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Motor-Language Cascades: How Fine Motor Relates to Language Outcomes Across Early Development

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MOTOR-LANGUAGE CASCADES: HOW FINE MOTOR RELATES TO LANGUAGE OUTCOMES ACROSS EARLY DEVELOPMENT

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Sandy Laura Gonzalez

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To: Dean Michael R. Heithaus
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This dissertation, written by Sandy Laura Gonzalez, and entitled Motor-Language Cascades: How Fine Motor Relates to Language Outcomes Across Early Development, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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The dissertation of Sandy Laura Gonzalez is approved.

Dean Michael R. Heithaus
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Vice President for Research and Economic Development
and Dean of the University Graduate School

Florida International University, 2019

DEDICATION

For Kat, whose first steps sparked this adventure.

For Mami, Papi, and Abuela who made it all possible.

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ABSTRACT OF THE DISSERTATION

MOTOR-LANGUAGE CASCADES: HOW FINE MOTOR RELATES TO LANGUAGE OUTCOMES ACROSS EARLY DEVELOPMENT

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The current dissertation examined the role of motor skills on children's language outcomes across early development. For study one a systematic review was conducted to examine differences in how gross and fine motor skills foster language development from 0-5 years of age. Results derived from 22 articles indicated that while both gross and fine motor skills are related to language outcomes, too few studies have measured fine motor skills to conclusively determine differences in how gross and fine motor skills differentially relate to language outcomes.

The aim of study two was to investigate whether gross or fine motor skills were predictive of language growth during the second year of life, while accounting for other common predictors of language skill. Both gross motor and fine motor skills were assessed in a sample of 95 infants at 12-months-old, with expressive language growth measured across 12- to 24-months-old. Hierarchical regression analyses indicated that fine motor skills at 12-months-old predicted language growth above and beyond gross motor skills, maternal education, infant sex, baseline language, visual reception, and gesture skills.

Study three assessed the role of fine motor skills on language outcomes via individual differences in handedness for role differentiated bimanual manipulation (RDBM). Hand preference for RDBM was measured monthly from 18- to 24-month-old (*N* = 90). Receptive and expressive language skills were assessed at 5-years-old. Latent class growth analysis identified three toddler hand preference trajectories: left hand preference with moderate right hand use (left-moderate right), right hand preference with moderate left hand use (right-moderate left), and right hand preference with only mild left hand use (right-mild left). Analyses indicate that toddlers in the right-mild left handedness trajectory scored significantly higher on receptive and expressive language at 5-years-old compared to children with a left-moderate right hand preference. Children with a right-mild left RDBM hand preference also scored significantly higher on receptive language compared to children with a right-moderate left RDBM hand preference. Children with left-moderate right and children with a right-moderate left RDBM hand preference as toddlers did not differ in receptive or expressive language at 5-year-olds. Implications and suggestions for future work are discussed.

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ABSTRACT

Changes in motor development provide children with new learning opportunities to interact with objects, their environment, and with caregivers. Previous research finds that both gross and fine motor skills are predictive of later language outcomes across early infancy and childhood. However, gross and fine motor skills afford different types of interactions. Thus, gross and fine motor skills may potentially differ in the developmental trajectories through which cascading changes in language may occur. The aim of the present study was to investigate whether there are differences in the predictive capacities of gross and fine motor skills towards language outcomes across infancy and early childhood in typical development. A systematic review of existing literature on motor-language cascades was conducted in across studies measuring gross and/or fine motor and language development in children from 0 to 5 years old. Searches were conducted in PsycINFO, PubMed, and MEDLINE. Keywords used were a combination of "gross motor," "fine motor," "motor performance," "motor development," or "psychomotor development" along with "language," "language development," or "communication skills". Two independent reviewers screened abstracts and full texts using inclusion and exclusion criteria. A total of 22 articles were retained. Of these, six studies measured only gross motor skills, four studies measured only fine motor skills, and 12 studies measured both gross and fine motor skills in the same study. Studies used a variety of measures to assess gross motor skills, fine motor skills, and language development (e.g., parent report, in lab observations, standardized assessment), and findings varied according to the analyses used. Results demonstrated that both gross and fine motor skills are related to language outcomes, but because of the low number of studies testing fine motor skills, conclusions regarding whether one is more important for language outcomes cannot be drawn. We conclude that both gross and fine motor skills help foster language development from infancy to early childhood. Limitations regarding current knowledge regarding the mechanisms that underlie motor-language cascades are discussed, as well as the need for more studies on fine motor skills.

Keywords: motor, fine motor, gross motor, language, infancy, toddlerhood, preschool

LITERATURE REVIEW

Introduction

Motor development research has previously been considered the Cinderella of developmental science: central to children's experiences, but rarely in the spotlight (Adolph, Tamis-Lemonda, & Karasik, 2010; Rosenbaum, 2005). A historically maturational approach to motor skills was predominant in the early 20th century, which mainly argued that motor development unfolds via predetermined biological changes, with little to no intervention from environmental or cognitive domains (e.g., Gesell & Amatruda, 1945). Isolation of motor skill from cognition resulted in very little research focusing on the role of motor skills, instrumental to infant independence and exploration, on other domains of development such as language. Similarly, views of language as modular and universal (Chomsky, 1975) likely also contributed to further divorcing motor skills and language. However, continuing shifts towards ecological and systems approaches to development have allowed recent research to embrace the possibility of cross domain interactions resulting in cascading changes throughout periods when the developing system is in flux (Gibson, 1988; Masten & Cicchetti, 2010; Spencer, Perone, & Buss, 2011; Thelen & Smith, 2006). In the burgeoning literature on motor-language cascades, increasingly more research finds that motor skills matter for children's language outcomes (e.g., Iverson, 2010; Oudgenoeg-Paz, Volman, & Leseman, 2012; Walle & Campos, 2014).

Motor development is often broadly divided into gross motor and fine motor skills. Gross motor skills pertain to skills involving large muscle movements, such as independent sitting, crawling, walking, or running. Fine motor skills involve use of smaller muscles, such as grasping, object manipulation, or drawing. While many studies have investigated the role of motor skills on language development (e.g., Choi, Leech, Tager-Flusberg, & Nelson, 2018; Leonard, Bedford, Pickles, & Hill, 2015; Walle & Campos, 2014), it is unclear whether one type of motor skill is more consistently related to language outcomes then the other. On the basis of recent research indicating that delays in motor development are linked to diagnoses such as Autism Spectrum Disorder and Specific Language Impairment, it is imperative that research investigate potential differences in how motor skill types relate to language development in typical samples to inform additional research in clinical settings (Leonard & Hill, 2014; West, 2018).

Thus, the current systematic review will discuss existing literature on gross and fine motor skills in relation to language outcomes, and will focus on disentangling the cross relations between language development and gross and fine motor skills. We will focus on infancy through early childhood (0-5 years of age) to capture findings during early development, as both motor skills and language abilities are rapidly changing during the time period, allowing for a better understanding of how motor and language relate while the system is in flux (Masten & Cicchetti, 2010; Thelen & Smith, 2006).

METHODS

Study Design

A systematic review was conducted on existing literature spanning infancy through early childhood on the cascading relations between motor and language development using PRISMA guidelines.

Search Strategy

Article searches across the following databases were conducted: PsycINFO, PubMed, and MEDLINE beginning on July, 6th, 2018. Keywords used were a combination of "gross motor," "fine motor," "motor performance," "motor development," or "psychomotor development" along with "language," "language development," or "communication skills". When available, database options for peer-reviewed articles only, human, and age limits of participants (infancy through 5 years old) were selected to better tailor search results for the focus of the current review. A total of 6,210 articles were identified as potentially relevant.

Two independent reviewers (the first and second author) further screened abstracts using the online program Abstrackr, an open-source tool for systematic reviews (Wallace, Small, Brodley, Lau, & Trikalinos, 2012). Abstrackr allows users to apply semi-automated algorithm determined rejection stemming from machine-learned patterns from previous rejections made by human reviewers. Research demonstrates that the Abstrackr algorithm has good precision with low levels of false-negatives depending on the complexity of the systematic review (Rathbone, Hoffmann, & Glasziou, 2015). To maximize accuracy of the Abstrackr algorithm while balancing expediency, both independent reviewers screened 3000 abstracts manually, and the remaining 3210 abstracts were screened utilizing the Abstrackr algorithm. Of the abstracts screened by the Abstrackr algorithm, only two were tagged as potentially relevant for further review. Among the full sample of 6,210 articles, 2049 were identified as duplicates and were removed from further full text review. Two additional articles were added by the first author using prior knowledge of their relevance to the systematic review, resulting in a total of 128 articles selected for full text review.

Eligibility Criteria

Abstracts were screened using the following inclusion criteria: 1) studies that included a typically developing sample, 2) studies with a sample within the range of 0 to 5 years of age, 3) studies that measured both motor and language skills, and 4) studies reported in English. Exclusion criteria included: 1) case studies, 2) studies with only atypical populations, 3) studies where only motor or only language skills were measured and results were only suggestive of motor-language links, 4) studies that did not differentiate gross and fine motor skills (e.g., had one global motor score), 5) studies where the measured motor skills were exclusively speech-motor/oro-motor control, rhythmic arm movement, handedness, gesture, motor imitation, or synchronized finger tapping, 6) studies where language skills were only measured using babbling or vocalizations/pre-vocal behaviors. If it was unclear whether a study met inclusion or exclusion criteria reading the abstract alone, the reviewers discussed the abstract together. If an agreement could not be made between reviewers reading the abstract alone, the article was included for further full text review.

Full text review was conducted by the first and second author, with any disagreements/final decisions regarding inclusion and exclusion discussed among all three authors when necessary. The criteria discussed above continued to be implemented during full text review. Articles were thoroughly read for inclusion of analyses that detailed motor-language cascades in typical samples, as studies with an atypical focus often included control groups which passed inclusion criteria during abstract review, but upon full text reading 1) did not conduct analyses on motor-language cascades with the typically developing samples (i.e., conducted typical vs. atypical group comparisons only, or did not measure motor or language skills in the typical sample), or 2) grouped atypical and typical samples for power purposes for motor-language cascade analyses which did not allow for reporting of typical results alone. Only studies in which clear results for typically developing children were reported were included for final article inclusion. Studies which included children 0-5 years, but also included older age ranges were only included if results for ages from 0-5 years were reported separately from the full sample and if motor and language results were both measured at a time point between 0-5 years old. The PRISMA flow chart (Figure 1) indicates how many full text articles were excluded and why.

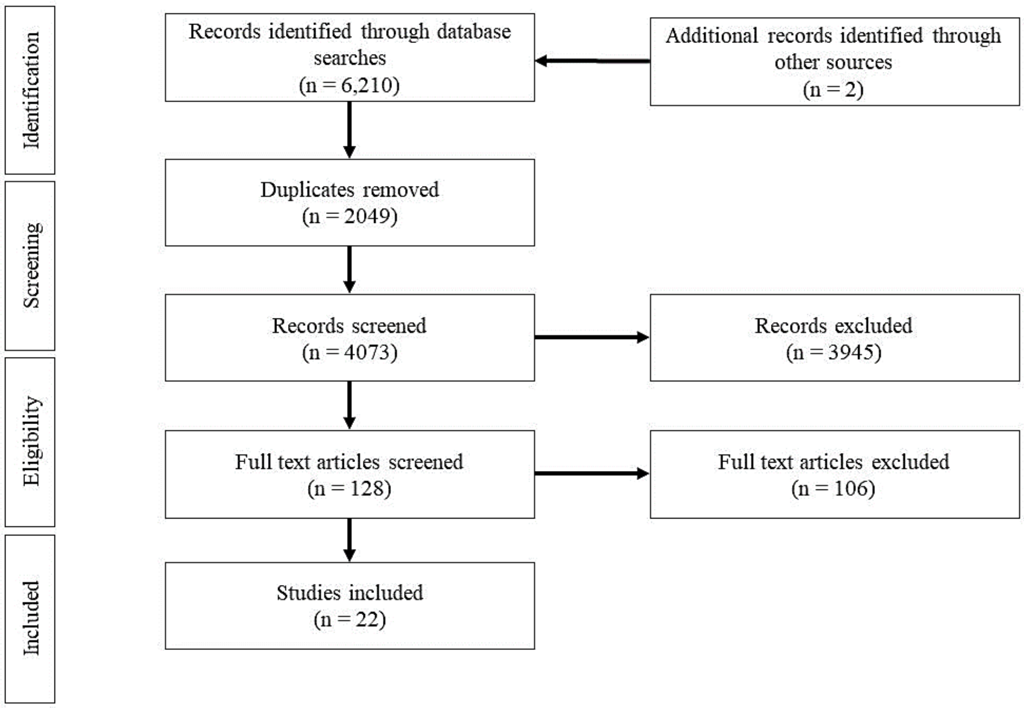

Figure 1. PRISMA flow diagram of study selection process

Prevention of Bias and Quality Assessment

In an effort to reduce bias, abstracts and articles were screened by two independent screeners. Training on how to use Abstrackr was conducted using tools available through the Abstrackr website prior to any screening. Both authors also practiced scoring a subset of articles together prior to independent screening, and discussed the thought process behind inclusion and exclusion decisions during the training period. Abstrackr allows users to keep track of disagreements between the two reviewers. Thus, at a half way point during independent screening; the two independent screeners discussed existing conflicts flagged by Abstrackr in order to adjust all further abstract screening accordingly. Disagreements were settled via discussion. Moreover, in an effort to further reduce bias, the authors included results from typically developing control samples reported in studies focused on atypical development, which aimed to reduce biased reporting of only “positive results,” more likely with studies that solely focus on typical samples.

All articles selected for final inclusion in the current systematic review were assessed for quality following Downes and colleagues (2016) Appraisal tool for Cross-Sectional Studies (AXIS) tool. Quality assessment with AXIS determined on the basis of 20 questions regarding inclusion or exclusion of information in the introduction, methods, results, and discussion. The original AXIS measure does not provide a numerical score. However, all studies received scores of “Yes” for more than half of the items on AXIS. On average, studies received about 15/20 “Yes” responses, with highest scored receiving 17 out of 20. No studies were excluded on the basis of quality assessment. Results are detailed in Appendix A in Supplementary Material.

RESULTS

Synthesis

At total of 22 articles were included in the current systematic review ((Alcock & Krawczyk, 2010; Butterworth & Morissette, 1996; Choi et al., 2018; He, Walle, & Campos, 2015; Iverson & Braddock, 2010; Leonard et al., 2015; Libertus & Violi, 2016b; Lyytinen et al., 2001; Muluk, Bayoğlu, & Anlar, 2016; Muluk, Bayoğlu, & Anlar, 2014; Oudgenoeg-Paz, Leseman, & Volman, 2015; Oudgenoeg-Paz et al., 2012; Oudgenoeg-Paz, Volman, & Leseman, 2016; Rhemtulla & Tucker-Drob, 2011; Suggate & Stoeger, 2014; E. A. Walle, 2016; E. A. Walle & Campos, 2014; West, Leezenbaum, Northrup, & Iverson, 2017; Wolff & Wolff, 1972)). Information was extracted regarding the main purpose, study design, sample size, ages tested, measures used to test gross and/or fine motor, measures used to measure language. All extracted information can be found in Table 1. Studies included in the present systematic review spanned 1972 to 2018, with the most publications occurring in 2016 (*n* = 5). The majority of studies used longitudinal methods (*n* = 11), with eight studies using cross sectional methods. One study had multiple studies and used both longitudinal and cross-sectional methods (Walle & Campos, 2014), and two studies used longitudinal methods, but results reported in this systematic review only pertain to cross-sectional results at one age as the studies also included older ages and analyses allowed for reporting results only for the ages of interest to this systematic review (Cameron et al., 2012; Rhemtulla & Tucker-Drob, 2011). Sample size varied across studies ranging from 16 to 11,999 (sample sizes reported refer only to number of typically developing children). Overall, 17 studies focused solely on typically developing children, while six studies included both typically and atypical developing samples.

Study	Study Design	N_a	Ages Tested[b]	Motor assessment	Language assessment
Alcock, & Krawczyk (2010)	CS	129	21 m/o	GM & FM: BSID or ASQ items	MCDI (UK)
Butterworth & Morissette (1996)	LG	27	8.5-14.5 m/o (monthly assessments)	FM: Pincer grip (4 trials)	MCDI
Cameron et al. (2012)	CS[c]	213	3-5 y/o	GM & FM: Early Screening Inventory –Revised	Woodcock Johnson-Picture Vocabulary
Choi et al. (2018)	LG	69	Motor: 6-24 m/o (assessments every 6 months) Language: 36 m/o	GM & FM: MSEL	MSEL
He et al. (2015)	CS	US sample: 40 Chinese sample: 42	US sample: 12.5 m/o Chinese sample: 13-14.5 m/o	GM: Parent reported age of crawling or walking onset	MCDI (US & Mandarin)
Houwen et al. (2016)	CS	130	0-3 y/o	BSID (Netherlands)	BSDI (Netherlands)
Iverson & Braddock (2010)	CS	16	3-5 y/o	FM: CDI and Batelle Developmental Screening Inventory	PLS and measures from in lab observation
Leonard et al. (2015)	LG	55	Motor: 7 m/o Language: 14, 24, & 36 m/o	GM & FM: MSEL	VABS
Libertus & Violi (2016)	LG	29	Motor: 3-5 m/o (8 weekly assessments) Language: 10 & 14 m/o	GM: Sitting duration FM: Grasping duration	MCDI

Lyytinen et al. (2001)	LG	93	0-5 y/o	GM & FM: Parent reported milestones	MCDI
Muluk et al. (2014)	CS	347	6, 12, 18, & 24 m/o	GM & FM: Denver Developmental screening items (Turkey)	Denver Developmental screening items (Turkey)
Muluk et al. (2016)	CS	505	Motor: behavior onset[d] Language: 6, 12, & 18 m/o	GM & FM: Denver Developmental screening Items (Turkey)	Denver Developmental screening items (Turkey)
Oudgenoeg-Paz et al. (2012)	LG	55	Motor: behavior onset[d] Language: 6, 12, & 18 m/o	GM: Parent reported age of sitting or walking onset	MCDI (Netherlands)
Oudgenoeg-Paz et al. (2015)	LG	31	Motor: behavior onset[d] & 20 m/o Language: 36 m/o	GM: Parent reported age of crawling or walking onset & observation of exploration through self-locomotion FM: Observation of object exploration	Spatial language
Oudgenoeg-Paz et al. (2016)	LG	59	Motor: behavior onset[d] Language: 43 m/o	GM: Parent reported age of crawling or walking onset & observation of exploration through self-locomotion	PPVT (Netherlands), spatial language, & sentence repetition task

Rhemtulla & Tucker-Drob (2011)	CSc	8,950	4 y/o	GM Assessed jumping, balancing, skipping, walking backwards, and catching a bean bag FM: Assessed building a gate with blocks, copying a square, triangle, & an asterisk	"Let's Tell Stories" oral language task
Suggate & Stoeger (2014)	CS	76	3-5 years	FM: Pegboard task, bead threading, & block turning	PPVT (German), body-object interaction words, manipulable words
Walle (2016)	LG	43	10-13.5 m/o (bi-weekly assessments)	GM: Parent reported age of crawling or walking onset	MCDI
Walle & Campos (2014)	LG/CS	LG: 44 CS: 75	LG: 10-13.5 m/o (bi-weekly assessments) CS: 12.5 m/o	GM: Parent reported age of crawling or walking onset	MCDI
Wang et al. (2014)	LG	11,999	3 & 5 y/o	GM & FM: ASQ	ASQ
West et al. (2017)	LG	25	2-19 m/o (bi-weekly assessments)	GM: Parent reported age of walking onset	MCDI
Wolff & Wolff (1972)	CS	55	4 & 5 y/o	GM & FM: Teacher report	Teacher report

Table 1. Articles Included in Systematic Review. CS = cross-sectional; LG =longitudinal; m/o = months old; y/o = years old; GM = gross motor' FM = fine motor; BSID = Bayley Scales of Infant Development; ASQ = Ages and Stages Questionnaire; MSEL = Mullen Scales of Early Learning; CDI = Child Development Inventory; MCDI = MacArthur-Bates Communicative Development Inventory; PLS = Preschool Language Scales; VABS = Vineland Adaptive Behavior Scales; PPVT= Peabody Picture Vocabulary Test.

[a] *Sample sizes reported include only typically developing children*
[b] *Ages reported for systematic review include only ages of interest, full study included older ages*
[c] *Results reported for systematic review are cross-sectional, full study is longitudinal*
[d] *Exact ages not reported given variability in onset age*

In terms of measurement, 12 studies assessed gross motor skills and fine motor skills for motor-language analyses. However, one study by Muluk and colleagues (2016) did not provide clear results for fine motor skills, and thus only gross motor results are discussed in our review. Six studies measured only gross motor skills, and four studies measured only fine motor skills. Studies used a variety of assessment types to measure motor skill. Studies measuring gross motor skill most frequently used parent reported age of skill acquisition (n = 6), while studies measuring fine motor skill used in lab tasks/observations (n = 6). In terms of language, most studies on measuring fine motor skills used a parent report measure for language skills (n = 11; e.g., MacArthur Bates Communicative Development Inventories, Ages and Stages Questionnaire). Studies measuring gross motor skills also largely used parent report for language skills (n = 10). Although studies were not selected using measures that differentiated between receptive and expressive language skills, the majority of studies measured both receptive and expressive skills separately (n = 11). Additionally, two studies measured language skills related to words relevant to actions (e.g., spatial words, word related to high levels of body interaction) in addition to other language measures, and one study only measured production of spatial language.

Gross Motor Skills Results

Results for this section will first detail the relation between gross motor and language skills, categorized by ages studied and study methodology (cross-sectional versus longitudinal). At the end of this section, commonalities across gross motor studies will then be discussed.

Cross-sectional studies with infants and toddlers

Five articles measured the relation between gross motor skills and language development utilizing cross-sectional methods in infants and toddlers (Alcock & Krawczyk, 2010; He, Walle, & Campos, 2015; Houwen, Visser, van der Putten, & Vlaskamp, 2016; Muluk, Bayoğlu, & Anlar, 2016; Walle & Campos, 2014). Overall, the studies reviewed in detail below do find concurrent relations between gross motor skills and language development within U.S., U.K., Chinese, Turkish, and Dutch samples of infants. However, for two of the five studies, accounting for additional covariates such as cognitive skills or other motor skills and demographic variables, reduces gross motor's significant contribution to language (Alcock & Krawczyk, 2010; Houwen et al., 2016). Studies have used a variety of methods to operationalize "gross motor": two studies used parent reported walking onset exclusively (He et al., 2015; Walle & Campos, 2014), one study used both standardized assessment and parent questionnaires (Alcock & Krawczyk, 2010), and two studies utilized a standardized assessment or items derived from a standardized assessment (Houwen et al., 2016; Muluk et al., 2016). Most (three out of five) relied on parent report for measures of language skill (Alcock & Krawczyk, 2010; He et al., 2015; Walle & Campos, 2014). Overall, 60% of studies reviewed in this section suggest that gross motor and language skills are related concurrently in infancy, particularly when assessing gross motor skills from a single behavior (e.g., walking) rather than a global gross motor score.

Using a wide cross-sectional sample spanning three months to three years of age, Houwen, Visser, van der Putten, & Vlaskamp (2016) measured gross motor skill and language using the Dutch Bayley Scales of Infant Development (BSID) which includes subscales for gross motor skills and expressive and receptive language. Gross motor scores were significantly positively correlated with both expressive and receptive communication scores, however this relation did not hold once controlling for cognitive level. Focusing on a sample of Turkish children, Muluk, Bayoğlu, and Anlar (2016) measured gross motor skills and language ability using a cross-sectional sample of children at 6, 12, 18 and 24 months of age. Gross motor skills and receptive and expressive language skills were measured using individual items form the Denver Developmental Screening standardized for use with Turkish children. Items used for gross motor and language varied across age groups. At 6 months, the “pull to sit (no head lag)” item was positively significantly correlated to the language item “turns to sound.” Infant’s ability to “lift chest with arm support” was also significantly positively correlated to the language item “turns to voice” at 6 months. Both of these 6-month relations were significant when controlling for each other along with various covariates (sex, SES, maternal education, and “working for a toy out of reach”). At 12 months, being able to “stand holding on” was positively significantly related to the language item “mama/dada specific” and to being able to “say 4 words other than mama/dada.” The item “stands alone for 10 seconds” was also positively significantly correlated to being able “to say 4 words other than mama/dada.” These 12 month relations were significant when controlling for each other along with other covariates (SES, maternal age, and indicates needs not crying). At 18 months, the ability to “throw a ball” was significantly negatively correlated with “saying 4 words other than mama/dada,” while controlling for sex as a covariate. No results were reported for gross motor and language at 24 months.

Investigating motor and language development at 12 months of age, Walle & Campos (2014) measured the relation between quality of locomotion and language comparing same aged crawlers and walkers in a cross-sectional sample. Results indicated that walking infants had larger receptive and expressive vocabularies as measured via parent report on the MacArthur Bates Commutative Developmental Inventory: Words and Gestures (MCDI: WG) short form. He, Walle, & Campos (2015) reproduced these results in a cross-cultural study comparing U.S. and Chinese infants, with findings demonstrating that for both U.S. infants (about 12.5 months old) and for Chinese infants (between 13-14.5 months old), walkers demonstrated significantly greater receptive and expressive vocabulary, in English and Mandarin respectively, compared to crawlers. When accounting for U.S. infants self-produced locomotion experience, walking status only marginally predicted receptive vocabulary, but a continued significant relation between walking status and expressive vocabulary remained. In Chinese infants, walking status continued to significantly predict both receptive and expressive vocabulary even when controlling for self-produced locomotion experience. When focusing specifically on receptive and expressive vocabulary for nouns, U.S. and Chinese infants who could walk both had larger noun and non-noun vocabularies compared to crawlers. However, the proportion of nouns to non-nouns for both receptive and expressive vocabulary was not significantly different between walkers and crawlers, indicating locomotor status did not matter in this case for U.S. infants. For Chinese infants, the proportion of nouns to non-nouns for receptive was not significantly different between walkers and crawlers, but the proportion of nouns to non-nouns for expressive language differed significantly, indicating that Chinese children who could walk were likely to know more nouns than non-nouns in Mandarin than crawlers.

At 21 months of age, Alcock & Krawczyk (2010) measured gross motor skills using the BSDI or with a questionnaire that was adapted to include gross motor questions from the Ages and Stages Questionnaire (ASQ) parent report measure. Language skills were measured using the Oxford MCDI, with additional questions about word combinations and grammatical usage (e.g., complexity) from the U.S. English MCDI: Words and Sentences (MCDI: WS). For infants with parent reported gross motor scores via questionnaire, gross motor skills were significantly positively correlated to receptive and expressive vocabulary, but not complexity. When utilizing standardized scores to combine infants who completed the BSDI or the gross motor questionnaire, gross motor skills were not significantly correlated with language comprehension, production, or complexity. Standardized gross motor scores and questionnaire gross motor scores did not significantly predict receptive, expressive vocabulary, or complexity when accounting for oral motor movement, fine motor score, gesture, and symbolic gesture. However, when removing oral motor movement from included covariates, gross motor skill based on parent report did predict vocabulary production, but did not predict language comprehension or complexity.

Longitudinal studies with infants and toddlers

Nine articles investigated the longitudinal relations between gross motor skills and language development (Leonard, Bedford, Pickles, & Hill, 2015; Libertus & Violi, 2016; Lyytinen et al., 2001; Oudgenoeg-Paz, Leseman, & Volman, 2015; Oudgenoeg-Paz, Volman, & Leseman, 2012, 2016; Walle, 2016; Walle & Campos, 2014; West, Leezenbaum, Northrup, & Iverson, 2017). Longitudinal methods help inform researchers about length of cascading effects, and can provide knowledge regarding growth over time for both motor and language development. In the current subset of longitudinal articles, eight out of nine articles (about 89%) demonstrate that gross motor skills are related to language skills (Libertus & Violi, 2016; Lyytinen et al., 2001; Oudgenoeg-Paz, Leseman, & Volman, 2015; Oudgenoeg-Paz, Volman, & Leseman, 2012, 2016; Walle, 2016; Walle & Campos, 2014; West, Leezenbaum, Northrup, & Iverson, 2017). Importantly, because longitudinal studies can provide information about skills over time, results here begin to show that the length of certain motor to language relations may change over time, and the contributions of motor to language may depend on skill type (e.g., Oudgenoeg-Paz et al., 2015). The discussed longitudinal studies also expand beyond parent reported onset of locomotion (i.e., crawling versus walking) and begin to report on motor-language relations pertaining to behaviors such as sitting and locomotor exploration (Libertus & Violi, 2016; Oudgenoeg-Paz et al., 2015, 2016). Samples reviewed here included Dutch, Finnish, U.K., and U.S. infants. A total of six studies included covariates when analyzing gross motor to language relations. Results from these studies indicated that gross motor skills predicted language outcomes above and beyond age, concurrent motor abilities, and parental social factors such as parent initiated joint engagement and viewing the infant as an individual (e.g., Libertus & Violi, 2016; Walle, 2016; West et al., 2017). Similarly, to the cross-sectional studies reported in section 3.2.1, existing literature supports the idea that gross motor skills play an important role in language development across infancy and toddlerhood.

Using video conferencing technology to measure infant sitting in the home, Libertus and Violi (2016) calculated growth in sitting skill (i.e., duration in independent sitting) over time from three to five months of age. Language skill was measured using the MCDI: WG later at 10 and 14 months old. Greater growth in duration of sitting was significantly positively related to receptive vocabulary at 10 and 14 months of age, even when including concurrent general motor skills as a covariate. In a study on the longitudinal relations between motor and language in typically developing infants and infants at high-risk for autism, Leonard, Bedford, Pickles and Hill (2015) assessed gross motor skills at 7 months using the gross motor subscale of the Mullen Scales of Early Development (MSEL). Language skill was measured at 7, 14, 24, and 36 months using the Vineland Adaptive Behavior Scales (VABS). Results accounted for visual receptive skill at 7 months, and found that for the typically developing sample gross motor ability at 7 months was not predictive of growth in receptive of expressive language skills from 7 to 36 months.

In another study focused on predicting language growth from early gross motor skills, Oudgenoeg-Paz, Volman and Leseman (2012) found that age at which independent sitting was attained significantly predicted productive language skill (as measured by the Dutch short form versions of the MCDI) at 20 months, with younger sitting age predicting greater productive vocabulary. Age of independent walking significantly predicted rate of expressive vocabulary growth from 16 to 28 months, with younger walking age predicting greater language growth. Age of independent walking did not predict language skill at 20 months, and age of sitting did not predict language growth. Expanding on these results, Oudgenoeg-Paz, Leseman and Volman (2015) measured spatial language production at 36 months using interactive in lab assessments. In addition to utilizing parent reported age of acquisition of sitting and walking, exploration through self-locomotion was also measured during an in lab observation at 20 months. Results indicated that age of independent sitting did not significantly predict spatial language use, but age of walking acquisition did. Amount of exploration through self-locomotion was also significantly positively related to productive spatial language. Importantly, exploration through self-locomotion partially mediated the relation between walking age and spatial language, indicating the effect of walking age on spatial vocabulary is partly explained by amount of self-locomotor exploration. Additional work by Oudgenoeg-Paz et al. (2016) measured general receptive vocabulary using the Peabody Picture Vocabulary Test (PPVT), grammatical and lexical categories during a sentence repetition task, and productive spatial language based on knowledge of locative prepositions and directional verbs using in lab tasks at 42 months. Gross motor skills were assessed based on parent reported age of walking onset, and an in lab observation of exploration through self-locomotion at 20 months. Age of walking did not significantly predict spatial language. Exploration through self-locomotion completely significantly positively mediated the relation between walking age and spatial language. Walking age did not significantly predict receptive vocabulary or use of grammatical and lexical categories, and exploration through self-locomotion did not mediate any of these relations. Across these three studies, a more complex picture of motor-language cascades is seen for gross motor skills. Independent sitting is important for language outcomes, but with more time between sitting acquisition and when language is measured, it is likely that the cascading effects of sitting are no longer as strong, or that they are superseded by more novel skills (e.g., walking). However, even in the case of walking, by 42 months there is no relation between age of walking onset and general vocabulary, although walking was predictive of language growth across earlier time points. Similarly, walking onset no longer was predictive of spatial language at 42 months, although it had been at 36 months. Instead, amount of self-locomotor exploration at 20 months predicted spatial language at 42 months.

As part of a larger longitudinal study, Lyytinen and colleagues (2001) compared typically developing infants and infants with children at risk for dyslexia. Gross motor skill was measured using parent report of age of onset of gross motor milestones with analyses using each infant’s deviation from a calculated median growth curve constructed using gross motor skill attainment across various skills over the first year of life. Language development was measured using the MCDI: WG for receptive and expressive vocabulary at 12 and 14 months, and MCDI: Words and Sentences (MCDI: WS) for productive vocabulary at 24 and 30 months. For results specific only to typical children, gross motor skills were significantly positively correlated with vocabulary comprehension at 12 and 14 months, but not with vocabulary production at 14, 24 or 30 months. Focusing on changes in locomotion style over time in relation to language development, Walle and Campos (2014) longitudinally followed infants across the transition from crawling to walking. Specifically, gross motor skill was assessed using parent reported age of walking and crawling onset to calculate length of walking experience. Language was measured using the MCDI: WG to measure receptive and expressive vocabulary. Results indicated that walking experience was significantly predictive of receptive vocabulary size, with greater walking experience predicting larger receptive vocabulary. Significant increases in receptive vocabulary were seen at the transition from crawling to walking, and between walking onset and 2 weeks post walking onset. No significant increases in vocabulary were seen between 2 weeks after and 4 weeks after walking onset, or at 4 and 6 weeks of walking experience, or at 6 and 8 weeks of walking experience. For productive vocabulary, more walking experience significantly predicted greater expressive vocabulary. There was no significant increase in expressive vocabulary during the transition from crawling and walking. There was also no significant increase in expressive vocabulary between walking onset and 2 weeks post walking onset, or between 2 weeks after and 4 weeks after walking onset, or at 4 and 6 weeks of walking experience. A significant increase in expressive vocabulary was seen between 6 and 8 weeks post walking onset. Overall, results indicate that walking onset is correlated with immediate growth in receptive vocabulary, and with later growth in expressive vocabulary.

Findings by Walle and Campos (2014) have spurred additional replications that further support the role of walking onset within language development. Results from Walle (2016) indicate that walking experience (calculated using walking onset) was significantly positively predictive of receptive and productive vocabulary size (as measured by the MCDI: WG). Importantly, walking experience significantly predicted receptive and expressive vocabulary, even when controlling for parent initiated joint engagement, parent report of viewing the infant as an individual, and age. In a study comparing the effects of walking onset on language in typically developing infants and in infants at high risk for autism, West, Leezenbaum, Northrup, & Iverson (2017) followed infants longitudinally across the transition from crawling to walking, and found that both receptive and expressive vocabulary (as measured by the MCDI: WS) increased after infants final crawling visit and after walk onset while controlling for infant's age at the time of walk onset.

Cross-sectional studies spanning pre-kindergarten and early childhood

Expanding into preschool and early childhood age ranges, four studies investigated the role of gross motor skill on language development using cross-sectional methods and are reviewed in detail below (Cameron et al., 2012; Muluk, Bayoğlu, & Anlar, 2014; Rhemtulla & Tucker-Drob, 2011; Wolff & Wolff, 1972). The majority of the samples discussed in the current section were of U.S. children, with one study reporting on Turkish children (Muluk et al., 2014). In general, measures and methods considered here are mixed with two studies that utilized gross motor and language measures based performance on individual tasks (Muluk et al., 2014; Rhemtulla & Tucker-Drob, 2011), and two studies using global gross motor scores from assessments or questionnaires (Cameron et al., 2012; Wolff & Wolff, 1972). Novel to the review thus far, one article also opted to use teacher report for both gross motor and language skills (Wolff & Wolff, 1972). In general, use of such disparate measurements results in a limited understanding regarding gross motor skills at a global level, but highlights potential differences across individual skills beyond crawling or walking that were common in infant studies and their relation to language.

For the studies by Cameron and colleagues (2012) and Rhemtulla and Tucker-Drob (2011), both used longitudinal methods, however results reported in the current systematic review only include only ages 5 years or younger. Rhemtulla and Tucker-Drob (2011) provided cross-sectional correlations at 4 years of age, which are reviewed below. Cameron and colleagues (2012) indicated in their results that the oldest child to complete a motor assessment at the beginning of their study (beginning of kindergarten) was 5.75 years old (69 months). Measurements at a second time point were described as being in spring of kindergarten, which indicates that the older children may have already turned six (72 months) by that time point. The only cross-sectional study within this age range that included covariates utilized backwards regression and reported only on the best fitting models per age group, which limits our interpretation of gross motor to language relations as covariates varied widely across ages and individual language measures (Muluk et al., 2014). In cross-sectional studies spanning pre-kindergarten and early childhood, three studies (75%) reviewed support the idea that gross motor skills continue to be related to language outcomes concurrently, but we would argue that more recent and rigorous cross-sectional studies are required.

In a sample that includes 3, 4, and 5 year olds, Muluk, Bayoğlu, and Anlar (2014) measured gross motor skills and receptive and expressive language skills using selected items from the Denver II for use in Turkey. Both gross motor and language measures varied in skills measured and number of items by age group. At 3 years, being able to "ride a tricycle" was significantly correlated to "comprehension of one preposition," but did not hold significance when accounting for other covariates. The ability to "jump up" was significantly positively correlated to "use of plurals" and "comprehending one preposition," and continued to be related to "comprehending one preposition" when accounting for other covariates. When accounting for other covariates, "jump up" was significantly related to and "gives first and last name" and being able to "define six words." Balancing on one foot was also significantly positively correlated to using plurals and being able to give first and last name at 3 years, but was no longer related to these items after controlling for other covariates. When accounting for variability in other skills and factors, “balancing on one foot” was related to the language item “knowing one function.” At 3 years, being able to run was significantly negatively correlated to the language item “naming three pictures”, however this relation did not hold when accounting for other covariates. At 4 years “hopping on one foot” and “broad jumping” ability were not correlated to any language items, however hopping on one foot was related to knowledge of “how to use on object” once accounting for other covariates. At 5 years, “heel-to-toe walking” ability was significantly positively correlated to language items “defines six words” and “counting two blocks,” however none of these relations were maintained when accounting for other covariates.

In a similar study utilizing individual lab assessed items to measure gross motor and language skills, Rhemtulla and Tucker-Drob (2011) utilized longitudinal growth modeling methods across 3 to 7 years of age, but provide single time point data using intercept values on motor language relations at 4 years of age. Experimenters measured gross motor skills during specific tasks: jumping, balancing, hopping, skipping, walking backwards, and catching a beanbag. Oral language skills were measured using the Lets Tell Stories task. Oral language skills at 4 years were significantly positively correlated to concurrent gross motor scores. In the Cameron et al. (2012) study on motor and executive function in relation to kindergarten achievement, motor skills were measured at the beginning using the Early Screening-Inventory-Revised, with analyses related to gross motor skills based on a composite score. Language production skills were assessed using the Woodcock Johnson Vocabulary subtest. Gross motor skills were not significantly correlated to language skills measured in the fall of kindergarten above and beyond fine motor skills, or other covariates such as executive functioning, age, sex, ethnicity, maternal education, or motor age.

In a departure from lab assessed or parent reported measures, Wolff and Wolff (1972) utilized teacher ratings on a Likert scale to measure both gross (e.g., degree to which the child is motorically active, degree to which she engages in gross bodily movements, etc.) and verbal language skills (e.g., verbal output and skill level). Gross motor skills were significantly positively related to verbal output scores, but not to verbal skill indicating that potentially at preschool age gross motor skills still related to quantity of language use (similar to some results from infancy and toddlerhood), but not to quality.

Longitudinal studies spanning pre-kindergarten and early childhood

One study measured the relation between gross motor and language development across preschool and early childhood (Wang, Lekhal, Aaro, Holte, & Schjolberg, 2014). On the basis of one study reviewed below, results indicate that in this age range gross motor skills continue to predict language outcomes, but not as consistently longitudinally as seen in infancy and childhood. In general, Wang and colleague's (2014) study demonstrates that covariates such as fine motor skill, baseline language, and other individual differences potentially attenuate gross motor relations over time with language during preschool and early childhood. Further work is necessary in this age range using longitudinal methods, as we caution drawing conclusion from a single study.

Wang, Lekhal, Aaro, Holte, and Schjolberg (2014) tested gross motor and language skills longitudinally, using a sample of Norwegian children followed at 3 and 5 years of age. Both gross motor and language skills were measured using the ASQ parent report questionnaire, which provides separate gross and fine motor scores, and a global language score. Correlations across time points for gross motor and language scores indicated that greater gross motor skill at 3 years was significantly positively correlated to higher language scores at both 3 and 5 years. However, when controlling for concurrent relations between gross motor, fine motor, language, and other demographic covariates, gross motor skills at 3 years did not predict language at 5 years. Analyses on concurrent gross motor and language relations that controlled for covariates did indicate that gross motor at 3 years was related to language at 3 years, and gross motor at 5 years was related to language at 5 years.

Synthesis of gross motor and language across infancy to early childhood

Overall, existing literature finds that gross motor skills demonstrate both concurrent and longitudinal relations with language skill across infancy, toddlerhood, preschool, and early childhood. A total of 15 articles found significant links between gross motor and language, even when accounting for other covariates. Thus, about 79% of articles that assess gross motor and language relations published thus far report significant findings for gross motor. Interestingly, 100% of cross-sectional studies during preschool and early childhood, and 89% of longitudinal studies with infant and toddler samples reported significant relations between gross motor and language. In particular, measuring the onset of specific gross motor skills during infancy such as sitting and walking has provided powerful evidence demonstrating that experience in new postures and locomotion styles can predict receptive and expressive language at single time points, and growth over time (Libertus & Violi, 2016; Walle & Campos, 2014; West et al., 2017). Frequently, gross motor skills have been found to predict language ability above and beyond other factors such as age, general locomotion experience, SES, or parental influences (e.g., He et al., 2015; Muluk et al., 2016; Walle, 2016). However, global scores from standardized assessments have also provided insight on gross motor skills and language relations, but have sometimes not found significant relations to language longitudinally (Leonard et al., 2015; Wang et al., 2014). Changes in the predictive capacity of gross motor skills over time is particularly clear as gross motor and language relations are explored at older ages closer to preschool entry (Cameron et al., 2012; Oudgenoeg-Paz et al., 2016). Importantly, it is possible that the inconsistency in gross motor to language relations seen at older ages simply demonstrates that cascading effects from motor to language are limited in time. Behaviors such as walking may no longer foster the same level of growth in language once the behavior is no longer novel and the infant system is not in the process of learning a new skill (e.g., Oudgenoeg-Paz et al., 2016). While cross-sectional studies during the ages spanning preschool and early childhood have found relations between gross motor and language, studies focusing on outcomes over time find mixed results, with gross motor prior to kindergarten predicting expressive language skills in Spring of kindergarten, but studies with time points further apart demonstrating less of an influence of earlier motor skill on later language (Cameron et al., 2012; Wang et al., 2014). In terms of quantity however, more studies have been conducted during infancy and toddlerhood on the relation between gross motor and language compared to early childhood, which limits our interpretation of findings for the older age ranges.

Fine motor skills and language development

The following section will provide existing evidence regarding the relation between fine motor skills and language outcomes. Some of the studies reported in this section are the same studies from the gross motor skills and language development section, as multiple studies included in this review measured both gross and fine motor skills. Here, results will only focus on fine motor measures and language of these articles. A synthesis of all studies included in the fine motor skills and language development section will be provided at the end of this section.

Cross-sectional studies with infants and toddlers

There are only two studies in the current review that utilized cross-sectional samples to analyze fine motor skills in relation to language development in infancy and toddlerhood (Alcock & Krawczyk, 2010; Houwen et al., 2016). Results reviewed here are based on UK and Dutch infants. One study utilized standardized assessments to measure both fine motor and language skills (Houwen et al., 2016), and the other study used a combination of standardized assessments and parent report (Alcock & Krawczyk, 2010). Both studies find at least one link between fine motor skills and receptive and productive language prior to analyses with covariates. Both studies utilized covariates, with Houwen and colleagues (2016) indicating that fine motor skills continued to predict language skills after controlling for cognitive levels. In comparison, Alcock and Krawczyk (2010) found that when controlling for numerous covariates such as gross motor skill, oral motor skill, and gesture among other variables, fine motor skills were no longer related to language skills. Overall, the set of cross-sectional studies on fine motor skills and language reviewed below demonstrate that concurrent relations do exist between fine motor and language, but highlight that this relation may sometimes be explained via other variables. However, too few cross-sectional studies are available at this age range to make concrete conclusions regarding concurrent relations between fine motor and language.

Studying children across 3 months to 3 years using the BSID to measure fine motor and receptive and expressive language, Houwen and colleagues (2016) found that fine motor skills were significantly positively correlated with expressive and receptive communication scores, above and beyond cognitive level. Alcock and Krawczyk (2010) measured fine motor skills across two subsets of children at 21 months of age using the BSDI or an adapted questionnaire that included fine motor questions from the ASQ parent report questionnaire. Language skills assessed using the Oxford MCDI with additional questions on from the U.S. English MCDI concerning word combinations and grammatical usage (e.g., complexity). Fine motor scores obtained via parent report were significantly positively correlated to receptive and expressive vocabulary, but not complexity. When standard scores were used to combine parent reported fine motor scores and BSDI scores, a significant and positive correlation was found for fine motor skill and receptive and expressive vocabulary, but not complexity. Neither standardized fine motor scores or fine motor questionnaire scores alone were significantly related to receptive, expressive vocabulary, or language complexity when accounting for oral movement, gross motor score, gesture, and symbolic gesture, among other control variables.

Longitudinal studies with infants and toddlers

Six studies measured longitudinal relations between fine motor skills and language outcomes across infancy and toddlerhood (Butterworth & Morissette, 1996; Choi, Leech, Tager-Flusberg, & Nelson, 2018; Leonard et al., 2015; Libertus & Violi, 2016; Lyytinen et al., 2001; Oudgenoeg-Paz et al., 2015). Samples reported on here include U.S., Dutch, and Finnish infants. The majority of the studies reported here (five out of six) measured fine motor and language skills via parent report or in lab measures, with only one study utilizing a standardized measures (Choi et al., 2018). Only two studies (about 34%) found a significant relation between fine motor skill at an early time point and later language outcomes (Choi et al., 2018; Lyytinen et al., 2001). However, both studies do not share much communality in methodology: one study found cascading effects of fine motor skills at 6 months to later language at 36 months, indicating that fine motor skills measured based on standardized assessment can have a cascading relation to language development over a 30-month time span (Choi et al., 2018). The second study assessed fine motor ability based on infant deviation from the median growth curve of fine motor skill milestones and used parent reported language at 12, 14, and 24 months (Lyytinen et al., 2001). Measures across both studies differed, as did the ages assessed. Choi, Leech, Tager-Flusberg, and Nelson (2018) did however control for visual reception skills among other demographic covariates and continued to find a significant link between fine motor and later language, which supports the idea that fine motor skills predict language beyond general cognitive skills. More detailed summaries for this set of studies are included below.

Using parent reported onset of fine motor skills and the MCDI: WG as a measure of language skills, Lyytinen and colleagues (2001) found that infant's deviation from a calculated median growth curve based on fine motor skill milestone attainment over the first year of life was predictive of vocabulary comprehension at 12 and 14 months, and vocabulary production at 14 and 30 months (but not production at 24 months). Libertus and Violi (2016) measured longitudinal changes in grasping ability from 3 to 5 months of age, and measured language using the MCDI: WG at 10 and 14 months. Findings indicated that growth in grasping duration was not significantly correlated with receptive vocabulary at 10 and 14 months of age.

Similarly, Choi, Leech, Tager-Flusberg, and Nelson (2018) also measured growth in fine motor skill in typically developing infants and in a sample of infants at high risk for ASD. Using the MSEL fine motor subscale, fine motor skills were measured from 6 to 24 months every 6 months. Expressive language skill was measured at 36 months using the MSEL expressive language subscale. For typically developing infants, high levels of fine motor skill at 6 months was predictive of greater expressive language scores at 36 months, while controlling for visual receptive skills, sex, and SES. Linear growth and quadratic growth in fine motor skills were not predictive of language scores at 36 months while accounting for covariates. Comparably, when measuring fine motor skills at 7 months using the MSEL, and receptive and expressive language at 7, 14, 24, and 36 months using the Vineland Adaptive Behavior Scales, Leonard and colleagues (2015) found that fine motor skills were not predictive of receptive or expressive language growth while controlling for visual-reception skills.

A study by Butterworth and Morissette (1996) measured pincer grip skills monthly from 8.5 to 14.5 months of age. Language was also measured monthly using the MCDI: WG. Pincer grip onset was not significantly related to MCDI comprehension or production scores at 14.5 months. Measuring fine motor skills and language later, Oudgenoeg-Paz and colleagues (2015) observed exploration through relational object exploration in lab at 20 months, and assessed production of spatial language at 36 months based on two in lab tests. Results indicated that duration of spatial relational object exploration at 20 months was not related to spatial language at 36 months.

Cross-sectional studies spanning pre-kindergarten and early childhood

A total of six studies assessed the relation between fine motor skills and language during early childhood and preschool age using cross-sectional methods and analyses (Cameron et al. 2012; Iverson & Braddock, 2010; Muluk et al., 2014; Rhemtulla & Tucker-Drob, 2011; Suggate & Stoeger, 2014; Wolff & Wolff, 1972). Samples discussed here include U.S., German, and Turkish children. Four out of the six studies (about 67%) found significant relations between fine motor ability and language skills. Two studies calculated composite scores or a factor for fine motor skills based on actions observed in lab (Rhemtulla & Tucker-Drob, 2011; Suggate & Stoeger, 2014), one study created a composite score from parent a parent report questionnaire and an in lab standardized assessment (Iverson & Braddock, 2010), one study used teacher report to measure fine motor skills (Wolff & Wolff, 1972), and another study utilized individual items drawn from a standardized assessment (Muluk et al., 2014). Cameron and colleagues (2012) measured fine motor skills using a standardized assessment, but used both a global score and individual items from the larger assessment to investigate links between fine motor and language. When measuring language skills, one study created a composite score from in lab observations and a standardized assessment (Iverson & Braddock, 2010), one study used items derived from a standardized assessment (Muluk et al., 2014), one used in lab observation exclusively (Rhemtulla & Tucker-Drob, 2011), and one only used a standardized assessment for language (Cameron et al. 2012). Suggate and Stoeger (2014) used a standardized assessment to measure receptive language skills, but also measured receptive vocabulary regarding body related objects and actions to test potential links between fine motor and language via the concept of embodiment. Four studies included covariates, with two of these studies demonstrating continued relations between fine motor and language while accounting for variability in other domains (Muluk et al., 2014; Suggate & Stoeger, 2014). In general, results in this section indicate that fine motor skills are concurrently related to language ability during preschool age and early childhood.

In a sample of typically developing children and children with language impairment ranging from 3 to 5 years old, Iverson and Braddock (2010) measured fine motor skills using the Child Development Inventory parent report instrument and the Battelle Developmental Screening Inventory. Language skills were measured using the PLS and also measures of verbal utterances per minute, number of different words used, and mean length of utterance were generated from a 10 minute in lab observation. A single composite score was created for fine motor and another composite score for language skills. Results indicated that for the typical group, fine motor was not predictive of language skills when including gesture skills as a covariate.

In their cross-sectional study, Muluk and colleagues (2016) provided separate correlations and analyses for children 3 to 6 years old with results of interest for the current review including only 3 to 5 years. Fine motor and language skills were measured using individual items from the Denver II adapted for use in Turkey. At 3 years, the fine motor skill of "imitating a vertical line" was positively significantly correlated with the language skills of "using plurals," "defining six words," and being able to "give first and last name." However, these relations were no longer significant when accounting for a host of covariates determined via backwards regression. The ability to "imitate a bridge" was significantly positively correlated with the ability to "use plurals," "name three pictures," "point to four pictures," "produce fully understandable speech," "define six words," and being able to "give first and last name." However, when controlling for various covariates, the ability to imitate a bridge was significantly related to "using plurals," "naming three pictures," and being able to "give first and last name." The ability to "build a tower of 7 blocks" was significantly positively correlated with language skills such as "knowing one function," and "being able to define six words," but these relations were no longer significant when accounting for various covariates. At 4 years, the ability to "copy a circle" was significantly positively correlated to language skills such as "knowing the use of one object," but was not significant when accounting for other covariates during backwards regression analyses. At 5 years, being able to copy a circle, cross, and a square were all significantly positively correlated with being able to "define six words," and "counting two blocks." Being able to "draw a man" was significantly positively correlated with "defining six words," "counting two blocks," and being able to "tell opposites." Copying a cross continued to be significantly related to “defining six words,” and “drawing a man” also continued to be significantly related to being able to “tell opposites” when accounting for various other covariates.

Suggate and Stoeger (2014) also measured fine motor skills and language development during preschool age. Fine motor skills were measured using 3 tasks: pegboard task, peg threading, and block turning. A single factor was created for fine motor skills. General receptive language skills were measured using the German adaptation of the PPVT. Suggate and Stoeger’s (2014) study was specifically interested in words with high levels of body-object interaction (e.g., belt; BOI), so and additional measure of BOI receptive vocabulary based on words selected from the PPVT was used as well. Receptive vocabulary for words that pertain to referents that are easily manually manipulated were also selected from the PPTV as a separate language measure. Fine motor skills were significantly positively correlated with general vocabulary, BOI vocabulary, and manipulable vocabulary, even when controlling for age. Mediation analyses suggested that BOI vocabulary significantly mediated the relation between both general and manipulation vocabulary and fine motor skill. Using exclusively teacher report measures, Wolff and Wolff (1972) also assessed the relation between fine motor and language skills. Fine motor skills were significantly positively related to both verbal output and verbal skill scores.

A longitudinal study by Rhemtulla and Tucker-Drob (2011) provided separate cross-sectional data regarding fine motor skills and language outcomes at 4 years. Fine motor skills as measured in lab by experimenters based on activities such as building a gate from wooden blocks after watching an experimenter build it out of a second set of blocks, and copying three shapes (a square, a triangle, and an asterisk) with a composite score calculated from all activities. Oral language skills were also measured using the Lets Tell Stories task. Results indicated that oral language skills at 4 years were significantly positively correlated to fine motor scores measured concurrently.

Cameron and colleagues (2012) investigated the relation between fine motor skills prior to kindergarten entry and language in kindergarten using the Early Screening-Inventory-Revised to measure fine motor skills and the Woodcock Johnson Vocabulary subtest to measure language production. Although the Early Screening-Inventory-Revised provides a composite fine motor score, Cameron et al. (2012) also used the individual fine motor items (block use, design copy, and drawing-a-person) when analyzing fine motor and language relations. The fine motor composite was significantly positively correlated with expressive vocabulary in fall of kindergarten. Specifically, block use was significantly positively correlated with fall expressive language, while design copy skills were not significantly correlated to fall expressive vocabulary. The ability to Draw-a-Person was not correlated to expressive language. However, fine motor skills did not predict expressive language skill above and beyond gross motor skills, or other covariates such as executive functioning, age, sex, ethnicity, maternal education, or age at motor assessment.

Longitudinal studies spanning pre-kindergarten and early childhood

One study selected for this systematic review examined the relation between fine motor skills and language outcomes longitudinally spanning preschool age and early childhood (Wang et al., 2014). Wang and colleagues (2014) used an established parent questionnaire to measure both fine motor and language skills. Analyses utilized covariates, with results indicating that longitudinal fine motor and language links may potentially be explained via other variables. However, more work is needed to draw stronger conclusions regarding longitudinal links between fine motor and language skills during preschool and early childhood given the limited amount of studies available.

Results from Wang and colleagues (2014) demonstrated that fine motor skills at 3 years were correlated to language at 5 years, but not when accounting for Apgar score, birthweight, gestational age, parent’s age, education, income, native language, and maternal psychological distress, and fine motor and language scores at 3 years. Fine motor skills at 3 years were significantly related to concurrent language skill at 3 years (even when accounting for covariates). Similarly, fine motor skills at 5 years were significantly related to language at 5 years, while controlling for covariates. Fine motor and a global language scores from the ASQ were used for this study.

Synthesis of fine motor and language across infancy to early childhood

Overall, studies measuring fine motor and language relations demonstrate mixed findings. Of the 15 studies total that measured fine motor skills, only 8 found that fine motor skill was significantly related to language outcomes. The prevailing pattern indicates that currently only about 53% of articles that measure fine motor skills demonstrate a significant relation with language outcomes. The most consistent findings originate from cross-sectional studies during preschool and early childhood, where about 67% of studies found significant relations between fine motor and language. Concurrent links between fine motor and language are also supported in this age group by Wang and colleagues (2014), who found in their longitudinal study that fine motor skills and language ability were related within time points, but fine motor skills at 3 years did not predict language at 5 years. Choi and colleagues (2018) did find longitudinal relations between fine motor and language, with fine motor skills at 6 months of age predicting expressive language skills at 3 years old. Similarly, Lyytinen and colleagues (2001) also demonstrate that fine motor skills relate to language in infancy and toddlerhood

However, fine motor skills have been measured less than gross motor in the current literature (15 fine motor inclusive articles versus 19 gross motor inclusive articles). In order to more thoroughly conclude whether gross motor or fine motor skills provide a better predictor for language outcomes, the final section of the results will compare results from studies that measured both gross and fine motor skills together, and assess the frequency fine motor and gross motor were found to significantly predict language outcomes from this subset of articles.

Concurrent measurement of gross motor versus fine motor skills

Eleven studies included in the current systematic review measured both gross motor and fine motor skills (Alcock & Krawczyk, 2010; Cameron et al., 2012; Houwen et al., 2016; Leonard et al., 2015; Libertus & Violi, 2016; Lyytinen et al., 2001; Muluk et al., 2014; Oudgenoeg-Paz et al., 2015; Rhemtulla & Tucker-Drob, 2011; Wang et al., 2014; Wolff & Wolff, 1972). Five studies were cross-sectional (Alcock & Krawczyk, 2010; Houwen et al., 2016; Muluk et al., 2014; Rhemtulla & Tucker-Drob, 2011; Wolff & Wolff, 1972) and six studies were longitudinal (Cameron et al., 2012; Leonard et al., 2015; Libertus & Violi, 2016; Lyytinen et al., 2001; Oudgenoeg-Paz et al., 2015; Wang et al., 2014). Six studies spanned infancy and toddlerhood (Alcock & Krawczyk, 2010; Houwen et al., 2016; Leonard et al., 2015; Libertus & Violi, 2016; Lyytinen et al., 2001; Oudgenoeg-Paz et al., 2015), and five studies were based on samples of children at preschool age and in early childhood (Cameron et al., 2012; Muluk et al., 2014; Rhemtulla & Tucker-Drob, 2011; Wang et al., 2014; Wolff & Wolff, 1972).

When focusing on only studies that measure both gross motor and fine motor, fine motor skills demonstrate a higher frequency of significant findings than gross motor skills. Three studies find that fine motor skills relate to language outcomes more frequently than gross motor skills (Houwen et al., 2016; Lyytinen et al., 2001; Wolff & Wolff, 1972). Houwen and colleagues (2016) found that fine motor scores were significantly positively correlated to expressive and receptive language above and beyond cognitive level in a cross-sectional sample with infants from 3 months to 3 years. Gross motor scores were not positively correlated to language while accounting for cognitive level. Lyytinen and colleagues (2001) also found that fine motor skills were significantly correlated to language at more time points than gross motor. Fine motor skills were significantly correlated at 12 and 14 months with vocabulary comprehension, and vocabulary production at 14 and 30 months, while gross motor skill was only significantly correlated with vocabulary comprehension at 12 and 14 months, but not with productive vocabulary at any time point across 14, 24 and 30 months. During preschool, Wolff and Wolff (1972) similarly found that fine motor skills were concurrently related to both verbal output and verbal quality, while gross motor skills were only correlated with verbal output. Two studies found that gross motor skills predicted language outcomes more frequently than fine motor skills (Libertus & Violi, 2016; Oudgenoeg-Paz et al., 2015).

However, three studies also found that both gross and fine motor skills are significantly predictive of language skills with similar frequency (Muluk et al., 2014;

Rhemtulla & Tucker-Drob, 2011; Wang et al., 2014). In the case of Muluk and colleagues, (2014), use of multiple individual behaviors to measure gross, fine motor, and language skills revealed three gross motor skills were predictive of five language skills across three to five years, and three fine motor skills that were predictive of five language skills as well. Rhemtulla & Tucker-Drob (2011) found that both gross motor and fine motor skills were correlated to oral language skills. To further attempt to disentangle these results, a more detailed focus on effect sizes finds that the correlation coefficient for fine motor skills and language was .32 and the correlation coefficient for gross motor skill and language was .29, indicating that both results had roughly a medium effect. For the study by Wang and colleagues (2014), both gross motor and fine motor scores were correlated with language skills at concurrent time points (3 and 5 years of age), but not longitudinally. Effect sizes for gross motor skill and language were .56 and .35 for 3 and 5 years respectively, and .44 and .34 for fine motor skill. Comparably however, three studies also found that neither gross motor skill or fine motor skill predict language abilities when accounting for additional covariates (Alcock & Krawczyk, 2010; Cameron et al., 2012; Leonard et al., 2015).Overall, when limiting findings to studies that measure both gross and fine motor skills for comparison between the two skill types, frequency of significant findings are closely balanced, with fine motor skills demonstrating a slight edge on gross motor skills by only one study.

Overall, we find that both gross and fine motor are related to language outcomes. However, given the low frequency of fine motor research in relation to language, we no conclusions can be drawn at the moment regarding whether one skill is more closely related to language than the other.

Discussion

The current systematic review assessed existing literature on the relation between motor and language development, and aimed to discern whether gross or fine motor skills predicted language skills more frequently. Given the available studies to draw from, a main take away from this systematic review is that both gross and fine motor skills help foster language development. However, fine motor skills have been less studied in relation to language. Thus, we caution against claiming that one motor skill type is more important than the other.

Our conclusion that both gross and fine motor skills matter for language does not mean that both motor skill types provide for language development via the same mechanisms. Although focusing on mechanism was not a goal of the current review, it is important to note that it is likely that gross and fine motor development may support language via different means. Gross motor skills such as crawling and walking allow infants to travel independently throughout their immediate environments, traversing long distances to encounter objects and caregivers. However, even within these two skills that seemingly provide the same advantage (locomotion), infants are in widely different postures, which reframes what infants are able to observe (Kretch, Franchak, & Adolph, 2014). Similarly, fine motor skills such as grasping and drawing are both related as they fall under the same motor skill umbrella, but may provide very different affordances for language learning. Recent work in infants has begun to explore potential mechanisms that underlie motor-language links (McQuillan, Smith, Yu, & Bates, 2019; Walle, 2016; West & Iverson, 2017), but further research is needed to better understand what it is about motor skills, both gross and fine, that fosters language development.

The length of motor-language cascades was a common theme of the systematic review results. Both gross motor and fine motor skills demonstrated longitudinal effects towards later language outcomes (Choi et al., 2018; Libertus & Violi, 2016; Lyytinen et al., 2001; West et al., 2017). However, some findings indicate that the length of these cascades are limited, or perhaps even constrained to concurrent relations depending on the age range (Oudgenoeg-Paz et al., 2016; Wang et al., 2014). We speculate that the temporal frame in which a motor skill is measured in relation to language likely matters for finding relations depending on the age of interest. For example, Oudgenoeg-Paz and colleagues (2016) no longer find that age of walking acquisition predicts spatial language at 43 months, but exploration via self-locomotion measured at 20 months does predict later spatial language. For fine motor skills, the majority of findings that indicate a relation between fine motor and language are derived from analyses of concurrent fine motor and language measurements, which may indicate that fine motor measures used in existing longitudinal studies may not fully tap into the appropriate fine motor skill at the appropriate age.

Fairly, it is possible that the smaller number of studies on fine motor skills and language seen in this review stems from a lack of a "holy grail" fine motor measure from 0 to 5 years of age. Gross motor measures were mostly based on parent report, which included report of motor milestones such as sitting and walking (Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014). Fine motor skills are arguably hidden in plain sight during what many would label as play: opening a box, learning to use a marker to draw, or playing with blocks. It is imperative that researchers interested in motor development begin to consider fine motor skills potentially from a milestone perspective. Researchers need not look far to find potential fine motor skills that could fit milestone criteria, as research on handedness provides a rich literature on measuring development in skills such as grasping, unimanual manipulation, and role differentiated bimanual manipulation, the latter of which continues to be a challenging fine motor skill across infancy to early childhood (Campbell, Marcinowski, Babik, & Michel, 2015; Michel, Nelson, Babik, Campbell, & Marcinowski, 2013; Nelson, Campbell, & Michel, 2013; Nelson, Gonzalez, El-Asmar, Ziade, & Abu-Rustum, 2018).

Language development has long captivated researchers, and with good reason: language allows our species to communicate with one another in ways that other forms of communication may not readily provide (Corballis, 2009). However, just as memorable as children's first words are their first steps and the time they draw their first scribbles. Motor development has for several decades provided researchers with the ability to measure and quantify behavior, with motor skills often playing a central but quiet role in some of our field's most important research paradigms and findings (e.g., Piaget, 1954; Rovee-Collier, Sullivan, Enright, Lucas, & Fagen, 1980; Walk & Gibson, 2011). As evidenced by the current systematic review, a recent revival has occurred in bringing motor development back into the fold of cognition (Adolph et al., 2010; Iverson, 2010; Rosenbaum, 2005). We hope that researchers embrace motor skills, gross and fine, as important towards our understanding of language development.

STUDY II: FINE MOTOR SKILL PREDICTS GROWTH IN EXPRESSIVE VOCABULARY FROM 12 TO 24 MONTHS

ABSTRACT

Motor skills are linked to language outcomes across infancy and toddlerhood. However, knowledge gaps remain concerning whether motor skills matter beyond traditional language predictors, and if so, whether gross motor or fine motor skills are the better predictor of language outcomes. The current study examined gross and fine motor skill development at 12-months in relation to expressive language growth from 12- to 24-months (N=95). Hierarchical regression found that fine motor, but not gross motor, skills significantly predicted expressive language growth above and beyond maternal education, infant sex, baseline language, visual reception, and gesture skills. Results indicate that fine motor skills play a distinct role in expressive language growth, and merit further investigation and inclusion in language research.

Keywords: fine motor, expressive language, infant

LITERATURE REVIEW

Introduction

Motor skills provide children with the opportunity to explore and learn about their environment with increasing independence. Broadly, motor skills can be parsed into two major categories: gross and fine motor skills. Gross motor skills refer to actions requiring coordination of large muscle groups, such as sitting, crawling, or walking. Fine motor skills refer to actions executed using smaller muscles, such as grasping and object manipulation. By the beginning of their second year, infants demonstrate a wide range of gross and fine motor abilities, generating a host of individual differences in how infants interact with objects, their environment, and caregivers as they transition from infancy to toddlerhood across 12 to 24 months (Focaroli & Iverson, 2017; Karasik, Tamis-Lemonda, & Adolph, 2011). Crucially, just as infant’s motoric independence is on the rise, children also experience dramatic changes throughout the second year of life related to communication and language abilities (Fenson et al., 1994; Samuelson & McMurray, 2017). Recent work finds that gross and fine motor skills support language development (Choi, Leech, Tager-Flusberg, & Nelson, 2018; Walle & Campos, 2014). However, it is not known whether motor skills provide any additional predictive power for language outcomes above and beyond more traditional indicators of language ability, such as parental factors or earlier language and communication levels (Friend, Schmitt, & Simpson, 2012; Hart & Risley, 1995; Hoff, 2003; Kuhn, Willoughby, Wilbourn, Vernon-Feagans, & Blair, 2014). Moreover, it is unclear whether one motor skill type—gross or fine motor—may be a better predictor of language development than the other. Answering these outstanding questions may help guide the design of future interventions.

The current study addresses these knowledge gaps over the second year of life using a longitudinal multi-measure design.

Motor Development as a Catalyst for Change

Building on the concept of embodiment, cognition is inseparable from sensorimotor experiences, and it is those physical experiences that co-act at different levels of the system to bring about new and emergent behaviors across motor and cognitive domains (Campos et al., 2000; Iverson, 2010; Masten & Cicchetti, 2010; L. B. Smith & Thelen, 2003). In particular, motor development can constrain and guide infant behavioral affordances and opportunities for learning, transforming how infants view and interact with their environment (K. Adolph et al., 2010; Campos et al., 2000; Gibson, 1988; Iverson, 2010). For example, changes in posture from crawling to walking alter infants' field of view, where being in a crawling posture limits infant's visual field to the floor, while upright walking provides infants with a view of faraway objects and people (Kretch, Franchak, & Adolph, 2014). Moreover, actively scaffolding infant grasping is linked to changes in motor development, along with changes in attention towards social stimuli and goal directed actions (Libertus, Joh, & Needham, 2015; Libertus & Needham, 2010, 2011; Sommerville, Woodward, & Needham, 2005; but see Williams, Corbetta, & Guan, 2015). Recent work further highlights the cascading role of motor development on seemingly "non-motor" domains, such as spatial ability, social skills, and academic outcomes (Bornstein, Hahn, & Suwalsky, 2013; Dinehart & Manfra, 2013; Libertus & Needham, 2011a; Soska & Adolph, 2014; Woods & Wilcox, 2012).

Motor-Language Cascades

A growing corpus of research indicates that individual differences in motor development can have cascading effects on language outcomes spanning the second and third year of life (e.g., Lebarton & Iverson, 2013; Oudgenoeg-Paz, Leseman, & Volman, 2015; Oudgenoeg-Paz, Volman, & Leseman, 2012; Walle & Campos, 2014). Much early work on motor-language cascades focused on gross motor skills in relation to language by measuring individual differences in gross motor as the presence or absence of a skill (e.g., Oudgenoeg-Paz, Volman, & Leseman, 2012; Walle & Campos, 2014). Research by Walle and Campos (2014) found that the onset of walking was predictive of increases in infant's receptive and productive vocabulary, regardless of age at walking acquisition. Similarly, findings by Oudgenoeg-Paz, Volman, & Leseman (2012) indicate that earlier onset of sitting predicted greater productive vocabulary at 16 months, and earlier walking onset predicted subsequent language growth from 16 to 28 months. Oudgenoeg-Paz and colleagues (2015) also found that age of sitting and walking onset both predicted spatial vocabulary size at 36 months of age. However, by 46 months, age of walking onset no longer significantly predicted spatial vocabulary, indicating that motor-language cascades are likely time sensitive and may be linked to periods when motor and language skills are both in flux (Oudgenoeg-Paz et al., 2016). Shifting away from measuring motor development as the presence or absence of a skill, more recent research finds that trajectories of gross motor skill growth can predict language skills at single time points (e.g., Libertus & Violi, 2016).

By comparison, studies assessing fine motor skills have more frequently utilized continuous measures of motor ability using standardized assessments to index skill level (e.g., Franchini et al., 2018; Lebarton & Iverson, 2013). It is important to note that most research on motor-language cascades that includes measures of fine motor skill has conducted comparisons between typical and atypical samples, where atypical samples largely focused on infants at high risk for autism spectrum disorder (ASD). Continued work on how motor-language cascades function within a typically developing framework will inform basic developmental science, and will advance our understanding of what atypical interactions between motor and language may look like. For example, Franchini and colleagues (2018) recently included measures of both gross and fine motor skills at 6 months as predictors of latent class trajectories for language outcomes across 9 to 24 months of age in infants at low and high risk for ASD. Although gross motor and fine motor skills were not predictive of expressive language outcomes across latent classes, gross and fine motor skills did predict differences between infants with high levels of receptive language growth (predominantly typically developing infants) and infants with low levels of receptive language growth (mostly infants who were diagnosed with ASD at 36 months). Findings by Choi and colleagues (2018) also indicate that fine motor skills at 6 months predict language outcomes at 36 months for typically developing infants. Alternatively, gross and fine motor skills at 7 months did not predict expressive language growth from 7 to 36 months for typically developing infants (Leonard et al., 2015).

Thus, both gross and fine motor skills have been identified as important for language development, with some inconsistencies across studies which may be a result of the ages tested or measures used. However, it is not known whether gross and fine motor skills provide additional predictive power above and beyond other notable predictors for language development such as infant sex, parental factors, and infant language and communication skills at earlier time points (Caselli, Rinaldi, Stefanini, & Volterra, 2012; Larry Fenson et al., 2000, 1994; Hoff, 2006; Rowe & Goldin-Meadow, 2009). Research on motor-language cascades has only recently begun to control for common language predictors such as child sex and socioeconomic status (Choi et al., 2018), and for baseline language abilities (Franchini et al., 2018). Additionally, as interest in motor-language cascades grows, it is critical for researchers to investigate whether gross or fine motor skills can function as separate and distinct indicators for language growth when compared concurrently, as research has mostly looked at gross and fine motor skills separately. To our knowledge, no study has accounted for both gross and fine motor skills in addition to baseline language, gesture, and other notable language predictors such as parent education and infant sex in the same model when predicting language growth.

The Current Study

The current study investigated the role of gross and fine motor skills at 12 months on expressive language growth from 12 to 24 months of age. We asked: 1) can gross or fine motor skills predict language outcomes above and beyond other established predictors of language ability? and if so, 2) between gross and fine motor skills, which is the better predictor for language outcomes?

Periods of transition and reorgzanization are critical for developmental cascades, thus we focused on the second year of life (12 to 24 months) when both motor and language skills change dramatically (Masten & Cicchetti, 2010; Thelen & Smith, 2006). For language development, the second year of life builds towards an exponential growth in productive language (Fenson et al., 1994; Goldfield & Reznick, 1990). Similarly, the beginning of the second year of life provides a great window into individual differences in motor skills (e.g., Adolph et al., 2012; Kretch et al., 2014). Critically, infants are notably vulnerable to language delays in the second year of life (Fernald, Marchman, & Weisleder, 2013; Hart & Risley, 1995). Thus, further understanding motor-language cascades during this time period may be beneficial for potential interventions.

Given that previous literature finds that both gross and fine motor skills separately predict language outcomes and that work on motor-language cascades has only sporadically controlled for other known predictors of language ability, we did not make a priori predictions regarding the predictive power of gross and fine motor skills on language growth when controlling for parent education, infant sex, baseline language level, and gesture.

METHOD

Participants

Ninety-five typically developing infants (51 male) were examined. Data were drawn from a larger longitudinal study (*N*=124) spanning 1 through 24 months of age on individual differences in social development (Reeb-Sutherland, Levitt, & Fox, 2012). Participants were recruited from the area surrounding the University of Maryland, College Park. Of the original sample, 111 families returned for at least one time point across 12, 18 and 24 months. Of these 111 infants, 10 infants were excluded because of parent reported exposure to a primary language other than English. To characterize typical development, an additional five infants were excluded due to expressive language delay measured by the McArthur Bates Communicative Development Inventories (CDI; Fenson et al., 2004) scores below the 10^{th} percentile across both 18 and 24 month time points, and one infant was excluded using the Mullen Scales of Early Learning (MSEL;

Mullen, 1995) composite score more than two standard deviations below the standardized norm (see Measures section for details).

The ethnic composition of the final sample of 95 infants was as follows: 49% White non-Hispanic, 23% Black or African American, 1% Hispanic, 2% Asian, 19% of mixed ethnicity, and 4% did not report ethnicity. Reported maternal education level included: 14% High School, 3% Associate's degree, 38% College degree, 36% Graduate Degree, 4% Other, and 5% did not report maternal education level. Paternal education level included: 8% High School, 1% Associate's degree, 77% College degree, 8% Graduate Degree, 1% Other, and 8% did not report paternal education level.

Procedure

Data were collected on motor development at 12 months, and on language development at 12, 18, and 24 months. Data at 12 and 24 months were collected in laboratory by trained experimenters. Parent reported language data at 18 months was collected via mail. The procedures described were approved by the Institutional Review Board at the University of Maryland, with secondary data analysis for the current study approved by the Institutional Review Board at Florida International University. Written informed consent was obtained from a parent or caregiver at each visit. Families received $40 per visit as compensation for participation.

Measures

The MSEL (Mullen, 1995) was administered at 12 months (N = 68). The MSEL is a standardized test of cognitive ability for use with children 0 to 69 months containing 5 subscales measuring different domains of functioning: gross motor (GM), fine motor (FM), visual reception (VR), receptive language (RL), and expressive language (EL). The

MSEL provides an Early Learning Composite score measuring overall cognitive functioning. Participants with low cognitive functioning using their Early Composite score (i.e., greater than two standard deviations below the standardized norm) were excluded from analyses (Bahrick, Todd, & Soska, 2018).

Data on expressive vocabulary at 12 (*N* = 69), 18 (*N* = 78), and 24 (*N* = 76) months was collected utilizing the CDI (Fenson et al., 2004) parent report checklists. Parents completed the CDI: Words and Gestures at 12 and 18 months, and the CDI: Words and Sentences at 24 months. The CDIs are widely used measures of language development, and are considered reliable and valid measures of infant language development (Fenson et al., 1994). Both CDIs allow parents to indicate the words their child can produce from a pre-established checklist, allowing for quantification of expressive vocabulary scores. The Words and Gestures form vocabulary checklist includes a total of 396 items. The Words and Gestures form also includes a checklist on infant action-gesture production comprised of 63 symbolic actions/gestures. The Words and Sentences vocabulary checklist is comprised of 680 items. Infants with CDI vocabulary scores below the 10th percentile at 18 and 24 months of age were excluded from the final sample as they met criteria for language delay (Northrup & Iverson, 2015; Roemer, West, Northrup, & Iverson, 2019).

Analyses

To address concurrent relations between language and motor development, correlations between MSEL GM, FM, RL, and EL scores, CDI gesture scores, and CDI expressive vocabulary scores at 12 months were conducted. Moreover, to investigate the relation between language growth and motor development, a hierarchical multiple regression analysis was conducted with 12-month MSEL GM and FM standard scores predicting CDI expressive vocabulary growth from 12 to 24 months. Rate of expressive vocabulary growth was determined by calculating linear slopes for participants with CDI total expressive vocabulary scores across 12, 18, and 24 month time points ($N = 56$). In step 1 of the hierarchical regression, maternal education, infant sex, and MSEL VR scores were included as covariates. Maternal education and infant sex were included given prior research indicating their relation to language outcomes (e.g., Fenson et al., 1994; Hart & Risley, 1995). The MSEL VR scores were included to control for non-verbal cognitive development, such that potential effects of GM or FM skills on language growth could parsed from more general cognitive development (Choi et al., 2018; Leonard et al., 2015). At step 2, MSEL RL and EL scores, and CDI gestures scores were included as covariates within the regression model to test whether any potential effects of motor could be noted above and beyond additional predictors specific to baseline language and communication at 12 months (e.g., Fenson et al., 1994; Kuhn, Willoughby, Wilbourn, Vernon-Feagans, & Blair, 2014; Rowe & Goldin-Meadow, 2009). Missing data patterns were not dependent on existing data values (Little's Completely at Random test $p > .05$; Little, 1988). Full information maximum likelihood estimation was used to reduce bias caused by missing values (Dong & Peng, 2013; Craig K. Enders, 2001; Schlomer, Bauman, & Card, 2010). Analyses were conducted in MPlus (version 6.12) with an alpha level of .05.

RESULTS

Means and standard deviations for all MSEL GM, FM, VR, RL, and EL scores, CDI expressive language scores at 12, 18, and 24 months, and CDI expressive language growth are displayed in Table 2.

Variable	*Mean*	*SD*
MSEL GM	51.40	13.40
MSEL FM	51.21	10.84
MSEL VR	52.18	10.82
MSEL RL	46.05	7.36
MSEL EL	50.87	9.94
CDI 12-Month Expressive Vocabulary	8.23	8.34
CDI 18-Month Expressive Vocabulary	80.74	73.40
CDI 24-Month Expressive Vocabulary	354.02	154.85
CDI 12-Month Gesture	25.70	9.75
CDI Expressive Vocabulary Growth	172.89	76.56

Table 2. Means and Standard Deviations for MSEL Subscale Scores at 12 months, CDI Expressive Vocabulary Scores at 12, 18, and 24 months, CDI Gesture Scores at 12 months, and CDI Expressive Vocabulary Growth. MSEL = Mullen Scales of Early Learning; GM = Gross Motor; FM = Fine Motor; VR = Visual Reception; RL = Receptive Language; EL = Expressive Language; CDI = MacArthur Bates Communicative Development Inventories.

Correlations between MSEL GM, FM, RL, and EL scores, CDI gesture scores, and CDI expressive vocabulary scores at 12 months were analyzed, with results displayed in Table 3. Overall, at 12 months, FM and GM scores were not significantly related to language outcomes. However, GM scores were significantly correlated with CDI gesture scores.

	1	2	3	4	5	6
1. MSEL GM	-					
2. MSEL FM	.147	-				
3. MSEL RL	.251*	.211	-			
4. MSEL EL	.152	.040	.572***	-		
5. CDI 12-month Gesture	.335**	.122	.353**	.317**	-	
6. CDI 12-month Expressive Vocabulary	.107	-.041	.335**	.541**	.577***	-

*Table 3. Correlations between MSEL Gross Motor, Fine Motor, Receptive Language, and Expressive Language Subscale Scores at 12 months, CDI Gesture Scores at 12 months, and CDI Productive Vocabulary Scores at 12 months. *p ≤. 05; **p ≤.01; ***p ≤ 001. MSEL = Mullen Scales of Early Learning; GM = Gross Motor; FM = Fine Motor; RL = Receptive Language; EL = Expressive Language; CDI = MacArthur Bates Communicative Development Inventories.*

Step 1 of the hierarchical regression demonstrated that FM scores at 12 months were significant predictors of CDI expressive vocabulary growth from 12 to 24 months, above and beyond MSEL GM scores, as well as above and beyond control variables of maternal education level, infant sex, and MSEL VR, $t(89)=2.166$, $\beta=.317$, $p=.03$. For every 1-point increase in MSEL FM scores at 12 months, rate of expressive vocabulary growth increased by 2.22 words. For full model estimates for step 1, see Table 4.

In step 2 of the hierarchical regression, MSEL RL and EL scores, and CDI gesture scores were added to the model. Even after controlling for MSEL RL and EL scores, and CDI gesture scores, MSEL FM remained a significant predictor of CDI expressive vocabulary growth from 12 to 24 months, $t(86)=2.334$, $\beta=.332$, $p=.02$. Specifically, for every 1-point increase in MSEL FM scores at 12 months, rate of expressive vocabulary growth from 12 to 24 months increased by 2.26 words. Variance inflation factors for all predictors in the final model were below 2, indicating that multicollinearity was not an issue (Kutner, Nachtsheim, Neter, & Li, 2004). Full model estimates for step 2 are included in Table 4.

Predictor	*B*	*SE B*	*β*	*t*	R^2	*F*
Step 1						
Maternal Education	-5.10	8.96	-0.07	-0.57		
Sex	-3.82	20.21	-0.03	-0.19		
MSEL VR Score	-1.44	1.09	-0.21	-1.35		
MSEL GM Score	.738	0.79	0.13	0.95		
MSEL FM Score	2.215*	1.07	0.32*	2.17		
					.11	1.25
Step 2						
Maternal Education	-3.815	8.70	-0.05	-0.44		
Sex	-9.82	19.87	-0.07	-0.50		
MSEL VR Score	-1.08	1.09	-0.16	-1.00		
MSEL GM Score	0.11	0.81	0.00	0.01		
MSEL FM Score	2.26*	1.09	.033*	2.33		
CDI 12 Months Gesture	1.88	1.21	0.24	1.58		
MSEL RL Score	-2.21	1.76	-0.21	-1.27		
MSEL EL Score	2.35	1.37	0.31	1.78		
					.22*	2.09*

Table 4. Summary of Hierarchical Regression Analysis Predicting Expressive Vocabulary Growth $*p \leq .05$. *CDI=MacArthur Bates Communicative Development Inventories; MSEL = Mullen Scales of Early Learning; GM = Gross Motor; FM = Fine Motor; VR = Visual Reception; RL = Receptive Language; EL = Expressive Language.*

DISCUSSION

The reported results support research that identifies motor development as important to language outcomes (e.g., Iverson, 2010). Infant fine motor skill at 12 months was predictive of expressive vocabulary growth from 12 to 24 months, above and beyond other common predictors of language development such as maternal education, infant sex, and language and gesture at 12 months. Results also indicate that this was not an effect of general non-verbal cognition (e.g., visual reception). Moreover, fine motor skills significantly predicted language growth across the second year of life, while gross motor skills did not.

Although we identified a link between fine motor skills and expressive language growth, this study cannot address the mechanism that underlies this relation. One possibility is that motor development transforms infant independence (Campos et al., 2000): newly acquired motor skills allow infants to interact with their environment in novel ways when prior motor skills were limited. In the case of fine motor development, more independent experience with manual object engagement is linked to greater attention to faces (Libertus & Needham, 2011). Such changes in infant behavior likely alters the language information infants can gather from their environments and caregivers. Infants with better fine motor skills may be at an advantage when mapping words on to their appropriate referent during object play (West & Iverson, 2017; Yu & Smith, 2012). Recent work finds that being able to efficiently hold and manipulate an object during play helps position the play object in the infant's dominant field of view (Yu & Smith, 2012). Moreover, during periods of infant object manipulation, caregivers are more likely to produce more instances of object labeling (West & Iverson, 2017).

Thus, fine motor skills during triadic interactions may help afford new language learning opportunities.

The current findings indicate that gross motor development was not a significant predictor of expressive language growth. Gross motor skills here were measured as a standardized score based on overall skill level. Prior research that does find a relation between gross motor and language has often utilized other measures to quantify one specific gross motor skill such as the absence or presence of a skill, age of skill onset, or weeks of experience (e.g., Oudgenoeg-Paz, Volman, & Leseman, 2016a; Walle & Campos, 2014). The current data set did not allow for analyses regarding infant's gross motor attainment or length of experience with specific gross motor skills. Analyzing the data at a single time point, gross motor scores were significantly correlated with receptive language on the MSEL at 12 months. However, we were not able to look at receptive language growth across 12 to 24 months, as receptive vocabulary was only measure at 2 time points (12 and 18 months), limiting our ability to analyze longitudinal growth. Overall, it is important to note that while gross and fine motor skills are different in type, advances in one domain likely contribute to advances in the other. Changes in posture such as sitting or walking free up infant's hands allows for new opportunities in object manipulation (e.g., Karasik, Adolph, Tamis-Lemonda, & Zuckerman, 2012; Karasik et al., 2011; Soska & Adolph, 2014; Soska, Adolph, & Johnson, 2010). Thus, it is likely that gross motor skills may be a rate limiter on fine motor skills, such that children must first achieve specific postures prior to demonstrating advancements in fine motor ability. Future work is needed to address these potential motor-motor cascades.

For a long time, motor development was relegated to "Cinderella" status within developmental psychology (Adolph et al., 2010; Iverson, 2010; Rosenbaum, 2005). Although motor development is the substrate of most measured behaviors involved in infant cognition research, the motor domain was seldom investigated as an important towards cognition in and of itself. Great strides have since been made towards highlighting motor development as an important predictor for cognitive outcomes. It is exciting to see motor research take a more central role in research relating to what are typically viewed as "non-motor" domains. However, while the current study demonstrates that fine motor skills are predictive above and beyond other measures of individual differences that affect language development, we do not advocate for placing motor skills as the *only* important predictor of language development. Factors such as SES, language environment in the home, gesture production, early vocabulary comprehension and production, as well as a host of other variables continue to be relevant for language development, and merit continued discussion. Specifically, these variable do not only pertain to language but to a host of other domains important for healthy child development (e.g., Golinkoff, Hoff, Rowe, Tamis-LeMonda, & Hirsh-Pasek, 2019). The current study was a first step in understanding the role of motor development in conjunction with other common language predictors. We also advocate for examining more naturalistic measures beyond what we have used here. For example, the quality of parent verbal input during dyadic interactions may provide a richer parental measure than parent education (e.g., Rowe, 2012).

In conclusion, we suggest that researchers interested in language development consider that motor development has been an often unmeasured and underutilized skill at their disposal (Iverson, 2018). Moreover, focusing on motor skill may provide researchers with an accessible way to detect potential delays and intervene early in development prior to adverse outcomes in language abilities. Broadly, given the implications motor development may have towards early intervention in disorders such as Autism Spectrum Disorder (West, 2018), Developmental Coordination Disorder, and Specific Language Impairment (Leonard & Hill, 2014), it is important to continue to investigate the mechanisms that underlie individual differences in motor skills that may influence language outcomes.

STUDY III: PRESCHOOL LANGUAGE ABILITY IS PREDICTED BY TODDLER HAND PREFERENCE TRAJECTORIES

ABSTRACT

Prior work has found links between consistency in toddler handedness for the fine motor skill role-differentiated bimanual manipulation (RDBM), and language development at two and three 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 three 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

LITERATURE REVIEW

Introduction

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 visual and 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 et al., 2018; Libertus & Needham, 2011b; Soska et al., 2010; E. Walle & Campos, 2014). Moreover, motor skills have been recently associated with school readiness, as children with more advanced motor skills early in development demonstrate advantages in school outcomes such as reading, math, and science (Cameron et al., 2012; 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 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 bimanual 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 towards 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 illustrate 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 towards 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 “non-motor” 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, 2011b; J. A. 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). 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., 2014, 2013; Nelson et al., 2013).

Handedness and Language

A consistent bias for hand use during fine motor actions 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, Gottfried, & Bathurst, 1991; Kee et al., 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 Bayley Scales of Infant and Toddler Development, third edition (Bayley-III; Bayley & Reuner, 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; Zimmer- man, 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. Importantly, because most prior work focused on monthly fluctuations in hand use rather than patterning over time, handedness has frequently been framed as a trait rather than a developmental phenomenon. In contrast, studies from the FLS sample and recent work by Nelson and colleagues 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 towards 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). 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.

The 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 3 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.

METHODS

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 one 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 7 time points from 18 to 24 months, with 10 children missing data at one RDBM time point, and 1 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 PLStm-5.

Procedure

The following procedures were approved by the University of North Carolina at Greensboro Institutional Review Board. 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 $10 gift card for each lab visit. Children received an additional small toy at the 5-year visit. Hand preference for RDBM was measured in lab at monthly intervals from 18 to 24 months. Each hand preference assessment was conducted within ± 7 days of the child's monthly birthday. Language development was measured in lab using the PLS$_{tm}$-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.

Measures

RDBM Hand Preference. Hand preference for RDBM was assessed using the RDBM test battery established by Nelson, Campbell, & Michel, 2013. Twenty-nine objects that afford actions where one hand stabilizes the object (non-preferred 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 minutes 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$_{tm}$-5). The PLS$_{tm}$-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$_{tm}$-5 includes two standardized scales: Auditory Comprehension (PLSAC) and Expressive Communication (PLSEC), and also provides a Total Communication score. Scores on the PLS$_{tm}$-5 are normed at 100 with a standard deviation of 15. The PLS$_{tm}$-5 is widely used. It is sensitive to even mild language difficulties, and is reliable (Zimmerman, Steiner, & Pond, 2011). Administration of the PLS$_{tm}$-5 lasted approximately 1 to 2 hours 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 2, 3, and 4 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 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 (C. K. Enders & Bandalos, 2001).

Correlations between HI scores from 18 to 24 months and PLSAC and PLSEC scores at 60 months were also conducted. While LCGA allows for determination of individual trajectory groups, past research has largely approached the relation between handedness and language using cross-sectional analyses at individual time points (e.g., Esseily et al., 2011; Vauclair & Cochet, 2013). 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. All analyses were conducted in MPlus (version 6.12) with an alpha level of .05.

RESULTS

Comparison of the LMR LR test 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 5 displays the values for class intercepts, slopes, and percentage of children in each class. Figure 2 displays the three latent class trajectories from 18 to 24 months.

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

*Table 5. Latent class membership size, intercepts and slopes for the selected model. L-Mod R = Left hand preference with a moderate amount of right hand use, R-Mod L = Right hand preference with a moderate amount of left hand use, R-Mild L = Right hand preference with a mild amount of left hand use. *** Denotes p < .001.*

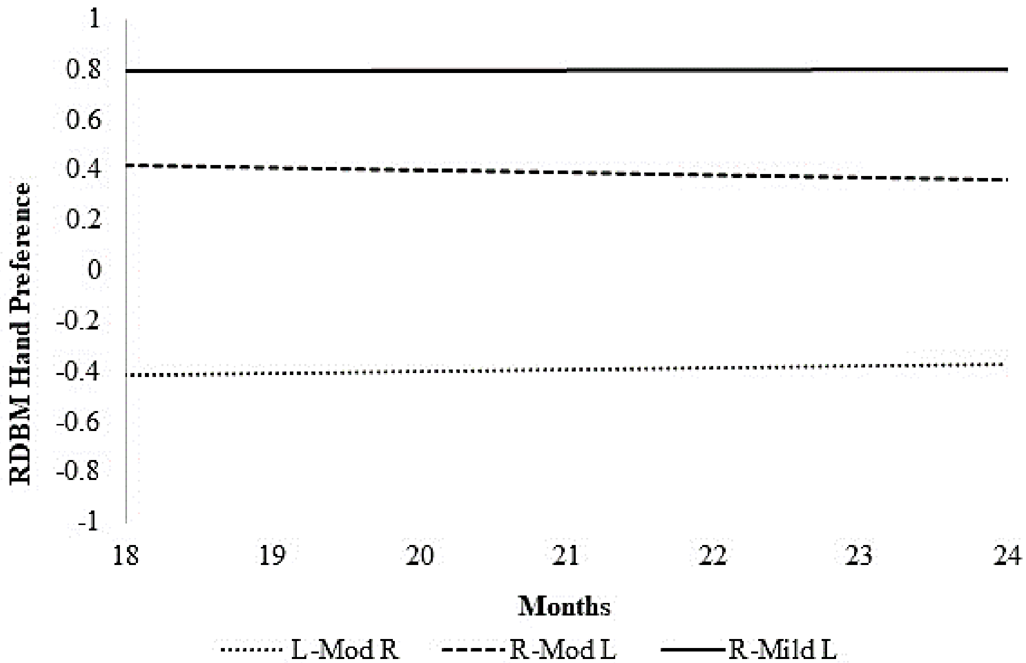

Figure 2. Predicted latent class trajectories for RDBM hand preference from 18 to 24 months. HI= Handedness Index, L-Mod R = Left hand preference with a moderate amount of right hand use, R-Mod L = Right hand preference with a moderate amount of left hand use, R-Mild L = Right hand preference with a mild amount of left hand use.

The majority of the sample (41.1%) 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, 34.4%, 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 .38. Finally, 24.4% of the sample was classified 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 to -0.05, $p = .04$) and the R-Mod R class (95% CI = −3.64 to -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 to 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 ($M = 108.46$, ± 14.68), and PLSEC scores ranged from 90 to 144 ($M = 109.50$, ± 17.59). For the R-Mod L class, PLSAC scores ranged from 69 to 122 ($M = 100.90$, ± 11.76), and PLSEC scores ranged from 65 to 122 ($M = 101.58$, ± 13.87). For the L-Mod R class, PLSAC scores ranged from 80 to 114 ($M = 99.72$, ± 9.17), and PLSEC scores ranged from 81 to 127 ($M = 98.95$, ±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 10^{th} 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, $F(2, 87) = 4.55$, $p = .01$. 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 to −0.28, $p = .04$; **Fig. 2A**), and between the R-Mild L class and the L-Mod R class (95% CI = -16.79 to −0.70, $p = .03$; **Fig. 2A**). There was no significant difference between the R-Mod L class and the L-Mod

R class (95% CI = -9.52 to 7.15, $p > .05$). Significant differences were also found between the three classes on PLSEC scores, $F(2, 87) = 4.05$, $p = .02$. 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 to -.83, $p = .03$; **Fig. 2B**). No significant difference in PLSEC scores was found between the R-Mild L and the R-Mod L classes (95% CI = -16.72 to .87, $p > .05$), or between R-Mod L and the L-Mod R classes (95% CI = -12.70 to 7.44, $p > .05$).

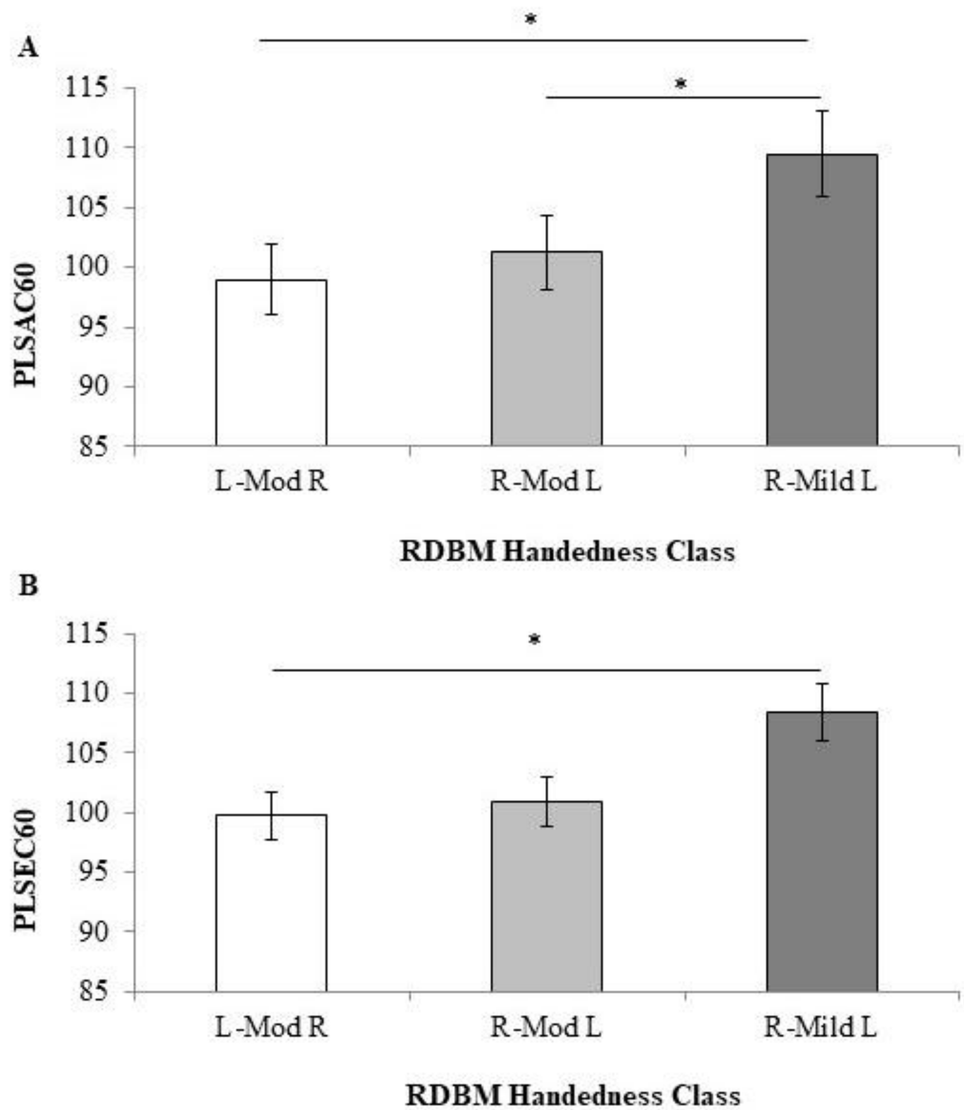

Figure 3. *Comparison of receptive language skills (A) and expressive language skills (B) across RDBM hand preference trajectories. Error bars indicate standard error. L-Mod R = Left hand preference with a moderate amount of right hand use, R-Mod L = Right hand preference with a moderate amount of left 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. *Denotes $p < .05$.*

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 (Table 6). 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 ($p < .001$).

	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***	-

*Table 6. Correlations between monthly HI scores and PLS-5 scores at 60 months. HI = Handedness Index. PLSAC60 = PLS Auditory Comprehension at 60 months. PLSEC60 = PLS Expressive Communication at 60 months. *Denotes p < .05, *** Denotes 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 predominantly right hand use for RDBM 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 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. Future work should aim to investigate language trajectories alongside handedness trajectories.

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). Thus, the cascading effect of hand preference for RDBM on language outcomes at 5 years may be greater for auditory comprehension given potentially rapid change in related language areas 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 towards early literacy. Early success in literacy is closely tied to children’s abilities in skills such as phonological awareness and vocabulary comprehension (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 for 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, 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, Gottfried, & Bathurst, 1991; Kee, Gottfried, Bathurst, & Brown, 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 towards 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 (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 3-year-old children, only 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, 2018). Similarly, in a sample of 1051 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 towards reading highlights the potential impact that consistency in hand preference during 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 2nd 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). 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 via embodiment (e.g., Iverson, 2010). 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).

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 consistency in hand preference matters for the occurrence of rich language interactions during object interactions, which may in turn cascade into later language outcomes. Michel (1992) demonstrated that maternal hand preference scaffolds infant hand preference during a play session 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 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. Is it possible that infants who are experiencing 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, parents and caregivers may influence the course of these cascades.

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 towards language development and beyond, including other domains such as school readiness.

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Appendix 1 - Detailed quality assessments of peer-reviewed studies

	Alcock & Krawczyk (2010)	Butterworth & Morissette (1996)	Cameron et. al (2012)	Choi et. al (2018)	He, Walle & Campos (2015)
Were the aims/objectives of the study clear?	Yes	Yes	Yes	Yes	Yes
Was the study design appropriate for the stated aim(s)?	Yes	Yes	Yes	Yes	Yes
Was the sample size justified?	No	No	No	No	No
Was the target/reference population clearly defined? (Is it clear who the research was about)	Yes	Yes	Yes	Yes	Yes
Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	Yes	No	Yes	Yes	Yes
Was the selection process likely to select subjects/participan ts that were representative of	Yes	Yes	Yes	Yes	Yes

the target/reference population under investigation?					
Were measures undertaken to address non-responders?	No	No	Yes	Yes	No
Were the independent and dependent variables measured appropriate to the aims of the study?	Yes	Yes	Yes	Yes	Yes
Were the independent and dependent variables measured correctly using instruments/ measurements that had been trialed, piloted or published previously?	Yes	Yes	Yes	Yes	Yes
Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., p values, CIs)	Yes	Yes	Yes	Yes	Yes
Were the methods (including	Yes	Yes	Yes	Yes	Yes

statistical methods) sufficiently described to enable them to be repeated?					
Were the basic data adequately described?	Yes	Yes	Yes	Yes	Yes
Does the response rate raise concerns about non-response bias?	No	No	No	No	No
If appropriate, was information about non-responders described?	Yes	Yes	Yes	Yes	Yes
Were the results internally consistent?	Yes	Yes	Yes	No	Yes
Were results for analyses described in the methods presented?	Yes	Yes	Yes	Yes	Yes
Were the authors' discussions and conclusions justified by the results?	Yes	Yes	Yes	Yes	Yes
Were the limitations of the study discussed?	Yes	No	Yes	Yes	Yes

Were there any funding or conflicts of interest that may affect result interpretation?	No	No	No	No	No
Was ethical approval attained?	N/A	N/A	N/A	Yes	N/A
Comments	Ethics statement not included	Ethics statement not included	*Labelled as cross-sectional based on results reported for systematic review; Ethics statement not included		Ethics statement not included; discuss missing data but unclear what actions were taken

	Houwen et. al (2016)	Iverson & Braddock (2010)	Leonard, Bedford & Pickles (2015)	Libertus & Violi (2016)	Lyytinen et. al (2001)
Were the aims/objectives of the study clear?	Yes	Yes	Yes	Yes	Yes
Was the study design appropriate for the stated aim(s)?	Yes	Yes	Yes	Yes	Yes
Was the sample size justified?	Yes	No	No	No	No
Was the target/reference population clearly defined? (Is it clear who the research was about)	Yes	Yes	Yes	Yes	Yes
Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	Yes	Yes	Yes	Yes	Yes
Was the selection process likely to select subjects/participants that were representative of	Yes	Yes	Yes	Yes	Yes

the target/reference population under investigation?					
Were measures undertaken to address non-responders?	No	No	Unclear	No	Unclear
Were the independent and dependent variables measured appropriate to the aims of the study?	Yes	Yes	Yes	Yes	Yes
Were the independent and dependent variables measured correctly using instruments/ measurements that had been trialed, piloted or published previously?	Yes	Yes	Yes	Yes	Yes
Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., p values, CIs)	Yes	Yes	Yes	Yes	Yes
Were the methods (including statistical methods)	Yes	Yes	Yes	Yes	Yes

sufficiently described to enable them to be repeated?					
Were the basic data adequately described?	Yes	Yes	Yes	Yes	Yes
Does the response rate raise concerns about non-response bias?	No	No	N/A	No	N/A
If appropriate, was information about non-responders described?	No	Yes	N/A	Yes	N/A
Were the results internally consistent?	Yes	Yes	Yes	Yes	Yes
Were results for analyses described in the methods presented?	Yes	Yes	Yes	Yes	Yes
Were the authors' discussions and conclusions justified by the results?	Yes	Yes	Yes	Yes	Yes
Were the limitations of the study discussed?	Yes	Yes	Yes	Yes	No
Were there any funding or conflicts of interest that may affect result	N/A	No	No	No	No

interpretation?					
Was ethical approval attained?	Yes	N/A	N/A	Yes	N/A
Comments	Funding/Conflict of Interest statement not included	Ethics statement not included	Unclear if there were any non-responders; Ethics statement not included		Unclear if there were any non-responders; Ethics statement not included

	Muluk, Bayoğlu, & Anlar (2014)	Muluk, Bayoğlu, & Anlar (2016)	Oudgenoeg-Paz, Volam, Lesemam (2012)	Oudgenoeg-Paz, Volam, Lesemam (2015)	Oudgenoeg-Paz, Volam, Lesemam (2016)
Were the aims/objectives of the study clear?	Yes	Yes	Yes	Yes	Yes
Was the study design appropriate for the stated aim(s)?	Yes	Yes	Yes	Yes	Yes
Was the sample size justified?	Yes	No	No	No	No
Was the target/reference population clearly defined? (Is it clear who the research was about)	Yes	Yes	Yes	Yes	Yes
Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	Yes	Yes	Yes	Yes	Yes
Was the selection process likely to select subjects/participan ts that were	Yes	Yes	Yes	Yes	Yes

representative of the target/reference population under investigation?					
Were measures undertaken to address non-responders?	Unclear	Unclear	Yes	Yes	Yes
Were the independent and dependent variables measured appropriate to the aims of the study?	Yes	Yes	Yes	Yes	Yes
Were the independent and dependent variables measured correctly using instruments/ measurements that had been trialed, piloted or published previously?	Yes	Yes	Yes	Yes	Yes
Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., p values, CIs)	Yes	Yes	Yes	Yes	Yes
Were the methods (including	Yes	Yes	Yes	Yes	Yes

statistical methods) sufficiently described to enable them to be repeated?					
Were the basic data adequately described?	Yes	No	Yes	Yes	Yes
Does the response rate raise concerns about non-response bias?	N/A	N/A	No	No	No
If appropriate, was information about non-responders described?	N/A	N/A	No	Yes	Yes
Were the results internally consistent?	Yes	Yes	Yes	Yes	Yes
Were results for analyses described in the methods presented?	Yes	No	Yes	Yes	Yes
Were the authors' discussions and conclusions justified by the results?	Yes	Yes	Yes	Yes	Yes
Were the limitations of the study discussed?	No	No	Yes	Yes	Yes
Were there any funding or conflicts of interest that may	No	No	No	N/A	No

affect result interpretation?					
Was ethical approval attained?	N/A	N/A	N/A	N/A	Yes
Comments	Unclear if there were any non-responders; Ethics statement not included	Do not mention non-responders; Did not provide full results for all variables; Ethics statement not included	Ethics statement not included	Funding/Conflict of interest statement not included/ Ethics statement not included	
	Rhemtulla & Tucker-Drob (2011)	**Suggate & Stoeger (2014)**	**Walle (2016)**	**Walle & Campos (2014)**	**Wang et. al (2014)**
Were the aims/objectives of the study clear?	Yes	Yes	Yes	Yes	Yes
Was the study design appropriate for the stated aim(s)?	Yes	Yes	Yes	Yes	Yes
Was the sample size justified?	No	No	No	No	No
Was the target/reference population clearly defined? (Is it clear who the research was about)	Yes	Yes	Yes	Yes	Yes
Was the sample frame taken from an appropriate population base so	Yes	Yes	Yes	Yes	Yes

that it closely represented the target/reference population under investigation?					
Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?	Yes	Yes	Yes	Yes	Yes
Were measures undertaken to address non-responders?	Yes	Yes	Yes	Yes	Yes
Were the independent and dependent variables measured appropriate to the aims of the study?	Yes	Yes	Yes	Yes	Yes
Were the independent and dependent variables measured correctly using instruments/ measurements that had been trialed, piloted or published	Yes	Yes	Yes	Yes	Yes

previously?					
Is it clear what was used to determined statistical significance and/or precision estimates? (e.g., p values, CIs)	Yes	Yes	Yes	Yes	Yes
Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	Yes	Yes	Yes	Yes	Yes
Were the basic data adequately described?	Yes	Yes	Yes	Yes	Yes
Does the response rate raise concerns about non-response bias?	No	No	No	No	No
If appropriate, was information about non-responders described?	Yes	Yes	Yes	Yes	No
Were the results internally consistent?	Yes	Yes	Yes	Yes	Yes
Were results for analyses described in the methods presented?	Yes	Yes	Yes	Yes	Yes

Were the authors' discussions and conclusions justified by the results?	Yes	Yes	Yes	Yes	Yes
Were the limitations of the study discussed?	No	Yes	Yes	Yes	Yes
Were there any funding or conflicts of interest that may affect result interpretation?	No	No	No	N/A	No
Was ethical approval attained?	N/A	N/A	Yes	N/A	Yes
Comments	*Labelled as cross-sectional based on results reported for systematic review; Ethics statement not included	Ethics statement not included		Funding/Conflict of interest statement not included/ Ethics statement not included	

	West et. al (2017)	Wolff & Wolff et. al (1972)
Were the aims/objectives of the study clear?	Yes	Yes
Was the study design appropriate for the stated aim(s)?	Yes	Yes
Was the sample size justified?	No	No
Was the target/reference population clearly defined? (Is it clear who the research was about)	Yes	Yes
Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?	Yes	Yes
Was the selection process likely to select subjects/participants that were	Yes	Yes

representative of the target/reference population under investigation?		
Were measures undertaken to address non-responders?	Yes	Unclear
Were the independent and dependent variables measured appropriate to the aims of the study?	Yes	Yes
Were the independent and dependent variables measured correctly using instruments/ measurements that had been trialed, piloted or published previously?	Yes	Yes
Is it clear what was used to determined statistical significance and/or precision	Yes	Yes

estimates? (e.g., p values, CIs)		
Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	Yes	Yes
Were the basic data adequately described?	Yes	Yes
Does the response rate raise concerns about non-response bias?	No	N/A
If appropriate, was information about non-responders described?	Yes	N/A
Were the results internally consistent?	Yes	Yes
Were results for analyses described in the methods presented?	Yes	Yes
Were the authors' discussions and conclusions	Yes	Yes

justified by the results?		
Were the limitations of the study discussed?	Yes	No
Were there any funding or conflicts of interest that may affect result interpretation?	No	No
Was ethical approval attained?	N/A	N/A
Comments	Ethics statement not included	Unclear if there were any non-responders; Ethics statement not included

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SELECT PUBLICATIONS & PRESENTATIONS

1. Gonzalez, S.L., & Nelson, E.L. (2019). Factor analysis of the home handedness questionnaire: Unimanual and role differentiated bimanual manipulation as separate dimensions of handedness. Applied Neuropsychology: Adult. doi: 10.1080/23279095.2019.1611578

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