Preschool Language Ability Is Predicted by Toddler Hand Preference Trajectories

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Prior work has found links between consistency in toddler handedness for the fine motor skill role-differentiated bimanual manipulation (RDBM), and language development at 2 and 3 years of age. The current study investigated whether consistency in handedness from 18 to 24 months ($N = 90$) for RDBM predicts receptive and expressive language abilities assessed using the Preschool Language Scales 5th edition (PLS-5) at 5 years old. Latent class growth analyses identified 3 stable RDBM hand preference trajectories: a left hand preference with moderate right hand use (left–moderate right), a right hand preference with moderate left hand use (right–moderate left), and a right hand preference with only mild left hand use (right–mild left). At 5 years of age, children with a right–mild left handedness trajectory as toddlers scored significantly higher on receptive and expressive language abilities compared to children with a left–moderate right hand preference. Children with a right–mild left hand preference for RDBM also scored significantly higher on receptive language abilities compared to children with a right–moderate left RDBM hand preference. Children with left–moderate right and children with a right–moderate left hand preference for RDBM as toddlers did not differ in receptive or expressive language abilities at 5 years. Results indicate that individual differences in hand preference consistency for fine motor skill in toddlerhood have cascading effects on language outcomes into the preschool years.

Keywords: handedness, language, motor, preschool, toddlers

Motor development in early infancy and toddlerhood is central to children's learning and exploration (Campos et al., 2000; Gibson, 1988). It is through active interactions with their environments, objects, and other people that children acquire knowledge about the world around them. Research indicates that changes in motor skills can dramatically alter infant perception and abilities. Infants must relearn how to explore in a new body and posture

after changes in motor skill, which may afford different possibilities for manual exploration (Adolph, Eppler, & Gibson, 1993; Soska, Adolph, & Johnson, 2010; Tamis-LeMonda et al., 2008). Critically, changes in the motor domain may result in cascading changes in other domains such as spatial, social, and language skills (Choi, Leech, Tager-Flusberg, & Nelson, 2018; Libertus & Needham, 2011; Soska et al., 2010; Walle & Campos, 2014). Recent work highlights the role of motor development in language skill, with both gross and fine motor skills predicting children's language abilities across early childhood (for a review, see Gonzalez, Alvarez, & Nelson, 2019). In particular, fine motor skills have been recently associated with school readiness, as children with more advanced fine motor skills early in development demonstrate advantages in school outcomes such as reading, math, and science (Dinehart & Manfra, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). Specifically, because school readiness involves literacy, which is linked to early language development, it is important to further investigate the role of individual differences in fine motor skills on later language outcomes (NICHD Early Child Care Research Network, 2005). A common but underutilized individual difference in early development is handedness during fine motor tasks. Thus, the current study focuses on individual differences in toddler hand preference for role differentiated bi-

manual manipulation (RDBM), a sophisticated fine motor ability where the hands work together but asymmetrically during object manipulation. Here we investigate how these individual differences in hand use for RDBM may relate to language abilities at 5 years of age when most children in the United States are preparing to enter kindergarten.

The Cascade Theory of Handedness and Developmental Cascades

About 85% of human adults are right-handed (Annett, 2002). This striking bias has been studied at length, with much discussion concerning how handedness develops (Coryell & Michel, 1978; Gesell & Ames, 1947; McManus et al., 1988). Michel and colleagues have proposed that handedness develops throughout infancy from the cascading and multiplicative effects of continuous individual–environment interactions (Michel, Nelson, Babik, Campbell, & Marcinowski, 2013; Michel, Sheu, & Brumley, 2002). Using the cascade theory of handedness as a framework, an early bias in neonatal head orientation likely contributes to differential visual attention to one hand over the other, which in turn leads to more haptic stimulation of the observed hand, and subsequently greater use of the observed hand for reaching (Coryell & Michel, 1978; Michel, 1981; Michel & Harkins, 1986). Increased use of one hand for reaching then develops into continued use of the same hand for acquiring objects, which then concatenates toward a hand preference for object manipulation (Campbell, Marcinowski, Babik, & Michel, 2015). Over time, a hand preference for object manipulation leads into a hand preference for role-differentiated bimanual manipulation (RDBM), a fine motor skill where both hands are used together asymmetrically to manipulate an object (e.g., unscrewing a lid from a jar; Babik & Michel, 2016; Nelson, Campbell, & Michel, 2013).

Recent work within the framework of the cascade theory of handedness finds that while most infants and toddlers will exhibit reaching and manipulation skills in a similar order, individual differences in hand preference over time are notable when measuring hand preference longitudinally at monthly intervals (Michel, Babik, Sheu, & Campbell, 2014; Nelson et al., 2017). Largely, it is the use of robust hand preference measures within longitudinal methods that best illustrates the cascade theory of handedness: multiple measurements over time help demonstrate both similarities and individual differences in patterning and growth in hand use that, in turn, concatenate toward divergent hand preferences (Campbell, Marcinowski, Latta, & Michel, 2015; Gonzalez & Nelson, 2015).

The concept of cascades is not unique to handedness. Individual differences in motor skill are also considered important for changes across skills in other "nonmotor" domains. Recent work finds that individual differences in fine motor skills are closely tied to changes in cognitive and social skills, with motor skills predicting differences in attention to social events and spatial abilities (Libertus & Needham, 2011; Sommerville, Woodward, & Needham, 2005; Soska et al., 2010). For example, fine motor skills such as manual exploration are important for 3D object completion (Soska et al., 2010). Specifically, research has identified links between fine motor skills and language development, further highlighting cascades across development. Recent work by Choi and colleagues (2018) found that greater fine motor skill at 6 months

was predictive of language skills at 36 months. In older children, Dinehart and Manfra (2013) found that both fine motor writing and object manipulation in preschool were predictive of second grade reading scores on standardized tests. In general, these cross domain cascades provide new insight on how changes in one area of development can spread into other seemingly (according to functional classification but perhaps not according to mechanism) unrelated skills (Masten & Cicchetti, 2010; Thelen & Smith, 2006).

Handedness can provide a behavioral marker of individual differences in fine motor skill, although it has been underutilized in the developmental literature. Importantly, research focused on handedness during fine motor performance richly illustrates how individual differences in a motor skill change over time (e.g., Michel et al., 2014). Recent research utilizing growth modeling finds that individual differences in fine motor growth across 6 to 24 months can predict atypical development, with children with slower growth in fine motor skills more likely to receive an autism spectrum diagnosis at 3 years (Choi et al., 2018). Using typically developing samples, recent work in the area of handedness has also employed the use of growth modeling, and has generated distinct classes of hand preference for fine motor skills such as grasping, unimanual manipulation, and RDBM (Campbell, Marcinowski, Babik et al., 2015; Michel et al., 2013; Nelson et al., 2017). Focusing on handedness can provide researchers interested in fine motor development with a new measure of individual differences early in motor development, as consistency in handedness is detectable in some infants from 6 months of age (Campbell, Marcinowski, Babik et al., 2015; McCormick & Maurer, 1988; Michel et al., 2013, 2014; Nelson et al., 2013).

Handedness and Language

A consistent bias for hand use during fine motor actions (i.e., greater and more frequent use of one hand) has been linked to language outcomes across infancy and childhood (Kee, Gottfried, & Bathurst, 1991; Nelson, Campbell, & Michel, 2014; Nelson et al., 2017; Wilbourn, Gottfried, & Kee, 2011). Research based on the Fullerton Longitudinal Study (FLS) examined the relation between hand preference and cognitive development longitudinally in children across 18 months to 17 years old (Gottfried & Bathurst, 1983; Kee et al., 1991; Kee, Gottfried, Bathurst, & Brown, 1987; Wilbourn et al., 2011). Hand preference was determined as the hand used during a drawing task, with children who used the same hand across all five time points at 18, 24, 30, 36, and 42 months subsequently classified as consistent in their hand preference, and children who did not use the same hand for drawing across all assessments classified as inconsistent in their hand preference (Gottfried & Bathurst, 1983). Verbal intelligence and reading achievement was then measured in middle childhood between 5 to 9 years of age (Kee et al., 1991). Consistent hand preference from 18 to 42 months was associated with significantly higher scores on assessments of verbal intelligence and reading achievement compared to an inconsistent hand preference. In an additional follow up of the FLS sample into adolescence, Wilbourn and colleagues (2011) found that having a consistent hand preference from 18 to 42 months was linked to significantly higher scores on verbal intelligence and reading achievement measures at

12, 15, and 17 years old compared to when inconsistent hand preferences were observed.

Recent research also demonstrates that consistency in hand preference early in development is linked to language skills (Nelson et al., 2014, 2017). Nelson and colleagues (2014) measured unimanual hand preference at monthly intervals from 6 to 14 months, and measured hand preference for RDBM monthly from 18 to 24 months. Children were then classified into one of three types of hand use trajectories. One group of children demonstrated an early right hand preference for both unimanual and RDBM skills. A second group of children showed a late right hand preference where they exhibited no hand preference as infants, but a right hand preference as toddlers. A third group of children demonstrated a late left hand preference, where they had no hand preference as infants but a left hand preference as toddlers for RDBM. Importantly, when language was measured at 24 months, children's hand preference trajectory mattered for their language outcomes. Children with an early right hand preference across infancy and toddlerhood scored higher on the language scale of the Bayley Scales of Infant and Toddler Development, third edition (Bayley-III; Bayley, 2006) compared to children with late right or late left trajectories (Nelson et al., 2014).

Building on these prior findings, Nelson and colleagues tested whether differences in hand preference trajectories from 18 to 24 months were linked to language outcomes at 3 years utilizing latent class growth analysis (LCGA), which permits tracking of individual differences in growth over time, while grouping children with similar trajectories together. Results indicated that from 18 to 24 months, toddlers demonstrated three types of hand preference trajectories: right–mild left (largely right hand use with little left hand use), right–moderate left (mostly right hand use with some left hand use), and left–moderate right (mostly left hand use with some right hand use). Overall, children's hand preference did not significantly change over the 6-month study, indicating that hand preference was stable from 18 months to 24 months. Again, hand preference trajectory was linked to language skill, now at age 3. Specifically, children who demonstrated a right–mild left preference scored significantly higher on receptive language skills at 3 years of age as measured by the Preschool Language Scales, 5th edition (PLS-5; Zimmerman, Steiner, & Pond, 2011) compared to children who had a right–moderate left preference. Moreover, children in the right–mild left trajectory also scored higher on expressive language skills in comparison to children in the right-moderate left and the left–moderate right trajectories (Nelson et al., 2017). Importantly, it was only via the use of powerful longitudinal statistical measures like LCGA that Nelson and colleagues (2017) were able to identify these differences in hand use across toddlers, as results utilizing a traditional correlation approach between hand preference at individual time points from 18 to 24 months and language at 3 years old did not demonstrate the same pattern.

Research on the links between hand preference and language has a long and rich history (e.g., Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; Cochet, Jover, & Vauclair, 2011; Esseily, Jacquet, & Fagard, 2011; Ramsay, 1984; Vauclair & Imbault, 2009). However, much of this previous work implemented cross-sectional methods or examined only a small number of developmental time points, yielding mixed results regarding consistency and long term cascades. For example, Esseily and colleagues (2011) measured hand preference and language at the single time point of 14 months. Focusing on a single time point limited further understanding regarding hand use over time and language. Cochet and colleagues (2011) observed hand use over a 5-month period, but did not employ adequate longitudinal analyses to decipher patterning in hand use over time, and found no relation between hand use for object manipulation and language at individual time points. Importantly, focus on monthly fluctuations in hand use rather than patterning over time in prior handedness work has resulted in the framing of handedness as a trait rather than a developmental phenomenon. In contrast, studies from the FLS sample and recent work by Nelson and colleagues (2014, 2017) have implemented longitudinal methods with multiple time points measuring hand preference, which allow for further research on consistency in handedness rather than only directionality, while also focusing on predicting distal language outcomes and not just concurrent changes. Moreover, trajectory-based methods help shift research on handedness away from a trait framework toward a developmental framework.

Overall, if individual differences in hand preference in early development can help predict later language outcomes, it is important for researchers to continue to test the length of these cascades, and what they may mean during periods of developmental transitions (Masten & Cicchetti, 2010; Thelen & Smith, 2006). Not all cascades may be long term (e.g., Oudgenoeg-Paz, Volman, & Leseman, 2016), thus testing the length of developmental cascades is critical for establishing and modifying existing theories of development regarding the importance of individual differences, and whether their earlier impact on outcomes continues to have reverberating effects. In particular, how early consistency in hand preference during toddlerhood relates to language outcomes during the transition to the preschool years merits further investigation. Language development is foundational for skills related to academic achievement such as reading (e.g., Dickinson, Golinkoff, & Hirsh-Pasek, 2010). Moreover, motor skills are also linked to academic achievement, with fine motor skills in particular linked to reading (e.g., Cameron et al., 2012; Carlson, Rowe, & Curby, 2013; Dinehart & Manfra, 2013; Grissmer et al., 2010). Testing whether hand preference relates to language during early childhood could provide researchers with a novel indicator of language outcomes prior to school entry.

Current Study

The current study investigated the longevity of the relation between handedness trajectories on language skills using LCGA methods. Here we investigated how handedness relates to language outcomes at 5 years, when children are beginning more formal education in preschool as they prepare to enter kindergarten. Understanding how laterality in fine motor skills is linked to language abilities at school entry will provide further insight on how motor behaviors relate to individual differences in child development. Utilizing the original sample from Nelson and colleagues (2017), hand preference for RDBM was measured at monthly intervals from 18 to 24 months, and receptive and expressive language skills were measured at 5 years of age. Based on the prior study using LCGA, we hypothesized that hand preference across 18 to 24 months would be stable in growth, with infants demonstrating individual differences in hand use. Specifically, we

predicted three latent classes for toddler hand preference based on prior studies (Michel et al., 2014; Nelson et al., 2017). We hypothesized that hand preference trajectory would continue to be related to language skills at 5 years, and we predicted that any language differences between classes would favor children with a consistent hand preference.

Additionally, the current study also conducted more traditional cross-sectional correlational analyses used in prior research on hand preference and language (e.g., Cochet and colleagues, 2011; Esseily et al., 2011). We predicted that some, but not all correlations of hand preference at single time points would correlate with language outcomes at 5 years, while LCGA would identify more robust and consistent relations over time. By analyzing the present data using both LCGA and more traditional methods, we seek to clarify the mixed findings reported by prior traditional correlational approaches on the role of hand preference in language outcomes, and will highlight that an analytical approach focused on trajectory of hand use over time is a more powerful strategy for predicting later outcomes consistently compared to analyses that use a single time point when measuring hand preference.

Method

Participants

The current study included 90 children (44 girls). Families were recruited via Guilford County public birth records from a midsized metropolitan city in the Southeastern United States (Greensboro, North Carolina). Children who participated in the study had no major complications at birth following full-term pregnancy of at least 37 weeks gestation. The racial and ethnic distribution of the sample based on parent report is as follows: 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 level was also reported, with incomes ranging from $10,000–$19,000 to $150,000 or more. Median income level was $60,000–$69,000. Eighteen families did not report income level. Mother's education level ranged from a high school diploma or GED equivalent to a professional degree, with a bachelor's degree being the median mother's education level. Seventeen families did not report mother's education level. Father's education level ranged from 1 or more years of high school/no degree to a doctorate degree, with a bachelor's degree being the median father's education level. Nineteen families did not report father's education level.

A total of 79 children had complete RDBM hand preference data across the seven time points from 18 to 24 months, with 10 children missing data at one RDBM time point, and one child missing data at two RDBM time points. All 90 children were included in the reported analyses on hand preference. At 5 years old, 64 children (27 girls) returned for testing on the PLS-5.

Procedure

The following procedures were approved by the University of North Carolina at 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 toddler assessment at 18 months, and again at the 5-year follow-up visit. Compensation for study participation included a $10 gift card for each lab visit. Children received an additional small toy at the 5-year visit. Hand preference for RDBM was measured in lab at monthly intervals from 18 to 24 months. Each hand preference assessment was conducted within ±7 days of the child's monthly birthday. Language development was measured in lab using the PLS-5 at 5 years of age ($M = 60.20$ months, $SD = ±1.12$, range = 58–63 months). Data were used in secondary analyses under approval from the Florida International University Institutional Review Board (project title: "PLS"; research protocol number: IRB 13–0288).

Measures

RDBM hand preference. Hand preference for RDBM was assessed using the RDBM test battery established by Nelson et al., 2013. Twenty-nine objects that afford actions where one hand stabilizes the object (nonpreferred hand) while the other hand manipulates the object (preferred hand), were presented individually at the child's midline while they sat on their parent's lap. Possible RDBM actions afforded by the objects included removing a lid, unzipping a bag, removing a toy from inside another toy, unlatching a container, and peeling a sticker from its backing. The RDBM test battery took about 10 min to complete.

Children were video recorded during the RDBM assessment. Video data were scored offline by trained observers using the Observer XT software program (Noldus Information Technology, v.10.5). The hand that successfully performed the target RDBM action based on the object's affordance was scored as the preferred hand. Twenty percent of the data (124 videos) were independently coded by two observers to determine interrater reliability (i.e., percent agreement between two coders for each object presentation). Interrater reliability for RDBM hand preference was 96%. Disagreements were resolved through discussion.

Preschool Language Scales-5 (PLS-5). The PLS-5 was administered at the 5-year visit. The PLS-5 is a standardized measure of language skills for use with children from birth to 7 years 11 months. The PLS-5 includes two standardized scales: Auditory Comprehension (PLSAC) and Expressive Communication (PLSEC), and also provides a Total Communication score. Broadly, the PLSAC and PLSEC subscales assess various areas of language development including vocal development, social communication, semantics, language structure, and emerging literacy skills. Scores on the PLS-5 are normed at 100 with a standard deviation of 15. It is sensitive to even mild language difficulties, and is reliable with reported interrater reliability between .95 to .98 and test–retest reliability ranging from .86 to .95 (Zimmerman et al., 2011). The PLS-5 is widely used, and was recently noted as one of four other existing language assessments for use with children 4 years and older with the best evidence of reliability and validity (Denman et al., 2017). Administration of the PLS-5 lasted approximately 1 to 2 hr depending on the individual child. The PLSAC and PLSEC scores were used in the following analyses.

Statistical Analysis

A Handedness Index (HI) was calculated for each child at each monthly visit from 18 to 24 months. The HI formula is as follows:

HI = (R − L)/(R + L), where R is the number of RDBM actions produced with the right hand and L is the number of RDBM actions produced with the left hand. The HI formula provides scores ranging from −1.00 (exclusively left hand RDBM actions) to 1.00 (exclusively right hand RDBM actions). Developmental trajectories for children's RDBM hand preference from 18 to 24 months were determined utilizing latent class growth analysis (LCGA, Jung & Wickrama, 2008). LCGA allows for estimation of individual growth over time, while also identifying homogenous subgroups of individuals with similar trajectories. LCGA has been successfully used in previous literature on both infant and toddler hand preference (e.g., Michel et al., 2014; Nelson et al., 2017).

LCGA models with two, three, and four latent classes were conducted, with parameter estimates from each model used as the starting values for the subsequent model with one additional class. Sex, paternal education, maternal education, family income, and PLSAC and PLSEC scores at 60 months were included in the model to assess differences between classes on these variables. PLSAC and PLSEC means and variances were allowed to vary across class. Model fit was assessed using Lo-Mendell-Rubin (LMR) likelihood ratio test, bootstrap likelihood ratio test (BLRT), and sample-size adjusted BIC (saBIC), according to best practices (Nylund, Asparouhov, & Muthén, 2007; Tein, Coxe, & Cham, 2013). Little's Completely at Random test (Little, 1988) indicated that missing data patterns were not dependent on existing data values ($p > .05$). Full information maximum likelihood estimation (FIML) was used to address missing data across variables and reduce bias (Enders & Bandalos, 2001).

Correlations between HI scores from 18 to 24 months and PLSAC and PLSEC scores at 60 months were also conducted to compare more traditional analyses of hand preference and language to LCGA. All analyses were conducted in MPlus (Version 6.12) with an alpha level of .05.

Results

Comparison of the LMR, BLRT and saBIC fit indices across models indicated that a model with three latent classes was the best fitting model. Entropy for the model was .976, suggesting excellent model classification. Classification percentages per class ranged from .977 to .999, meaning that the probability of correct classification of individuals was high (a value of 1.000 denotes perfect classification). Intercept values for all three classes were significant, indicating that all three classes demonstrate a hand preference significantly different from zero at 18 months. Slope values for all three classes were not significantly different from zero, indicating that hand preference across 18 to 24 months did not change for any of the three classes. Table 1 displays the values for class intercepts, slopes, and percentage of children in each class. Figure 1 displays the three latent class trajectories from 18 to 24 months.

The majority of the sample fit a right–mild left (R-Mild L) classification of hand use for RDBM. The average HI score for the R-Mild L class was about .79, indicating that this group predominantly used their right hand for RDBM, with little left hand use. The second largest portion of the sample fit a right–moderate left (R-Mod L) classification for RDBM hand use. Children in the R-Mod L class demonstrated a largely right-hand preference for RDBM with moderate left hand use, with an estimated mean HI of

Table 1

*Latent Class Membership Size, Intercepts, and Slopes for the Selected Model*

Class	N (%)	Intercept	Slope
L-Mod R	22 (24.4%)	−0.411***	0.006
R-Mod L	31 (34.4%)	0.417***	−0.009
R-Mild L	37 (41.1%)	0.791***	0.002

Note. 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.
*** $p < .001$.

.38. Finally, a third class of children was identified as having a left–moderate right (L-Mod R) preference for RDBM, with children in this class demonstrating largely a left hand preference for RDBM with moderate right hand use. Mean HI for the L-Mod R class was −.38. The three classes for hand preference did not differ in proportion of girls versus boys, $F(2, 87) = 0.18, p > .05$, mothers education, $F(2, 87) = 2.82, p > .05$, or father's education, $F(2, 87) = 2.15, p > .05$. There was a significant difference in income between classes, $F(2, 87) = 3.74, p = .03$. Tukey's HSD post hoc test found that the L-Mod R class had significantly lower income levels than the R-Mild L class (95% CI [−3.52, −0.05], $p = .04$) and the R-Mod R class (95% CI [−3.64, −0.05], $p = .04$). There was no significant difference in income between the R-Mild L and the R-Mod L classes (95% CI [−1.51, 1.63], $p > .05$).

The latent classes for RDBM hand preference were tested for differences in PLSAC and PLSEC language scores at 5 years old. For the R-Mild L class, PLSAC scores ranged from 76 to 139 ($M = 108.46, \pm 14.68$), and PLSEC scores ranged from 90 to 144 ($M = 109.50, \pm 17.59$). For the R-Mod L class, PLSAC scores ranged from 69 to 122 ($M = 100.90, \pm 11.76$), and PLSEC scores ranged from 65 to 122 ($M = 101.58, \pm 13.87$). For the L-Mod R class, PLSAC scores ranged from 80 to 114 ($M = 99.72, \pm 9.17$), and PLSEC scores ranged from 81 to 127 ($M = 98.95, \pm 12.03$). Note that the means for all three groups were within the normal range, and significance did not change when children with both PLSAC and PLSEC scores below the 10th percentile were excluded. Therefore, all of the following language results use the full sample. An analysis of variance comparing classes on language outcomes found significant differences between the three classes on PLSAC scores, $F(2, 87) = 4.55, p = .01, f = .32$. Tukey's HSD post hoc test found a significant difference in PLSAC scores between the R-Mild L class and the R-Mod L class (95% CI [−14.84, −0.28], $p = .04, f = .25$; Figure 2A), and between the R-Mild L class and the L-Mod R class (95% CI [−16.79, −0.70], $p = .03, f = .28$; Figure 2A). There was no significant difference between the R-Mod L class and the L-Mod R class (95% CI [−9.52, 7.15], $p > .05, f = .06$). Significant differences were also found between the three classes on PLSEC scores, $F(2, 87) = 4.05, p = .02, f = .31$. Based on Tukey's HSD post hoc test, a significant difference in PLSEC scores was found between the R-Mild L class and the L-Mod R class (95% CI [−20.28, −.83], $p = .03, f = .28$; Figure 2B). No significant difference in PLSEC scores was found between the R-Mild L and the R-Mod L classes
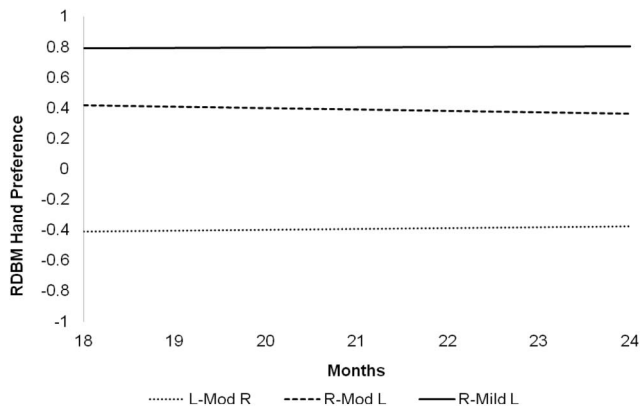
Figure 1. Predicted latent class trajectories for RDBM hand preference from 18 to 24 months. HI = Handedness Index; L-Mod R = Left hand preference with a moderate amount of right hand use; R-Mod L = Right hand preference with a moderate amount of left hand use; R-Mild L = Right hand preference with a mild amount of left hand use.

(95% CI $[-16.72, .87]$, $p > .05$, $f = .23$), or between R-Mod L and the L-Mod R classes (95% CI $[-12.70, 7.44]$, $p > .05$; $f = .07$).

For comparison with findings between the RDBM hand preference classes and language, correlations between RDBM hand preference HI scores at 18, 19, 20, 21, 22, 23, and 24 months, PLSAC, and PLSEC were conducted (see Table 2). In summary, HI scores at 19, 20, and 24 months were significantly positively correlated with PLSAC scores at 5 years. Additionally, HI scores at 19, 20, and 22 months were significantly positively correlated with PLSEC scores at 5 years. HI scores across 18 to 24 months were significantly positively correlated with each other (all $ps < .001$). Moreover, PLSAC and PLSEC scores at 5 years were significantly positively correlated ($p < .001$).

Discussion

Findings from the present study indicate that hand preference for RDBM across 18 to 24 months is related to both receptive and expressive language outcomes at 5 years old. Specifically, toddlers with consistent right hand use for RDBM (i.e., greater and more frequent use of the right hand based on HI score) had greater receptive language skills at 5 years compared to toddlers with a right hand preference but moderate left hand use, and compared to toddlers with a left hand preference but moderate right hand use. Moreover, toddlers with more consistent right hand use also demonstrated greater expressive language skills at 5 years compared to toddlers with a left hand preference but with moderate right hand use. An income difference between the left–moderate right and the two right preference groups was observed, however there was no negative effect on language outcome, with the mean language scores for all classes within normative range for the PLS-5. These results lend continued support to prior studies that demonstrate that consistency in hand preference serves an important role in language outcomes across toddlerhood and early childhood (Kee et al., 1991; Nelson et al., 2014, 2017).

Prior work on hand preference trajectories and language outcomes by Nelson and colleagues (2017) indicated that children with a right–mild left hand preference trajectory from 18 to 24

months were more likely to demonstrate higher receptive language at 3 years compared to children with a right–moderate left preference, and higher expressive language at 3 years compared to both right–moderate left and left–moderate right trajectories. Notably in the present study, the relations between consistency and language outcomes shifted from 3 to 5 years: both left–moderate right and right–moderate left groups demonstrate significantly lower receptive language scores compared to the right–mild left trajectory at 5 years. Based on previous LCGA based findings at 3 years, children in the left–moderate right group did demonstrate lower receptive language scores compared to the right–mild left group, however the difference was not significant (Nelson et al., 2017). It is possible that over time from 3 to 5 years the difference in receptive language between the two groups widened, leading to the significant difference seen in the current study. Regarding expressive language, a significant difference was found between the right–mild left and the left–moderate right trajectories at 5 years, which was also seen previously at 3 years (Nelson et al., 2017). However, the previous difference in expressive language at 3 years between the right–mild left and the right–moderate left trajectories was no
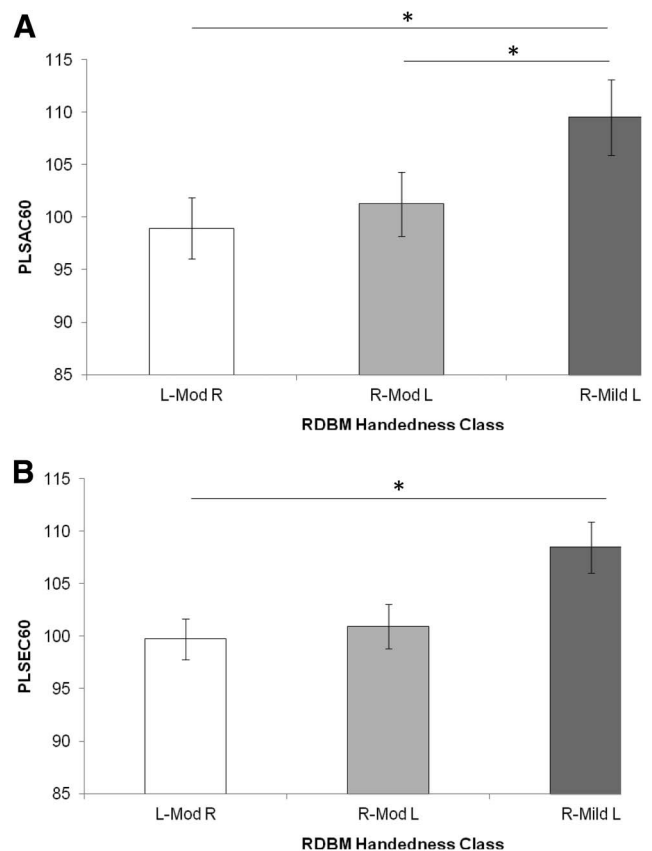
Figure 2. Comparison of receptive language skills (A) and expressive language skills (B) across RDBM hand preference trajectories. Error bars indicate standard error. L-Mod R = Left hand preference with a moderate amount of right hand use; R-Mod L = Right hand preference with a moderate amount of left hand use; R-Mild L = Right hand preference with a mild amount of left hand use. PLSAC60 = PLS Auditory Comprehension at 60 months. PLSEC60 = PLS Expressive Communication at 60 months. * $p < .05$.

Table 2
Correlations Between Monthly HI Scores and PLS-5 Scores at 60 Months

Variables	1	2	3	4	5	6	7	8	9
1. 18 mo. HI	—								
2. 19 mo. HI	.754***	—							
3. 20 mo. HI	.776***	.822***	—						
4. 21 mo. HI	.788***	.777***	.842***	—					
5. 22 mo. HI	.727***	.766***	.800***	.817***	—				
6. 23 mo. HI	.747***	.704***	.768***	.778***	.849***	—			
7. 24 mo. HI	.731***	.761***	.708***	.711***	.747***	.807***	—		
8. PLSAC60	.165	.238*	.248*	.112	.165	.165	.240*	—	
9. PLSEC60	.186	.250*	.255*	.131	.232*	.201	.212	.855***	—

Note. HI = Handedness Index; mo. = months; PLSAC60 = PLS Auditory Comprehension at 60 months; PLSEC60 = PLS Expressive Communication at 60 months.
* $p < .05.$ *** $p < .001.$

longer seen at 5 years. It is unclear why children in the right–moderate left trajectory would catch up the right–mild left group in expressive, but not receptive language, at 5 years. It may be that language comprehension begins to plays a different role in development at 5 years than it did at 3 years of age.

Specifically, cascading relations between domains such as motor and language are more likely to emerge during periods of fluctuation and change in the system (e.g., Masten & Cicchetti, 2010; Thelen & Smith, 2006). For our sample here at 5 years, children were just beginning or had already begun kindergarten, a period denoting an important shift in language use for formal education. It may be possible that the cascading effect of hand preference for RDBM on language outcomes at 5 years is more notable for auditory comprehension due to shifts in how children begin to use comprehension for new skills important for academic success such as reading. For example, during their first year of schooling, children are beginning to actively utilize their language comprehension skills toward early literacy and must coordinate their prior knowledge of what language concepts mean within a new skill. Early success in literacy is closely tied to children's language comprehension abilities in skills such as phonological awareness and receptive vocabulary (Friend, Smolak, Liu, Poulin-Dubois, & Zesiger, 2018; Scarborough, 2009; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004).

Comparably, right–mild left and the left-moderate right groups demonstrate differences in language skills at 5 years, with the left–moderate right trajectory scoring lower on both auditory comprehension and expressive communication. LCGA in the current sample did not reveal a left–mild right comparison group (likely a consequence of the rather small sample size of toddlers, see Michel, Babik, Nelson, Campbell, & Marcinowski, 2018). Thus we caution against claims that directionality is what underlies these differences in language skills, or that a left hand preference is indicative of delay. Rather, the results as a whole indicate that greater consistency in hand use for fine motor skills during toddlerhood is important for language in early childhood. The current findings are supported by prior FLS findings where consistent hand use from 18 to 42 months was predictive of higher verbal intelligence and reading achievement across 5 to 9 years of age, as well as from 10 to 17 years of age (Kee et al., 1991, 1987; Wilbourn et al., 2011).

As seen in prior work (Nelson et al., 2017), all three hand preference trajectory groups demonstrated distinct hand preferences at 18 months, and did not change over time from 18 to 24 months, indicating that hand preference for RDBM was stable throughout toddlerhood. Work on RDBM at younger ages finds that hand preference for RDBM begins to emerge between 9 to 14 months, with trajectories indicating increasing hand use by 14 months (Babik & Michel, 2016). Due to a gap in existing literature on RDBM from 15 to 17 months, it is unclear at what point during the second year of life RDBM hand preference stabilizes toward the trajectories seen in the present study (Gonzalez & Nelson, 2015). Although a right–mild left trajectory was identified, a comparable left–mild right trajectory was not. Previous work spanning 8 to 14 months does find that about 14% of infants demonstrate a left hand preference for unimanual reaching; thus it is possible to identify a left preference early on in development (Campbell, Marcinowski, Latta et al., 2015; Michel et al., 2014). However, the trajectory for left-handed individuals does not mirror that of right handers, as growth in hand use for reaching fluctuates at different time points for infants with a left preference compared to infants with a right preference (Michel et al., 2014). Moreover for RDBM, recent research finds that in a sample of 64 three-year-old children, about 7.8% demonstrated a left hand preference for RDBM, compared to about 76.6% of children with a right hand preference for RDBM, and about 15.6% with no preference for RDBM (Nelson, Gonzalez, El-Asmar, Ziade, & Abu-Rustum, 2019). Similarly, in a sample of 1,051 adults, the rate of left hand preference for RDBM was 4.1%, compared to 61.2% with a right hand preference for RDBM, and about 34.7% with no preference for RDBM (Gonzalez & Nelson, 2019). The low proportion of both children and adults with a left hand preference for RDBM further supports the possibility that a left hand preference for RDBM is likely expressed differently than a right hand preference, with the possibility that a left–mild right trajectory is rare or nonexistent. Overall, further work is required to understand how left hand preference develops in general, in addition to investigating how left handedness may relate to cognitive outcomes.

In contrast to some prior research on hand preference in early development, the current study utilized a large longitudinal sample with measures that robustly capture hand preference across multiple trials (Campbell, Marcinowski, Latta, et al., 2015; Gonzalez & Nelson, 2015). Employing these methods has allowed for essential work on handedness that finds that some children do demonstrate stability in hand preference in infancy and toddlerhood with little fluctuation in preference over time (e.g., Michel et

al., 2014). Continued work is needed to fully understand how hand preference develops and, in particular, why children demonstrate different patterns of hand use. Use of adequate methods to capture change over time are essential to answering these developmental questions (Adolph, Robinson, Young, & Gill-Alvarez, 2008), as the use of cross-sectional methods or single time point analyses even with longitudinal data may not uncover the nuances based on individual differences, as revealed in the correlational analyses conducted for the current study for comparison to LCGA results. While some correlations were significant between single month time points and receptive and expressive language outcomes at 5 years, the pattern of results based on correlations alone would not have indicated that individual differences in consistency in toddler hand preference for RDBM were related to differences in language outcomes at 5 years in comparison to LCGA results.

Although the current study did not specifically measure school readiness, the importance of language development toward reading highlights the potential impact that consistency in hand preference for fine motor skills may have on outcomes important to school readiness. Language in the present study was tested when children were on average 5 years old, an age when many children are about to enter or have already begun kindergarten. Critically, consistency in hand preference during toddlerhood was predictive of language outcome at 5 years, indicating that handedness had a cascading relation with language in a time when children must begin to utilize language skills toward school. Future work should aim to directly measure traditional metrics of academic achievement in relation to hand preference during fine motor behaviors over this developmental time period. Evidence suggests that early fine motor skills in writing and object manipulation in preschool contribute to reading abilities in second grade (Dinehart & Manfra, 2013). Moreover, fine motor skills in kindergarten are also predictive of academic achievement, including reading ability, in the fifth grade (Grissmer et al., 2010).

Recently, fine motor skills have been associated with language development in infancy and toddlerhood, with infants who score higher on fine motor assessments also demonstrating more advanced language abilities (e.g., Choi et al., 2018; Franchini et al., 2018; LeBarton & Iverson, 2013). Stemming from the concept of embodiment, children's opportunities for learning and interacting with the broader world can change and shift in tune with their own changing bodies and skills (Marshall, 2016). Fine motor skills such as RDBM, where infants must actively manipulate an object to explore and successfully execute its affordances likely provides infants with a host of opportunities to practice important skills for language (e.g., Iverson, 2010). An interesting avenue for further research is whether hand preference relates to differences in the amount of object manipulation children engage in, and potentially how the development of handedness aids said object engagement. Recent research utilizing head-mounted eye tracking indicates that given the constraints of their shorter arms, infants visual fields are dominated by the objects they engage with during holding and manipulation (Smith, Yu, & Pereira, 2011). Synchronized parent labeling of the object while the infant holds it likely results in an optimal context for word learning that is only possible through infants' motor abilities and parental contingency (McQuillan, Smith, Yu, & Bates, 2019; West & Iverson, 2017; Yu & Smith, 2012). If we were to add in hand use to these scenarios, based on the cascade theory of handedness (Michel, Babik, Nelson, Camp-

bell, & Marcinowski, 2018), it is possible that recursive visual and haptic input of one hand during motor activity concatenates toward a hand preference. Further work on how infant hand use, embodied visual and haptic information during object engagement, and parent language input interact is imperative toward further deciphering motor-language relations in regards to hand preference.

The underlying mechanisms for motor-language cascades require further investigation, but it is possible that engaging in object manipulation such as RDBM can provide important opportunities for language learning during dyadic interactions (Karasik, Tamis-Lemonda, & Adolph, 2011, 2014; West & Iverson, 2017; Yu & Smith, 2012). Currently untested is whether children's consistency in hand preference matters for rich language use to occur during object interaction, or how parents' own motor actions matter. Research on motor-language cascades is nascent, and little is known regarding the role of parent input as a mediating factor between motor development and language development in naturalistic settings, and much less is known regarding whether handedness matters for input. However, Michel (1992) demonstrated that maternal hand preference scaffolds infant hand preference during in-lab play sessions when infants were 7, 9, and 11 months of age. Although several factors were examined, maternal hand use was more strongly associated with infant hand use than the other variables that were examined. The proportion of hand-use matching increased as infants aged. Not only does this study support the idea of parental scaffolding of hand-use during development, but it also shows a difference in scaffolding according to hand preference. Specifically, Michel (1992) found that right-handed infants matched maternal hand use more often. Thus, mothers' own actions mattered for infant hand use. Is it possible that infants who experience differences in hand-use scaffolding also experience differences in language scaffolding? Is it then probable that infants across different hand preference trajectories experience differences in language input, and if so, why? Largely the focus on handedness and language in early development has been on infant behaviors, but as research from the broader motor domain demonstrates, caregivers may influence the course of these cascades.

Another possible mechanism underlying the relation between hand preference and language is hemispheric specialization. Cross innervation of the motor pathways in the brain result in right-handed actions being largely controlled by the left hemisphere, and left-handed actions by the right hemisphere (Serrien, Ivry, & Swinnen, 2006; Volkmann, Schnitzler, Witte, & Freund, 1998). Moreover, the left hemisphere has long been linked to speech and language functions (Josse & Tzourio-Mazoyer, 2004). Generally, findings indicate that adults demonstrate a left hemisphere dominance for both right handedness and language (Knecht et al., 2000). However, continuing advances in neuroimaging in adults have demonstrated that left hemisphere dominance for language is not as straightforward as was previously thought, but rather speech-language processing in the brain is more multidimensional (Josse & Tzourio-Mazoyer, 2004; Tremblay & Dick, 2016). In infant and toddlers, our knowledge regarding the relation between hand preference and hemispheric specialization continues to be limited given the challenges involved in neuroimaging young children longitudinally, and the difficulty in generating ecologically valid motor tasks, which do not interfere with neural signal collection, during neural data collection (e.g., Bell & Cuevas, 2012; Cusack, McCuaig, & Linke, 2018).

In conclusion, the current study provides further support for the link between early consistency in hand preference and language ability across early development. Here we found that individual differences in hand preference across 18 to 24 months were predictive of language skills at 5 years of age. Although further research is necessary in order to disentangle the mechanisms that underlie the relations between handedness and language cascades, it is increasingly clear that investigators interested in language outcomes should consider how individual differences in hand preference may provide additional information regarding infant language development. Moreover, further work is needed regarding how children may leverage motor advantages both toward language development and beyond, including other domains such as school readiness.

We look forward to future studies that advance neurodevelopmental work regarding handedness and language; as such work will help enlighten our current understanding of motor–language relations. More broadly, we argue that it is of paramount importance in moving the field of motor–language relations forward, and in particular the field of handedness and language, to delve deeper into questions concerning parental language input and motor behaviors during dyadic interactions, and how these behaviors unfold in synchrony at both the behavioral and neural levels. Understanding the neural-behavioral links within the infant–parent dyad will aid in disentangling the cascading effects between motor and language.

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