2014

Number Sense Development During the Preschool Years: Relations Within and Between Key Skill Indicators

Joy C. Polignano
Lehigh University

Recommended Citation

Polignano, Joy C., "Number Sense Development During the Preschool Years: Relations Within and Between Key Skill Indicators" (2014). *Theses and Dissertations.* Paper 1595.

Number Sense Development During the Preschool Years:
Relations Within and Between Key Skill Indicators

by

Joy C. Polignano

Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Doctor of Philosophy
in
School Psychology

Lehigh University
June 2014

Certificate of Approval

Approved and recommended for acceptance as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

____
Date

____
Robin L. Hojnoski, Ph.D.
Dissertation Director
Associate Professor of School Psychology

____
Accepted Date

Committee Members:

____
Edward S. Shapiro, Ph.D.
Professor of School Psychology

____
Grace I. L. Caskie, Ph.D.
Associate Professor of Counseling

____
Randy G. Floyd, Ph.D.
Associate Professor of School Psychology
University of Memphis

Acknowledgments

I would like to begin by expressing my sincerest appreciation and gratitude to my dissertation chair and academic advisor, Dr. Robin Hojnoski, whose mentorship over the past several years has been invaluable. Dr. Hojnoski, your support and personal commitment have positively guided me through the dissertation process and throughout the course of my graduate studies. I am truly fortunate to have you as my advisor and role model. Your tremendous knowledge, dedication to the field, and personal commitment to students have been inspirational. Thank you for all the professional opportunities you have extended to me and for also allowing me to get to know your wonderful family. You were always there to offer sound advice, encouragement, or a good laugh, and for that, I am grateful.

I am also thankful for the contributions of my committee members: Dr. Edward Shapiro, Dr. Grace Caskie, and Dr. Randy Floyd. You are each remarkable leaders in the field, and your individual and collective expertise has been instrumental in the development and completion of my dissertation. Your time, thoughtful feedback, and support have made this project possible.

Last, but not least, I would like to extend my gratitude to my family and friends. Your unconditional love, support, and understanding have strengthened me during my professional journey and throughout my life. Mom, your unwavering encouragement, humor, and friendship have inspired me every step of the way. Dad, your pride in my achievements and belief in my abilities have heightened my confidence and persistence. Kelly and Mark, I have relied on your kind words and genuine reassurance to keep me going when times were tough. Thank you all for seeing me through the difficult times and celebrating my accomplishments, however small. I would never have gotten this far without you.

TABLE OF CONTENTS

Chapter 2: Literature review

Chapter 3: Method

- 3.2. Measures

Chapter 4: Results

- 4.3. Research Question 1 Results

Chapter 5: Discussion

List of Tables

List of Figures

Abstract

Early numeracy skills are predictive of later mathematics achievement; therefore, technically adequate screening tools are needed to identify young children who may be at risk for developing mathematics difficulties. The Individual Growth and Development Indicators – Early Numeracy (myIGDI-EN) is a curriculum-based measure of four key early numeracy skills: quantity comparison fluency (QCF), oral counting fluency (OCF), one-to-one correspondence counting fluency (OOCCF), and number naming fluency (NNF). MyIGDI-EN yields scores found to be technically adequate at one point in time and sensitive to growth across the preschool year in mixed-age samples of preschool children. However, age-based developmental trajectories of numeracy skills have yet to be modeled and are needed to inform assessment schedules and expectations for growth in the context of educational decision-making. Using an accelerated longitudinal design, this study sought to evaluate the developmental progression within and between the four skills measured by myIGDI-EN. Utilizing data from 408 preschool children, linear and latent basis growth curve models were evaluated in a structural equation modeling framework. Results indicated growth was represented nonlinearly across all myIGDI-EN tasks. Each task demonstrated significant age-based sensitivity to growth over the measured developmental period with the most growth evident on OCF and OOCCF. Significant variation in initial level of performance at 45 months was evident across tasks, as was significant variation in slope for all tasks except QCF. Intercept values suggest QCF is an earlier emerging skill and NNF a later emerging skill. Results strengthen and advance what is known about patterns of early numeracy growth and the suitability of myIGDI-EN for repeated measurement across the preschool years. Implications for practice and future research are discussed.

CHAPTER I: INTRODUCTION

There has been increased attention to raising standards for mathematics education of young children. In 2000, the National Council of Teachers of Mathematics (NCTM) included prekindergarten for the first time in their principles and standards for school mathematics, and that same year, a conference on standards for prekindergarten and kindergarten mathematics was held to discuss critical issues in early mathematics education (Clements, Sarama, & DiBiase, 2004). Precipitated by the Good Start, Grow Smart initiative of 2002, which is the early childhood counterpart of No Child Left Behind, states increasingly developed research-based standards for early childhood education. By 2010, all U.S. states established early learning standards in key developmental domains including mathematics to outline the skills children ages 3 to 5 should learn prior to entering kindergarten in recognition that quality early learning experiences are critical for later school success (National Center on Child Care Quality Improvement, 2011; Scott-Little, Lesko, Martella, & Milburn, 2007).

Two widespread social concerns have largely contributed to the growing interest in improving standards for mathematics education. First, despite improving trends in the mathematics achievement of American students (Fleischman, Hopstock, Pelczar, & Shelley, 2010; Mullis, Martin, & Arora, 2012), performance of students in the U.S. continues to lag behind many international comparisons, particularly East Asian and European countries (Ginsburg, Cooke, Leinwald, Noell, & Pollock, 2005; Sarama & Clements, 2009). Further, research consistently indicates the majority of American students fail to achieve mathematics proficiency (National Center for Education Statistics, 2011). This is highly detrimental within our growing system of globalization wherein science, technology, engineering, and mathematics fields are rapidly accelerating to maintain the competitiveness of our domestic technical workforce. Second, intra-national comparisons indicate there are persistent disparities in mathematics achievement that are evident as early as prekindergarten (Ginsburg, Lee, & Boyd, 2008; Jordan, Kaplan, Olah, & Locuniak, 2006; Starkey, Klein, & Wakeley, 2004). For example, longitudinal studies found that children from low-income families are more likely to enter school with less foundational knowledge for learning mathematics than their high-income counterparts, as are children from diverse sociocultural backgrounds (Denton & West, 2002; Jordan et al., 2006; Reardon & Galindo, 2009; Roberts & Bryant, 2011).

In addition to early emerging differences in mathematical skill development, research indicates these skills tend to be stable over time. For example, mathematics performance measured in kindergarten is strongly associated with mathematics achievement in later elementary school years (Jordan, Kaplan, Locuniak, & Ramineni, 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Locuniak & Jordan, 2008; Missall, Mercer, Martinez, & Casebeer, 2012). Similarly, children with persistently low levels of mathematics performance in kindergarten continue to demonstrate low rates of growth across elementary school (Aunola, Keskinen, Lerkkanen, & Nurmi, 2004; Morgan, Farkas, & Wu, 2009). Also underscoring the importance of long-term learning trajectories emerging prior to formal schooling, a meta-analysis of six longitudinal data sets indicated that school-entry mathematics skills are the strongest predictors of subsequent achievement outcomes, even more predictive than early reading and attention-related skills (Duncan et al., 2007). Overall, these findings suggest that much of the differences in later mathematics achievement are the perpetuation of differences that were present in prekindergarten and point to the need to modify beginning mathematics trajectories through early identification and intervention.

Number Sense as a Foundational Skill

There is general consensus that the development of mathematical knowledge and skills begins very early in life and continues to expand extensively throughout early childhood (Baroody, Lai, & Mix, 2006; Perry & Dockett, 2002; Sarama & Clements, 2009). Through everyday experiences, young children develop a fundamental, informal sense of mathematics that is more complex and sophisticated than previously assumed (Ginsburg et al., 2008; National Mathematics Advisory Panel [NMAP], 2008). For example, infants demonstrate the ability to discriminate between small quantities, and many begin to count soon after they learn to talk (Fuson, 1988; Geary, 2000; Mack, 2006). Very young children spontaneously enumerate sets, sort objects, search for patterns, and compare sizes prior to formal schooling (Baroody & Wilkins, 1999). It is clear that young children are capable of and interested in thinking mathematically.

Mathematics is a multidimensional construct comprised of many skills, of which number sense is the cornerstone (NCTM, 2006; NMAP, 2008). Although there are different definitions of number sense (Berch, 2005; Gersten, Jordan, & Flojo, 2005), in general, the term refers to one’s understanding of numbers, ways of representing numbers, and relationships among numbers. A well-developed number sense promotes fluency in estimation and magnitude comparison, greater ease and flexibility in computation, and the ability to recognize unreasonable results (Kalchman, Moss, & Case, 2001). Specific skills identified as part of number sense include verbal and object counting, quantity comparison, numeral identification, and basic calculation (Howell & Kemp, 2009; Lago & DiPerna, 2010).

Several indicators of number sense have been identified as predictive of later mathematics achievement. For example, young children’s counting strategies and quantity comparison abilities have been found to be valid predictors of children's ability to profit from mathematics instruction (Case, Harris, & Graham, 1992; Geary, 1990; Landerl, Bevan, & Butterworth, 2004; Mazzocco & Thompson, 2005; Okamoto & Case, 1996; Siegler & Shrager, 1984). At least one study indicated that children entering preschool with low levels of counting ability have lower levels of mathematics achievement and slower rates of mathematics growth across elementary school years than children entering preschool with high levels of counting ability (Aunola et al., 2004). In addition, research indicates both symbolic (e.g., printed numerals and number words) and non-symbolic (e.g., arrays of dots on a page) magnitude comparison skills in kindergarten predict calculation skills and number fact knowledge in first and second grade (Desoete, Ceulemans, De Weerdt, & Pieters, 2012). Finally, research suggests that speed and accuracy in number naming at kindergarten accounts for considerable variance in basic numerical skills and has an influence on mathematical achievement at the end of fourth grade (Krajewski & Schneider, 2009). Collectively, research supports the notion that later mathematical difficulties may be associated with early deficits in number sense. In light of this, the National Mathematics Advisory Panel (NMAP, 2008) emphasized that the development of early number sense is critical for setting children's learning trajectories in elementary school mathematics.

Early Identification of Number Sense Deficits

To facilitate the early identification of young children who may be at risk for developing difficulties in mathematics, systems for assessment are needed in early childhood settings. Curriculum-Based Measurement (CBM; Deno, 1985, 2003) is an assessment framework that can be successfully utilized to screen for early academic deficits in key domains such as mathematics and monitor children's progress over time. CBM is a set of formative evaluation tasks empirically linked to important outcomes and designed to detect children's responsiveness to instruction and intervention. CBM falls under the category of assessment referred to as General Outcome Measurement (GOM). In the GOM tradition, measured skills are linked to broad, long-term objectives and represent global indicators of valued educational goals (Fuchs & Deno, 1991). CBM tasks can be developed using a curriculum sampling approach or a robust indicator approach (Fuchs, 2004), frequently referred to in early childhood research as a key skill indicator approach (e.g., Carta et al., 2005). The curriculum sampling approach requires a systematic sampling of skills that are representative of the annual curriculum; whereas, key skill indicators are not necessarily tied to a particular curriculum, but rather correlate robustly with the component skills constituting a targeted domain.

CBM tasks are designed to be technically adequate, time- and cost-efficient, capable of having multiple forms, and suitable to repeated measurement (Deno, 1985). They are not intended to be diagnostic and comprehensive, but are intended to serve as indicators of a child’s performance in a given domain (Walker, Carta, Greenwood, & Buzhardt, 2008). With regard to technical adequacy, CBM tasks must demonstrate empirical support across three research stages prior to their use as screening and progress monitoring tools (Fuchs, 2004). The first stage focuses on the technical features of scores at one point in time such as interscorer, test–retest, and alternate-form reliabilities and criterion-related validity. The second stage addresses the technical features of slope to determine whether the tasks are sensitive to growth over time. These first two stages are critical in considering whether the tasks are adequate for screening across the school year. Finally, the instructional utility of the tasks are evaluated to determine whether they yield instructionally-relevant data to aid decision-making, which is essential in determining their use as progressing monitoring tools (Fuchs, 2004).

Research on mathematics CBM designed specifically for preschool children lags much further behind that focused on elementary populations (Foegen, Jiban, & Deno, 2007), and in fact, CBM did not exist in early childhood programs prior to 2002 (Greenwood, Carta, & McConnell, 2011). A challenge in the development of screening and progress monitoring tools for preschool children is the lack of a shared curriculum from which to sample; as such, researchers must select skills to assess on the basis of developmental expectations for performance. As a result, mathematics CBM for preschoolers has been designed exclusively within the key skill indicator approach and mainly focus on number sense (e.g., Floyd, Hojnoski, & Key, 2006; Hojnoski, Silberglitt, & Floyd, 2009; Lei, Wu, & Morgan, 2009; Polignano & Hojnoski, 2011; Reid, Morgan, DiPerna, & Lei, 2006; VanDerHeyden, Broussard, Fabre, Stanley, Legendre, & Creppell, 2004; VanDerHeyden, Broussard, & Cooley, 2006). For example, in one of the few studies conducted with preschoolers, Floyd et al. (2006) developed and evaluated the Preschool Numeracy Indicators, recently renamed the Individual Growth and Development Indicators – Early Numeracy (myIGDI-EN), which include tasks measuring quantity comparison, oral counting, one-to-one correspondence counting, and number naming. These four tasks have demonstrated moderate to strong test–retest and alternate-form reliabilities and concurrent validity with measures of mathematics and school readiness (Floyd et al., 2006). In addition, myIGDI-EN is the only mathematics CBM for preschoolers for which sensitivity to growth over time has been systematically examined. Specifically, the tasks have the potential to model growth across fall, winter, and spring assessment periods in samples of children attending Head Start (Hojnoski et al., 2009), with children who speak Spanish as their primary language (Hojnoski, Caskie, Polignano, & Brittain, 2012), and with children receiving special education services (Hojnoski, Caskie, & Young, 2012).

Limitations of the Research

Despite the importance of early identification of mathematics deficits in the prevention of later achievement difficulties, research on CBM for early childhood mathematics is limited (Foegan et al., 2007). This is problematic given that data-based decision-making in the preschool years has the potential to effectively promote mathematical skill development and change early learning trajectories. As such, in line with the recommendations of the NMAP (2008), continued research on the development and technical adequacy of mathematics assessment tools for young children is needed.

Because early mathematics CBM have been developed exclusively using the key skill indicator approach, it is imperative that we establish a more comprehensive understanding of the developmental progression of the key skills targeted by such measures in order to inform assessment practices and instructional targets. Detailed documentation of the developmental connections within and across key mathematical skills will enable us to identify children who demonstrate a level and rate of growth comparable to same-age peers and those children who need additional support to achieve developmental expectations for mathematics performance. Stated differently, educational decisions need to be based on empirically-supported expectations for performance and the developmental progression of key skills over time. Measurement researchers studying other early childhood developmental domains (e.g., communication, social skills, problem-solving, and cognitive abilities) have recognized the importance of measures' developmental sensitivity and have investigated longitudinally the dynamic interplay within and between various key skills comprising these domains (e.g., Carta, Greenwood, Luze, Cline, & Kuntz, 2004; Greenwood, Carta, Walker, Hughes, & Weathers, 2006; Greenwood, Walker, &

Buzhardt, 2010; Greenwood, Walker, Carta, & Higgins, 2006; Walker, Carta, Greenwood, & Buzhardt, 2008): researchers in the area of early mathematics assessment should follow suit.

Further, in the area of reading, researchers have begun to calibrate measurement schedules to developmental learning trajectories. For example, the skills assessed in kindergarten using DIBELS Next (Good & Kaminski, 2011), the most recent version of the Dynamic Indicators of Early Literacy Skills (Good & Kaminski, 1996; Kaminski & Good, 1996), are aligned with developmental expectations for reading during the kindergarten year. Specifically, students are assessed in initial sounds and letter naming at the beginning of kindergarten; initial sounds, letter naming, phoneme segmentation, and nonsense words in the middle of kindergarten; and letter naming, phoneme segmentation, and nonsense word fluency in the end of kindergarten. In the area of early mathematics assessment, researchers have not yet empirically investigated the development of number sense as it unfolds in relation to assessment practices. It is important to identify the early numeracy skills that show promising growth over time in order to ensure the CBM used assesses only the skills with the potential to reflect developmental changes in mathematical knowledge and yield instructionally-relevant data (Fuchs, 2004; Mazzocco, 2005). Assessing only the skills empirically deemed important during a given developmental window will also contribute to the time and cost efficiency of the measures.

Thus far, the only early mathematics CBM that has begun to investigate skill growth across the preschool period has been myIGDI-EN. MyIGDI-EN has demonstrated sensitivity to growth from the fall to spring of the preschool year (Hojnoski et al., 2009), aligned with Fuch’s (2004) second stage of CBM development; however, the potential for the tasks to demonstrate developmental sensitivity has not yet been systematically examined because growth has been modeled only in an aggregated sample of mixed-age preschool children. Age-based developmental trajectories of numeracy skills should be examined to inform the development of early numeracy CBM, assessment schedules, and expectations for growth in the context of educational decision-making.

Developmental and cognitive research indicates number sense does not develop in a strictly linear fashion, but rather as an interconnected web of skills that build off of each other (Purpura, Baroody, & Lonigan, 2013). Beginning in infancy and toddlerhood, young children demonstrate an innate ability to enumerate and compare small sets through subitizing (i.e., automatically recognizing the quantity of a set; Baroody & Wilkins, 1999; Ginsburg, Klein, & Starkey, 1998). A key transition in young children's mathematical development is recognition that counting, in addition to subitizing, can be used as a means of labeling and comparing quantities (Clements et al., 2004). As children gradually acquire knowledge of the counting sequence and realize that numbers represent quantities, they begin to apply the conventional number-word sequence to objects (Sarama & Clements, 2009). Finally, with increased exposure to formal mathematics instruction, children's numeracy knowledge continues to expand through the learning of culture-specific numeric symbols (e.g., Arabic numerals) and manipulation of these symbols (Baroody & Wilkins, 1999). Although developmental and cognitive research has provided evidence suggesting a continuum of early numeracy skills, researchers in the area of preschool numeracy CBM have not yet modeled age-based growth. Modeling growth on myIGDI-EN across the preschool period will allow for an empirical examination of the developmental progression of key numeracy skills over time.

Purpose of the Study

This study seeks to examine the developmental progression of key early numeracy skills measured by myIGDI-EN. Specific research questions are as follows:

(1) What is the developmental progression within each of the four tasks comprising myIGDI-EN (i.e., Quantity Comparison Fluency, Oral Counting Fluency, One-to-One Correspondence Counting Fluency, and Number Naming Fluency) across the preschool years?

(2) What are the relations between each of the myIGDI-EN tasks during the preschool years?

Because research on preschool numeracy CBM is limited, it is difficult to specify hypotheses regarding the relations within and across the skills measured by myIGDI-EN; however, it is expected that each of the tasks will demonstrate developmental sensitivity to growth over time in accordance with prior research. More specifically, it is hypothesized that Quantity Comparison Fluency (QCF) will be an earlier developing skill because children as young as infancy can distinguish which of two small sets has “more” or “less” (Sarama & Clements, 2009; Starkey & Cooper, 1995). The ability to compare quantities arguably results from one’s ability to subitize, or immediately recognize the number of items in a set, which is a key foundational skill present from a very early age (Clements, 1999; Ginsburg et al., 1998). The inclusion of larger quantities in QCF (>4) that may not be immediately recognized through subitizing, however, may provide a greater range of difficulty. Given early competency in this skill, it is likely that QCF will demonstrate the least growth over the time, demonstrating a potential ceiling effect. In addition, it is hypothesized that initial levels of Oral Counting Fluency (OCF) scores will be greater than initial levels of One-to-One Correspondence Counting

Fluency (OOCCF) scores because children must learn the counting sequence before mapping number words onto objects and coordinating number words with actions (Sarama & Clements, 2009); however, some temporal relationship between these two areas of development is expected. Finally, developmental literature indicates that numeral identification is a formal mathematics skill requiring the learning of culture-specific symbols, and thus, skill in this area usually coincides with the introduction to more formal education experiences and increased exposure to the written form of number over time (Baroody & Wilkins, 1999; Sarama & Clements, 2009). The preschool CBM literature also suggests that number naming progresses later in the developmental sequence. Specifically, an examination of the sensitivity to growth of myIGDI-EN (Hojnoski et al., 2009) found less growth on Number Naming Fluency (NNF) than the other three tasks, and greater growth rates on NNF for 4-year-olds than 3-year-olds. As such, it is hypothesized that initial levels of this skill will be lower than the other measured skills and growth will be less steep across the preschool period.

CHAPTER II: LITERATURE REVIEW

Development of Number Sense

Number sense emerges at a young age and serves as the foundation for the acquisition of higher order mathematical skills (NMAP, 2008; Sarama & Clements, 2009). As such, the area of number is the most well researched domain in early mathematics (Ginsburg, Cannon, Eisenband, & Pappas, 2006). Despite consensus that number sense is a multidimensional construct and prerequisite to continued mathematics learning, researchers have not agreed on a conceptual definition of the term or how it should be measured (Berch, 2005; Gersten et al., 2005). Attempts to operationalize number sense generally involve an understanding of the meaning of numbers, representation of numbers, and relationships among numbers (NCTM, 2006). Measurable skills within the domain of number sense have included oral counting, comparing, ordering, estimating, numeral identification, and basic arithmetic (Howell & Kemp, 2009; Lago & DiPerna, 2010). Growth within many of these skills appears to develop in a hierarchical fashion, and children develop an increasingly complex and flexible web of mathematical concepts and skills as they connect new information to previously learned knowledge (Ginsburg et al., 2006; Purpura et al., 2013).

Number sense develops informally prior to explicit mathematics instruction, with evidence suggesting the existence of math knowledge in infancy and toddlerhood (Brannon, 2002; Wynn, 1992; Wynn, Bloom, & Chiang, 2002). Very young children seem to possess innate competencies related to the enumeration of small quantities, quantity comparison, and simple arithmetic reasoning (Ginsburg et al., 1998) and have an inherent interest in searching for patterns, explanations, and solutions in everyday experiences (Baroody & Wilkins, 1999). Just as children learn language by hearing it spoken in the everyday environment, children actively learn about number through interactions with their physical and social world (Ginsburg et al., 2006). Daily occurrences such as playing games and distributing items (e.g., allocating playing cards, setting the table, and sharing snacks) provide opportunities for children to learn and apply mathematical concepts and provide the foundation for later mathematical learning (Baroody & Wilkins, 1999; Ginsburg et al., 1998).

For many children, the preschool period marks the introduction to formal mathematics instruction. Formal mathematics builds on children's existing informal knowledge and involves learning culture-specific numeric symbols (e.g., Arabic numerals and operation symbols) and manipulations of these symbols (Baroody & Wilkins, 1999). For example, research has demonstrated that informal mathematical knowledge in preschool significantly predicts numeral knowledge and written calculation in kindergarten (Purpura et al., 2013). Although a distinction has been made between informal to formal mathematics, the application of these skills is somewhat fluid. For example, children's understanding of the mental number line requires the integration of informal and formal knowledge (Griffin, Case, & Siegler, 1994). That is, children must coordinate both informal and formal systems to understand that the verbally expressed "three" corresponds to an array of three items (e.g., ●●●) and the written numeral "3" and to understand that "three" is less than "four" but more than "two."

Subitizing and Quantity Comparison

Subitizing, or the automatic recognition of quantity, appears to be a keystone skill in early numeracy development (Sarama & Clements, 2009). Children as young as age 2 and 3 demonstrate the ability to subitize by enumerating small sets up to three objects, and by age 4 and 5, recognizing sets up to five (Ginsburg et al., 1998; Starkey & Cooper, 1995). Even 6-month-old infants can discriminate among and match small configurations of objects, and 18-

month-old children can differentiate which set has more objects (Cooper, 1984; Starkey & Cooper, 1995; Starkey, Spelke, & Gelman, 1990).

There are two types of subitizing: perceptual and conceptual (Sarama & Clements, 2009). The type of subitizing evident in infancy is considered perceptual subitizing in its most primitive form. Perceptual subitizing is used with small collections up to three items; the numerosity is recognized by abstracting the number of items in the set and matching it to a number word (Sarama & Clements, 2009). As quantities become larger, children will not be able to rely solely on perception to ensure accuracy of their quantity estimation and comparison. Instead, they must rely on the more advanced skill of conceptual subitizing which involves the ability to compose and decompose a set into smaller units (Sarama & Clements, 2009). For example, a set of six objects can be perceived as two collections of three or a collection of two and a collection of four. Experiences with different arrangements of a collection will eventually help young children understand that sets can have the same number of objects despite their arrangement (von Glasersfeld, 1982).

Subitizing forms much of the foundation for the general learning of number (Sarama & Clements, 2009). It helps children make relative judgments about which set is “more” and which is “less” even before they demonstrate the ability to count (Starkey & Cooper, 1995), and this acuity in discriminating between sets becomes sharper with age (Halberta & Feigenson, 2008). In addition, through experiences comparing small and unequal collections, subitizing may help children understand that larger quantities are represented by number words farther along in the number-word sequence (Baroody & Wilkins, 1999). Finally, subitizing is implicated in the development of the cardinality principle, or the understanding that the last count represents the numerosity of the set (Clements, 1999). That is, children's first use of cardinal words are generally labels for small sets of subitized objects.

Verbal and Object Counting

Although subitizing is used throughout the lifespan as an efficient means of enumerating small sets, a key transition in the mathematical development of young children is recognizing that counting can be used as a means of labeling and comparing quantities (Clements et al., 2004). Mathematics learning gradually shifts from a more qualitative focus (i.e., attending to perceptual patterns) to a more quantitative focus (i.e., numerical patterns). The fundamental process through which children make this shift is through learning the counting sequence. Verbal counting skills may be developed before a child is 2 years old (Fuson, 1988; Fuson & Hall, 1983; Ginsburg et al., 1998), and during the preschool period, counting is typically extended through 20 (Fuson, 1992).

Initially, young children may perceive oral counting as a pattern of sounds without an understanding that numbers represent quantities, but eventually they learn that a number represents a specific quantity and apply counting in meaningful ways (Fuson, 1988). Thus, verbal counting involves both an understanding of the conventional sequence of number words and relationships between number words. As children realize numbers represent quantities, they begin to apply the conventional number-word sequence to objects, which requires the integration of number words and physical actions (e.g., pointing or moving objects; Sarama & Clements, 2009). At first, children may have trouble coordinating verbal counting and pointing to one object at a time, but once they coordinate counting and pointing, the primary difficulty is keeping track of the items that have been counted and those that have not (Fuson, 1988). The number of objects in a set, arrangement of objects, and ability to manipulate objects predict young children's counting accuracy, with more accurate counting of numerically small, linearly arranged sets of touchable objects (Clements et al., 2004; Greeno, Riley, & Gelman, 1984). By counting objects in a collection and adding or taking away objects from a collection, children learn that collections can be made larger or smaller, thereby laying the groundwork for later arithmetic tasks (Baroody & Wilkins, 1999).

Object counting is reliant on three principles: the one-to-one principle, stable order principle, and cardinality principle (Gelman & Gallistel, 1978). The one-to-one principle upholds that only one label can be given to individual objects in a set as they are counted; the stable order principle maintains that the labels assigned to objects being counted are arranged in a stable, repeatable order; and the cardinal principle asserts that the final label used in counting a set represents the number of objects in the set (Gelman & Gallistel, 1978). Cardinality, which has been referred to as the "capstone of early numerical knowledge, and the necessary building block for all further work with number and operations" (Clements et al., 2004, p. 19), is generally the last of the principles to be acquired. Children 2 and 3 years of age may be able to recite the number sequence but may not realize that the last number word stated represents the quantity of the collection (Baroody & Wilkins, 1999; Fuson, 1988). That is, they may correctly count the collection, but not be able to answer the question, "How many objects are there?" When asked, children without a grasp of cardinality often interpret the question as a cue to re-count the objects. Around 4 years of age, the cardinal meanings of "one" through "three" and perhaps "four" are learned in sequential order by means of subitizing, and children know not to assign these number words to unknown quantities (Sarnecka & Lee, 2009; Slusser & Sarnecka, 2011). That is, they realize that number words are mutually exclusive. Also around this time, a conceptual shift occurs in which children realize the cardinal meaning of a number word is fixed by the word's ordinal position in the list, and shortly thereafter, this knowledge is generalized to words "five" and higher (Sarnecka & Lee, 2009).

Numeral Identification

An understanding of the symbolic representation of quantity provides a critical link between children's informal and formal mathematics development. Informal mathematical skills, including learning the counting sequence and mapping quantities onto number words, lay the groundwork for learning numeric representations (Purpura et al., 2013). When learning the language of mathematics, young children must realize that numerals are distinct from other symbols (e.g., letters) and connect number names with written symbols. Initially, young children exhibit idiosyncratic and pictographic responses (e.g., scribble) to represent number before relying on iconic (e.g., tallies) and symbolic (e.g., numerals) responses (Hughes, 1986). To read numerals, children must construct a mental image of each numeral (Baroody & Wilkins, 1999). During the preschool years, children are increasingly able to construct a mental image of numerals 1 to 9, but may confuse numerals like 2 and 5 and 6 and 9 that share the same features (Baroody & Wilkins, 1999). When learning double-digit numerals, children interpret new cases on the basis of existing knowledge (e.g., stating "one-six" for 16). Finally, research suggests that children learn to read single-digit and teen numerals before they can write them. Writing numerals requires not only an accurate mental image of a numeral, but also a plan for translating the mental image into motor action (Clements et al., 2004). During the process of learning to write numerals, commonly occurring errors include flipped or reversed numerals and reversing digits in teen numerals (e.g., 41 for "fourteen") (Clements et al., 2004).

It is important to note that procedural knowledge related to the identification and writing of numerals does not always correspond with children's conceptual understanding of quantity, or the ability to map number words and numerals to quantities (Sarama & Clements, 2009). For example, a child may be able to identify a numeral without knowing its position on the mental number line. The potential lack of congruence between a child's procedural and conceptual knowledge may be due to the fact that development across mathematical skill areas does not follow a strict stage-like progression (Ginsburg et al., 2006); instead, children exhibit varying degrees of numeracy knowledge and employ many different strategies at any given point in time. Before developing other formal mathematics skills, however, children will need to relate their understanding of quantity, number words, and numerals (Purpura et al., 2013). In fact, research indicates that numeral knowledge (i.e., numeral identification and mapping numerals onto quantities) mediates the relation between informal knowledge and formal calculation skills in preschool and kindergarten (Purpura et al., 2013), and accuracy and speed in number naming at kindergarten is associated with mathematical achievement in fourth grade (Krajewski & Schneider, 2009). Further, children's later developing ability to compare numerals in kindergarten predicts procedural calculation in second grade (Desoete et al., 2010).

Curriculum-Based Measurement of Early Number Sense

Because number sense is a foundational skill that is predictive of later academic growth, a system for monitoring number sense development during the preschool period is critical. Tiered models of service delivery, such as Response to Intervention, are being increasingly applied in early childhood settings to identify and remediate early academic deficits in key developmental domains, such as mathematics (Greenwood, Bradfield et al., 2011). A critical component of these multi-tiered systems is universal screening several times throughout the school year to identify children falling below a benchmark standard given the general classroom curriculum and instructional strategies. These children can then be provided with more targeted instruction and their progress monitored to determine their responsiveness to more intensive services.

Curriculum-Based Measurement (CBM; Deno, 1985, 2003) is an assessment framework that can be successfully utilized within multi-tiered systems of support to evaluate young children's numeracy knowledge and inform instructional changes to accelerate skill growth. Before CBM tasks can be used as screening and progress monitoring tools, there must be evidence of the reliability and validity of the scores yielded by such measures. Specifically, CBM tasks must demonstrate empirical support across three research stages prior to their use as screening and progress monitoring tools (Fuchs, 2004). Research must evaluate the technical features of scores at one point in time (Stage 1), sensitivity to growth over time (Stage 2), and instructional utility to aid decision-making (Stage 3; Fuchs, 2004). Research in the area of early numeracy CBM has grown substantially within the past decade and has led to the development of several assessment tools that have the potential to be used to screen young children for potential academic difficulties.

Kindergarten Curriculum-Based Measures

Early Numeracy Curriculum-Based Measures. The Early Numeracy Curriculum-Based Measures (EN-CBM) developed by Clarke and Shinn (2004) have been the most well-researched CBM in early mathematics. The technical adequacy of four tasks – Oral Counting (OC), Number Identification (NI), Quantity Discrimination (QD), and Missing Number (MN) – was originally supported in a sample of first grade students and has since been examined in kindergarten samples. Chard and colleagues (2005) piloted 10 CBM tasks for kindergarten children including the EN-CBM tasks of NI, QC, and MN, as well as Count to 20, Count from 3, Count from 6, Count by 2, Count by 5, Count by 10, and Number Writing. The tasks for first grade students included numerals to 20; however, several of the kindergarten tasks were modified to include only numerals to 10. The NI, QD, and MN tasks demonstrated significant criterion-related validity with the Number Knowledge Test (Okamoto & Case, 1996); thus, these tasks were retained in future studies of EN-CBM.

Subsequent research has provided additional support for the reliability and validity of EN-CBM and modified versions of the tasks. Specifically, test–retest and alternate-form reliabilities have consistently been found to be moderate to strong (Baglici, Codding, & Tryon, 2009; Hampton, Lembke, Lee, Pappas, Chiong, & Ginsburg, 2012; Lembke & Foegan, 2009; Lembke, Foegan, Whittaker, & Hampton, 2008; Martinez, Missall, Graney, Aricack, & Clarke, 2009). In addition, validity has been demonstrated through concurrent and predictive relations with the following: teacher ratings of mathematics proficiency, the mathematics subtest of the Stanford 10 Achievement Test (SAT-10; Harcourt Educational Measurement, 2002), Test of Early Mathematics Ability (TEMA-3; Ginsburg & Baroody, 2003), mathematics subtests of the Woodcock–Johnson III Tests of Achievement (WJ III; Woodcock, McGrew, & Mather, 2001), calculation and reasoning and concepts subtests of the Woodcock–McGrew–Werder Mini Battery of Achievement (Woodcock, McGrew, & Werder, 1994), first grade AIMSweb computation probes (Shinn, 2004), first grade report card grades, and third grade Indiana Statewide Testing for Educational Progress-Plus (ISTEP+; Baglici et al., 2009; Hampton et al., 2012; Lee, Lembke, Moore, Ginsburg, & Pappas, 2012; Lembke & Foegan, 2009; Lembke et al., 2008; Martinez et al., 2009; Missall, Mercer, Martinez, & Casebeer, 2012).

In addition to Stage 1 research, the sensitivity to growth over time of EN-CBM and modified versions of the tasks has been examined. Chard et al. (2005) examined changes in mean scores across the school year and concluded that children in kindergarten and first grade demonstrated growth in NI, QD, and MN from fall to winter to spring, with NI demonstrating the most substantial growth over time. Corroborating these results, Lembke and Foegen (2009) and Martinez et al. (2009) found the greatest weekly growth rate from fall to spring of kindergarten for NI (0.79 and 0.46 respectively), followed by QD and MN. In contrast to the former two studies, results of Baglici et al. (2009) suggested that NI showed the least weekly growth (0.11) from the winter to spring during the kindergarten year relative to QD, MN, and OC. This was the only study that examined growth in OC in addition to the other three EN-CBM tasks and found that this task had the greatest weekly growth rate (0.65). Disparities in growth rates may be due to differences in the age of the samples, task variations (e.g., NI range from 0-20 versus 0-100), or period of time between assessment periods (e.g., fall to spring versus winter to spring).

Finally, two studies utilized growth curve analysis to examine the potential of EN-CBM for progress monitoring. Clarke, Baker, Smolkowski, and Chard (2008) examined the added value of slope for OC, NI, QD, and MN in predicting spring scores on the Stanford Early School Achievement Test (SESAT-2; Harcourt Brace Educational Measurement, 1996) in kindergarten. They found that the slope of only QD fit a linear growth curve and contributed to predicting spring SESAT scores, thereby calling into question the ability of the other tasks to reliably monitor student progress over time. In a similar study, Lembke et al. (2008) examined the potential of NI, QD, and MN to reliability monitor student progress in kindergarten and first grade. In contrast to Clarke et al. (2008), significant linear growth was found only for NI. Collectively, results suggest that numeracy skills in kindergarten and first grade may not follow a linear trajectory and point to the need for more research evaluating the potential of the EN-CBM for progress monitoring.

Kindergarten Early Numeracy and Literacy Assessments. The Kindergarten Early Numeracy and Literacy Assessments developed by VanDerHeyden, Witt, Naquin, and Noell (2001) included four mathematics-related tasks. Draw Circles required children to draw circles that corresponded to a given numeral; Circle Number required children to circle the numeral that corresponded to a set of circles; Write Number required children to write the numeral that corresponded to a set of objects; and Discrimination required children to identify the symbol (e.g., number, shape, and letter) that did not match the others. Thus far, two studies have been conducted to support the technical adequacy of these kindergarten measures at the Stage 1 level (VanDerHeyden et al., 2011; VanDerHeyden et al., 2001). Initial research indicated strong interscorer and alternate-form reliability in sample of kindergarten children in a suburban setting (VanDerHeyden et al, 2001). However, concurrent validity estimates with subtests of the Comprehensive Inventory of Basic Skills, Revised (CIPS-R; Brigance, 1999) were inconclusive. The kindergarten CBM tasks were not significantly correlated with the rote counting, read numerals, numeral comprehension, and write numerals subtests of the CIPS-R, and only Circle Number and Discrimination were correlated with the understands quantitative concepts subtest and overall math composite. In addition, moderate to strong non-domain specific correlations with the letter identification and letter sounds subtests called into question the construct being measured by the CBM tasks.

VanDerHeyden et al. (2011) further evaluated these tasks and piloted additional mathematics-related tasks (i.e., Pattern Completion, Shape Completion, Comparison of Sets with Equal and Unequal Items per Set, Adding or Taking Away Objects, and Subitivity) in a sample of children diverse in ethnicity and from low-income backgrounds. Interscorer agreement was high for all tasks, and test–retest reliability for the new tasks was moderate to strong. All the tasks except for Adding or Taking Away Objects were moderately correlated with kindergarten TEMA-3 scores. Predictive validity with researcher-constructed addition and subtraction CBM administered in first grade was moderate for all the tasks with the exception of Shape Completion and Subitivity.

Early Numeracy Skill Indicators. Initial research was also conducted on the Early Numeracy Skill Indicators (ENSI) developed by Methe, Hintze, and Floyd (2008). Researchers originally piloted four tasks in a sample of kindergarten children in a rural setting: Counting-On Fluency (COF) required children to count starting from a specified number other than 1; Ordinal Position Fluency (OPF) required children to identify ordinal positions to "fifth;" Number Recognition Fluency (NRF) required the naming of numerals to 20; and Match Quantity Fluency (MQF) required children to point to the numeral that matched a quantity of objects. Results indicated strong internal consistency for COF and OPF, though low internal consistency for MQF. Test-retest reliability estimates across tasks were moderate to strong. All of the tasks demonstrated moderate concurrent relations with the TEMA-3 in the fall and spring of kindergarten, with the exception of MQF which was only weakly correlated with the TEMA-3 in the spring. All tasks also demonstrated concurrent and predictive relations with teacher ratings of children's mathematical performance. In addition, the diagnostic accuracy of cut-scores for OPF and NRF facilitated accurate classification decisions with sensitivity and specificity within the range of 0.75. Based on these findings, the authors concluded that OPF and NRF demonstrated greater reliability, validity, and diagnostic accuracy than COF and MQF.

Methe, Begeny, and Leary (2011) modified some of the original ENSI tasks (i.e., Matching Quantities and Ordinality) and developed others (i.e., Touch Counting, Relative Size, Equal Partitioning, Group by Five, Decomposition, and Verbal Facts). Children in kindergarten were administered Touch Count (counting up to 30 dots), Match Quantity (matching an array of dots with a numeral), Relative Size (selecting the quantity with more or less), Equal Partitioning (dividing quantities into equal parts and identifying if items were shared equally), and Ordinality to Five (identifying ordinal positions to “five”). First graders were administered Group by Five (identifying how many groups of five items and how many items altogether), Ordinality to 10 (identifying ordinal positions to “ten”), Decomposition (matching two different arrays and basic arithmetic with picture cues), and Verbal facts (basic arithmetic without picture cues). Internal consistency and test–retest reliability of the tasks were strong, though concurrent correlations with the Calculation, Math Fluency, and Applied Problems subtests of the Woodcock–Johnson III Normative Update (Woodcock, McGrew, Schrank, & Mather, 2007) were weak to moderate. Concurrent and predictive relations were stronger for kindergarteners than first graders, and concurrent relations were stronger than predictive relations overall. Strongest criterion-related validity was found for the Equal Partitioning (EP) and Ordinality (OP) tasks, with the most robust correlations between EP and the Applied Problems subtest and OP with the Applied Problems and Computation subtests in kindergarten. In addition, the EP and OP tasks administered in the fall, winter, and spring of kindergarten were the only tasks to demonstrate adequate diagnostic accuracy in predicting performance on the Math Calculation Composite in the spring of kindergarten.

Preschool Curriculum-Based Measures

Research on screening and progress monitoring tools designed specifically for preschool children has lagged behind that for kindergarteners. In general, number sense concepts targeted in preschool and kindergarten CBM are very similar and primarily focus on skill development in quantity comparison, counting, and numeral identification. Among the main differences between kindergarten and preschool CBM tasks are the numerosities of the quantities and numerals represented.

Preschool Early Numeracy Measures. VanDerHeyden and colleagues (2004) developed the Preschool Early Numeracy Measures which included five CBM tasks. Choose Number required children to point to the number the examiner named; Count Objects required children to count quantities of objects up to 10; Free Count required children to verbally count in sequence; Discrimination required children to choose an object that was different out of a set; and Choose Shape required children to point to the shape the examiner named. Results of an initial investigation in a sample of children deemed at-risk due to demographic indicators and living in a rural setting indicated strong interscorer reliability and moderate to strong alternate-form reliability (VanDerHeyden et al., 2004). Concurrent correlations with the TEMA-2 (Ginsburg & Baroody, 1990) and the Brigance Screens (Brigance, 1985) were weak to moderate. Correlations were strongest for the Choose Number and Discrimination tasks and weakest for the Choose Shape task. Concurrent relations with teacher rankings of children's mathematics ability were mainly moderate to strong, with the weakest correlations evident for Free Count.

In subsequent research, VanDerHeyden et al. (2006) revised the Choose Number and Count Objects tasks to include numerals and quantities up to 20 instead of 10, and these modified tasks were found to strongly correlate with the original tasks. Performance on the Count Objects, Choose Number, Discrimination, Number Naming, and Free Count tasks demonstrated inconsistent predictive relations with VanDerHeyden and colleagues' (2001) kindergarten Circle Number and Discrimination tasks, with correlation coefficients ranging from .31 (preschool Choose Number and kindergarten Circle Number) to .60 (preschool

Discrimination and kindergarten Circle Number). In general, the preschool Discrimination and Free Count tasks demonstrated the strongest correlations with scores on the kindergarten CBM.

Regarding Stage 2 research, a comparison of mean scores obtained during preschool and kindergarten indicated that kindergarten children scored higher on each of the tasks (VanDerHeyden et al., 2006). Although growth across the preschool year was not examined, significant growth across a 7-week period was not evident for any task. Further, diagnostic accuracy of the preschool tasks in predicting low performers on the Brigance Screens based on cut scores recommended by test developers was found to result in 70% accurate identification with sensitivity at 0.52 and specificity of 0.88. In the same study, VanDerHeyden et al. (2006) evaluated whether the preschool measures would be sensitive to the effects of intervention. Six low-performing preschool children participated in seven sessions of direct instruction in the four skill areas tested by the measures. Although the scores of the children who received the intervention improved, growth was not significant.

Early Arithmetic and Reading Learning Indicators. The Early Arithmetic and Reading Learning Indicators (EARLI) were developed by Reid et al. (2006) as a tool for monitoring the academic growth of children attending Head Start. The EARLI included six mathematics tasks: Counting Aloud, Counting Objects, Subitizing (up to 6 objects), Number Identification, Measurement, and Pattern Recognition. As a whole, the EARLI exhibited strong item and scale reliability properties (i.e., high internal consistency and item discrimination indices) and moderate to large concurrent correlations with the Math Reasoning, Applied Problems, and Quantitative Concepts subtests of the WJ III (Woodcock et al., 2001).

Multiple short forms of the measures designed to be developmentally appropriate based on child age (3 or 4 years old) and assessment period (fall, winter, and spring) were later created by Lei, Wu, DiPerna, and Morgan (2009). Data were collected for 3- and 4-year-olds three times across the school year using two modified EARLI tasks: Numbers and Shapes consisted of 38 items requiring children to name numerals or shapes, and Measurement consisted of 20 items requiring children to identify basic measurement concepts using basic shapes. Data analysis suggested similar performance on Numbers and Shapes across all assessment periods at age 3 and in the fall of age 4, while performance was similar for winter and spring of age 4 and significantly different from the former time period; thus, two difficulty levels were created for the short form of Numbers and Shapes. Regarding the Measurement task, performance in the fall of age 3 was different from the other time points, while performance across winter and spring of age 3 and fall of age 4 were similar. Finally, performance in winter and spring of age 4 were similar and significantly different from the other time periods. Hence, short forms of the Measurement task were created to reflect three difficulty levels. Item response theory, classical test theory, and maximizing item usage selection rules were then utilized to create and compare the short forms. Internal consistency of the short forms created using all three methods were similar and acceptably high, though lower than that of the longer forms. Concurrent validity estimates of the short forms with the WJ III Applied Problems and Quantitative Concepts subtests were also lower than those of the long forms but did not differ significantly.

Individual Growth and Development Indicators – Early Numeracy. The Individual Growth and Development Indicators – Early Numeracy (myIGDI-EN) developed by Floyd et al. (2006), formally the Preschool Numeracy Indicators, are also among the few early numeracy CBM for preschoolers. Quantity Comparison Fluency (QCF) required children to determine which of two sets of objects has “more”; Oral Counting Fluency (OCF) required children to count in sequence from 1; One-to-One Correspondence Counting Fluency (OOCCF) required children to count up to 20 circles; and Number Naming Fluency (NNF) required children to name numerals up to 20. Across four preschool samples, myIGDI-EN demonstrated moderate to strong test–retest reliability and concurrent relations with the TEMA-3 and School Readiness Composite of the Bracken Basic Concept Scale (BBCS; Bracken, 1998).

After obtaining preliminary evidence at the Stage 1 level, Hojnoski et al. (2009) evaluated the sensitivity to growth of myIGDI-EN in a sample of 3- to 5-year-olds across the school year. Findings indicated the tasks yielded growth data large enough to be visually detected. Specifically, growth rates for QCF, OCF, and OOCCF were estimated to be approximately one unit per month, and the growth rate for NNF was estimated to be an increase of approximately one-half unit per month. When age was added to the linear mixed model, findings suggested that myIGDI-EN did not demonstrate differences in growth rate based age with the exception of NNF which showed steeper growth for older children.

Polignano and Hojnoski (2012) further evaluated myIGDI-EN and also developed five additional tasks (i.e., Cardinality, Pattern Completion, Shape Naming Fluency, Shape Selection Fluency, and Shape Composition). The reliability and concurrent validity of the original and new tasks were examined in a sample of preschool children identified as at-risk due to demographic characteristics. One-week alternate-form reliability was strong across all tasks, and 2-week test–retest reliability estimates were moderate to strong. Similar to earlier research, myIGDI-EN demonstrated moderate to strong correlations with the TEMA-3 and Bracken Basic Concepts Scale: Receptive (BBCS-3: R; Bracken, 2006). Further, Cardinality (CAR), the new task most closely linked to early number sense, was moderately to strongly correlated with the original myIGDI-EN tasks and strongly correlated with the TEMA-3 and School Readiness Composite of the BBCS-3: R. Interestingly, in addition to moderate to strong correlations with mathematics-related subtests of the BBCS-3:R (i.e., Numbers, Sizes/Comparisons, Shapes, Direction/Position, and Quantity), CAR also demonstrated moderate concurrent correlations with the Colors and Letters subtests of the BBCS-3:R.

Summary and Analysis of Early Numeracy CBM Literature

Utilizing Fuchs' (2004) three stages as a framework for evaluating CBM, several assessment tools for preschool and kindergarten children demonstrate potential for screening. At the kindergarten level, EN-CBM (Clarke & Shinn, 2004) has yielded the most research support at Stage 1 and 2 across multiple samples. EN-CBM demonstrate reliable and valid static scores and have the ability to model growth across the school year, though more Stage 2 research is warranted to definitively establish expected growth rates. The next step will then be to determine whether the tasks yield instructionally-relevant data to aid decision-making (Fuchs, 2004). At present, less research has evaluated the technical adequacy of the Kindergarten Early Numeracy and Literacy Assessments (VanDerHeyden et al., 2001) and ENSI (Methe et al., 2008). Although preliminary evidence supports the technical adequacy of the numeracy tasks of the Kindergarten Early Numeracy and Literacy Assessments at one point in time, research supporting their sensitivity to growth is necessary. In addition, due to the presence of non-domain specific concurrent relations, future research should focus on determining the construct being measured by the tasks. With regard to the ENSI, further investigation supporting the technical adequacy of the measures at one point in time should be conducted prior to the initiation of research on the sensitivity of the measures to model growth over time.

At the preschool level, preliminary evidence of the technical adequacy of the Preschool Early Numeracy Measures (VanDerHeyden et al., 2004), EARLI (Reid et al., 2006), and myIGDI-EN (Floyd et al., 2006) at one point in time has been established. Regarding Stage 2 research, growth has been systematically modeled across the preschool period only for myIGDI-EN (Hojnoski et al., 2009). Researchers of the EARLI, however, have provided preliminary evidence of growth based on a comparison of mean scores across the school year and developed shorter test forms to be appropriate in difficulty level for children of different ages and at different assessment periods (Lei et al., 2009; Reid et al., 2006). Although growth rates for EARLI tasks have not yet been established, researchers attended to developmental considerations (e.g., maturation and exposure to schooling) that influence number sense performance by aligning difficulty levels to age and assessment period. Finally, sensitivity to growth of the Preschool Early Numeracy Measures has not yet been investigated, but an initial exploration of the tasks' intervention utility was conducted. Because performance differences following a 7-week intervention were not significantly different than pre-intervention scores, researchers maintained that the tasks may not demonstrate sufficient sensitivity to detect change over a short duration of time and called for further investigation in this area.

Collectively, all early numeracy CBM have been developed using the key skill indicator, or robust indicator, approach. Within this assessment approach, measured skill elements are a subset of skills selected from the universe of possible skills based on their representativeness of a global outcome (Fuchs & Deno, 1991). This is in contrast to specific subskill mastery monitoring in which a skill hierarchy is derived from the curriculum and ordered as short-term objectives (Fuchs & Deno, 1991). Whereas master monitoring requires changes in content for each new skill introduced in the curriculum sequence, progress toward long-term goals in the key skill indicator approach is measured using the same tool across a longer designated age span or grade level. Because existing early numeracy CBM has been developed in the key skill tradition, it appears the global construct of number sense is conceptualized by assessment researchers as a composition of discrete skills that each contribute to the general long-term outcome. In order to better understand the development of number sense and the optimal way to measure the construct, the relations within and between each of the measured skills across the early childhood period should be investigated further.

A review of early numeracy CBM also indicates that research has primarily focused on evaluating scores at one point in time with some beginning to examine features of slope over time. Several studies that moved to Stage 2 research did not comprehensively model growth over time however; instead, many compared mean scores across assessment periods (e.g., fall, winter, and spring) or compared scores of preschool children to those of kindergarten children. Of the studies specific to preschoolers, myIGDI-EN has been the only measure for which sensitivity to growth has been systematically examined and growth rates estimated through linear mixed modeling (Hojnoski et al., 2009). However, because growth was modeled in an aggregated mixed-age sample across the preschool year, age-based developmental trajectories remain unknown. In addition, conclusions about the interplay between key skill elements over the preschool period cannot be drawn.

Researchers in the area of early mathematics CBM have not yet examined age-based growth trajectories across the preschool period. Rather, Stage 2 research has exclusively focused on measuring growth from the fall to spring of a preschool year in samples of mixed-age children. Perhaps an age-based developmental approach has been neglected because the development of CBM for young children reflects a downward extension of CBM evaluation practices for older children. Sensitivity to growth has historically been measured triannually in the fall, winter, and spring of a single school year in aggregated samples of children representing specific grade levels. Although an effective methodology for students at the elementary school level, this may not be maximally informative during the early childhood years when skills accelerate very rapidly and individual skill variation is considerable. To reflect the rapid attainment of new skills, early childhood assessment researchers in other developmental and academic domains have measured growth using smaller intervals (e.g., monthly), and applying this methodology to early numeracy CBM may prove valuable.

Alternative Conceptualization of Sensitivity to Growth

The Early Childhood Research Institute on Measuring Growth and Development (ECRI-MGD) has been a leader in the development of indicators measuring important developmental outcomes for young children from birth to preschool age. ECRI-MGD developed Individual Growth and Development Indicators (IGDI) for infants, toddlers, and preschoolers in the areas of communication, cognitive problem solving, social skills, movement, parent-child interaction, and literacy on the basis of developmental trajectories, psychometric standards, and predictive-utility (Greenwood, Carta et al., 2011). The IGDI development and validation process is consistent with Fuchs' (2004) three-stage framework, though when examining sensitivity to growth over time, greater emphasis is placed on age differences in performance since the purpose of the tasks is to identify children with developmental delays in the years before schooling and ensure they are benefitting from early intervention services (Greenwood, Carta et al., 2011).

IGDI scores are displayed in growth charts, similar to child height and weight charts, which allow for comparisons between children over time and within individual children across time. In order to obtain estimates of growth rates, ECRI-MGD researchers have commonly conducted growth curve analysis of data obtained longitudinally across short time intervals. For example, to examine the sensitivity to growth of the Early Communication Indicator (ECI), the most well-researched infant and toddler IGDI, hierarchical linear modeling was utilized to conduct growth curve analysis (Greenwood, Buzhardt, Walker, Howard, & Anderson, 2011; Greenwood et al., 2006; Greenwood et al., 2010; Greenwood et al., 2013; Luze et al., 2001). The ECI is an observational progress monitoring tool administered in the context of a 6-minute play session with a familiar adult and standard toy set that yields scores for gestures, non-word vocalizations, single-word utterances, multiple-word utterances, and a weighted total communication composite. Across studies, children of different age cohorts from birth to 3 years (i.e., 0-12, 13-24, and 25-26 months) were measured repeatedly on an approximate monthly basis, and individual and group trajectories were estimated and graphically displayed by age in years in the preliminary study (Luze et al., 2001) and by monthly intervals in future studies (Greenwood, Carta et al., 2006; Greenwood et al., 2010; Greenwood, Buzhardt et al., 2011). Initially, linear growth trajectories were computed (Greenwood, Carta et al., 2006; Luze et al., 2010), but curvilinear growth curves were later found to better fit ECI data (Greenwood et al., 2010; Greenwood, Buzhardt et al., 2011; Greenwood et al., 2013). Growth curve analyses across multiple samples allowed researchers to conclude that more complex elements of communication (single- and multiple-word utterances) gradually replace or add to the simpler elements of communication (gestures and vocalizations) that precede them between the period of birth to 3. In addition, comparisons of children with and without disabilities indicated that children with disabilities demonstrated slower growth rates for single- and multiple-word utterances and total communication scores than those without disabilities (Greenwood, Carta et al., 2006; Greenwood et al., 2010). Similar growth curve analysis techniques have been utilized with regard to the infant and toddler IGDIs measuring movement (Greenwood, Luze, Cline, Kunz, & Leitschuh, 2002), problem-solving (Greenwood, Walker et al., 2006), and social skills (Carta et al., 2004) to identify if measured skills show promising growth over time and to describe the relations among the skills representing the targeted developmental domain.

Analyzing sensitivity to growth incrementally by month has recently gained attention by preschool CBM researchers in the area of early literacy. Specifically, monthly growth rates for the Early Literacy IGDIs (EL-IGDI; Missall & McConnell, 2004), which included Picture Naming (PN), Rhyming (RHY), and Alliteration (ALL) tasks were estimated. In a preliminary study (Missall, McConnell, & Cadigan, 2006), IGDI data were collected monthly across a 5-month span in a sample preschool children (ages 44 to 68 months) with and without disabilities, and HLM was used to conduct growth curve analysis. Across all EL-IGDI tasks, average rates of growth showed significant increases over time, with PN demonstrating the steepest growth. Further, differences in growth rates were noted in children with special education needs and those attending Head Start in comparison to children without identified risk factors. In a subsequent study of EL-IGDI (Roseth, Missall, & McConnell, 2012), growth trajectories were modeled for a sample of 7,358 children whose data were inputted into the EL-IGDI online data entry and management system. Linear growth models were used to document change from 36 to 60 months, and linear-spline models were used to account for the possibility of distinct growth rates for 3- versus 4-year-olds. Results indicated significant rates of linear growth for all three tasks and different linear growth rates based on age, with 4-year-olds demonstrating steeper growth. Though research questions did not seek to describe relations between the PN, RHY, and ALL tasks, Roseth et al. (2012) provided a brief description of the interplay between the skills and speculated that proficiency in PN may be a prerequisite for growth in RHY and ALL. Taken together, research has supported the ability of EL-IGDI to detect age-based growth and facilitated the development of age-based normative data.

Purpose of the Study

As in other important developmental domains, growth in key early numeracy skills should be modeled developmentally across the early childhood period. The reliability and validity of scores yielded by myIGDI-EN have been supported at one point in time, and the four tasks have demonstrated the potential to model growth from the fall to spring of the preschool year. A logical extension of Stage 2 research is to document age-related change in myIGDI-EN scores across the preschool period. In addition, relations among indicators should be investigated to determine the developmental continuity of skills comprising the construct of number sense. To address these areas, the present study examined the age-based sensitivity to growth of myIGDI-EN in a large sample of preschool children and also described the relations between developmental growth trajectories across the preschool years.

The quantity comparison, oral counting, one-to-one correspondence counting, and number naming tasks included in myIGDI-EN all contribute to the measurement of number sense; however, it may not be necessary to administer every task at different time points during the preschool period. In order to make valid and efficient decisions regarding instructional decisions, only the tasks that are sensitive to small changes in age, time, and experience over the developmental period of interest should be utilized. MyIGDI-EN has demonstrated the ability to detect time-based change (Hojnoski et al., 2009), and the current study examined the potential of the tasks to model age-based growth.

CHAPTER III: METHOD

Participants and Setting

Data were drawn from a sample of 570 children enrolled in a public preschool program in the third largest school district in Illinois in the 2009-2010, 2010-2011, and 2011-2012 school years. In order to model age-based growth trajectories of typically developing children, 126 children (22%) receiving special education services were excluded from data analyses, leaving a sample size of 444. Given a minimum sample size recommendation of 200, the sample size was adequate for the latent growth curve methodology (Quintana & Maxwell, 1999; Weston & Gore, 2006). Boys accounted for 50% of participants. The racial/ethnic distribution of the sample was: White (40.1%), Asian (32.4%), Hispanic or Latino (14.0%), African American (8.6%), and two or more races (5.0%). As an indicator of socioeconomic status, 16.7% of the sample was entitled to free lunch, 0.9% was entitled to reduced lunch, and 82.4% was not eligible for free or reduced lunch. Of the sample, 73.4% of children attended the preschool program for 1 year and 26.3% attended the program for 2 years. One child attended for three years.

MyIGDI-EN data were obtained from 16 classes during the 2009-2010 year, 20 classes from the 2010-2011 year, and 20 classes during the 2011-2012 year. The preschool program from which the sample was drawn operated half-day morning or afternoon sessions, and classrooms were composed of up to 18 children. Each classroom was staffed by a teacher and two teacher assistants. All teachers were certified by the Illinois State Board of Education in both general education and special education. Classrooms used the Creative Curriculum and the Teaching Strategies GOLD Assessment System in addition to supplemental instructional resources.

Measures

Quantity Comparison Fluency (QCF). QCF targets children's ability to discriminate quantities of objects. Within 1 minute, students must identify which of two boxes presented on an 8.5- by 11-inch page contains more circles. Up to 30 pages are presented by the examiner in rapid succession, and each box contains 1 to 6 circles that are presented in a standard die arrangement. Children respond by touching the box with more circles. Children have 3 seconds to respond to each page. This task yields a fluency score indicating the number of correct quantity comparisons in 1 minute. Children can earn a time bonus if they respond correctly to all items in less than 60 seconds. The time bonus is calculated by dividing the product of 30 (number of items) and 60 (allotted time) by the actual number of seconds it took the child to complete the task. Children have to respond correctly to 1 of 2 sample items to be administered the task, otherwise receive a score of 0. Alternate forms of the task include the same items in a different prescribed order. Prior research indicated test–retest reliability coefficients of .89 across a 2- to 4-week interval and .94 across a 5- to 7-week interval (Floyd et al., 2006). Alternate-form reliability was .73 across a 1-week interval (Polignano & Hojnoski, 2011). Corrected correlations between QCF and scores from the Bracken Basic Concept Scale-Revised (BBCS-R; Bracken, 1998), WJ III Applied Problems test (Woodcock et al., 2001), and Test of Early Mathematics Ability-Third Edition (TEMA-3; Ginsburg & Baroody, 2003) ranged from .38 to .58 (Floyd et al., 2006). QCF growth rates obtained in a mixed-aged sample of preschool children are estimated to be approximately one unit, or one additional correct comparison per month (Hojnoski et al., 2009).

Oral Counting Fluency (OCF). OCF targets children's ability to state numbers sequentially starting from 1. The fluency score represents the last number stated correctly in sequence within 1 minute. If a number is the counting sequence is skipped or incorrect, the score is the last number correctly stated in the sequence. Prior research indicated test–retest reliability coefficients of .90 across a 2- to 4-week interval and .82 across a 5- to 7-week interval (Floyd et al., 2006). Corrected correlations between OCF and scores from the BBCS-R, WJ III Applied Problems test, and TEMA-3 ranged from .31 to .55 (Floyd et al., 2006). OCF scores demonstrated growth rates of approximately one unit, or one additional number counted per month in a mixed aged sample of preschool children (Hojnoski et al., 2009).

One-to-One Correspondence Counting Fluency (OOCCF). OOCCF targets children's ability to count objects using one-to-one correspondence. Students must point to and count up to 20 circles approximately an inch in diameter printed in a 4 by 5 arrangement within 30 seconds. This task yields a fluency score indicating the number of correct counts with one-to-one correspondence in 30 seconds. Children can earn a time bonus if they count all 20 circles correctly in less than 30 seconds. The time bonus is calculated by dividing the product of 20 (number of circles) and 30 (allotted time) by the actual number of seconds it took the child to complete the task. After a demonstration by the examiner, children have to correctly count 4 circles on a sample item in order to be administered the task, otherwise they receive a score of 0. Prior research indicated test–retest correlation coefficients of .62 across a 2- to 4-week interval and .96 across a 5- to 7-week interval (Floyd et al., 2006). Corrected correlations between OOCCF and scores from the BBCS-R, WJ III Applied Problems test, and TEMA-3 ranged from .29 to .64 (Floyd et al., 2006). Scores demonstrated growth rates of approximately one unit, or one additional object counted correctly per month in a mixed-aged sample of preschool children (Hojnoski et al., 2009).

Number Naming Fluency (NNF). NNF targets children's ability to name numerals. Children are required to state numerals (0 - 20) printed individually on 8.5- by 11-inch pages as they are presented up to three times each by the examiner in rapid succession. Children have 3 seconds to respond to each page. The fluency score represents the number of numerals named correctly in 1 minute. Alternate forms of the task include the same items in a different prescribed order. Prior research indicated test–retest reliability coefficients of .91 across a 2- to 4-week interval and .88 across a 5- to 7-week interval (Floyd et al., 2006). Alternate-form reliability was .95 across a 1-week interval (Polignano & Hojnoski, 2011). Corrected correlations between NNF and scores from the BBCS-R, WJ III Applied Problems test, and TEMA-3 ranged from .29 to .70 (Floyd et al., 2006). The monthly growth rate was estimated to be approximately one-half unit per month in a mixed-aged sample of preschool children, which suggests this measure is somewhat less sensitive than the other measures to growth over the course of one month (Hojnoski et al., 2009).

Procedures

Certified teachers employed by the school district were trained annually to administer myIGDI-EN by the preschool program's student services coordinator, a doctoral-level certified school psychologist. Training consisted of a review of administration and scoring procedures and practice assessments with feedback based on a fidelity checklist created by myIGDI-EN developers. Teachers also attended a seminar related to early mathematics and myIGDI-EN presented by a myIGDI-EN developer and were provided with online support as needed. MyIGDI-EN administration occurred as part of routine academic assessment procedures within a 2- to 4-week interval in the fall (late September to early October), winter (late January to early February), and spring (late April to early May) of the 2009-2010, 2010-2011, and 2011-2012 school years. Thus, children who attended the program for 1 year were administered myIGDI-EN up to three times, and children who attended the program for 2 years were administered myIGDI-EN up to six times.

Data Analysis

Research design. Developmental trends in numeracy skills across the preschool period were estimated using an accelerated longitudinal design. This type of design involves linking segments of overlapping repeated measurements of independent age cohorts to determine the existence of a common growth curve (Duncan, Duncan, & Hops, 1996). Stated differently, a long-term longitudinal trajectory was approximated on the basis of several converged short-term longitudinal trajectories. Previous research found growth estimates from accelerated longitudinal designs comparable to estimates from corresponding true longitudinal designs (Duncan et al., 1996; McArdle & Hamagami, 1992). Due to the potential for cohort differences resulting from unspecified demographic or history effects, particularly in studies conducted over extensive multi-year spans, analyses may be warranted to test the assumption of convergence across age cohorts (Miyazaki & Raudenbush, 2000). However, given the sufficiency of overlap in data points and stability of child and programming characteristics across age cohorts in this study (e.g., children from the same community were exposed to the same curriculum and group of teachers), convergence analysis was deemed unnecessary.

Data for this study were measured at three time points across 3 years (i.e., Fall 2009, Winter 2010, Spring 2010…Spring 2012). Aggregated across school years, children ranged in age from 37 to 67 months in the fall, 37 to 72 months in the winter, and 40 to 74 months in the spring. Only a limited number of children contributed data above 68 months of age ($N = 31$). Although there is not agreement in the literature about the minimum sample size required per observed variable (Velicer & Fava, 1998), data obtained when a child was older than 68 months were not included in analyses to reduce the potential for improper solutions. To examine developmental change based on chronological age, data were restructured by age. Four-month age intervals were established (i.e., 37-40, 41-44, 45-48, 49-52, 53-56, 57-60, 61-64, 65-68). This interval was chosen to ensure an adequate sample size within each age range, and also because it reflects a practical time interval for benchmark assessments (e.g., children are often screened in September or October, then January or February, and finally May or June). To ease interpretability, age ranges are referred from this point forward by the youngest month in age represented (e.g., 37-40 months is referred to as 37 months…65-68 months is referred to as 65 months). Because the focus of the proposed study is growth over time, children had to contribute myIGDI-EN data across a minimum of two waves of assessment to be included in the study.

Developmental progression within key skills. In order to answer the first research question, latent growth models (LGM) were calculated to examine change over time for each myIGDI-EN task within a structural equation modeling framework. This methodology supports the evaluation of growth trajectories based on repeated observations. LGM allows for the examination of a common growth curve across the sample, while also capturing interindividual variability in developmental trajectories over time (Duncan, Duncan, & Stryker 2006). In addition, when conducted in a structural equation model, the covariance of the intercept and slope can be estimated to determine the degree to which a child's value at the intercept is correlated with his or her rate of growth (Caskie, 2011). That is, one may be able to determine whether a higher initial score on a task is associated with a greater rate of growth or vice versa. Other advantages of this methodology over other methods such as repeated measures analysis of variance include tolerance of missing data when using Full Information Maximum Likelihood estimation, acceptability of unequal measurement frequencies, and accommodation of unequal intervals between measurement points (Caskie, 2011).

Within a LGM model, the estimates yielded are an intercept and slope factor for each individual in the sample, an average intercept and slope factor for the total sample based on individual-level trajectories, and variability of individual-level intercepts and slope factors. LGM can be conceptualized as an application of multilevel modeling represented by two equations. When assuming a linear model, the Level 1 equation describing within-person variation over time is expressed as

$$Y_{ip} = \pi_{0p} + \pi_{1p}t_i + \varepsilon_{ip}$$

where i = time point; p = person; t = time elapsed; π_{0p} = intercept parameter representing the value of Y for person p when $t_i = 0$; π_{1p} = slope parameter representing change in Y over time for person p; and ε_{ip} = measurement error. The equation indicates that a child's score at a particular time point is a combination of his or her true score at the intercept time point, the true rate of growth over time multiplied by the amount of time elapsed since the intercept time point, and some error.

The Level 2 equations describing between-person variation in the intercept (π_{0p}) and slope (π_{1p}) are expressed as

$$\pi_{0p} = \beta_{00} + u_{0p}$$

$$\pi_{1p} = \beta_{10} + u_{1p}$$

where β_{00} and β_{10} are fixed effects representing the average intercept and average slope for the group respectively, and u_{0p} and u_{1p} are random effects representing individual-specific variation around the average group intercept and slope respectively.

The Level 1 and 2 equations can be combined into a single equation expressing the model by substituting the Level 1 equation into the Level 2 equations and rearranging the terms. The resulting unconditional linear mixed model can be expressed as

$$Y_{ip} = \left(\beta_{00} + \beta_{10}t_i\right) + \left(u_{0p} + u_{1p}t_i\right) + \varepsilon_{ip}$$

First, the significance of the two fixed-effects (β_{00} and β_{10}) are tested to determine whether the average intercept differs significantly from zero and whether the average slope differs significantly from zero. Next, the significance of the two random-effects (u_{0p} and u_{1p}) are tested to determine the degree of interindividual variability in the intercept and slope values. This will indicate whether individuals differ significantly from each other in their intercept and rates of growth over time.

In addition to estimating linear growth, LGM also affords the flexibility to test for nonlinear trajectories across time, thereby providing information about the shape of growth curves (McArdle, 1988; Meredith & Tisak, 1990). When the shape of a trajectory is specified to be linear, the set of factor loadings (or basis coefficients) is held constant and defines the linear shape of the growth trajectory over time. Alternatively, one may not assume a priori that the trajectory is linear and instead choose to freely estimate the factor loadings using a latent basis model approach. When the set of factor loadings are unspecified, the slope factor is best interpreted as a general shape factor because the data determine the shape of the curve. The mean of the shape factor reflects the expected amount of growth, weighted by the estimated loading at each time point.

In this study, both linear and nonlinear trajectories were evaluated to determine the better fit to the data. The decision to test both models was based on an examination of unfitted mean raw score trajectories, which reflected potential nonlinear growth (see Figure 1). Model parameters were estimated using Amos 22.0 (Arbuckle, 2013). Figure 2 depicts the linear model and Figure 3 depicts the nonlinear model, with Y37 through Y65 representing the observed outcomes for each age range. Loadings on the intercept were fixed to 1 across both models because the value for each age range depends equally on the intercept term. The intercept was estimated at the first data point as to determine whether number sense skills varied significantly as early as age 3, which is a policy-linked age when children can be found eligible for Part B services under the Individuals with Disabilities Education Act (2006). The factor loadings plotted against the observed time metric indicate the shape of growth, and reflect the mean change in the observed variables. For the linear model, the loadings are fixed to 0 through 7, representing each age range. For the latent basis model, the factor loadings for the first and last factor are set respectively to 0 and 7, and the other factor loadings are unspecified to allow for free estimation.

The error structures of the models were also examined. Homoscedastic (equal) error structure means the variance of error terms is the same across all age ranges; whereas, heteroscedastic (unequal) error structure implies different error variances across age ranges. Given that data were collected over repeated measurements and by different administrators, homoscedasticity could not be assumed (Willett & Sayer, 1994). To test the assumption of homoscedasticity, the error variances of each model were fixed to 1 and then compared to a model with freely estimated errors terms using the chi-square difference test.

To determine the model that best fit the data for each myIGDI-EN task, first the linear model with homoscedastic error structure was compared to the linear model with heteroscedastic error structure using the chi-square difference test. Second, the latent basis model with homoscedastic error structure was compared to the latent basis model with heteroscedastic error structure. Third, the best fitting models determined by these two model comparisons were compared to determine which of the four competing models demonstrated better fit. Alternatively, the linear and latent basis models with homoscedastic error structures could have been compared first, followed by a comparison of the linear and latent basis models with heteroscedastic error structures. However, given there are no established guidelines regarding the order in which competing models should be evaluated, it was decided the models of the same form with different error structures would be first compared.

Criteria used to evaluate model fit included the root mean square error of approximation (RMSEA), Tucker–Lewis index (TLI), and comparative fit index (CFI). The chi-square statistic (χ^2) was also reported. A non-significant χ^2 value serves as an indicator of good fit, though χ^2 fit statistics are more likely to erroneously detect a significant effect when sample sizes exceed 200 as in this sample (Schumacker & Lomax, 2004). For RMSEA, maximum value of .08 represents acceptable fit*,* with values less than .05 indicating good fit; for CFI and TLI, a minimum value of .90 indicates acceptable fit, with values of .95 of greater indicating good fit (Brown & Cudeck, 1993*;* Hu & Bentler, 1999; Steigler 2007).

The models for each myIGDI-EN task were first evaluated with all age ranges included. When testing the models, the χ^2 and other fit indices were unable to be calculated across myIGDI-EN tasks due to limited covariance between the observed variables. The models were modified by removing the 37-month age range due to the much lower sample size relative to the other age ranges (*N* = 47-50), higher percent of zero scores (6%-42%), and more restricted ranges. Because the χ^2 and fit indices were unable to be calculated for the modified models, the 41-month age range was removed for the same former reasons allowing for the estimation of fit. As such, latent growth curves for each myIGDI-EN task were estimated for the 45- through 65-

month age ranges, which still captures a substantial portion of the preschool period, spanning 2 years.

Given that the 37- and 41-month age ranges were removed, it was necessary to ensure that children continued to meet the criterion of contributing data across a minimum of two waves of assessment. Thirty-six children no longer met the criterion, thus, data from 408 children who met the inclusion criterion were included in final analyses. The distribution of the remaining sample was: 51.5% male; 40.4% White, 31.9% Asian, 14.0% Hispanic or Latino, 8.8% African American, and 4.9% two or more races. Regarding socioeconomic status, 17.2% was entitled to free lunch, 0.7% was entitled to reduced lunch, and 82.1% was not eligible for free or reduced lunch. Of the children who contributed data between 45 and 65 months, 20.6% contributed data across two waves of assessment (*N* = 84), 52.0% across three (*N* = 212), 13.2% across four (*N* = 54), 11.5% across five (*N* = 47), and 2.7% across six (*N* = 11).

Relations between key skills. In order to evaluate relations between skills over time, a visual inspection of the growth trajectories was conducted. Specifically, the initial levels of children's performance on each myIGDI-EN task were examined, as was the steepness of growth over time for each task. Further, data were visually analyzed to determine the temporal stability of skills in relation to each other.

CHAPTER IV: RESULTS

Treatment of Outliers and Missing Data

Data were screened for univariate outliers using *z*-scores greater than 3.29 standard deviations above or below the mean, which is the standard score value that corresponds to a probability of .001 (two-tailed). Of 5,317 measurement occasions between the 45- and 65-month period, 22 values were 3.29 standard deviations above the mean, and 9 values were 3.29 standard deviations below the mean. Because outliers increase the likelihood of improper solutions (Bollen, 1987), these values were excluded from data analyses.

Given that an accelerated longitudinal design was utilized, children did not contribute data across all measurement occasions. Accelerated longitudinal designs fall in the class of research designs that strategically incorporate planned missing data. In planned missing data designs, participants are assigned to conditions in which they do not respond to all items, measures, or measurement occasions (Graham, Taylor, Olchowski, & Cumsille, 2006; Rhemtulla & Little, 2012). In this study, children had different numbers of repeated measurements due to their respective ages during each fall, winter, and spring assessment period, as well as differences in the number of years enrolled in the preschool, transfers, and absences. Detailed information regarding the number of data points children contributed across the age distribution is presented in Table 1. Of 9,792 possible observed values, 4,475 were missing, for a total of 46% missing data. It was estimated 90% of missing data was planned missing data. Planned missing data are missing completely at random (MCAR; Balardi & Enders, 2010; Rubin, 1976), meaning the cause of the missingness is completely unrelated to any of the observed or missing variables. The remaining 10% appeared to be missing as a result of uncontrolled variables such as transfers and absences, and can be considered missing at random (MAR; Balardi & Enders, 2010; Rubin, 1976). To address the missing data, Full Information Maximum Likelihood (FIML) procedures were utilized. This method is preferred over traditional deletion techniques or single imputation methods, and performs as well or better than multiple imputation methods (Balardi & Enders, 2010; Graham, Olchowski, & Gilreath, 2007). FIML estimates parameter values that have the highest probability of producing the sample data by utilizing all available data.

Descriptive Statistics

Means and standard deviations for all measurements are reported in Table 2. As previously noted, age ranges are referred to by the youngest month in age represented (e.g., 45-48 months is referred to as 45 months…65-68 months is referred to as 65 months). Skewness and kurtosis values are also reported, and all fall within the recommended interval of -2 to +2 and -7 to +7, respectively (Curran, West, & Finch, 1996), suggesting the assumption of approximate normality is tenable. In addition, Table 2 includes the percent of zero scores across tasks for each age range. The percent of zero scores is an important descriptive statistic as it has the potential to indicate the presence or absence of a floor effect, and for this sample, values suggest a potential floor effect for the youngest age range in NNF. Correlations among the observed variables across age ranges are available from the author.

Relations Within Numeracy Skills

QCF. In order to determine the best fitting trajectory representing skill growth on QCF, first the linear model with heteroscedastic error was compared to the linear model with homoscedastic error. The linear model with heteroscedastic error represented a better fit to the QCF data, $\Delta\chi^2(5, N = 408) = 40.68, p < .001$. Second, the latent basis model with heteroscedastic error was compared to the latent basis model with homoscedastic error, and the latent basis model with heteroscedastic error represented a better fit to the data, $\Delta\chi^2$ (5, *N* = 408) = 19.32, $p = .002$. Third, the latent basis and linear models with heteroscedastic error structures were compared, and the latent basis model with heteroscedastic error was the better fitting model, $\Delta\chi^2$ (4, *N* = 408) = 12.56, $p =.01$.

The latent basis model with heteroscedastic error represented a good fit to the data, χ^2 (12, *N* = 408) = 14.12, $p = 0.29$, RMSEA = .02, CFI = .99, TLI = .99. Results indicated an average intercept of 18.27 correct quantity comparisons per minute at 45 months ($p < .001$) and an average slope value of 2.64 ($p < .001$), indicating children's scores are expected to increase by 13.20 units on average from 45 to 65 months. As reported in Table 3, substantial variation among children's initial QCF score at 45 months was evident, though not in children's skill growth over time. The estimated covariance between the intercept and slope was not significant, indicating a child's initial QCF score does not covary with his or her rate of growth. Utilizing basis coefficients to estimate average percentages of growth across time, a child is expected to realize 31.5% of growth between 45 and 49 months, 18.6% between 49 and 53 months, 16.8% between 53 and 57 months, 16.5% between 57 and 61 months, and 16.6% between 61 and 65 months. Although the latent basis model with heteroscedastic error best represented the data, it should be noted that the linear model with heteroscedastic error also represented good fit, χ^2 (16, *N* = 408) = 26.67, $p = .05$, RMSEA = .04, CFI = .96, TLI = .95, with an average intercept of 19.69 ($p < .001$) and average linear slope of 2.45 per 4-month interval ($p < .001$).

OCF. Comparing the linear model with heteroscedastic error to the linear model with homoscedastic error, the linear model with heteroscedastic error represented a better fit to the OCF data, $\Delta\chi^2$ (5, *N* = 408) = 60.49, $p < .001$. When the latent basis model with heteroscedastic error was compared to the latent basis model with homoscedastic error, the latent basis model with heteroscedastic error represented a better fit to the data, $\Delta\chi^2$ (5, $N = 408$) = 62.68, $p < .001$. Finally, the latent basis model and linear models with heteroscedastic error structures were compared, and the latent basis model with heteroscedastic error best fit the data, $\Delta\chi^2$ (4, $N = 408$) = 23.61, $p < .001$.

The latent basis model with heteroscedastic error represented a good fit to the data, χ^2 (12, $N = 408$) = 15.29, $p = .23$, RMSEA = .03, CFI = 1.0, TLI = .99. Results indicated an average intercept of 13.84 oral counts per minute at 45 months ($p < .001$) and an average slope value of 5.90 ($p < .001$), indicating an increase of approximately 29.50 oral counts from 45 to 65 months. As reported in Table 4, substantial variation among children's OCF score at 45 months was evident, as was variability in children's skill growth over time. The estimated covariance between the intercept and slope was also significant, indicating children with higher initial OCF scores demonstrated greater rates of growth over time, and vice versa. Applying the average slope to the developmental curve, a child is expected to realize 12.5% of growth between 45 and 49 months, 20.5% between 49 and 53 months, 24.7% between 53 and 57 months, 21.1% between 57 and 61 months, and 21.2% between 61 and 65 months. The latent basis model with heteroscedastic error best fit the data, though the linear model with heteroscedastic error also represented acceptable fit, χ^2 (16, $N = 408$) = 38.90, $p = .001$, RMSEA = .06, CFI = .97, TLI = .96, with an average intercept of 12.82 ($p < .001$) and an average linear slope of 5.78 oral counts per 4-month interval ($p < .001$).

OOCCF. A comparison of linear models indicated the model with heteroscedastic error represented a better fit to the OOCCF data than the linear model with homoscedastic error, $\Delta\chi^2$ (5, $N = 408$) = 62.67, $p < .001$. Similarly, the latent basis model with heteroscedastic error was better fitting than the latent basis model with homoscedastic error, $\Delta\chi^2$ (5, $N = 408$) = 60.03, p

$< .001$. When the latent basis model and linear models with heteroscedastic error structures were compared, the latent basis model with heteroscedastic error was found to better represent the data, $\Delta\chi^2$ (4, *N* = 408) = 9.38, *p* = .05.

The latent basis growth model with heteroscedastic error represented a good fit to the data, χ^2 (12, *N* = 408) = 13.81, *p* = .31, RMSEA = .02, CFI = .99, TLI = .99. Results indicated an average intercept of 13.17 at 45 months (*p* < .001) and an average slope value of 4.68 (*p* < .001), indicating children's scores are expected to increase by 23.40 units on average from 45 to 65 months. Significant variability in children's initial OOCCF score and rate of growth over time was evident, though the covariance between the average intercept and slope was not significant as reported in Table 5. On average, children are expected to demonstrate 28.6% of growth between 45 and 49 months, 22.8% between 49 and 53 months, 17.5% between 53 and 57 months, 18.6% between 57 and 61 months, and 12.5% between 61 and 65 months. Although the latent basis model with heteroscedastic error best represented the data, the linear model with heteroscedastic error also represented good fit, χ^2 (16, *N* = 408) = 23.19, *p* = .12, RMSEA = .03, CFI = .98, TLI = .97, with an average intercept of 13.71 (*p* < .001) and average linear slope of 5.12 per 4-month interval (*p* < .001).

NNF. Comparing the linear model with heteroscedastic error to the linear model with homoscedastic error, the model with heteroscedastic error represented a better fit to the NNF data, $\Delta\chi^2$ (5, *N* = 408) = 24.98, *p* < .001. Of the latent basis models, the model with heteroscedastic error represented better fit to the data, $\Delta\chi^2$ (5, *N* = 408) = 32.07, *p* < .001. Finally, the latent basis and linear models with heteroscedastic error structures were compared, and the latent basis model with heteroscedastic error better fit the data, $\Delta\chi^2$ (4, *N* = 408) = 14.92, *p* = .005.

Although the chi-square statistic was significant, χ^2 (12, N = 408) = 54.95, $p < .001$, the fit indices for the latent basis model with heteroscedastic error suggest acceptable fit: RMSEA = .09, CFI = .96, TLI = .93. Given the recommendation to consider confidence intervals when interpreting fit indices (MacCallum, Browne, & Sugawara, 1996), the RMSEA fit index would be acceptable based on a 90% confidence interval of .07 and .12. Results indicated an average intercept of 8.61 numbers named correctly per minute at 45 months ($p < .001$) and an average slope value of 3.56 ($p < .001$). This indicates children's NNF scores are expected to increase approximately 17.80 units across the total developmental period. As seen in Table 6, there was significant variation among children's intercept and growth over time; however, the estimated covariance between the intercept and slope was not found to be significant. Applying the average slope to the developmental curve, a child is expected to demonstrate 24.8% of growth between 45 and 49 months, 24.2% between 49 and 53 months, 18.6% between 53 and 57 months, 17.0% between 57 and 61 months, and 15.4% between 61 and 65 months. A model comparison indicated the linear model with heteroscedastic error did not fit the data as well as the latent basis model with heteroscedastic error, but it did represent adequate fit, χ^2 (16, N = 408) = 69.87, RMSEA = .09, CFI = .95, TLI = .94. For the linear model, the average intercept was 9.20 numbers named correctly at 45 months ($p < .001$) and the average slope was an increase of 3.77 numbers named correctly per 4-month interval ($p < .001$).

Relations Between Key Skills

Given that the latent basis models with heteroscedastic error best represented the data across tasks, the latent basis growth curves were visually analyzed to compare initial levels of performance, growth over time, and temporal stability of skills in relation to each other. As seen in Figure 4, QCF demonstrated the highest initial level of performance, followed by OCF, OOCCF, and NNF. Children's average scores on QCF exceeded their performance on the other myIGDI-EN tasks at 45 and 49 months, as well as at 53 months for OCF and NNF. The greatest rate of growth on QCF occurred between 45 and 49 months before decelerating and remaining seemingly consistent between 49 and 65 months. Overall, growth rates suggest QCF demonstrated the least age-based growth over the preschool developmental period examined.

Children demonstrated the most growth over time on OCF and OOCCF relative to the other myIGDI-EN tasks. Initial performance on OCF and OOCCF at 45 months was very similar, and these skills maintained close temporal stability through 57 months. Between 53 and 57 months of age, the growth rate for OCF accelerated and surpassed children's average performance on OOCCF. The growth rate on OOCCF decelerated between 61 and 65 months, contributing to less temporal stability in these skills at 65 months.

Finally, as with QCF, NNF demonstrated the greatest escalation in growth between 45 and 53 months. Performance on NNF continued to increase over time, although the rate of growth was not as high as during the younger months. Performance never exceeded the average scores on the other myIGDI-EN tasks.

CHAPTER V: DISCUSSION

Psychometrically sound assessment tools such as CBM are needed to facilitate the early identification of young children at risk for academic difficulties. A critical feature of CBM is the ability to detect small increments of growth over time (Fuchs, 2004), reflecting typical skill development and learning. The purpose of this investigation was to strengthen the evidence for myIGDI-EN by modeling and describing age-related change in early numeracy performance across the preschool years. Growth in the four key skills measured by myIGDI-EN was examined in a large sample of preschool children to determine the age-based sensitivity of the tasks and improve our knowledge of the developmental patterns occurring within and between skills comprising number sense.

Strengths of this investigation included the large sample size, use of repeated measurements, and examination of developmental trends using latent growth curve methodology. This study advances the literature by testing the assumption of uniform growth rates in myIGDI-EN performance across the preschool years. Previous research on the development and evaluation of preschool numeracy CBM examined growth over time by comparing mean scores from fall, winter, and spring assessment periods (Floyd et al., 2006; Reid et al., 2009; VanDerHeyden et al. 2006). Hojnoski et al. (2009) extended the sensitivity to growth literature by using linear mixed modeling to establish myIGDI-EN growth rates from the fall to the spring of the preschool year in an aggregated sample of 3- to 5-year-olds. Until now, research has not yet examined age-based developmental trends in early numeracy performance and the potential for nonlinear growth in preschool numeracy skills as measured by CBM tools. This knowledge is needed to fully understand the developmental progression of key skills comprising number sense. In addition, evidence regarding the shape of growth trajectories is critical for making developmentally-informed and empirically-supported decisions about assessment schedules and instructional targets.

Relations Within Numeracy Skills.

To answer the first research question, linear and latent basis growth curve models for each of the four tasks comprising myIGDI-EN were conducted within a structural equation modeling framework. Based on previous research (Hojnoski et al., 2009), it was hypothesized that each task would be sensitive to small units of change over time. Data analyses supported the hypothesis, resulting in slope factors that were significantly different from zero. In addition, children's performance at the intercept (45 months) was significantly different from zero. Significant variability in initial performance was evident across tasks, with especially high variation in children's OOCCF skills at 45 months. This variability is consistent with prior research indicating that disparities in mathematics achievement manifest as early as the preschool years (Ginsburg et al., 2008; Jordan et al., 2006; Starkey et al., 2004). Differential performance in children as young as age 3 suggests there are considerable differences in children's early mathematical environments and indicate the need to enrich the early learning environments of children at risk.

Significant variation in slope was also indicated for all tasks except QCF, highlighting the extent to which children differ not only in initial status but also in growth rates. Heterogeneity in children's growth rates on OCF, OOCCF, and NNF indicates children's skills develop differently over time as measured by these myIGDI-EN tasks. In addition, differential growth rates suggest the potential of lower performing children to gradually catch up to their higher performing peers when provided further mathematics support. It is concerning, however, that children begin with significantly disparate scores on QCF, but demonstrate the same growth trajectories. This suggests QCF is not sensitive enough to detect differences in quantity comparison development or that lower performing children are simply less likely to catch up to peers in this skill area.

The only task for which initial status and growth over time significantly covaried was OCF. That is, children with higher levels of OCF performance at 45 months also demonstrated greater rates of growth over time, and conversely, children with lower levels of initial OCF performance demonstrated slower rates of growth. This finding is reflective of previous research indicating that children who enter preschool with low levels of counting ability demonstrate slower rates of mathematics growth across elementary school years compared to children who enter preschool with high levels of counting ability (Aunola et al., 2004). Findings suggest it is important to intervene early when a child demonstrates low oral counting abilities, as performance in this skill area serves as an indicator of growth over time. Non-significant covariance estimates for the other myIGDI-EN tasks indicate that children who initially demonstrate low performance will not necessarily demonstrate slower rates of growth and may catch up to higher performing peers provided exposure to rich early mathematical experiences.

Results also indicate it is not appropriate to assume linear growth in myIGDI-EN data across the preschool developmental period. The sample data for all myIGDI-EN tasks were best represented by a nonlinear shape, with typical monthly growth rates varying based on age. For QCF, growth was greatest between 45 and 49 months of age before decelerating between 49 and 53 months. QCF growth continued to decelerate between 53 and 57 months, with growth becoming highly consistent between 53 and 65 months. Similar to QCF, growth rates for OOCCF and NNF were greatest between 45 and 49 months. On these tasks, the second highest rate of growth was evident between 49 and 53 months, with the least growth occurring between 61 and 65 months. In contrast, children demonstrated the least OCF growth between 45 and 49 months of age. Growth on OCF was relatively consistent between 49 and 65 months, with the greatest growth occurring between 53 and 57 months.

From a theoretical standpoint, nonlinear trajectories reflect the varying patterns of numeracy growth over time, and knowledge that numeracy development tends to follow a nonlinear path is not surprising given prior research (e.g., Ginsburg et al., 2006; Purpura et al., 2013). However, from a measurement perspective, linear trajectories are typically preferred because they better lend themselves to progress monitoring. Further, when both linear and nonlinear models fit the data well, some researchers would likely recommend using a more parsimonious linear model because models with fewer unknown parameters stand a better chance of replication (Bentler & Mooijart, 1989). Stated differently, there is higher potential for instability when parameters are freely estimated, which may reduce the likelihood for cross-validation. In light of this, since both linear and latent basis models in the present study fit myIGDI-EN data acceptably well, parameter estimates for both models were reported.

Using a 4-month age interval, which reflects a practical time interval for benchmark assessments, a linear growth rate of 2.45 units was indicated for QCF, 5.78 units for OCF, 5.12 units for OOCCF, and 3.77 units for NNF. These growth rates are of a magnitude sufficient enough to be visually detected when graphing data. Prior myIGDI-EN research examining time-based growth in a mixed-age sample of 3- to 5-year-olds also found linear growth rates of approximately 2 to 4 units per benchmark period (Hojnoski et al., 2009); thus, research supports myIGDI-EN's potential to detect both age- and time-based growth.

Relations Between Key Skills

To answer the second research question, a visual analysis of the best fitting growth trajectories was conducted. It was hypothesized that QCF would be an earlier emerging skill given that very young children can enumerate small sets and distinguish between “more” and “less” (Sarama & Clements, 2009; Starkey & Cooper, 1995). Consistent with this hypothesis, initial performance was highest on this task. Children demonstrated the least growth on QCF over time, with scores increasing approximately 13 units total between 45 and 65 months. Growth on QCF may have been limited by task format. QCF is a selection task wherein children have a 50% chance of responding correctly, which increase the potential for error due to guessing and inflation of children’s scores.

The task demonstrating the second highest initial level was OCF, though OCF performance at 45 months was nearly identical to performance on OOCCF. The higher performance on OCF at 45 months is consistent with the hypothesis that children must learn the counting sequence before mapping number words onto objects (Sarama & Clements, 2009). Further, although scores from children in the 37- and 41-month age ranges were not included in LGM analyses, average OCF scores at 37 months (*N* = 47, *M* = 9.2) and 41 months (*N* = 118, *M* = 11.4) were higher than respective OOCCF scores at 37 months (*N* = 47, *M* = 6.9) and 41 months (*N* = 117, *M* = 9.3) months, providing additional support for the hypothesis although not empirically modeled. Of all myIGDI-EN tasks, OCF and OOCCF demonstrated the most temporal stability and the greatest rates of growth over time. Children’s performance on OCF increased approximately 30 units across the measured developmental period, and OOCCF performance increased approximately 23 units.

Finally, NNF demonstrated the lowest initial performance level, which is consistent with research indicating numeral identification is a formal mathematical skill that typically improves with increased exposure to schooling (Baroody & Wilkins, 1999; Sarama & Clements, 2009). Coupled with a high percent of zero scores for the youngest age range, NNF does not appear to be an appropriate screening tool for 3-year-old children. In addition, NNF exhibited the second lowest rate of growth over time, demonstrating an increase of approximately 18 units between 45 and 65 months. The lower growth rate on NNF is not surprising given that it takes children repeated exposures before numerals can be accurately and consistently identified. Naming numerals requires the construction of a mental image of each number and the ability to distinguish between numerals with similar features (e.g., 2/5 and 6/9). Further, children must gradually modify their existing knowledge of single-digit numerals when learning double-digit numerals that do not follow the same numeric pattern (e.g., stating "eleven" instead of "one-one").

Limitations

There are several limitations that must be considered when interpreting the results of this investigation. Because the study utilized an accelerated longitudinal design, data were both cross-sectional and longitudinal; thus, one cannot assume the cross-sectional data would be fully representative of data had it been collected completely longitudinally. However, to attenuate this concern to a degree, children had to contribute data across a minimum of two assessment periods. Further, there was a large percentage of missing data; albeit, most was planned missing data, inherent in this type of design (Graham et al., 2006; Rhemtulla & Little, 2012). Although this loss of information may have potentially impacted the precision of parameter estimates, FIML estimation was used to account for missing data while reducing bias in the estimated parameters.

The exclusion of children under 45 months of age should also be considered when interpreting conclusions drawn from this study. Although post-hoc model modification is generally not advised (Bullock, Harlow, & Mulaik, 1994), modifications were necessitated in order to estimate model fit and calculate fit indices. Specifically, the 37- and 41-month age ranges were excluded due to limited covariance between observed variables, lower sample sizes, higher percent of zero scores, and more restricted ranges as compared to the other age ranges. Jöreskog and Sörbom (1993) distinguished between three types of model evaluations: strictly confirmatory in which a single a priori model is accepted or denied, alternative models in which one of a set of a priori models is selected, and model generation in which a tentative model is specified and modified to fit the data. Model generation is the most common model fitting process (Jöreskog and Sörbom, 1993). Given that the purpose of this study was to generate preliminary latent growth models of early numeracy skills, the decision to exclude the two youngest age ranges was made based on data constraints. Although the developmental period evaluated in this study was reduced, results still capture a span of 2 years. Further, growth trajectories across the preschool year immediately preceding kindergarten (ages 4 to 5) appear to be well captured. In the future, it will be beneficial to evaluate growth trajectories of children representing the full preschool developmental period.

Another limitation of the data is a lack of interscorer reliability obtained during live administration. Without interscorer reliability, the accuracy with which myIGDI-EN was administered cannot be estimated. As a balance to this limitation, it should be noted that myIGDI-EN, like all CBM, emphasize ease of administration, and fidelity checklists accompany all myIGDI-EN tasks that detail required steps for reliable administration. Further, all myIGDI-EN recording forms were checked and entered by the author to ensure correct scoring, and 20% of recording forms were checked again by a blind rater to confirm accurate data entry. Less than 0.01% of the recording forms checked by the blind rater contained errors, with only one scoring error and three data entry errors indicated. This finding indicates accuracy in scoring does appear to be a significant concern for this dataset.

Error structure should also be considered when interpreting the results of this study. Given that myIGDI-EN tasks were administered by different classroom teachers to children changing over time, it could not be assumed that the precision with which skills were measured across time was identical (Willet & Sayer, 1994). As such, both homoscedastic and heteroscedastic error structures were tested, and across tasks, models with heteroscedastic error faired better. Although heteroscedastic error does not change the underlying covariance structure or result in biased parameter estimates (Korendijk, Maas, Moerbeek, & Van der Heijden, 2008; Willet & Sayer, 1994), it suggests a degree of imprecision in the data. For example, error may be due to individual differences in measurement across age and time or potential administration variations. In addition, measurement error may increase as the potential value of a variable increases. In this study, error variances were highest for OOCCF followed by OCF, and these tasks had the greatest range of scores represented, which may have contributed to higher error values, especially for older age ranges.

Finally, generalizability should be addressed. Although not necessarily a limitation, findings of this study generalize only to the population of children served by the preschool program in Illinois from which the data was drawn. It is possible that patterns in performance and growth over time would differ across samples, such as for children who are not enrolled in a preschool program or enrolled in a less academically rigorous program. Further, although children in the sample represented a variety of racial and ethnic groups, as well as a degree of socioeconomic diversity, performance and growth differences based on group membership was not examined.

Implications for Practice

This research provides preliminary knowledge of the typical pattern of children’s early numeracy development as measured by myIGDI-EN. Following continued research, this knowledge can improve early identification practices by enabling school psychologists and early childhood practitioners to detect children achieving or not achieving age-based expectations for mathematics performance within or across skills. Age-based growth in this sample was evident across myIGDI-EN tasks, suggesting this assessment tool is suitable for repeated measurement. Further, this research highlights that early mathematics skills may not develop uniformly during the preschool years. Although not established, it may be possible that accelerated growth during a developmental time frame may be associated with increased exposure to a targeted concept within that specific developmental period. Alternatively, acquisition and fluency in one skill may be needed before another skill can be demonstrated. Future examination of potential individual and environmental variables may help explain the acceleration and deceleration of growth rates over time.

A goal of this study was to provide an empirical basis for informing assessment schedules and instructional targets. CBM are useful only if they reflect small changes in age, time, and experience over the developmental period of interest and help differentiate between children of varying skill levels. Of the myIGDI-EN tasks, QCF demonstrated the least growth over time. In addition, QCF captured differential initial performance but did not capture differential growth rates, which has implications in terms of lower performing children’s ability to catch up to peers. Other limitations include the task format (i.e., 50% chance of responding correctly) and potential floor effect for 3-year-olds. On account of these limitations, QCF appears to be the least suitable for reliable repeated measurements.

In contrast, OCF and OOCCF yield data that are more useful for evaluating skill development over time. Of the four key skills, OCF and OOCCF demonstrated the greatest growth rates, supporting their potential to monitor children's progress more frequently than triannual benchmark periods in order to better inform instructional decisions. Given their close temporal stability and for the sake of efficiency, it does not appear necessary to administer both tasks concurrently. One may argue it is more beneficial to administer OCF because no administration materials are needed and the slope is slightly steeper, which may aid in differentiation. To note, it is possible that the less steep slope on OOCCF reflects the task format; that is, there are limits to how fast a child can count 20 circles due to the coordination of words and physical actions (i.e., pointing) compared to OCF which requires only a verbal response. An argument in support of using only OOCCF is that this task provides an indication of both oral and object counting. OOCCF likely provides a more comprehensive snapshot of children's numeracy skills: educators can observe a child's knowledge of the number-word sequence as well as the child's understanding that numbers meaningfully represent quantities. However, OOCCF may be less useful for 5-year-olds due a lower average growth rate between 61 and 65 months relative to the other age ranges.

Although the growth rate for NNF was not as high as those of OCF and OOCCF, this task appears valuable, especially given the significant association between preschool number naming and elementary school mathematics achievement (Krajewski & Schneider, 2009; Purpura et al., 2013). However, given the high percent of zero scores for children under age 4 and needed exposure to formal learning experiences, it is not recommended that this task be administered to 3-year-old children. In addition, the task appears to be less useful for children older than approximately 61 months of age, as suggested by the lower percentage of growth occurring between 61 and 65 months. This may be due to children's increased mastery in identifying numbers 0 to 20 around this time and a capped pace at which they are able to do so.

Given age-related changes in early numeracy performance, this research underscores the importance of taking a developmental perspective when interpreting myIGDI-EN data. It is important for school psychologists and early childhood practitioners to be knowledgeable of typical academic performance levels in order to identify children who are not meeting developmental expectations. By assuming a developmental perspective, it is also possible to determine the windows of time during which skill growth is most likely to occur. Moreover, significant variation in children's initial levels of performance and growth over time highlights the importance of examining growth trends across time rather than relying on single-point indicators of performance. Because preschool classrooms may be composed of 3-, 4-, and 5-year-old children and familiarity with mathematical concepts may differ considerably based on age and exposure to schooling, it is important to compare a child's current performance to his or her past performance, rather than relying solely on broad comparisons across children in a preschool classroom or program. This is especially true knowing that variability in numeracy knowledge and skills is evident as early as age 3. However, variation in performance within each age range may offer a supplemental means of differentiating children to target instruction, in addition to evaluating an individual child's growth over time.

Future Directions

While the current study and previous myIGDI-EN research provide a solid starting point, many questions remain unanswered. Because this is the first study to model age-based numeracy growth across the preschool years, cross-validation is of foremost importance. It is necessary to cross-validate the models with independent samples and also determine if the identified trajectories hold for various subpopulations of children (e.g., children with special education needs and children at-risk due to demographic indicators). If nonlinear growth better represents the data in future research, the consistency of growth patterns across samples should be evaluated to determine whether there are developmental periods in which children tend to demonstrate more skill growth and whether child characteristics (e.g., special education or low-income status) impact these growth patterns.

Given the significant variability in children's rates of growth across the preschool years on most myIGDI-EN tasks, examination of variables that may contribute to differential growth is warranted. The unconditional model examined in this study can be changed to a conditional model through the addition of predictors that may account for the random variance observed in estimated growth trajectories. Predictors may include frequency of parental math talk in the home setting, participation in supplemental preschool programming, or individual-level variables found to be implicated in early numeracy development such as working memory (e.g., Bull, Espy, & Wiebe, 2008; Raghubar, Barnes, & Hecht, 2010). Identifying these contributing factors may inform further targets for early intervention.

Future research should also examine whether predictive relations exist within and across skills. For example, one may evaluate whether growth trajectories across age 3 predict growth trajectories across age 4 on the same skill. Similarly, one can examine whether performance in one skill predicts later growth in a different skill area. Determining the existence of a continuum of skills would prove useful in establishing short-term instructional goals. That is, through awareness that growth in one skill predicts growth in another, one can design instruction that prioritizes the earlier emerging skill.

Finally, the utility of myIGDI-EN growth trajectories to predict mathematics performance in the elementary school years is not yet known. It is likely that knowledge of children's early numeracy growth provides information about learning that is not captured by a single measure of performance; therefore, future research should examine the added value of slope in predicting later mathematics outcomes. It will be beneficial to determine the myIGDI-EN task or combination of tasks that best predict later mathematical competency because this knowledge will aid in the early identification of skill deficits that have a longstanding educational impact.

Conclusions

Taken together, findings from this investigation strengthen and advance what is known about early numeracy growth and the ability of myIGDI-EN to detect this growth across the preschool years. This study provides further evidence that young children are able to think mathematically and demonstrate considerable improvements in their mathematical knowledge and skills over time. Given that the preschool period is a time of tremendous skill development, marked by considerable individual differences in early numeracy performance, it is imperative that screening and progress monitoring tools be critically examined to ensure they yield scores that are reliable and valid at one point in time and accurately reflect children's skill growth over time. As the early childhood field continues to move in the direction of utilizing multi-tiered systems of support, research in this area will facilitate the early identification of children at risk and the design of interventions to improve early mathematics outcomes.

References

Arbuckle, J. L. (2013). *IBM SPSS® Amos 22 User's Guide*. Chicago: SPSS.

Aunola, K., Leskinen, E., Lerkkanen, M., & Nurmi, J. (2004). Developmental dynamics of math performance from preschool to grade 2. *Journal of Educational Psychology, 96*, 699-713.

Baglici, S. P., Codding, R., & Tryon, G. (2010). Extending the research on the Tests of Early Numeracy: Longitudinal analyses over two school years. *Assessment for Effective Intervention, 35*, 89-102. doi: 10.1177/153450840934605

Baraldi, A. N., & Enders, C. K. (2010). An introduction to modern missing data analyses. *Journal of School Psychology*, *48*, 5-37. doi: 10.1016/j.jsp.2009.10.001

Baroody, A. J., & Wilkins, J. L. M. (1999). The development of informal counting, number, and arithmetic skills and concepts. In J. Copley (Ed), *Mathematics in the early years* (pp. 48-65). Reston, VA: National Council of Teachers of Mathematics.

Baroody, A. J., Lai., M., & Mix, K. S. (2006). The development of young children's early number and operation sense and its implications for early childhood education. In B. Spodek & O. N. Saracho (Eds.), *Handbook of research on the education of young children* (2nd Ed., pp. 187–221). Mahwah, NJ: Erlbaum.

Bentler, P. M., & Mooijaart, A. (1989). Choice of structural model via parsimony: A rationale based on precision. *Psychological Bulletin, 106*, 315-317. doi: 10.1037/0033-2909.106.2.315

Berch, D. B. (2005). Making sense of number sense: Implications for children with mathematical disabilities. *Journal of Learning Disabilities, 38*, 333-339.

Bollen, K. A. (1987). Outliers and improper solutions: A confirmatory factor analysis example. *Sociological Methods and Research, 15*, 375-384.

Bracken, B. A. (2006) *Bracken Basic Concept Scale- Third Edition: Receptive*. San Antonio, TX: Harcourt.

Bracken. B. A. (1998). *Bracken Basic Concept Scale- Revised.* San Antonio, TX: The Psychological Corporation, Harcourt.

Brannon, E. M. (2002). The development of ordinal numerical knowledge in infancy. *Cognition 83*, 223-40.

Brigance, A. (1985). *Brigance Preschool Screen*. North Billerica, MA: Curriculum Associates, Inc.

Brigance, A. (1999). *Comprehensive Inventory of Basic Skills* (rev. ed.). North Billerica, MA: Curriculum Associates, Inc.

Browne, M. W., & Cudeck, R. (1993). Single sample cross-validation indices for covariance structures. *Multivariate Behavioral Research, 24*, 445-455.

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology, 33*, 205-228. doi:10.1080/87565640801982312

Bullock, H. E., Harlow, L. L., & Mulaik, S. A. (1994). Causation issues in structural equation modeling research. *Structural Equation Modeling, 1*, 253-267.

Carta, J. J., Greenwood, C. R., Luze, G. L., Cline, G., & Kuntz, S. (2004). Developing a general outcome measure of growth in social skills for infants and toddlers. *Journal of Early Intervention, 26*, 91-114.

Carta, J. J., Greenwood, C. R., Walker, D., Kaminski, R., Good, R., McConnell, S. R., & McEvoy, M. (2005). Individual growth and development indicators (IGDIs):

Assessment that guides intervention for young children. *Young Exceptional Children, 4,* 15-27.

Case, L. P., Harris, K. R., & Graham, S. (1992). Improving the mathematical problem-solving skills of students with learning disabilities: Self-regulated strategy development. *The Journal of Special Education, 26,* 1-19.

Caskie, G. I. L. (2011). Latent growth models: A quantitative method for studying adult development and learning. In C. H. Hoare (Ed.), *The Oxford Handbook of Adult Development and Learning* (2nd ed., pp. 61-79). New York: Oxford University Press.

Chard, D., Clarke, B., Baker, S., Otterstedt, J., Braun, D., & Katz, R. (2005). Using measures of number sense to screen for difficulties in mathematics: Preliminary findings. *Assessment for Effective Intervention, 30*, 3-14.

Clarke, B., & Shinn, M. R. (2004). A preliminary investigation into the identification and development of early mathematics curriculum-based measurement. *School Psychology Review, 33*, 234-284.

Clarke, B., Baker, S., Smolkowski, K., & Chard, D. J. (2008). An analysis of early numeracy curriculum-based measurement: Examining the role of growth in student outcomes. *Remedial and Special Education, 29*, 46-57.

Clements, D. H. (1999). Subitizing: what is it? Why teach it? *Teaching Children Mathematics, 5,* 400-405.

Clements, J. Sarama, & A. M. DiBiase (Eds.) (2004). *Engaging young children in mathematics education: Standards for early childhood mathematics education*. Mahwah, NJ: Erlbaum.

Cooper, R. G. (1984). Early number development: Discovering number space with addition and subtraction. In C. Sophian (ed.), *Origins of cognitive skills* (pp.157-192). Hillsdale, NJ: Erlbaum.

Curran, P. J., West, S. G., & Finch, J. (1996). The robustness of test statistics to non-normality and specification error in confirmatory factor analysis. *Psychological Methods, 1*, 16-29.

Deno, S.L. (1985). Curriculum-based measurement: The emerging alternative. *Exceptional Children, 52*, 219-232.

Deno, S.L. (2003). Developments in Curriculum-Based Measurement. *The Journal of Special Education, 37*, 184-192.

Denton, K., and West, J. (2002). *Children's Reading and Mathematics Achievement in Kindergarten and First Grade* (NCES 2002–125). U.S. Department of Education, NCES. Washington, DC: U.S. Government Printing Office.

Desoete, A., Ceulemans, A., De Weerdt, F., & Pieters, S. (2012). Can we predict mathematical learning disabilities from symbolic and non-symbolic comparison tasks in kindergarten? Findings from a longitudinal study. *British Journal of Educational Psychology, 82*, 64-81.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., …Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*, 1428-1446. doi: 10.1037/0012-1649.43.6.1428

Duncan, S. C., Duncan, T. E., & Hops, H. (1996). Analysis of longitudinal data within accelerated longitudinal designs. *Psychological Methods, 3*, 236-248. doi: 10.1037/1082-989X.1.3.236

Duncan, T. E., Duncan, S. C., & Stryker, L. A. (2006). *An introduction to latent variable growth curve modeling: Concepts, issues, and applications*. Mahwah, NJ: Erlbaum.

Fleischman, H. L., Hopstock, P. J., Pelczar, M. P., and Shelley, B. E. (2010). *Highlights From PISA 2009: Performance of U.S. 15-Year-Old Students in Reading, Mathematics, and Science Literacy in an International Context* (NCES 2011-004). U.S. Department of Education, National Center for Education Statistics. Washington, DC: U.S. Government Printing Office.

Floyd, R. G., Hojnoski, R., & Key, J. (2006). Preliminary evidence for the technical adequacy of the preschool numeracy indicators. *School Psychology Review, 35*, 627-644.

Foegan, A., Jiban, C., & Deno, S. (2007). Progress monitoring measures in mathematics: A review of the literature. *The Journal of Special Education, 41*, 121-139.

Fuchs, L. S., & Deno, S. L. (1991). Paradigmatic distinctions between instructionally relevant measurement models. *Exceptional Children, 57*, 488-499.

Fuchs, L.S. (2004). The past, present, and future of curriculum-based measurement research. *School Psychology Review, 33*, 188-192.

Fuson, K. C. (1988). *Children's counting and concepts of number*. New York: Springer-Verlag.

Fuson, K. C. (1992). Research on whole number, addition and subtraction. In D. A. Grouws (Ed.), *Handbook of research on mathematics teaching and learning*. New York: Macmillan Library.

Fuson, K. C., & Hall, J. W. (1983). The acquisition of early number word meanings: A conceptual analysis and review. In H. P. Ginsburg (Ed.), *The development of mathematical thinking* (pp. 49–107). New York: Academic Press.

Geary, D. C. (1990). A componential analysis of an early learning deficit in mathematics. *Journal of Experimental Child Psychology, 49,* 363–383.

Geary, D. C. (2000). From infancy to adulthood: The development of numerical abilities. *European Child and Adolescent Psychiatry, 9*, 11-16.

Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.

Gersten, R., Jordan, N.C., & Flojo, J.R. (2005). Early identification and interventions for students with mathematics difficulties. *Journal of Learning Disabilities, 38,* 293-304. doi: 10.1177/00222194050380040301

Ginsburg, A., Cooke, G., Leinwand, S., Noell, J., & Pollock, E. (2005). *Reassessing U.S. international mathematics performance: New findings from the TIMSS and PISA.* Washington DC: American Institutes for Research.

Ginsburg, H. P., & Baroody, A. J. (1990). *Test of Early Mathematics Ability* (2nd ed.). Austin, TX: PRO-ED.

Ginsburg, H. P., & Baroody, A. J. (2003). *Test of Early Mathematics Ability* (3rd ed.). Austin, TX: Pro-ed.

Ginsburg, H. P., Cannon, J. Eisenband, J., & Pappas, S. (2006). Mathematical thinking and learning. In D.A. Phillips & K. McCartney (Eds.), *Blackwell handbook of early childhood development* (pp. 208-230). Malden, MA: Blackwell Publishing.

Ginsburg, H. P., Klein, A., & Starkey, P. (1998). The development of children's mathematical thinking: Connecting research with practice. In W. Damon, I. E. Sigel, & K. A. Renninger (Eds.), *Handbook of child psychology, Vol. 4: Child psychology in practice* (5th ed., pp. 401–476). New York: Wiley.

Ginsburg, H. P., Lee, J. S., & Boyd, J. S. (2008). Mathematics education for young children: What it is and how to promote it. *Social Policy Report, 22*, 1-23.

Ginsburg, H.P. (1989). *Children's Arithmetic.* (2nd Ed.) Austin, TX: Pro-Ed.

Good, R. H., & Kaminski, R.A., (with Cummings, K., Dufour-Martel, C., Petersen, K., Powell Smith, K., Stollar, S. & Wallin, J.) (2011). *DIBELS Next assessment manual.* Eugene, OR: Dynamic Measurement Group.

Good, R. H., III, & Kaminski, R. A. (1996). Assessment for instructional decisions: Toward a proactive/prevention model of decision-making for early literacy skills. *School Psychology Quarterly, 11*, 326-336.

Graham, J. W., Olchowski, A. E., & Gilreath, T. D. (2007). How many imputations are really needed? Some practical clarifications of multiple imputation theory. *Prevention Science, 8*(3), 206–213. doi: 10.1007/s11121-007-0070-9

Graham, J. W., Taylor, B. J., Olchowski, A. E., & Cumsille, P. E. (2006). Planned missing data designs in psychological research. *Psychological Methods, 11*, 323-343. doi: 10.1037/1082-989X.11.4.323

Greeno, J. G., Riley, M. S., & Gelman, R. (1984). Conceptual competence and children's counting. *Cognitive Psychology*, 16, 94-143. doi: 10.1016/0010-0285(84)90005-7

Greenwood, C. R., Bradfield, T., Kaminski, R., Linas, M. W., Carta, J. J., & Nylander, D. (2011). The response to (RTI) approach in early childhood. *Focus on Exceptional Children, 43*(9), 1-22.

Greenwood, C. R., Buzhardt, J., Walker, D., Howard, W. J., & Anderson, R. (2011). Program level influences on the measurement of early communication for infants and toddlers in Early Head Start. *Journal of Early Intervention, 33*,110-134.

Greenwood, C. R., Carta, J. J., & McConnell, S. (2011). Advances in measurement for universal screening and individual progress monitoring of young children. *Journal of Early Intervention*, 33, 254-267.

Greenwood, C. R., Carta, J. J., Walker, D., Hughes, K., & Weathers, M. (2006). Preliminary investigations of the application of the early communication indicator (ECI) for infants and toddlers. *Journal of Early Intervention, 28*, 178-196.

Greenwood, C. R., Luze, G. J., Cline, G., Kuntz, S., & Leitschuh, C. (2002). Developing a general outcome measure of growth in movement for infants and toddlers. *Topics in Early Childhood Special Education, 22*, 143-157.

Greenwood, C. R., Walker, D., & Buzhardt, J. (2010). The early communication indicator for infants and toddlers: Early Head Start growth norms from two states. *Journal of Early Intervention, 32*, 310-334.

Greenwood, C. R., Walker, D., & Buzhardt, J., Howard, W. J., McCune, L., & Anderson, R. (2013). Evidence of a continuum in foundational expressive communication skills. *Early Childhood Research Quarterly, 28*, 540-554.

Greenwood, C. R., Walker, D., Carta, J. J., & Higgins, S. K. (2006). Developing a general outcome measure of growth in the cognitive abilities of children 1 to 4 years old: The early problem-solving indicator. *School Psychology Review, 35*, 535-551.

Griffin, S., Case, R., & Siegler, R. (1994). Rightstart: Providing the central conceptual prerequisites for first formal learning of arithmetic to students at risk for school failure. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 24-49). Cambridge, MA: MIT Press.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the “number sense”: The approximate number system in 3-, 4-, 5-, 6-year-olds and adults. *Developmental Psychology, 44,* 1457-1465.

Hampton, D. D., Lembke, E. S., Lee, Y.S., Pappas, S., Chiong, C., & Ginsburg, H. (2012). Technical adequacy of early numeracy curriculum-based progress monitoring measures for kindergarten and first-grade students. *Assessment for Effective Intervention, 37*, 118-126. doi:10.1177/1534508411431256

Harcourt Brace Educational Measurement. (1996). *Stanford Early School Achievement Test* (4th ed.). Orlando, FL: Harcourt.

Harcourt Educational Measurement. (2002). *Stanford Achievement Test*. San Antonio, TX: Harcourt.

Hojnoski, R. L., Caskie, G. I. L., & Miller-Young, R. (2012). *Sensitivity of PNI measures to model early numeracy growth over time: Differences by education status*. Unpublished manuscript, College of Education, Lehigh University, Bethlehem, PA.

Hojnoski, R. L., Caskie, G. I. L., Polignano, J., & Brittain, A. (2012, June). *Curriculum-based assessment of early numeracy in preschoolers who speak Spanish as their primary language: Differences in performance and growth over time*. Presentation at the Head Start Research Conference, Washington, DC.

Hojnoski, R. L., Silberglitt, B., & Floyd, R. G. (2009). Sensitivity to growth over time of the preschool numeracy indicators with a sample of preschoolers in Head Start. *School Psychology Review, 38*, 402-418. doi: 10.1177/1534508411430323

Howell, S., & Kemp, C. (2009). A participatory approach to the identification of measures of number sense in children prior to school entry. *International Journal of Early Years Education, 17*, 47-65. doi: 10.1080/09669760802699902

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Coventional criteria versus new alternatives. *Structural Equation Modeling, 6*, 1-55.

Hughes, M. (1986). *Children and number: Difficulties in learning mathematics*. Buckingham: Open University Press.

Jordan, N. C., Kaplan, D., Locuniak, M. N., & Ramineni, C. (2007). Predicting first-grade math achievement from developmental number sense trajectories. *Learning Disabilities Research and Practice, 22*, 36-46.

Jordan, N. C., Kaplan, D., Olah, L. N., & Locuniak, M. N. (2006). Number sense growth in kindergarten: A longitudinal investigation of children at risk for mathematics difficulties. *Child Development, 77*, 153-175.

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*, 850-867.

Jöreskog, K. G., & Sörbom, D. (1993). *LISREL 8: Structural equation modeling with the SIMPLIS command language*. Chicago: Scientific Software International Inc.

Kalchman, M., Moss, J., & Case, R. (2001). Psychological models for the development of mathematical understanding: Rational numbers and functions. In S. Carver & D. Klahr (Eds.), *Cognition and Instruction* (pp. 1–38). Mahwah, NJ: Erlbaum.

Kaminski, R. A., & Good III, R. H. (1996). Toward a technology for assessing basic early literacy skills. *School Psychology Review, 25*, 215-227.

Korendijk, E. J. H., Maas, C. J. M., Moerbeek, M., & Van der Heijden, P. G. M. (2008). The influence of misspecification of the heteroscedasticity on multilevel regression parameter and standard error estimates. *Methodology: European Journal of Research Methods for the Behavioral and Social Sciences, 4*, 67-72. doi: 10.1027/1614-2241.4.2.67

Krajewski, K., & Schneider, W. (2009). Early development of quantity to number-word linkage as a precursor of mathematical school achievement and mathematical difficulties: Findings from a four-year longitudinal study. *Learning and Instruction, 19*, 513-526. doi: 10.1016/j.learninstruc.2008.10.002

Lago, R. M., & DiPerna, J. C. (2010). Number sense in kindergarten: A factor- analytic study of the construct. *School Psychology Review, 39*, 164-180.

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8 to 9-year-old students. *Cognition, 93*, 99-125.

Lee, Y., Lembke, E., Moore, D., Ginsburg, H. P., & Pappas, S. (2012). Item-level and construct evaluation of early numeracy curriculum-based measures. *Assessment for Effective Intervention, 37*, 107-117. doi: 10.1177/1534508411431255

Lei, P., Wu, Q., DiPerna, J. C., & Morgan, P. L. (2009). Developing short forms of the EARLI numeracy measures: Comparison of item selection methods. *Educational and Psychological Measurement, 69*, 825-842. doi: 10.1177/0013164409332215

Lembke, E. S., & Foegen, A. (2009). Identifying early number indicators for kindergarten and first-grade students. *Learning Disabilities Research and Practice, 24*, 12-20.

Lembke, E. S., & Foegen, A., Whittaker, T., & Hampton, D. (2008). Establishing technically adequate measures of progress in early numeracy. *Assessment for Effective Intervention, 33*, 206-214.

Locuniak, M. N., & Jordan, N. C. (2008). Using kindergarten number sense to predict calculation fluency in second grade. *Journal of Learning Disabilities, 41*, 451-459.

Luze, G. J., Linebarger, D. L., Greenwood, C. R., Carta, J. J., Walker, D., Leitschuh, C., & Atwater, J. B. (2001). Developing a general outcome measure of growth in expressive communication of infants and toddlers. *School Psychology Review, 30*, 383–406.

MacCallum, R. C., Browne, M. W., & Sagawara, H. M. (1996). Power analysis and determination of sample size for covariance structure modeling. *Psychological Methods, 1*(2), 130-149. doi: 1082-989X/96/S3.00

Mack, W. (2006). Numerosity discrimination: Infants discriminate small from large numerosities. *European Journal of Developmental Psychology, 3*, 21-47.

Martinez, R. S., Missall, K. N., Graney, S. B., Aricak, O. T., & Clarke, B. (2009). Technical adequacy of early numeracy curriculum-based measurement in kindergarten. *Assessment for Effective Intervention, 34*, 116-125.

Mazzocco, M. M., & Thompson, R. E. (2005). Kindergarten predictors of math learning disability. *Learning Disabilities Research and Practice, 20*, 142-155.

McArdle, J. J. (1988). Dynamic but structural equation modeling of repeated measures data. In J. R. Nesselroade & R. B. Cattell (Eds.), *The handbook of multivariate experimental psychology, Volume 2* (pp. 561-614). New York, NY: Plenum.

McArdle, J. J. & Hamagami, F. (1992). Modeling incomplete longitudinal and cross-sectional data using latent growth structural models. *Experimental Aging Research, 18*, 145-166.

Meredith, W., & Tisak, J. (1990). Latent curve analysis. *Psychometrika, 55*, 107-122.

Methe, S. A., Hintze, J. M., & Floyd, R. G. (2008). Validity and decision accuracy of early numeracy skill indicators. *School Psychology Review, 37*, 359-373.

Methe, S. M., Begeny, J. C., & Leary, L. L. (2011). Development of conceptually focused early numeracy skill indicators. *Assessment for Effective Intervention*, *36*, 230-242.

Missall, K. N., & McConnell, S. R. (2004). *Technical Report: Psychometric characteristics of individual growth and development indicators – Picture Naming, Rhyming & Alliteration.* Minneapolis, MN: Center for Early Education and Development.

Missall, K. N., McConnell, S. R. & Cadigan, K. (2006). Early literacy development: Skill growth and relations between classroom variables for preschool children. *Journal of Early Intervention, 29,* 1–21.

Missall, K. N., Mercer, S. H., Martinez, R. S., & Casebeer, D. (2012). Concurrent and longitudinal patterns and trends in performance on early numeracy curriculum-based measures in kindergarten through third grade. *Assessment for Effective Intervention, 27*, 95-106.

Miyazaki, Y., & Raudenbush, S. W. (2000). Tests for linkage of multiple cohorts in an accelerated longitudinal design. *Psychological Methods, 5*, 44-63. doi: 10.1037/1082-989X.5.1.44

Morgan, P. L., Farkas, G., & Wu, Q. (2009). Five-year growth trajectories of kindergarten children with learning difficulties in mathematics. *Journal of Learning Disabilities, 44*, 472-488. doi: 10.1177/0022219411414010

Mullis, I. V. S., Martin, M. O., and Arora, A. (2012). *TIMSS 2011 International Results in Mathematics*. Chestnut Hill, MA: TIMSS & PIRLS International Study Center, Boston College.

National Center for Education Statistics (2011). *The nation's report card: Mathematics 2011* (NCES Publication No. 2012-458). Washington DC: U.S. Department of Education.

National Center on Child Care Quality Improvement, Department of Health and Human Services (2011). *State early learning guidelines*. Accessed on April 22, 2013 from http://qi.childcare.gov/sites/default/files/state_early_learning_guidelines_75.pdf

National Council of Teachers of Mathematics. (2006). *Curriculum focal points for prekindergarten through grade 8 mathematics: A quest for coherence*. Reston, VA: Author.

National Council of Teachers of Mathematics. (2000). *Principles and standards for school mathematics*. Reston, VA: Author.

National Mathematics Advisory Panel (2008). *Foundations for success: The final report of the National Mathematics Advisory Panel*. Washington, DC: U.S. Department of Education.

Okamoto, Y., & Case, R. (1996). Exploring the microstructure of children's central conceptual structures in the domain of number. *Monographs of the Society for Research in Child Development, 61,* 27–59.

Perry, B., & Dockett, S. (2002). Young children's access to powerful mathematical ideas. In L. D. English (Ed.). *Handbook of international research in mathematics education: Directions for the 21st century* (pp. 81-111). Mahwah, NJ: Erlbaum.

Polignano, J. C., & Hojnoski, R. L. (2011). Preliminary evidence of the technical adequacy of additional curriculum-based measures for preschool mathematics. *Assessment for Effective Intervention, 37,* 70-83. doi:10.1177/1534508411430323

Purpura, D. J., Baroody, A. J., & Lonigan, C. J. (2013). The transition from informal to formal mathematical knowledge: Mediation by numeral knowledge. *Journal of Educational Psychology*, 105, 453-464. doi: 10.1037/a0031753

Quintana, S. M., & Maxwell, S. E. (1999). Implications of recent developments in structural equation modeling for counseling psychology. *Counseling Psychologist, 27*, 485–527. doi: 10.1177/0011000099274002

Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences, 20*, 110-122. doi: 10.1016/j.lindif.2009.10.005

Reardon, S. F., & Galindo, C. (2009). The Hispanic-White achievement gap in math and reading in the elementary grades. *American Educational Research Journal, 46*, 853-891. doi: 10.3102/0002831209333184

Reid, M. A., Morgan, P. L., DiPerna, J. C., & Lei, P. W. (2009). Reliability and validity evidence for the EARLI literacy probes. *Psychology in the Schools, 46*, 1023-1035. doi: 10.1002/pits.20441

Rhemtulla, M., & Little, T. D. (2012). Planned missing data designs for research in cognitive development. *Journal of Cognition and Development, 13*, 425-438. doi: 10.1080/15248372.2012.717340

Roberts, G., & Bryant, D. (2011). Early mathematics achievement trajectories: English-language learner and native English-speaker estimates, using the early childhood longitudinal survey. *Developmental Psychology, 47* (4), 916-930. doi: 10.1037/a0023865

Roseth, C. J., Missall, K. N., & McConnell, S. R. (2012). Early literacy individual growth and development indicators (EL-IGDIs): Growth trajectories using a large, internet-based sample. *Journal of School Psychology, 50,* 483-501.

Rubin, D. B. (1976). Inference and missing data. *Biometrika, 63*, 581−592. doi: 10.1093/biomet/63.3.581

Sarama, J., & Clements, D. H. (2009). *Early childhood mathematics education research: Learning trajectories for young children*. New York, NY: Routledge.

Sarnecka, B. W., & Lee, M. D. (2009). Levels of number knowledge during early childhood. *Journal of Experimental Child Psychology, 103*, 325-337. doi: 10.1016/j.jecp.2009.02.007

Schumacker, R. E., & Lomax, R. G. (2004). *A beginner's guide to structural equation modeling.* Mahwah, NJ: Erlbaum.

Scott-Little, C., Lesko, J., Martella, J., & Milburn, P. (2007). Early learning standards: Results from a national survey to document trends in state-level policies and practices. *Early Childhood Research and Practice, 9*, 1-22.

Shinn, M. R. (2004). *Administration and scoring of mathematics computation curriculum-based measurement (M-CBM) and math fact probes for use with AIMSweb*. Eden Prairie, MN: Edformation.

Siegler, R. S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *The origins of cognitive skills* (pp. 229-293). Hillsdale, NJ: Erlbaum.

Slusser, E. B., & Sarnecka, B. W. (2011). Find the picture of eight turtles: A link between children's counting and their knowledge of number word semantics. *Journal of Experimental Child Psychology, 110*, 38-51. doi: 10.1016/j.jecp.2011.03.006

Starkey, P., & Cooper, R. (1995). The development of subitizing in young children. *British Journal of Developmental Psychology, 19,* 399-420.

Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly, 19*, 99-120.

Starkey, P., Spelke, E. S., *&* Gelman, R. (1990). Numerical abstraction by human infants. *Cognition, 36,* 97-128.

Steiger, J. H. (2007). Understanding the limitations of global fit assessment in structural equation modeling. *Personality and Individual Differences, 42* (5), 893-98.

VanDerHeyden, A. M., Broussard, C., & Cooley, A. (2006). Further development of measures of early math performance for preschoolers. *Journal of School Psychology, 44*, 533-553.

VanDerHeyden, A. M., Broussard, C., Fabre, M., Stanley, J., Legendre, J., & Creppell, R. (2004). Development and validation of curriculum-based measures of math performance for preschool children. *Journal of Early Intervention, 27,* 27-41.

VanDerHeyden, A. M., Broussard, C., Snyder, P., George, J., Lafleur, S. M., & Williams, C. (2011). Measurement of kindergartners' understanding of early mathematical concepts. *School Psychology Review, 40*, 296-306.

VanDerHeyden, A. M., Witt, J. C., Naquin, G., & Noell, G. (2001). The reliability and validity of curriculum-based readiness probes for kindergarten students. *School Psychology Review, 30,* 363-382.

Velicer, W. F., & Fava, J. L. (1998). Effects of variable and subject sampling on factor pattern recovery. *Psychological Methods, 3*, 231-251. doi: 1082-989X/98/$3.00

von Glasersfeld, E. (1982). An interpretation of Piaget's constructivism. *Revue Internationale de Philosophie, 36*, 612–635.

Walker, D., Carta, J. J., Greenwood, C. R., & Buzhardt, J. F. (2008). The use of individual growth and developmental indicators for progress monitoring intervention decision making in early education. *Exceptionality, 16*, 33-47.

Weston, R., & Gore, P. A. (2006). A brief guide to structural equation modeling. *The Counseling Psychologist*, *34,* 719-751.

Willett, J. B., & Sayer, A. G. (1994). Using covariance structure analysis to detect correlates and predictors of change. *Psychological Bulletin*, *116*, 363-381.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock–Johnson III Tests of Achievement.* Itasca, IL: Riverside Publishing.

Woodcock, R. W., McGrew, K. S., & Werder, J. K. (1994). *Woodcock–McGrew–Werder Mini-Battery of Achievement*. Chicago: Riverside Publishing.

Woodcock, R. W., McGrew, K. S., Schrank, F. A., & Mather, N. (2007). *Woodcock–Johnson III Normative Update*. Rolling Meadows, IL: Riverside Publishing.

Wynn, K. (1992). Addition and subtraction by human infants. *Nature, 358*, 749–750.

Wynn, K., Bloom, P., & Chiang, W. C. (2002). Enumeration of collective entities by 5-month-old infants. *Cognition, 83*, B55–B62.

Table 1

Number of Data Points Across Age Ranges Per MyIGDI-EN Task

Ages at which data were contributed						*N*			
45	49	53	57	61	65	QCF	OCF	OOCCF	NNF
■	■					35	36	35	35
■	■	■				29	27	29	28
■	■	■	■			18	23	24	24
■	■	■	■	■		30	31	29	31
■	■	■	■	■	■	10	11	8	10
■	■	■	■		■	4	4	4	4
■	■	■		■		7	6	7	7
■	■		■			8	5	6	5
	■	■				14	16	15	16
	■	■	■			55	61	60	60
	■	■	■	■		2	2	5	3
	■	■	■	■	■	0	0	2	0
	■	■	■		■	0	1	1	1
	■	■		■	■	1	1	1	1
■	■		■	■	■	1	1	1	1
■		■	■	■	■	1	1	1	1
■	■		■	■		9	9	9	9
■	■	■		■	■	9	9	9	9
		■	■			9	0	0	0
		■	■	■		47	50	49	49
		■	■	■	■	3	7	7	7
■		■	■	■		1	1	1	1
■		■	■			6	4	4	4
■	■			■		1	1	1	1
■	■	■			■	0	0	1	0
	■		■			12	14	12	14
		■		■		10	11	10	10
			■	■	■	59	63	63	63
			■		■	1	1	1	1
			■	■		5	0	0	0
				■	■	12	13	13	13
						9	0	0	1

Note. QCF = Quantity Comparison Fluency; OCF = Oral Counting Fluency; OOCCF = One-to-One Correspondence Counting Fluency; NNF = Number Naming Fluency.

Table 2

Summary of Sample Sizes, Means, Standard Deviations, Ranges, Skewness and Kurtosis Values, and Percent of Zero Scores Across MyIGDI-EN Tasks Based on Age

Age	*N*	*M* (*SD*)	Range	Skewness	Kurtosis	Percent Zero Scores
QCF						
45	171	19.1 (7.5)	0-35	-0.8	0.1	3.5%
49	242	23.1 (5.5)	4-35	-1.1	1.2	0.4%
53	268	25.1 (5.7)	0-45	-1.1	3.8	0.7%
57	295	27.0 (5.6)	9-44	-0.3	1.7	0.7%
61	207	28.9 (5.5)	9-45	-0.1	1.5	0.5%
65	101	30.7 (5.8)	20-51	1.4	2.2	1.0%
OCF						
45	171	14.6 (8.6)	0-54	1.9	4.8	1.8%
49	249	18.3 (10.7)	0-59	1.3	1.7	1.6%
53	275	23.9 (15.5)	0-77	1.5	1.9	0.4%
57	303	30.4 (20.1)	1-93	1.1	0.4	0.3%
61	219	34.1 (22.7)	4-100	0.9	0.0	0.5%
65	114	37.0 (26.8)	4-100	0.9	-0.4	0.9%
OOCCF						
45	171	13.8 (10.3)	0-50	1.7	0.2	2.3%
49	254	20.5 (16.6)	0-75	1.2	0.2	1.2%
53	277	25.7 (18.3)	0-86	0.8	-0.4	1.4%
57	303	29.3 (19.4)	1-79	0.5	-1.1	0.7%
61	218	31.8 (20.0)	0-86	0.3	-1.2	0.5%
65	114	31.3 (20.0	0-67	0.3	-1.4	0.9%
NNF						
45	173	10.3 (8.2)	0-39	1.0	0.8	12.1%
49	252	14.2 (10.3)	0-44	0.8	0.0	5.6%
53	276	18.0 (11.7)	0-53	0.5	-0.5	5.8%
57	302	20.1 (12.3)	0-51	0.4	-0.6	4.0%
61	218	21.9 (12.3)	0-51	0.2	-0.9	1.8%
65	113	21.6 (12.9)	0-52	0.2	-0.7	2.7%

Note. QCF = Quantity Comparison Fluency; OCF = Oral Counting Fluency; OOCCF = One-to-One Correspondence Counting Fluency; NNF = Number Naming Fluency.

Table 3

Quantity Comparison Fluency Latent Growth Curve Model Parameters

Parameter Estimates	Linear Homoscedastic Error	Linear Heteroscedastic Error	Latent Basis Homoscedastic Error	Latent Basis Heteroscedastic Error
Fit Indices				
χ^2	67.35 *** (*df* = 21)	26.67 * (*df* = 16)	33.44 ** (*df* = 17)	14.12 (*df* = 12)
RMSEA	0.07	0.04	0.05	0.02
CFI	0.84	0.96	0.95	0.99
TLI	0.84	0.95	0.93	0.99
Fixed Effects				
Intercept	19.42 ***	19.69 ***	17.96 ***	18.27 ***
Slope	2.53 ***	2.45 ***	2.65 ***	2.64 ***
Random Effects				
Intercept Variance	25.39 ***	18.23 ***	7.17 ***	21.78 ***
Slope Variance	1.02 **	0.27	4.10 ***	0.47
Covariance	-3.10 ***	-0.60	-5.40 ***	-1.54
Factor Loadings				
Y45	0.00	0.00	0.00	0.00
Y49	1.00	1.00	1.78 ***	1.58 ***
Y53	2.00	2.00	2.66 ***	2.50 ***
Y57	3.00	3.00	3.43 ***	3.34 ***
Y61	4.00	4.00	4.22 ***	4.17 ***
Y65	5.00	5.00	5.00	5.00
Error Variances				
e45	16.57 ***	37.48 ***	15.41 ***	32.93 ***
e49	16.57 ***	16.42 ***	15.41 ***	15.81 ***
e53	16.57 ***	13.80 ***	15.41 ***	13.71 ***
e57	16.57 ***	13.50 ***	15.41 ***	13.66 ***
e61	16.57 ***	14.09 ***	15.41 ***	14.18 ***
e65	16.57 ***	18.98 ***	15.41 ***	18.92 ***

Note. χ^2 = chi-square; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index; TLI = Tucker–Lewis index.
*** $p < .001$, ** $p < .01$, * $p < .05$.

Table 4

Oral Counting Fluency Latent Growth Curve Model Parameters

Parameter Estimates	Linear Homoscedastic Error	Linear Heteroscedastic Error	Latent Basis Homoscedastic Error	Latent Basis Heteroscedastic Error
Fit Indices				
χ^2	99.39 *** (*df* = 21)	39.90 *** (*df* = 16)	77.97 *** (*df* = 17)	15.29 (*df* = 12)
RMSEA	0.10	0.06	0.09	0.03
CFI	0.89	0.97	0.92	1.00
TLI	0.89	0.96	0.90	0.99
Fixed Effects				
Intercept	12.46 ***	12.82 ***	14.00 ***	13.84 ***
Slope	6.01 ***	5.78 ***	6.18 ***	5.90 ***
Random Effects				
Intercept Variance	21.23 **	51.44 ***	37.15 ***	55.08 ***
Slope Variance	21.42 ***	22.04 ***	21.81 ***	21.75 ***
Covariance	3.12 ***	7.71 *	20.95 ***	13.44 ***
Factor Loadings				
Y45	0.00	0.00	0.00	0.00
Y49	1.00	1.00	0.56 ***	0.62 ***
Y53	2.00	2.00	1.55 ***	1.65 ***
Y57	3.00	3.00	2.73 ***	2.88 ***
Y61	4.00	4.00	3.71 ***	3.94 ***
Y65	5.00	5.00	5.00	5.00
Error Variances				
e45	74.72 ***	26.87 ***	71.08 ***	28.03 ***
e49	74.72 ***	42.31 ***	71.08 ***	41.94 ***
e53	74.72 ***	76.81 ***	71.08 ***	73.71 ***
e57	74.72 ***	87.65 ***	71.08 ***	84.03 ***
e61	74.72 ***	59.88 ***	71.08 ***	55.64 ***
e65	74.72 ***	176.74 ***	71.08 ***	179.66 ***

Note. χ^2 = chi-square; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index; TLI = Tucker–Lewis index.
*** $p < .001$, ** $p < .01$, * $p < .05$.

Table 5

One-to-One Correspondence Counting Fluency Latent Growth Curve Model Parameters

Parameter Estimates	Linear Homoscedastic Error	Linear Heteroscedastic Error	Latent Basis Homoscedastic Error	Latent Basis Heteroscedastic Error
Fit Indices				
χ^2	85.86 *** (*df* = 21)	23.19 (*df* = 16)	73.85 *** (*df* = 17)	13.81 (*df* = 12)
RMSEA	0.09	0.03	0.09	0.02
CFI	0.79	0.98	0.82	0.99
TLI	0.79	0.97	0.78	0.99
Fixed Effects				
Intercept	14.10 ***	13.71 ***	12.28 ***	13.17 ***
Slope	5.06 ***	5.12 ***	4.75 ***	4.68 ***
Random Effects				
Intercept Variance	44.50 **	90.21 ***	12.79	97.42 ***
Slope Variance	4.86 *	12.23 ***	2.13	11.04 ***
Covariance	19.87 ***	-9.23	22.74 ***	-4.95
Factor Loadings				
Y45	0.00	0.00	0.00	0.00
Y49	1.00	1.00	1.65 ***	1.43 ***
Y53	2.00	2.00	2.71 ***	2.57 ***
Y57	3.00	3.00	3.72 ***	3.45 ***
Y61	4.00	4.00	4.50 ***	4.38 ***
Y65	5.00	5.00	5.00	5.00
Error Variances				
e45	159.55 ***	22.92 *	168.79 ***	12.82
e49	159.55 ***	147.44 ***	168.79 ***	144.18 ***
e53	159.55 ***	199.89 ***	168.79 ***	196.35 ***
e57	159.55 ***	187.40 ***	168.79 ***	187.92 ***
e61	159.55 ***	163.48 ***	168.79 ***	167.18 ***
e65	159.55 ***	105.76 ***	168.79 ***	119.79 ***

Note. χ^2 = chi-square; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index; TLI = Tucker–Lewis index.
*** $p < .001$, ** $p < .01$, * $p < .05$.

Table 6

Number Naming Fluency Latent Growth Curve Model Parameters

Parameter Estimates	Linear Homoscedastic Error	Linear Heteroscedastic Error	Latent Basis Homoscedastic Error	Latent Basis Heteroscedastic Error
Fit Indices				
χ^2	94.85 *** (*df* = 21)	69.87 *** (*df* = 16)	87.02 *** (*df* = 17)	54.95 *** (*df* = 12)
RMSEA	0.09	0.09	0.10	0.09
CFI	0.93	0.95	0.94	0.96
TLI	0.93	0.94	0.92	0.93
Fixed Effects				
Intercept	9.20 ***	9.90 ***	8.72 ***	8.61 ***
Slope	3.74 ***	3.77 ***	3.67 ***	3.56 ***
Random Effects				
Intercept Variance	74.83 ***	72.90 ***	73.15 ***	73.08 ***
Slope Variance	3.59 ***	4.01 ***	3.23 ***	3.61 ***
Covariance	2.83	2.36	2.70	1.36
Factor Loadings				
Y45	0.00	0.00	0.00	0.00
Y49	1.00	1.00	1.12 ***	1.24 ***
Y53	2.00	2.00	2.30 ***	2.45 ***
Y57	3.00	3.00	3.25 ***	3.38 ***
Y61	4.00	4.00	4.09 ***	4.23 ***
Y65	5.00	5.00	5.00	5.00
Error Variances				
e45	22.65 ***	7.91 **	22.76 ***	5.39
e49	22.65 ***	20.85 ***	22.76 ***	20.60 ***
e53	22.65 ***	25.95 ***	22.76 ***	25.47 ***
e57	22.65 ***	28.64 ***	22.76 ***	29.59 ***
e61	22.65 ***	18.86 ***	22.76 ***	18.64 ***
e65	22.65 ***	29.71 ***	22.76 ***	31.33 ***

Note. χ^2 = chi-square; *df* = degrees of freedom; RMSEA = root mean square error of approximation; CFI = comparative fit index; TLI = Tucker–Lewis index.
*** $p < .001$, ** $p < .01$, * $p < .05$.

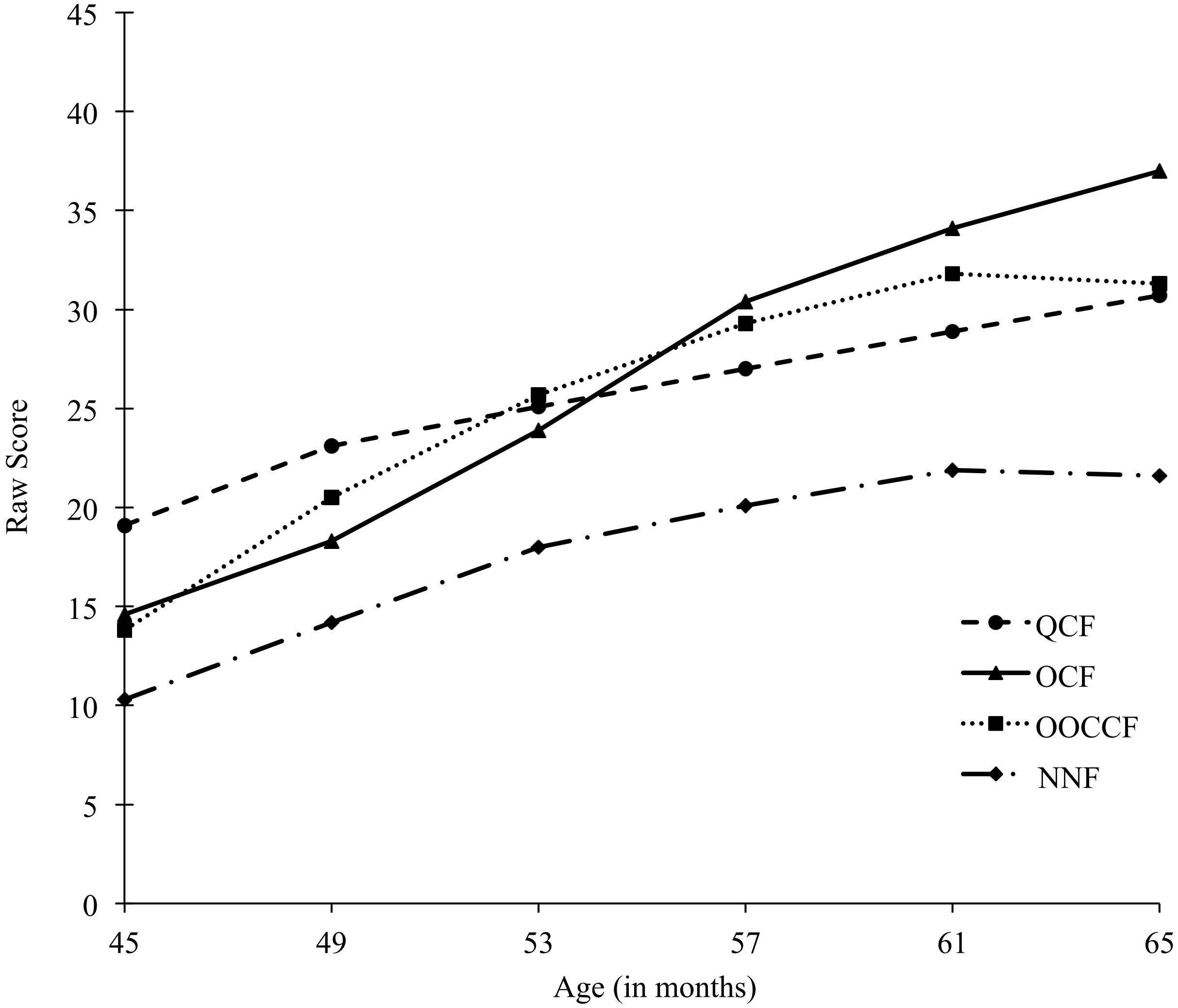

Figure 1. Unfitted mean trajectories. QCF = Quantity Comparison Fluency; OCF = Oral Counting Fluency; OOCCF = One-to-One Correspondence Counting Fluency; NNF = Number Naming Fluency.

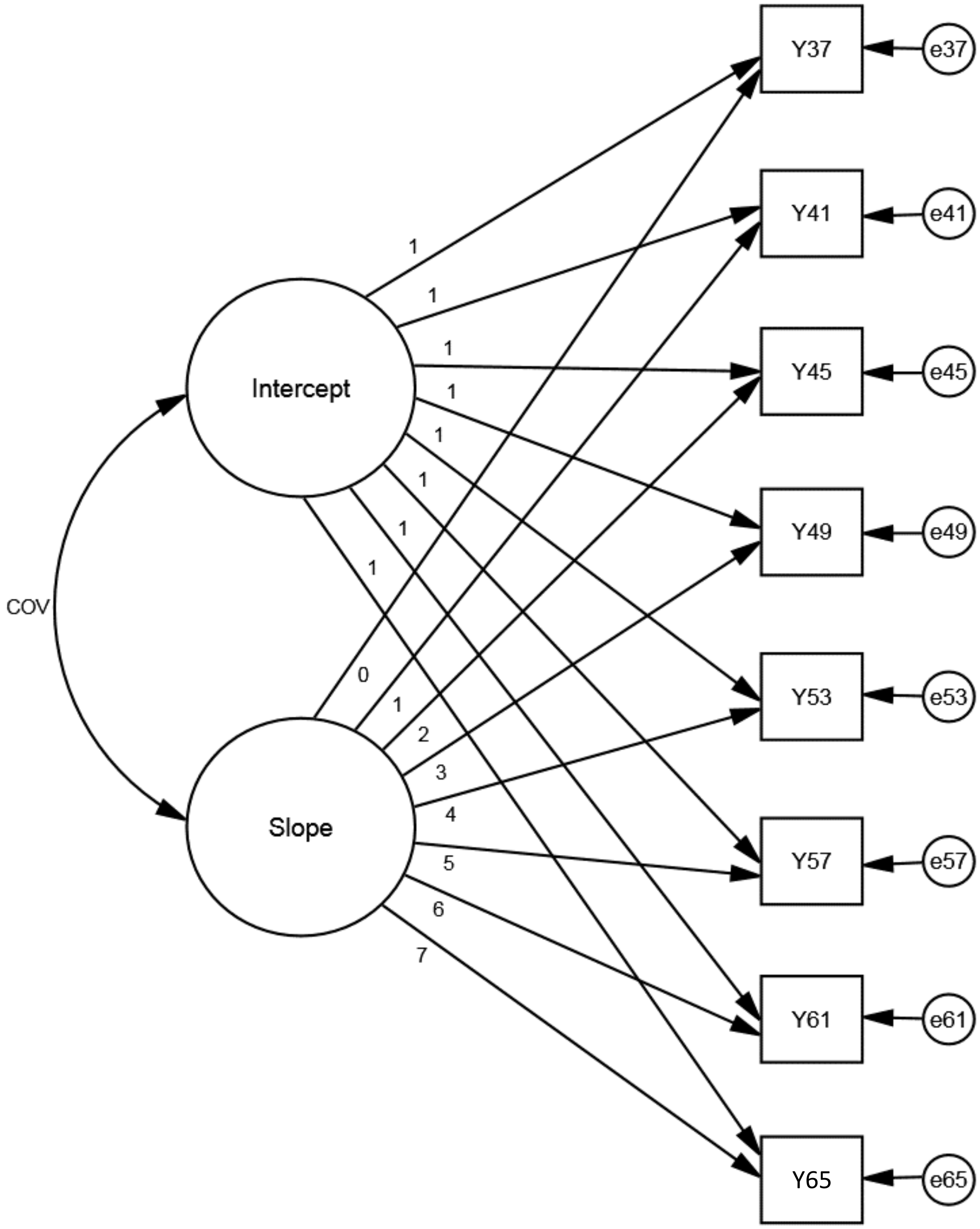

Figure 2. Linear latent growth model specification. COV = covariance; Y = observed outcome; e = error.

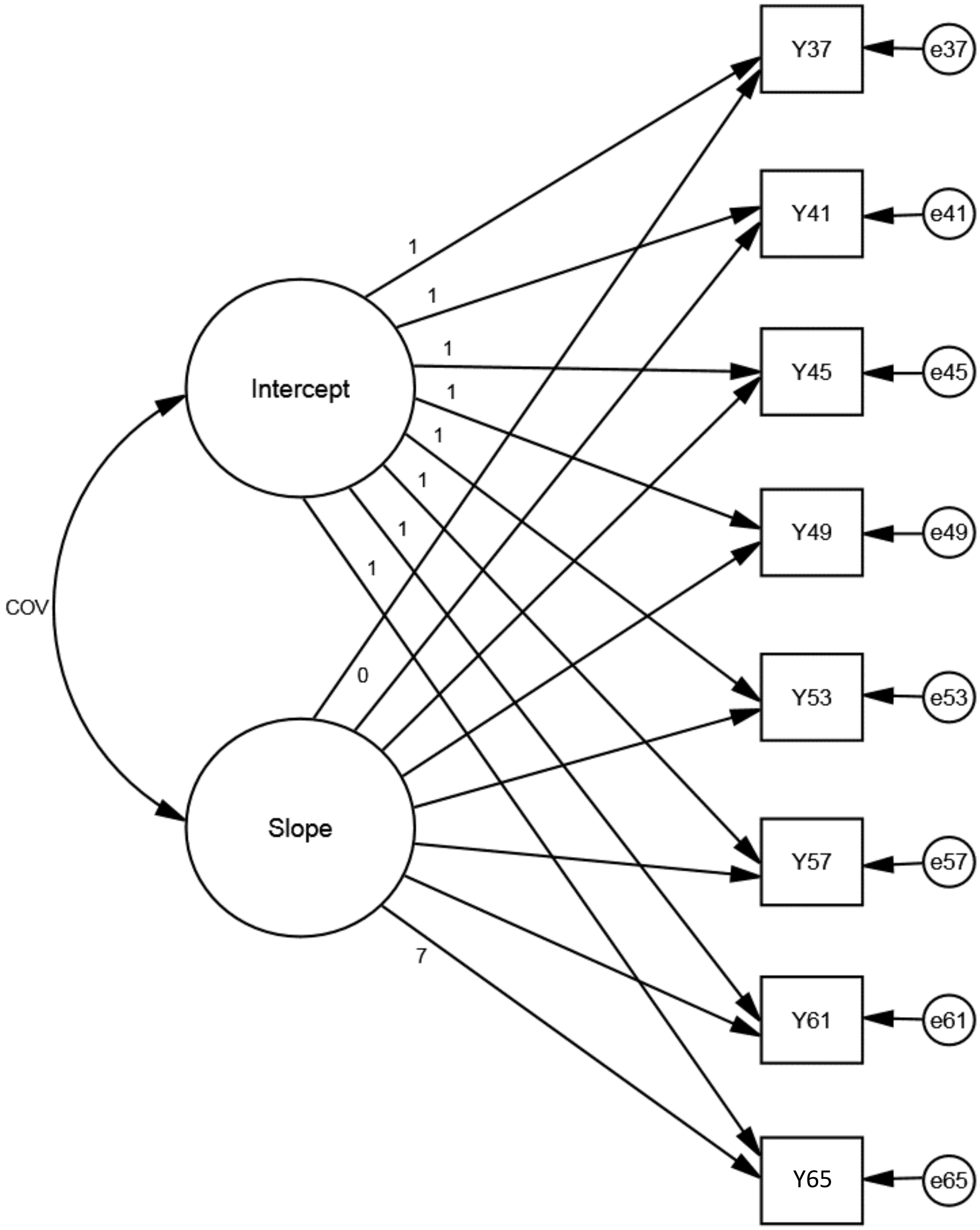

Figure 3. Latent basis growth model specification. COV = covariance; Y = observed outcome; e = error.

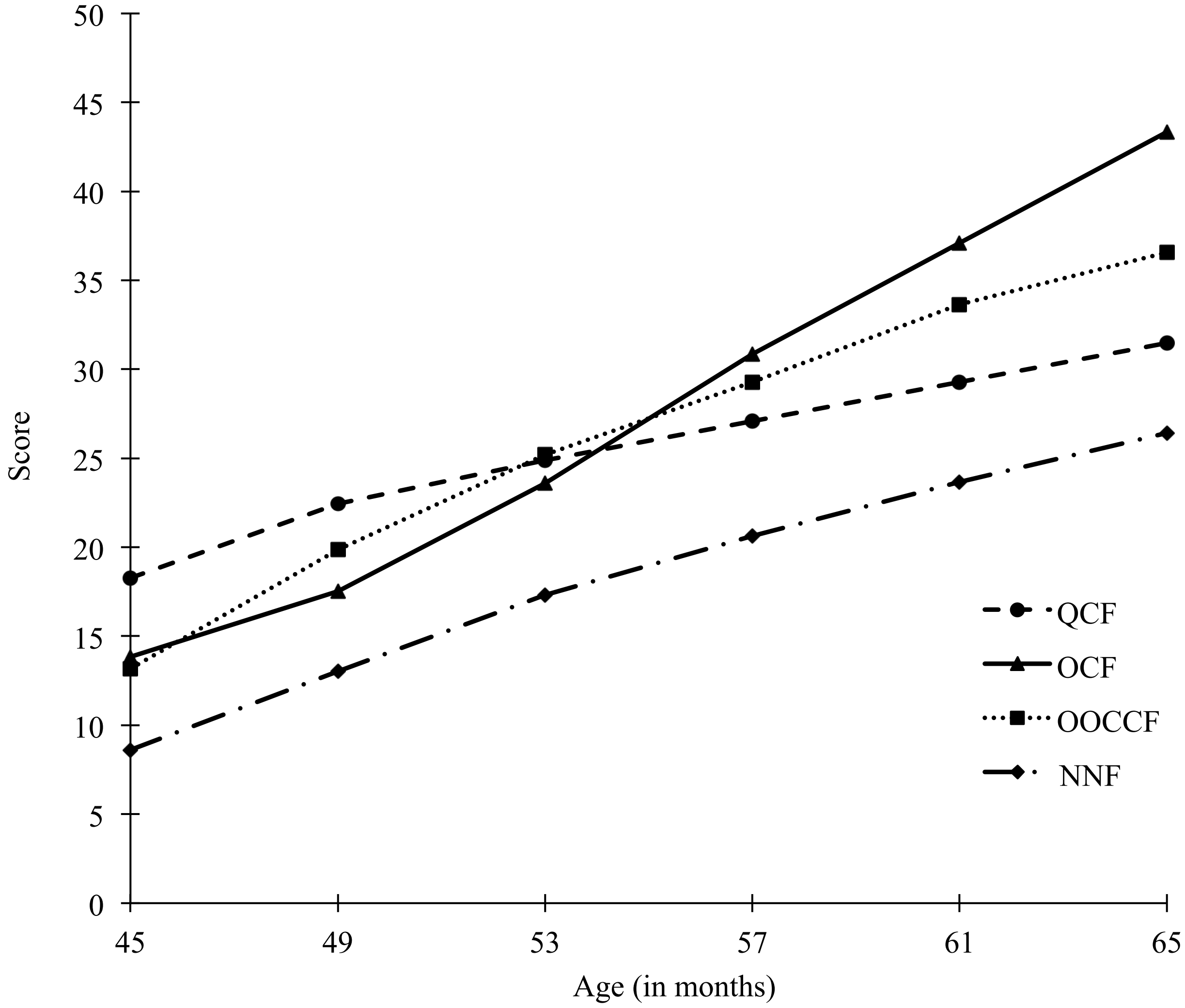

Figure 4. Best-fitting latent growth curves. QCF = Quantity Comparison Fluency; OCF = Oral Counting Fluency; OOCCF = One-to-One Correspondence Counting Fluency; NNF = Number Naming Fluency.

Joy C. Polignano

88 Robin Drive ◆ Mercerville, NJ 08619
(609) 658-0711 ◆ joypolignano@gmail.com

EDUCATION:

2014	**Doctor of Philosophy, School Psychology** Lehigh University (APA Accredited/NASP Approved), Bethlehem, PA
2010	**Master of Education, Human Development** Lehigh University, Bethlehem, PA
2008	**Bachelor of Arts, Psychology** Fairfield University, Fairfield, CT Summa Cum Laude

CERTIFICATIONS:

2014	Nationally Certified School Psychologist, National Association of School Psychologists
2013	Educational Specialist I School Psychologist K-12, Pennsylvania

CLINICAL EXPERIENCE:

Supervised Placements:

2013-2014 **Doctoral School Psychologist Intern**

Illinois School Psychology Internship Consortium (APA Accredited)
North Suburban Special Education District and Glenview School District 34, IL
Supervisors: Melissa Brown, Ph.D., Jill Bose-Deakins, Ph.D., & Ilene Holt-Turner, Ph.D.

Conducted comprehensive psychoeducational evaluations of students ages 3 to 14 including function-based, response-to-intervention (RTI), and play-based early childhood assessments; Facilitated an emerging RTI process in an early childhood setting by organizing universal screening, analyzing myIGDI data, and leading data-based decision-making meetings; Analyzed student performance data to facilitate a preschool program evaluation and evaluated the predictive utility of myIGDI tasks within the site; Participated in preschool and middle school problem-solving teams; Provided behavioral coaching and consultation in early childhood classrooms and an elementary autism support program; Delivered academic and social-emotional interventions (e.g., skill-building groups, individual counseling, video modeling, and the verbal behavior approach to language for children on the autism spectrum); Served as a member of a preschool curriculum mapping leadership team

2011-2012 **School Psychology Fourth Year Practicum Student**
Broughal Middle School, Bethlehem Area School District, PA
Supervisor: Lidia Cordero, M.Ed, MSW

Worked with the district bilingual/bicultural psychologist to implement culturally and linguistically appropriate assessments and interventions; Conducted comprehensive multidisciplinary psychoeducational evaluations to determine special education eligibility; Participated in crisis response and manifestation determination procedures; Provided direct counseling services to adolescents in need of emotional support services; Served on the district Student Assistance Program team by addressing referrals for students with general mental health concerns and connecting students and families to local community resources

2010-2011 **School Psychology Third Year Practicum Student**
Gockley and Steckel Elementary Schools, Whitehall-Coplay School District, PA
Supervisor: Kristin Stiles, Ph.D.

Assisted in the development and implementation of RTI in reading for grades K-5 and math for grades K-1; Assisted in the development and implementation of School-wide Positive Behavior Support (SWPBS) and participated in over 40 hours of SWPBS training; Conducted multidisciplinary psychoeducational evaluations to determine special education eligibility; Consulted with teachers and parents to develop and implement academic and behavioral interventions; Provided direct counseling services to students in need of emotional support services and autism support services

Course-Based Practica:

2010 **Psychology Trainee, Practicum in Assessment and Intervention in Educational Consultation**
Instructor: Edward S. Shapiro, Ph.D., Lehigh University

Conducted comprehensive evaluations of academic skills using curriculum-based assessment; Implemented a math intervention for an elementary student and utilized progress monitoring data to evaluate patterns of math performance; Communicated results to school and family

2009 **Psychology Trainee, Practicum in Behavioral Assessment**
Instructor: Edward S. Shapiro, Ph.D., Lehigh University

Conducted comprehensive behavioral assessments of students with ADHD and conduct issues; Communicated results and intervention recommendations to school and family

2009 **Psychology Trainee, Practicum in Consultation Procedures**
Instructor: Patricia Manz, Ph.D., Lehigh University

Conducted a formal consultation cycle with a teacher and family in a Head Start setting; Consultation involved a joint problem identification interview, problem analysis interview, development and implementation of an intervention program, and intervention evaluation

2009 **Psychology Trainee, Practicum in Assessment of Intelligence**
Instructor: Kevin Kelly, Ph.D., Lehigh University

Developed skills in administering, scoring, and interpreting various cognitive and achievement tests

RESEARCH EXPERIENCE:

2012-2013 **Assessment Coordinator, Reading Achievement Multi-Component Program**
Center for Promoting Research to Practice, Lehigh University
Advisors: Edward S. Shapiro, Ph.D. & Mary Beth Calhoon, Ph.D.

Coordinated assessments for an Institute of Education Sciences randomized control trial examining the efficacy and replicability of two versions of an empirically supported peer-mediated multi-component remedial reading program designed for adolescents with reading difficulties; Coordinated and supervised recruitment, screening, and tri-annual assessment of participants across 37 schools in three school districts; Trained over 30 teachers and graduate students to administer a comprehensive test battery; Conducted evaluations of fidelity and interscorer agreement; Served as liaison with the Texas Institute for Measurement, Evaluation, and Statistics

2011-2012 **Project Coordinator, Lehigh University Faculty Innovation Grant**
School Psychology Program, Lehigh University
Advisor: Robin L. Hojnoski, Ph.D.

Coordinated a study investigating whether preschool teachers in a culturally and linguistically diverse preschool setting could be trained to increase mathematical discourse using a systematic shared storybook reading intervention, and whether such an intervention would have a demonstrated effect on children's early mathematical skills and knowledge; Contributed to the development of the intervention and research design; Developed and implemented the training protocol and provided weekly consultation to the teachers in two experimental conditions; Coordinated data collection and analysis; Participated in manuscript preparation and dissemination at conferences

2008-2012 **Graduate Assistant**
School Psychology Program, Lehigh University
Advisor: Robin L. Hojnoski, Ph.D.

Coordinated academic universal screenings and provided consultation on data-based decision-making in early math and literacy at the preschool level in the Bethlehem Area School District; Initiated a line of research examining differences in early numeracy performance based on primary language; Contributed to the development, implementation, data analysis, and presentation of a single-subject research study investigating whether parents can be trained to increase their use of "math talk" during shared storybook reading; Contributed to planning and data analysis for a single-subject research study investigating the use of teachers' mathematical discourse in the preschool classroom; Conducted literature searches on early numeracy development and vocabulary acquisition

2008-2010 **Research Assistant**
Center for Promoting Research to Practice, Lehigh University
Advisor: Edward S. Shapiro, Ph.D.

Assisted in the program evaluation of Early Reading First within Head Start preschool classrooms by organizing and conducting assessments, maintaining and analyzing data, and report writing; Assisted in the evaluation of the iStation online reading intervention by conducting observations of student engagement, monitoring intervention fidelity, maintaining databases, and report writing; Assisted in the program evaluation of a parent training program implemented by a rural school district to foster early literacy skills by monitoring fidelity, conducting assessments, and report writing

2010-2011 **Doctoral Qualifying Project**
School Psychology Program, Lehigh University
Title: The Technical Adequacy of a General Outcome Measure of Geometry for Preschool Children
Committee Members: Drs. Robin Hojnoski, Edward Shapiro, & Grace Caskie

Developed and piloted a set of curriculum-based measures to assess early geometry and numeracy knowledge of preschool children; Evaluated the measures with regard to interscorer, test-retest, and alternate-form reliabilities and concurrent validity; Disseminated findings through presentation and publication; Several of the piloted tasks are currently being further evaluated in larger samples

2007-2008 **Research Assistant, Cognitive Aging Project**
Department of Psychology, Fairfield University
Advisor: Linda A. Henkel, Ph.D.

Conducted cognitive research related to recall and memory distortions; Designed and conducted an independent research project on memory distrust requiring recruitment of young and older adult participants, intake interviews, administration of general mental health and memory-related assessments, data analysis, and manuscript writing

OTHER PROFESSIONAL EXPERIENCE:

2005-2008 **Infant and Toddler Associate Teacher**
(part-time) Bright Horizons Family Solutions (NAEYC Accredited), Princeton, NJ

Assisted in lesson plan preparation and implementation for infants and toddlers; Guided children in sensory and early learning experiences to promote early skill development; Provided behavioral consultation to caregivers from diverse cultural backgrounds

2007-2008 **Undergraduate Guidance Intern**
Fairfield College Preparatory High School, Fairfield, CT

Met individually with students referred to the guidance department for academic concerns to collaboratively design and implement interventions and monitor their progress

2006-2008 **Volunteer at Giant Steps School**
Fairfield, CT

Volunteered at a school for students diagnosed with autism spectrum disorders and other neurological impairments, ages 3-21 years; Provided support to teachers in creating and modifying instructional materials and direct support to students

2005-2008 **Founder of the American Red Cross Club**
Fairfield University, Fairfield, CT

Developed proposal and constitution to initiate club on campus; Recruited members; Developed goals and planned fundraising activities; Organized biannual blood drives; Organized a campus event that raised $3,500 for Hurricane Katrina victims; Awarded Fairfield University's Rookie Club of the Year Award and nominated for Connecticut's Higher Education Award for community service

SCHOLARLY PUBLICATIONS:

Hojnoski, R. L., Columba, L., & **Polignano**, J. C. (2014). Embedding mathematical dialogue in parent–child shared book reading: A preliminary investigation. *Early Education and Development, 0*, 1-24. doi: 10.1080/10409289.2013.810481

Polignano, J. C., & Hojnoski, R. L. (2011). Preliminary evidence of the technical adequacy of additional curriculum-based measures for preschool mathematics. *Assessment for Effective Intervention, 37*, 70-83. doi:10.1177/1534508411430323

MANUSCRIPTS IN PREPARATION:

Hojnoski, R. L., & **Polignano**, J. C. (in preparation). Comparing early numeracy performance of English and Spanish speaking preschoolers: A curriculum-based assessment approach.

Hojnoski, R. L., **Polignano**, J. C., & Columba, L. (in preparation). Effect of book type on mathematical talk during shared book reading in the preschool classroom.

Hojnoski, R. L., **Polignano**, J. C., & Columba, L. (in preparation). The effect of shared storybook reading in the preschool classroom on children's mathematical skill development.

SCHOLARLY PRESENTATIONS:

Polignano, J. C. & Hojnoski, R. L. (2014, February). *Patterns of growth within and between key numeracy skills across the preschool period.* Poster presented at the biennial C*onference* on R*esearch Innovations in Early Intervention,* San Diego.

Henkel, L. A., & **Polignano**, J. C. (2013, June). *On second thought: Memory distrust in young and older adults*. Paper presented at the 10th biennial meeting of the Society for Applied Research on Memory and Cognition, Rotterdam, the Netherlands.

Hojnoski, R. L., Caskie, G. I. L., **Polignano**, J., & Brittain, A. (2012, June). *Curriculum-based assessment of early numeracy in preschoolers who speak Spanish as their primary language: Differences in performance and growth over time*. Presentation at Head Start's 11th National Research Conference, Washington, DC.

Hojnoski, R. L., & **Polignano**, J. C. (2012, February). *Number knowledge in English- and Spanish-speaking preschoolers*. Poster presented at the annual meeting of the National Association of School Psychologists, Philadelphia.

Hojnoski, R. L., & **Polignano**, J. C. (2012, February). *Promoting early mathematics through shared storybook reading at home and preschoo*l. Poster presented at the biennial C*onference* on R*esearch Innovations in Early Intervention*, San Diego.

Polignano, J. C., & Hojnoski, R. L. (2011, November). *Using shared storybook reading to promote early mathematics at home and preschool.* Paper presented at the annual international meeting of the Division for Early Childhood, National Harbor, MD.

Polignano, J. C. (2011, June). *Developmental patterns of early numeracy skills: An accelerated longitudinal design.* Poster presented at the Cross University Collaborative Mentoring Conference, Bethlehem, PA.

Columba, L., Hojnoski, R. L., & **Polignano**, J. C. (2011, April). *Promoting students' "math talk" through shared reading.* Paper presented at the annual meeting of the National Council of Teachers of Mathematics, Indianapolis, IN.

Polignano, J. C. (2011, March). *The technical adequacy of a general outcome measure of geometry for preschool children.* Poster presented at the Lehigh University 2011 Academic Symposium, Bethlehem, PA.

Polignano, J. C. (2011, March). *The development and evaluation of general outcome measures of preschool mathematics.* Poster presented at the College of Education Third Biennial Research Symposium, Bethlehem, PA.

Polignano, J. C., & Hojnoski, R. L. (2011, February). *The technical adequacy of a general outcome measure of geometry for preschool children.* Poster presented at the annual meeting of the National Association of School Psychologists, San Francisco.

Hojnoski, R. L., Columba, L., & **Polignano**, J. C. (2010, March). *Embedding mathematical discourse in shared storybook reading.* Poster presented at the annual meeting of the National Association of School Psychologists, Chicago, Illinois.

Hojnoski, R. L., Missall, K. N., Smith, A., & **Polignano**, J. C. (2009, April). *What shall we play?: Gender and early math performance.* Poster presented at the biennial meeting of the Society for Research in Child Development, Denver, Colorado.

PROFESSIONAL AFFILIATIONS:

Student Affiliate, National Association of School Psychologists, Convention Proposal Reviewer
Student Affiliate, American Psychological Association, Division of School Psychology
Student Affiliate, Council for Exceptional Children, Division of Early Childhood

AWARDS AND HONORS:

2011	Lehigh University Leiser Scholar
2011	Lehigh University Academic Symposium Nominated Exhibitor
2007	Sigma Xi, The Scientific Research Society Inductee
2007	Psi Chi, National Honor Society in Psychology Inductee
2007	Alpha Mu Gamma, National Foreign Language Honor Society Inductee
2007	Alpha Sigma Nu, National Jesuit Honor Society Inductee
2004-2008	Fairfield University Fellows Scholar
2004-2008	Fairfield University Honors Program