent was obtained from parents for their child to participate in the study at the first infant visit at 6 months. Families were re-consented at the 5-year follow-up assessment. Families received a \$10 gift card at each laboratory visit, and children received an additional small toy at the 5-year visit. Hand preference for object acquisition was measured in laboratory monthly from 6 to 14 months. Each hand preference assessment was conducted within  $\pm 7$  days of the child's monthly birthday. Language was measured in laboratory using the Preschool Language Scales, 5th edition (PLS-5) at 5 years ( $M = 60.20$  months,  $SD = \pm 1.12$ , range = 58–63 months). Data were used in secondary analyses under approval from the Florida International University Review Board (project title: "PLS"; research protocol number IRB 13-0288). Neither the original study nor the secondary analyses were preregistered.

## 2.4 | Measures

### 2.4.1 | Infant object acquisition hand preference

Hand preference for acquiring objects (i.e., reach-to-grasp) was assessed using a procedure first introduced by Michel et al. (1985), which has been shown to have good validity and test-retest reliability. This 32-item procedure has been rigorously compared with another commonly used 9-item infant assessment. The 32-item procedure used in the current study is more conservative (i.e., less likely to overestimate) in assigning a hand preference to infants (Campbell, Marciniowski, Latta, & Michel, 2015).

Infants sat on a parent's lap at table height for the acquisition hand preference procedure. Thirty-two medium-sized objects of varying shapes and colours were quasi-randomly presented to the infant. Twenty-two single toys were presented at midline; 17 of these were placed on the table, and five were held in the air at the infant's eye level. The remaining 10 toys were identical toy pairs; for doubles, seven pairs were placed on the table and three pairs were held in the air. Each presentation lasted approximately 12 s for the infant to acquire the toy. After acquisition, the toy was removed, and the next item was presented. The entire procedure lasted 20 min. Infants were assessed for acquisition hand preference nine times from 6 to 14 months.

All presentations were videorecorded from two synchronized cameras providing side and overhead views for later coding. Videos were coded offline frame by frame with the software Noldus Observer XT 10. Coders identified the first hand to lift the toy for table presentations or move the toy for aerial presentations. Interrater reliability was calculated from 20% of the videos (Cohen's Kappa  $M = 0.91$ ,  $Mdn = 0.91$ , range = 0.82–0.99). Interrater reliability was calculated from another 20% of the videos (Cohen's Kappa  $M = 0.94$ ,  $Mdn = 0.94$ , range = 0.88–0.99).

### 2.4.2 | Preschool language scales, 5th edition (PLS-5)

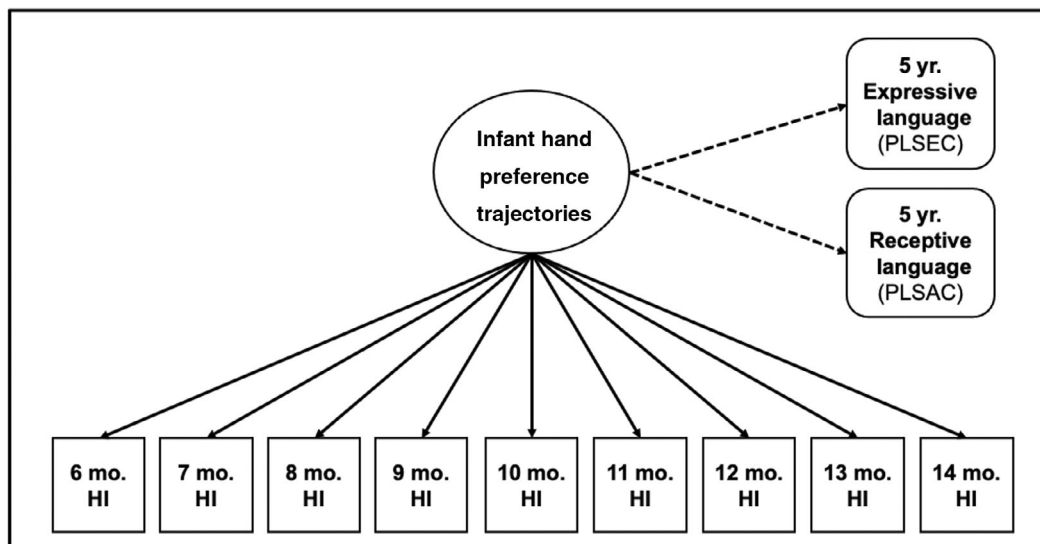
Trained observers administered the Preschool Language Scales, 5th edition (PLS-5; Zimmerman et al., 2011) when children were 5 years old. The PLS-5 is a standardized language assessment that measures a child's receptive and expressive language abilities. The PLS-5 is a widely used assessment with excellent reliability ranging from 0.95 to 0.98 as well as test-retest reliability between 0.86 and 0.95 (Zimmerman et al., 2011). The PLS-5 has two standardized subscales: Preschool Language Scales Auditory Comprehension (PLSAC) and Preschool Language Scales Expressive Communication (PLSEC) and additionally provides a total communication score. PLS-5 scores are normed at

100 and have a standard deviation of 15. PLS-5 administration took 1–2 h per child. PLSAC and PLSEC standard scores were used in the following analyses.

## 2.5 | Statistical analysis

A Handedness Index (HI) score was calculated for each infant at each visit from 6 to 14 months (a total of 9 HI scores). HI scores used the following formula:  $HI = (R-L)/(R+L)$ , where  $R$  is the number of right-hand acquisitions and  $L$  is the number of left-hand acquisitions. HI scores range from  $-1.00$  (exclusively left-hand reach-to-grasp actions) to  $1.00$  (exclusively right-hand reach-to-grasp actions). HI scores were entered as observed variables in latent class growth models to determine trajectories of infant hand preference for acquisition (cf. Gonzalez et al., 2020; Nelson et al., 2017). LCGA (Jung & Wickrama, 2008) is a powerful approach that estimates individual growth over time while also identifying subgroups of infants with similar hand preference trajectories. Figure 1 shows the LCGA model that was tested.

Linear time coefficients (e.g., 0, 1, 2, 3...) in the growth model were transformed using a natural log transformation because prior work has found that the shape of infants' hand use preference trajectories increases to asymptote, rather than having linear or quadratic profiles (Campbell et al., 2018; Michel et al., 2014). The model was time-centred on the first timepoint using a log transform of a number close to 0 (0.0001) because the log of 0 is undefined. LCGA models with two, three and four latent classes were conducted in MPlus (version 6.12), with parameter estimates from each model used as the starting values for the subsequent model with one additional class. The number of classes tested corresponded to prior literature examining infant hand preference trajectories for object acquisition and one fewer class given our smaller sample size (Campbell et al., 2018; Michel et al., 2014). Receptive language (i.e., PLSAC scores) and expressive language (i.e., PLSEC scores) at 5 years were included in the model to assess differences between classes on these language outcomes. The means and variances of the PLSAC and PLSEC scores were allowed to vary across classes. Because SES is



**FIGURE 1** Latent class growth analysis model. Squares denote observed variables (HI scores), the circle represents the latent class variable (infant hand preference trajectories), and the rounded boxes are the distal outcome variables (5-year expressive language, measured as PLSEC standard score, and 5-year receptive language, measured as PLSAC standard score). The dashed line indicates the hypothesis that was tested: infant hand preference trajectories predict language at 5 years.



a well-established predictor of language outcomes (e.g., Fernald et al., 2013; Hoff, 2013; Schwab & Lew-Williams, 2016), maternal education and family income were examined in models along with child sex. Model fit was assessed using entropy, the Akaike information criterion (AIC), the Bayesian information criterion (BIC), the adjusted BIC (aBIC) and the Lo-Mendell-Rubin (LMR) likelihood ratio test according to best practices (Nylund et al., 2007; Tein et al., 2013). Missing data were addressed using full information maximum likelihood (FIML) estimation (Arbuckle, 1996). FIML allows for missing data to be estimated by using all available data in the dataset.

The proportion of variance accounted for by infant hand preference above and beyond SES was computed in R version 4.1.2 (R Core Team, 2022) using custom scripts appropriate for analysis in which FIML is used to handle missing data (Hayes, 2021). Conceptually, these analyses proceeded in three steps. In a first step, a reduced model with only mother's education level and family income as a set of SES predictors was run. In a second step, the full model including all three predictor variables (mother's education level, family income, hand preference trajectory classification) was run. In the third step, the difference in  $R^2$  values from the full and reduced models was calculated. In addition, we replicated the analyses from Gonzalez et al. (2020) to calculate the proportion of variance accounted for by toddler hand preference above and beyond SES. We then compared these values to the proportion of variance explained by infant hand preference in the current study.

### 3 | RESULTS

#### 3.1 | Infant hand preference at single timepoints was not reliably correlated with later language

Correlations between infant hand preference HI scores at 6, 7, 8, 9, 10, 11, 12, 13 and 14 months, and expressive and receptive language PLS standard scores at 5 years are given in Table 1 (computed using SPSS v. 27). A traditional approach of correlating hand preference measured at single timepoints to language revealed only two significant pairs. Small to medium associations were found between infant hand preference at 10 months and expressive and receptive language at 5 years. No other pairings between monthly infant hand preference and 5-year language were significant.

#### 3.2 | Infant hand preference was best characterized by three latent classes

The model with three latent classes was selected as the best model based on a comparison of statistical criteria across the models tested (i.e., entropy, AIC, aBIC, BIC, LMR fit indices; see Table 2) together with interpretability according to best practices (Weller et al., 2020). Entropy for the selected model was 0.871, suggesting excellent model classification. Classification percentages per class ranged from 0.97 to 0.90, meaning that the probability of correct classification of individuals was high (a value of 1.000 denotes perfect classification). Table 3 lists the number of infants in each class along with the class intercepts and slopes. The classes were labelled by interpreting the slope and intercept values. Positive intercept values indicate a right preference whereas negative intercept values indicate a left preference. Slope values for the Early Right and Left classes did not differ from zero, indicating that hand preference across the nine time points did not change in these classes. Slope for the Late Right class was significantly different from zero, indicating that hand preference across 6–14 months was changing in this class only. Figure 2 shows the three predicted latent class trajectories for acquisition hand preference from 6 to 14 months.

Most infants were classified in the *Late Right* class. Infants in this trajectory had mean HI scores of  $-0.06$  at 6 months and  $0.37$  at 14 months. A significant slope indicated that hand preference in this class changed over the nine time points. Therefore, the *Late Right* class was interpreted as inconsistent relative to the other two infant

**TABLE 1** Means, standard deviations and correlations between monthly HI scores and 5-year PLS-5 scores.

Variables	M	SD	1	2	3	4	5	6	7	8	9	10
1. 6 mo. HI	0.02	0.45	—									
2. 7 mo. HI	0.10	0.48	0.178	—								
3. 8 mo. HI	0.15	0.50	0.145	0.197	—							
4. 9 mo. HI	0.08	0.45	0.143	0.082	0.235*	—						
5. 10 mo. HI	0.20	0.46	-0.146	0.146	0.123	0.256*	—					
6. 11 mo. HI	0.22	0.46	-0.018	0.145	0.345**	0.333**	0.359**	—				
7. 12 mo. HI	0.24	0.45	0.065	0.193	0.288**	0.306**	0.278**	0.466**	—			
8. 13 mo. HI	0.24	0.46	0.066	0.137	0.319**	0.344**	0.204	0.464**	0.480**	—		
9. 14 mo. HI	0.19	0.40	0.044	0.171	0.380**	0.171	0.372**	0.363**	0.486**	0.630**	—	
10. 5 yr. PLSEC	104.36	15.36	0.154	0.161	-0.064	0.194	-0.357**	-0.194	-0.078	0.002	-0.175	—
11. 5 yr. PLSAC	103.63	13.11	0.205	-0.165	0.112	0.231	-0.296*	-0.096	-0.041	0.006	-0.139	0.859**

Note: Descriptive statistics.

Abbreviations: HI, handedness index score; M, mean; mo., months; PLS-5 = preschool language scales, 5th edition; PLSAC, preschool language scales auditory comprehension; PLSEC, preschool language scales expressive communication; SD, standard deviation; yr., years.

\* $p < 0.05$ ; \*\* $p < 0.001$ .

**TABLE 2** Latent class membership size, intercepts and slopes for the selected model.

Class	N (%)	Intercept	Slope
Early Right	20 (22.2%)	0.360*	0.019
Late Right	42 (46.7%)	0.283*	0.042*
Left	28 (31.0%)	-0.118*	-0.017

Note: \* $p < 0.05$ ; \*\* $p < 0.001$ .

**TABLE 3** Fit indices for latent growth curve analysis models tested with two, three and four classes.

No. of classes	Entropy	AIC	aBIC	BIC	$p$ LMR
2	0.875	2668.804	2640.585	2776.296	<0.001
3	0.871	2628.816	2586.159	2791.304	0.38
4	0.911	2615.685	2558.590	2833.169	0.56

Note: Model selection used fit indices alongside interpretability according to best practices in latent class analysis. Entropy ranges from 0 to 1, and higher values represent better classification of models. Lower AIC, BIC and aBIC represent better model fit relative to models being compared. The LMR compares the estimated model with the model having one fewer class than the estimated model. A  $p$ -value of  $< 0.05$  shows that the estimated model is better and that the model with one fewer class should be rejected.

Abbreviations: aBIC, adjusted BIC; AIC, Akaike information criterion; BIC, Bayesian information criterion; LMR, Lo–Mendell–Rubin adjusted likelihood ratio test.

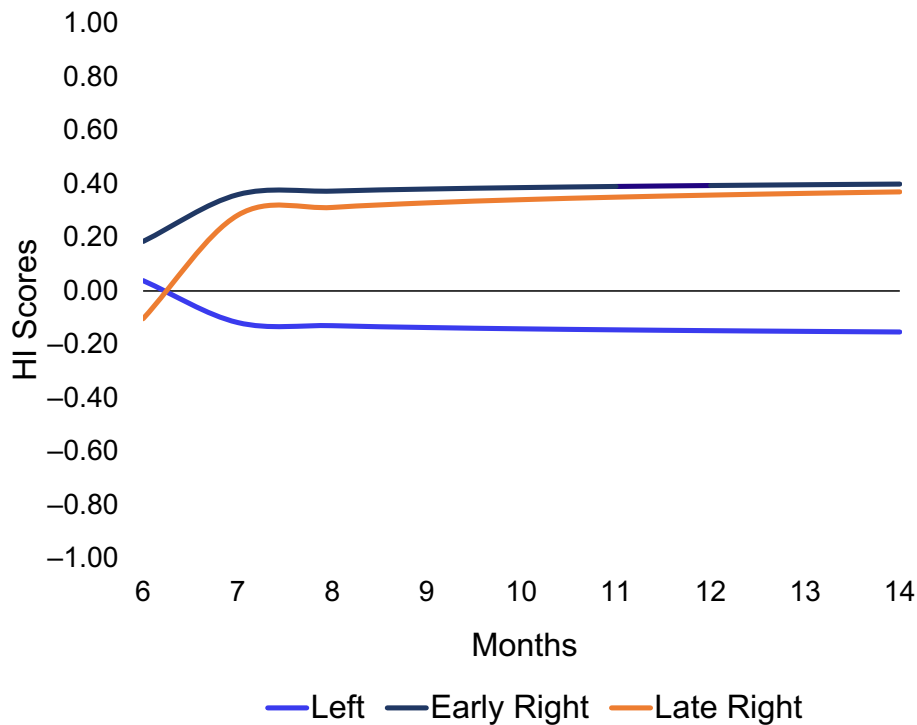
classes. The next highest percentage of infants in the sample were classified in the *Left* class. Infants in this trajectory had mean HI scores of 0.03 at 6 months and  $-0.19$  by 14 months. The third trajectory was infants in the *Early Right* class who had mean HI scores of 0.20 at 6 months and 0.32 at 14 months. Slopes for the *Left* and *Early Right* classes did not differ significantly from 0, indicating that hand preference for the infants in these classes did not change over the nine time points. Thus, *Left* and *Early Right* were consistent hand preference trajectories as compared to *Late Right*.

To ascertain the demographic composition of class membership,<sup>1</sup> the three latent classes for acquisition hand preference were tested for differences in sex, mother's education and family income level (for a discussion of this hard classify-analyse approach, see Bray et al., 2015). There was no significant difference in the number of boys versus girls between classes,  $X^2(2, N = 90) = 0.547, p > 0.05$ . There were also no significant differences in mother's education level across the three hand preference trajectories,  $F(2,87) = 2.06, p > 0.05$ . There was a significant difference in family income across classes,  $F(2,87) = 40.26, p < 0.001$ . Tukey's HSD post hoc test found that the *Late Right* class had a lower family income than the other two classes (*Left* 95% CI [0.59, 2.92],  $p < 0.01$ ; *Early Right* 95% CI [4.89, 6.18],  $p < 0.001$ ). Family income in the *Left* class was also significantly higher than the *Early Right* class (95% CI [-4.53, -1.73],  $p < 0.001$ ).

### 3.3 | Infant hand preference classes predicted receptive and expressive language at 5 years

The three latent classes for acquisition hand preference were then tested for differences in receptive language (i.e., PLSAC) and expressive language (i.e., PLSEC) scores at 5 years old. For the *Early Right* class, receptive

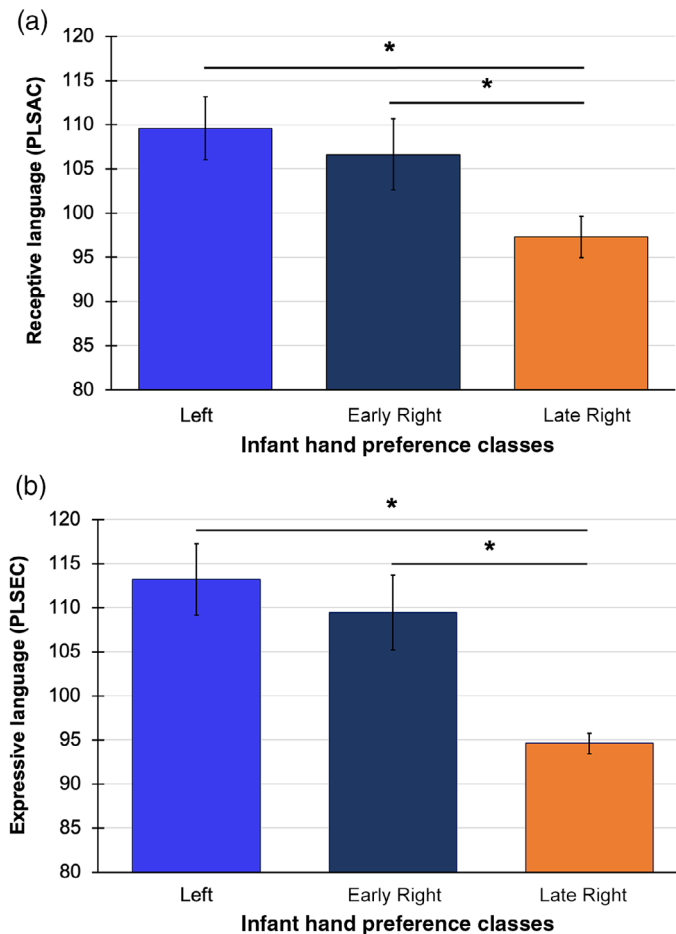
<sup>1</sup>Defined as the class with highest posterior probability of membership for each individual.



**FIGURE 2** Predicted latent class trajectories for infant acquisition hand preference from 6 to 14 months. HI = Handedness Index calculated with the formula  $HI = (R - L)/(R + L)$ , where R is the number of right-hand reach-to-grasp actions and L is the number of left-hand reach-to-grasp actions. Positive HI scores indicate a right preference and negative HI scores indicate a left preference. Early Right and Left represent consistent hand preference trajectories because the slopes for these two classes did not differ significantly from 0. Late Right is an inconsistent hand preference trajectory. The Late Right trajectory exhibited a significant positive slope, indicating that hand preference changed across the nine time points.

language scores ranged from 94 to 139 ( $M = 106.97 \pm 12.16$ ) and expressive language scores ranged from 94 to 132 ( $M = 109.35 \pm 13.03$ ). For the Late Right class, receptive language scores ranged from 69 to 112 ( $M = 97.12 \pm 10.91$ ) and expressive language scores ranged from 65 to 112 ( $M = 94.55 \pm 10.00$ ). For the Left class, receptive language scores ranged from 88 to 139 ( $M = 109.34 \pm 12.44$ ) and expressive language scores ranged from 81 to 144 ( $M = 113.04 \pm 15.34$ ). The means for receptive language scores and expressive language scores for all classes were in the normal range ( $100 \pm 15$ ). Significance did not change when receptive language scores and expressive language scores below the 10th percentile were excluded from analyses. Therefore, the following language results use the full sample.

Comparing classes on language outcomes with ANOVA revealed a significant effect of hand preference on receptive language,  $F(2,87) = 10.60$ ,  $p < 0.001$  (Figure 3a). Tukey's HSD post hoc test found significant differences in receptive language between the Late Right class and the Early Right class (95% CI [2.28, 17.42],  $p < 0.01$ ), and between the Late Right class and the Left class (95% CI [5.43, 19.02],  $p < 0.001$ ). The Early Right class and Left class did not differ from each other on receptive language (95% CI [5.79, 10.52],  $p > 0.05$ ). This model explained 21% of the total variance in receptive language scores at 5 years (13% hand preference and 7% SES; Table 3). There was also a significant effect of hand preference on expressive language,  $F(2,87) = 20.97$ ,  $p < 0.001$ , Figure 3b. Tukey's HSD post hoc test significant differences in expressive language between the Late Right class and the Early Right class (95% CI [6.67, 22.92],  $p < 0.001$ ), and between the Late Right class and the Left class (95% CI [11.20, 25.79],



**FIGURE 3** Comparison of language skills across the three infant hand preference classes. Panel (a) shows class differences for receptive language (PLSAC standard scores). Consistent hand preference classes (Left, Late Right) differed from the inconsistent hand preference class (Early Right). Consistent hand preferences did not differ from each other. Panel (b) shows class differences for expressive language (PLSEC standard scores). Consistent hand preference classes (Left, Late Right) differed from the inconsistent hand preference class (Early Right). Consistent hand preferences did not differ from each other. PLSAC = PLS Auditory Comprehension standard score. PLSEC = PLS Expressive Communication standard score. \* $p < 0.05$ .

$p < 0.001$ ). There was no difference in expressive language between the Early Right and the Left classes (95% CI  $[-5.06, 12.45]$ ,  $p > 0.05$ ). Turning to regression (path) analyses of these outcomes, class membership explained 33% of the total variance in expressive language at 5 years, controlling for income and maternal education (23% hand preference and 10% SES; Table 4).

### 3.4 | Infant hand use explained more language variance at 5 years than toddler hand use

Gonzalez et al. (2020) reported that toddler hand preference measured from 18 to 24 months from RDBM was best characterized by three latent classes, and these patterns predicted receptive and expressive language at 5 years.

**TABLE 4** Regression coefficients, standard errors and 95% CI for those coefficients, and *p*-values for the full models examining the variance explained in receptive and expressive language at 5 years of age by infant hand preference classes above and beyond SES covariates.

Variable	Estimate	SE	95% CI	<i>p</i>
Receptive language full model				
Maternal education	2.182	1.548	(−0.852, 5.216)	0.16
Family income	0.215	0.0837	(−1.426, 1.856)	0.80
Early Right class	6.519	5.476	(−4.214, 17.252)	0.23
Left class	11.843	3.837	(4.322, 19.364)	<0.01**
		Total $R^2$		0.21
		$R^2$ with only covariates		0.07
		$R^2$ change		0.13
Expressive language full model				
Maternal education	2.138	1.647	(−1.090, 5.366)	0.19
Family income	0.198	0.875	(−1.517, 1.913)	0.82
Early Right class	12.178	5.798	(0.814, 23.542)	0.04*
Left class	18.195	4.112	(10.135, 26.254)	<0.001***
		Total $R^2$		0.33
		$R^2$ with only covariates		0.10
		$R^2$ change		0.23

Note: Estimates are unstandardized. The proportion of variance accounted for by infant hand preference classes above and beyond SES was computed in a three-step process (Hayes, 2021; see text for details).  $R^2$  change is the variance explained by infant hand preference classes controlling for overlapping variance from maternal education and family income.

Abbreviations: CI, confidence interval; SE, standard error.

\* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ .

Using data shared from this paper, we were able to replicate these authors' analyses and determine the proportion of variance explained by toddler hand preference classes for the first time and directly compare the results to our infant hand preference analyses in the same children. The models with toddler hand preference classes explained 14% of the total variance in receptive language at 5 years (7% hand preference; 7% SES; Table 5) and 20% of the variance in expressive language at 5 years, controlling for income and maternal education (7% hand preference; 14% SES; Table 5). Using guidelines from Cohen (1988) to interpret the proportion of variance-explained effect ( $R^2$ ) where 0.02 is small, 0.13 is medium and 0.26 is large, the effect of toddler hand preference was small for receptive and expressive language. By comparison, the effect of infant hand preference was medium for receptive language and approaching large for expressive language (Table 4). Therefore, infant hand preference predicted 5-year language with larger effect sizes, overall, particularly for expressive language ability, relative to toddler hand preference.

## 4 | DISCUSSION

The goals of the current study were threefold: (1) to identify the number of classes for infant acquisition hand preference (reach-to-grasp actions) over the period of 6–14 months, (2) to examine whether membership in these infant hand preference classes predict expressive and receptive language at 5 years of age and, if so, (3) to determine whether infant hand preference classes or toddler hand preference classes explain more variance in language outcomes. LCGA identified three acquisition hand preference classes: infants with a left-hand preference (Left), infants

**TABLE 5** Regression coefficients, standard errors and 95% CI for those coefficients, and *p*-values for the full models examining the variance explained in receptive and expressive language at 5 years of age by toddler hand preference classes above and beyond SES covariates.

Variable	Estimate	SE	95% CI	<i>p</i>
Receptive language full model				
Maternal education	0.735	1.594	(−2.389, 3.859)	0.65
Family income	0.913	0.657	(−0.375, 2.201)	0.17
Early Right class	6.389	4.034	(−2.518, 13.296)	0.11
Left class	−1.334	4.219	(−9.603, 6.935)	0.75
		Total $R^2$		0.14
		$R^2$ with only covariates		0.07
		$R^2$ change		0.07
Expressive language full model				
Maternal education	0.624	1.850	(−3.002, 4.250)	0.74
Family income	1.835	0.755	(0.355, 3.315)	0.02*
Early Right class	6.485	4.715	(−2.756, 13.296)	0.17
Left class	−2.850	4.953	(12.558, 6.935)	0.57
		Total $R^2$		0.20
		$R^2$ with only covariates		0.14
		$R^2$ change		0.07

Note: Estimates are unstandardized. The proportion of variance accounted for by toddler hand preference classes above and beyond SES was computed in a three-step process (Hayes, 2021; see text for details).  $R^2$  change is the variance explained by toddler hand preference classes controlling for overlapping variance from maternal education and family income.

\* $p < 0.05$ ; \*\* $p < 0.01$ ; \*\*\* $p < 0.001$ .

Abbreviations: CI, confidence interval; SE, standard error.

with an early right-hand preference (Early Right) and infants who manifested a later right preference (Late Right). Hand preference classes were further classified into two groups: consistent (Left and Early Right) and inconsistent (Late Right). Children in a consistent infant hand preference class for acquisition had higher receptive and expressive language scores at 5 years of age as compared to children in an inconsistent infant acquisition hand preference class. Children in the two consistent hand preference trajectories did not differ from each other in language ability. Infant hand preference explained variance in language outcome above and beyond that of SES predictors (i.e., family income and mother's education level). Moreover, infant hand preference was a better predictor of 5-year language ability than toddler hand preference.

#### 4.1 | Infant hand preference for reaching is characterized by multiple trajectories

Our findings confirmed a three-class solution for acquisition hand preference trajectories in infancy from 6 to 14 months reported in prior research (Michel et al., 2014). The largest proportion of infants in both the current study and Michel et al. (2014) were those in the late/trending right category, followed by smaller numbers of infants with an identifiable left or early right preference. However, the current study and Michel et al. (2014) differed from Campbell et al. (2018), who reported a four-class solution for infant reaching hand preference trajectories across the same developmental period. The study by Campbell and colleagues had the largest sample size of the three studies, which may explain why a fourth class—infants with no hand preference for acquiring objects—was able to be detected.

Proportionally, the no preference group reflects a split from the late/trending right trajectories. In the current study, a four-class solution was examined but was not the best model based on statistical criteria and interpretability. How language outcomes align with an early developmental period of no hand preference for a subset of infants relative to other hand preference trajectories remains an open question. Our results extend the prior studies that have used trajectories to characterize infant hand preference for acquiring objects by using the differences in infant hand use patterning to predict a motor-language cascade for the first time. Practically, what this finding means is that researchers measuring early hand use should account for multiple patterns in the structure of their data and adjust their design/analyses accordingly.

#### 4.2 | Hand preference does not reliably predict language when single time points are correlated

In the current study, using traditional correlational methods between monthly infant hand preference (HI scores) and later language (PLSAC and PLSEC scores) did not yield a robust pattern. Infant hand preference was correlated with receptive and expressive language at 10 months only. While using correlations provided weak support for our hypothesis that infant hand preference would predict 5-year language, these results align with prior research. When hand preference has not been systematically parsed into trajectory patterns, findings linking hand preference and language have been mixed (Bates et al., 1986; Cochet et al., 2011; Esseily et al., 2011; Nicoladis & Barbosa, 2021; Ramsay, 1980, 1984, 1985; Vauclair & Cochet, 2013; Vauclair & Imbault, 2009). To draw from a recent publication relative to the current study, Nicoladis and Barbosa (2021) did not find correlations between hand preference measured at 9 months and language measured at 9, 12 or 18 months. Similarly, the current study found no link between 9-month hand preference and language at 5 years. Gonzalez et al. (2020) also found that few individual time points from toddlers' hand preference trajectories were related to language at 5 years. These findings are perhaps not surprising when as many as 45% of infants may be misclassified when hand preference is based on an assessment at 1 month versus a trajectory (Michel et al., 2014). We encourage investigators interested in links between hand preference and language across development to utilize a trajectory approach to capture hand preference because hand preference measured at individual time points does not reliably predict language.

#### 4.3 | Consistent hand preference trajectories reliably predict distal language outcomes

Children with a consistent hand preference trajectory for acquiring objects as infants, regardless of the direction of that preference, had significantly higher expressive and receptive language scores than children with an inconsistent hand preference trajectory. These results confirm the findings from Nelson et al. (2014) who reported that children with a consistent hand preference as infants had greater language achievement at 2 years of age relative to children who exhibited an inconsistent infant hand preference during infancy. Findings also support the general pattern linking consistent toddler hand preference trajectories to 3-year and 5-year expressive and receptive language as reported by Nelson et al. (2017) and Gonzalez et al. (2020). A difference between the current study and the prior work examining toddler hand preference trajectories is the way in which trajectory consistency was defined. For infants, consistency was characterized by class slopes, which yielded two consistent patterns and one inconsistent (i.e., significant change over time) pattern. For prior work examining children as toddlers, all trajectories were stable, but the classes were able to be differentiated by the amount of use of the preferred hand. Consistency may mean different things at different times (i.e., infancy versus toddlerhood) and/or how hand preference was measured (i.e., reach-to-grasp versus RDBM). We encourage researchers to consider factoring hand preference consistency into their design/analyses. Categorizing hand preference trajectories as consistent or inconsistent offers meaningful insights into language and other developmental outcomes (Gottfried & Bathurst, 1983; Kee et al., 1987; Kee et al., 1991; Nelson et al., 2014; Nelson et al., 2017; Wilbourn et al., 2011).



#### 4.4 | Infant hand preference is a better predictor of later language than toddler hand preference

To strengthen what our findings add to the literature, we additionally compared our results to the prior study by Gonzalez et al. (2020) that used hand preference trajectories from a different time period (i.e., 18 to 24 months) in the same longitudinal sample to predict language at 5 years. While both studies found that children with consistent hand preference outperformed children with an inconsistent hand preference on receptive language, only the current study reported the same effect for expressive language. Gonzalez et al. (2020) found that children in the consistent hand preference trajectory for RDBM differed from children with an inconsistent left preference, but not an inconsistent right preference. This difference may in part be explained by our new analyses on proportion of variance explained in our outcomes. Toddler hand preference only explained a small amount of variance for expressive language. The effect of infant hand preference on expressive language was more than three times that of toddler hand preference (23% vs. 7%).

The effect of SES on language was small as expected, with the exception of a medium effect of SES on expressive language in the toddler model. This finding is consistent with a recent study that also examined a novel predictor of language outcomes and reported a small effect of SES as measured by maternal education (Edgar et al., 2022). By comparison, we found a medium effect for infant hand preference class on receptive language. In the model for infant hand preference on expressive language, the effect was approaching large size. Thus, infant hand preference classes were a better predictor of 5-year language outcomes above and beyond SES. While additional work is needed to further compare the utility of hand preference as a predictor for later language at more time points, infant hand preference class appears to be the stronger predictor relative to toddler hand preference class. This finding suggests that future work should target the infancy period to directly test potential mechanisms for motor-language cascades. This dataset cannot address why the link exists between hand preference trajectories and later language, only that this finding is robust when we look at different time points and different ways children use their hands. Unfortunately, we did not collect any language data at the infant visits.

#### 4.5 | Limitations and future directions

In our view, the primary limitation of this work is that we did not measure caregiver language input, and this information is needed to disentangle the mechanism underlying hand preference and language cascades. In this study, parents were told explicitly not to engage with their infant during testing. While this approach is consistent with other laboratory-based developmental projects, we are limited in our interpretations because we do not know if parents change how they label objects depending on what their child is doing their hands. Parental language input has been shown to be related to children's language ability and academic outcomes (Reynolds et al., 2019), and accumulating evidence suggests that the way infants interact with objects changes their language learning environment (Herzberg et al., 2022; Iverson, 2021; Karasik et al., 2011; Schneider et al., 2023; Swirbul et al., 2022; Tamis-LeMonda et al., 2008; West et al., 2022; West & Iverson, 2017; Yu & Smith, 2012). During infant play, caregivers are more likely to label an object (noun), or the action of an object (verb), when the infant is actively interacting with/or holding an object (Custode & Tamis-LeMonda, 2020; West et al., 2022). Furthermore, objects manipulated by infants and/or labelled by the mothers are more likely to appear in infants' vocabularies and spontaneous speech patterns when compared to objects that were not manipulated by infants or labelled by the mother during play (Suarez-Rivera et al., 2022). These findings suggest that infants' early motor experiences provide essential social cues for object labelling opportunities and influence later word learning. It is possible that children in the consistent hand preference trajectories may manipulate objects differently than their inconsistent counterparts and in turn, elicit different caregiver object labels or language input linked to hand use during caregiver–infant interactions. This hypothesis could be directly tested in future work.

Infants' manual and oral object exploration ability may also provide further insight into the mechanisms that link hand preference and language outcomes (Malachowski & Needham, 2022). Muentener et al. (2018) found that infants who were more efficient at exploring objects had larger vocabularies as toddlers and higher verbal comprehension scores at 3 years of age. Infants who engaged in more oral and manual exploration from 6 to 9 months also had significantly greater language and cognitive performance scores at 24 months (Zuccarini et al., 2017). Object manipulation and vocal behaviours are seemingly tied in development; vocalizations directed to objects and caregivers tend to co-occur with mouthing and fingering (Orr, 2022). Moreover, trajectories of manual and oral exploration may differ across SES level. A study by Clearfield et al. (2014) found that low-SES infants demonstrate reduced overall levels of object exploration relative to high-SES infants. Furthermore, the transition to more advanced object exploration skills may be more difficult for low-SES infants than high-SES infants (Tacke et al., 2015). Whether infants' object exploration ability is linked to hand preference class membership is unknown. We hope to address connections between hand use/object exploration, language and SES in our future work.

## 5 | CONCLUSION

Overall, the current study reinforces that early consistency in hand preference is important for later advances in language ability. Children with consistent hand preference trajectories as infants for acquiring objects were found to have higher expressive and receptive language skills at 5 years old than children with inconsistent hand preference trajectories. Note that those children with inconsistent hand preference trajectories did not have poor language skills at 5 years of age; rather, those with consistent hand preference trajectories were somewhat more advanced in their language skills. While future research must disentangle the mechanisms underlying this motor-language cascade, infant manual skills, measured here as object acquisition hand preference trajectories, contribute in part to the development of children's language ability. Because we found infant hand preference explains a greater proportion of variance in language outcomes than toddler hand preference, we suggest researchers interested in mechanistic explanations for why hand preference is developmentally tied to language should target infancy for further study.

### AUTHOR CONTRIBUTIONS

**Kaityn Contino:** Conceptualization; data curation; formal analysis; writing – original draft; writing – review and editing. **Julie M. Campbell:** Data curation; investigation; writing – review and editing. **Emily C. Marcinowski:** Data curation; investigation; writing – review and editing. **George F. Michel:** Funding acquisition; supervision; writing – review and editing. **Michelle L. Ramos:** Formal analysis; writing – review and editing. **Stefany Coxo:** Formal analysis; writing – review and editing. **Timothy Hayes:** Formal analysis; writing – review and editing. **Eliza L. Nelson:** Conceptualization; data curation; funding acquisition; supervision; writing – original draft; writing – review and editing.

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### CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

### PEER REVIEW

The peer review history for this article is available at <https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/icd.2468>.

## DATA AVAILABILITY STATEMENT

Data that support the findings of this study are available on OSF, Infant Hand Preference Predicts 5-yr Language: <https://osf.io/v7r9g/>.

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