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Early numeracy skills in preschool-aged children: A review of neurocognitive findings and implications for assessment and intervention

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Abstract

Objectives: The goals are to 1) provide a review of the typical and atypical development of early numeracy; 2) present what is known about the neurocognitive underpinnings of early numeracy; and 3) discuss the implications for early assessment and intervention.

Method: Studies on the development of typical and atypical early numeracy are reviewed with a particular focus on longitudinal findings including those from our work on spina bifida myelomeningocele. Implications of this research for assessment are presented. The paper ends with a discussion of early math interventions.

Results: Learning to count, identify numbers, and compare and manipulate quantities are key early numeracy skills. These are powerful predictors of school-age mathematical learning and performance. General neurocognitive abilities such as working memory and language, are also important for the development of early numeracy. It is recommended that early assessment for risk of mathematical learning difficulties include tests of both early number knowledge and key neurocognitive abilities. Math-specific interventions are most effective for improving early numeracy. There is currently little evidence that training of general cognitive functions transfers to mathematical learning.

Conclusion: Understanding the development of early numeracy skills and their neurocognitive predictors offer important insights into early assessment and intervention for children at risk for or with mathematical learning difficulties.

Keywords

preschool; early numeracy; math; working memory; language

Although numeracy is far less studied than literacy, it is as important as literacy for predicting productivity, wages, and employment outcomes (Rivera-Batiz, 1992), and the cost

of innumeracy to individuals and society is high (Hudson, Price, & Gross, 2009). In recent years, analyses of data from large national longitudinal databases such as the Early Childhood Longitudinal Study, have shown that children's mathematical knowledge at school entry is the strongest predictor of both later math success as well as success in other academic domains (Duncan et al., 2007). Similar findings have been obtained with respect to risk for math learning disability or MLD. Morgan, Farkas and Wu (2009) found that 70 percent of children who started and ended kindergarten below the 10th percentile in mathematics were also below the 10th percentile in 5th grade, underlining the importance of early mathematical knowledge to later mathematical achievement. Together, these findings suggest that early numeracy is critically important for later mathematical development (Aunola, Leskinen, Lerkkanen, & Numri, 2004; Duncan et al., 2007; Toll, van der Ven, Kroesbergen, & van Luit, 2011). Given the essential role that early numeracy plays in the development of later mathematical ability and disability, it is important to understand: 1) what early numeracy skills are important for later mathematical development; 2) what early number-specific and general cognitive abilities are involved in the acquisition of these key early numeracy skills; and 3) the implications of such knowledge for early assessment and intervention.

Although studies on the typical and atypical development of literacy skills and interventions for reading have historically outnumbered those in the area of numeracy (Siegler, 2007), there has been a strong upsurge in research in mathematics over the past two decades (Geary, 2013). Given the importance of early numeracy skills to later mathematical development along with rapid changes in knowledge in this area, the goal of this paper is to review the emerging literature on the acquisition of early numeracy skills in typically developing children and in children at risk for math difficulties. Specifically, we provide a description of commonly studied early numeracy skills shown to be important for later mathematical achievement and present findings on number-specific and general neurocognitive abilities that are important for the development of these early numeracy skills and later mathematical achievement. Because there are more studies of early math in young typically developing children and in neurologically intact children at risk for math difficulties (e.g., children with socio-economic disadvantage) than there are of preschool children with neurological disorders, most of the review focuses on the former groups. However, we also present findings on select groups of preschool children with neurological disorders. These include spina bifida myelomeningocele (SBM), a neurodevelopmental disorder associated with high rates of math learning disability (about 50%), but low rates of reading disability (Fletcher et al., 2005). Because the rate of MLD at school-age is known and SBM is diagnosed before or at birth, we have been able to study these children's mathematical development over a much longer developmental time window than is typical of most other longitudinal studies. The high rate of specific MLD in this population, coupled with the fact that they have been followed from toddlerhood into the middle elementary school years makes the findings of relevance to understanding math disabilities more generally (Barnes & Raghubar, in press). We also briefly discuss math difficulties in two high incidence clinical populations; children with low birth weight and children with Fragile X syndrome. Importantly, we discuss the implications of the findings across populations for early assessment of risk, and discuss

evidence for and against the effectiveness of particular approaches to early numeracy interventions.

Early Numeracy Skills and Their Relation to Mathematical Achievement

Early numeracy is an umbrella term that encompasses several skills such as verbal counting, knowing the number symbols, recognizing quantities, discerning number patterns, comparing numerical magnitudes, and manipulating quantities (i.e., adding and subtracting objects from a set). Such *informal* math skills are acquired prior to or outside of the school setting. In comparison, *formal* math knowledge is acquired through explicit teaching within the school setting such as instruction in the concepts and steps involved in regrouping in multi-digit addition and subtraction. For most children, acquisition and mastery of early numeracy skills occurs spontaneously through activities in the home and other experiences in the child's everyday environment (LeFevre et al., 2009), though this is not true for all children. For example, children from low socioeconomic status households often demonstrate less well developed numerical knowledge during the preschool years and kindergarten than their middle-income peers (Griffin, Case, & Siegler, 1995; Jordan, Huttenlocher, & Levine, 1994; Starkey, Klein, & Wakeley, 2004), which has been associated with exposure to significantly fewer and less complex everyday number activities and experiences (e.g., Blevins-Knabe & Musin-Miller, 1996). Children with learning difficulties related to specific neurodevelopmental disorders or to other developmental factors also often struggle with the acquisition of informal mathematical knowledge. Consequently, children with low number skills at kindergarten entry, regardless of the source of this lack of mathematical knowledge, are at high risk for low math achievement over the early elementary school grades (Jordan, Kaplan, Ramineni & Lokuniak, 2009).

Early numeracy skills involve the understanding and manipulation of both symbolic and non-symbolic number. Early *symbolic* number skills include learning the count sequence and understanding the numerical meaning of number words (e.g., "three") and Arabic numerals (e.g., "3"). Children are considered to know the meaning of symbols once they have acquired the cardinality principle, or the understanding that the last number word used when counting a set indicates the number of objects in the set. Symbolic number knowledge in the preschool years has been reliably associated with later math achievement (Gobel, Watson, Lervag, & Hulme, 2014; also see Merkley & Ansari, 2016 for review).

Non-symbolic number skills and representations refer to ways of representing numbers without using symbols and typically involve numerical manipulations or transformations on objects as well as comparisons of the magnitude of sets of objects. For example, young children can perform simple addition and subtraction with non-symbolic numerical representations (e.g., with actual objects or pictures of objects; Bisanz, Sherman, Rasmussen, & Ho, 2005). These non-symbolic tasks that involve quantity manipulations (adding and subtracting from sets of objects) are related to later achievement on symbolic arithmetic tasks (adding and subtracting Arabic numerals). In contrast, the evidence for a relationship between performance on magnitude comparison tasks using non-symbolic representations of number (e.g., presenting two arrays and determining which one has more) and later math achievement is not as strong (Leibovich & Ansari, 2016). These symbolic and

nonsymbolic number skills are discussed in more detail below drawing on studies of typical and atypical development to demonstrate the relationship of these early numeracy abilities to later math achievement.

Symbolic Number Skills

The development of counting skills and its impact on arithmetic skill development has been well studied. Sequential counting refers to the ability to recite the number word sequence (e.g., 1, 2, 3, 4, 5...10) and acknowledge the position of a number word in this sequence (e.g., 1, 2, 3...what comes next? 4; or 4 comes after 3 and before 5) without explicitly understanding cardinal meaning (how many are there?). Gradually, children apply their knowledge of the counting sequence to enumerate sets of objects. This serial quantification process is referred to as cardinal counting and involves mapping each number word onto each item in a set (one-to-one correspondence) to acknowledge the exact number of items in a collection (Fuson, 1988; Gelman & Gallistel, 1978). Ultimately, children demonstrate an understanding of the numerical meaning of number words with acquisition of the cardinality principle (Gelman & Gallistel, 1978). In the research literature, counting skills in preschool and kindergarten children have commonly been assessed by asking young children to watch a hand puppet point to and count objects or dots on a page, and to tell the puppet whether or not he counted correctly. Incorrect counts typically violate one of three counting principles: one-to-one correspondence (one counting tag is applied to each object); stable order/ordinality (number tags must be applied in an invariant order); and cardinality (the last number counted refers to the total quantity). Early studies demonstrated that typically developing preschool-aged children are sensitive to violations of the one-to-one and cardinal principles, correcting the puppet when he double counted, skipped an item, or repeated an incorrect cardinal value (Gelman, Meck, & Merkin, 1986).

Young children employ counting procedures when solving arithmetic problems and rely on fingers or other external referents (e.g., blocks, drawings, stickers, etc.) (Siegler & Shrager, 1984). The most common counting procedures regardless of the use fingers are *counting-all* (counting both addends starting at 1, for example, for a 2 and 3 problem, counting 1,2, then 3,4,5), *counting-on max* (stating the smaller valued addend and then counting a number of times equal to the value of the larger addend, for example, 2, then 3,4,5), and *counting-on min* (stating the larger addend and then counting the smaller addend, for example, 3, then 4,5). Despite the mix of strategies employed, young children tend to shift to use of more efficient strategies, doing away with the more laborious *counting all* procedure in favor of the *counting-on min* procedure, which involves the least amount of counting. This shift in procedures is related, in part, to improvements in children's conceptual knowledge of counting (Siegler, 1987). The use of counting also results in the development of memory representations of basic math facts, facilitating direct retrieval of answers from memory (e.g., stating "five" without having to count when asked to solve $2 + 3$).

Early knowledge about number symbols predicts formal math skills and later math achievement. Number identification (i.e., children are told a number and they have to select the correct number from 4 or 5 options) assessed at the beginning of the first year of school was a powerful predictor of longitudinal growth in arithmetic skills over the next 11 months

(Gobel et al., 2014). Similarly, longitudinal studies examining early number skills including number identification and counting assessed at the end of kindergarten were strong predictors of math outcomes at the end of first grade (Chard et al., 2005; Clarke & Shinn, 2004). Longitudinal work conducted by Jordan and colleagues found that growth in early numeracy skills including symbolic skills from the start of kindergarten through the middle of first grade was highly predictive of first grade math achievement (Jordan, Kaplan, Locuniak, & Ramineni, 2007) and predicted both the rate of growth and levels of math achievement between 1st and 3rd grades (Jordan et al., 2009).

Longitudinal studies of young children at risk for MLD have largely focused on school-age children in the early grades. Findings from these studies suggest that children with low math achievement scores understand basic counting principles, such as cardinality and ordinality but have difficulty understanding unessential features of counting such as the idea that counting of objects can proceed in any order (Geary, Hamson, & Hoard, 2000; Geary, Hoard, & Hamson, 1999). Our longitudinal work with children with SBM and their typically developing peers (Barnes et al., 2011) shows that difficulties in symbolic aspects of arithmetic are discernable early in development as early as 36 months of age, children with SBM were significantly less able than their typically developing peers to answer the entry-level questions on the Test of Early Mathematics Ability (TEMA-2; Ginsburg & Baroody, 1990), which involve counting small sets of objects, showing the number of fingers corresponding to spoken number words, and understanding cardinality (Barnes et al., 2011). At 60 months of age, these same children with SBM were unable to count as high as their typically developing peers and they were also less skilled than their peers at detecting incorrect counts by the puppet in the counting task described above. In all, these longitudinal studies of children at risk for MLD show that 1) early difficulties in conceptual counting knowledge and in counting procedures are characteristic of children who go on to have difficulties in mathematics at school-age; and 2) difficulties in counting knowledge and procedures can be discerned quite early in development, before formal schooling.

Non-Symbolic Arithmetic

Preschool-aged children demonstrate success on non-symbolic addition and subtraction problems using relatively small numbers (Huttenlocher, Jorden, & Levine, 1994; Levine, Jordan, & Huttenlocher, 1992). These problems typically consist of having the examiner place an array of objects on a mat and then a screen is placed in front of the array so as to occlude the array from the child. The child watches while the examiner either adds chips to the array (addition) or removes chips from the array (subtraction) in a single trial. Although children cannot see the quantity behind the screen, they see the quantity that was added or removed. Finally, children are asked to use their chips to match the quantity that remains hidden after the transformation (Jordan, Huttenlocher, & Levine, 1992).

Typically developing preschoolers aged three years and older can add and subtract on these arithmetic tasks using non-symbolic quantities, though accuracy tends to be related to age and problem size, for example, accuracy is higher for smaller problems such as $2 + 2$ than it is for larger problems such as $4 + 3$ (Huttenlocher et al., 1994). When non-symbolic arithmetic problems (e.g., 2 chips are placed on a mat, a screen occludes the child's view

and three more chips are added. “How many do I have under here now? Show me on your mat?”) and symbolic arithmetic problems (i.e., simple word problems of the type, “How much is 2 and 3”?; or “John had 2 balls. He got 3 more. How many does he have altogether?”) were examined in children ages 4–6 years old, non-symbolic problems were found to be easier for the younger children (Levine et al., 1992; Huttenlocher et al., 1994), but this difference was diminished for the older children (Levine et al., 1992; Rasmussen & Bisanz, 2005).

Non-symbolic arithmetic tasks are considered to tap early conceptual knowledge about arithmetic such as the concepts of addition and subtraction as demonstrated above, well before children are able to articulate this conceptual knowledge or solve similar sized problems using symbols such as Arabic numerals or number words. In addition to early conceptual knowledge about addition and subtraction, typically developing preschoolers have also been shown to understand mathematical concepts such as *inversion* (the principle that $a + b - b$ must equal a). Klein and Bisanz (2000) demonstrated that 4-year-old children solve these three-term inversion problems more quickly than standard problems (e.g., $a + b - c$), suggesting the use of a selective strategy for inversion problems, which is confirmed by spontaneous reporting by children that counting was not needed because the second and third numbers were the same.

In terms of individual differences, non-symbolic arithmetic is correlated with math achievement throughout kindergarten to the middle of first grade (Jordan et al., 2007) and is a commonly used preschool math task in longitudinal studies of the prediction of later math achievement (Jordan et al., 2007; 2009). In our longitudinal studies of children with SBM, performance on this non-symbolic arithmetic task at 60 months of age strongly predicted performance on a standardized measure of multi-digit symbolic arithmetic 4 to 5 years later (Barnes & Raghubar, in press), suggesting developmental continuity in the ability to manipulate non-symbolic and symbolic quantities.

Non-symbolic Representations and Approximate Number System Acuity

Several recent studies on typical and atypical math development have focused on the concept of “number sense”, which has been defined as the ability to rapidly indicate which of two sets of non-symbolic quantities is larger without counting (Butterworth, Varma, & Laurillard, 2011). This ability is referred to as approximate number system (ANS) acuity (for a review of this literature see Geary, Berch & Mann Koepke, 2015). In a typical ANS task, two large arrays of quantities are presented briefly and their magnitudes compared. For an example, see www.panamath.org (Halberda & Feigenson, 2008; Halberda, Mazzocco, & Feigenson, 2008). As the ratio between the quantities to be compared decreases, accuracy on ANS acuity tasks also decreases. The ability of human infants and nonhuman animals to compare large approximate quantities is presumed to be evolutionarily important and, in the case of humans, to provide the “infant’s starter kit” for the development of number skills (Butterworth, 1999). Although this ability is presumed to be innate, there are both developmental changes and individual differences in ANS acuity, and the latter have been proposed to underlie individual differences in the acquisition of both early numeracy skills as well as math achievement and MLD at school-age (Geary et al., 2015).

Despite the recent intense interest in whether ANS acuity is importantly related to growth in mathematical abilities, there is currently a lack of evidence for a unidirectional causal relationship between ANS abilities and the acquisition of symbolic math skills. Instead, evidence suggests that children who have acquired symbolic skills such as the cardinality principle are more likely to succeed on non-symbolic tasks (Batchelor, Keeble, & Gilmore, 2015; Slusser, Ditta, & Samecka, 2013), leading some to conclude that acquiring symbolic knowledge likely influences non-symbolic skills, rather than the other way around (Merkley & Ansari, 2016). Similarly, relations between ANS acuity and math achievement are mediated by symbolic number knowledge such as Arabic numeral naming and cardinality (Chu, van Marle, & Geary, 2015; see also Merkley & Ansari for a review). Indeed, preschoolers' cardinality knowledge emerged as an important mediator of the relationship between ANS acuity and early math achievement (van Marle, Chu, Li, & Geary, 2014; Chu et al., 2015). Based on these recent findings, it has been suggested that explicit knowledge of the cardinal value of number symbols (i.e., that the last item counted represents the cardinal value of the set) may act as a critical early link between ANS acuity and math achievement given that the core implicit knowledge represented by the ANS is cardinal value, albeit an approximate value, of collections of objects. Consequently, Chu and colleagues (2015) proposed that young children who easily discriminate relative quantities of collections of objects also easily achieve insight that quantities represented by different number symbols differ in quantity.

In terms of individual differences, although performance on the ANS task correlates with mathematical achievement (Bonny & Lourenco, 2013; Halberda, et al., 2008; Mazzocco, Feigenson, & Halberda, 2011b), three meta-analyses (Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2016) have found that the relation between ANS acuity and mathematical performance, while significant and consistent, is small ($r = \sim .20$). Studies of children with MLD and of young children at risk for MLD have begun to address whether a deficit in ANS acuity is a defining feature of difficulties in mathematical learning. Some studies (Mazzocco, Feigenson, & Halberda, 2011a; Piazza et al., 2010) have reported poorer ANS acuity in children with MLD, but other studies have not (Iuculano, Tang, Hall, & Butterworth, 2008; Rousselle & Noel, 2007). In preschool children, ANS acuity at the beginning of prekindergarten was found to be predictive of math achievement at the end of the prekindergarten year, but only for children in the lowest quantile of the mathematics performance continuum (Purpura & Logan, 2015). In a micro-analytic approach to studying these relations, Bugden and Ansari (2015) found that children with MLD did not differ from typically developing peers on items in which number and area are correlated (i.e., where 10 dots take up more area than 5 dots), but did differ on items in which number and area are uncorrelated (i.e., where 10 dots take up the same area as 5 dots). Group differences on these uncorrelated trials were mediated by visual-spatial working memory, calling into question the idea that it is deficits in ANS acuity per se that discriminate children with and without MLD.

In sum, these studies of non-symbolic number skills suggest that ANS acuity (comparison of non-symbolic numerical magnitudes) may not have a strong and direct relationship with later math ability and disability. In contrast, performance on tasks in which non-symbolic quantities are manipulated arithmetically (the nonverbal addition and subtraction tasks

described above) do seem to be related to later math achievement in the domain of calculation. In keeping with the predictive value of such nonverbal arithmetic tasks, items involving non-symbolic arithmetic are part of the most recent version of the Test of Early Mathematics Ability, the TEMA-3 (Ginsburg & Baroody, 2003), an assessment of number and operations that covers the age range from 36 months to 8 years.

Neurocognitive Skills and Their Relation to Math Achievement

A variety of neurocognitive factors have been related to mathematical performance in school-age children, including language abilities, processing speed, working memory, attention, and other executive skills such as set switching (Peng, Namkung, Barnes, & Sun, 2015; Peterson et al., 2016; Willcutt, et al., 2013). Fewer of these neurocognitive correlates have been examined in relation to early numeracy skill development. We provide a review of the math-related neurocognitive correlates that have been related to the acquisition of early numeracy, namely, working memory, language, and finger skills.

Working Memory

Working memory refers to an individual's ability to hold information in memory while simultaneously processing other information (Baddeley, 1992; Engle, Tuholski, Laughlin, & Conway, 1999). Working memory capacity increases from preschool through the elementary school years, and it has been shown to be a significant predictor of children's academic achievement in general, and math achievement specifically. Moreover, children with MLD typically do not perform as well as their typically developing peers on a variety of working memory measures (Bull, Johnston, & Roy 1999; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; see Raghubar, Barnes, & Hecht, 2010 for review).

Most research connecting working memory and math achievement has focused on school-aged children and formal mathematics but there is some evidence that working memory is just as important to the development of informal math concepts and early numeracy skills in preschoolers and kindergarteners. Purpura and Ganley (2014) examined the relation of verbal working memory to several early math skills in children in preschool and kindergarten. After accounting for many other math-related variables (age, grade, sex, broad calculation ability, and single word expressive vocabulary), verbal working memory emerged as a significant predictor of cardinality, guessing the number of objects without counting (with set sizes ranging from 1 to 7), set comparison (determining which set of four has the most dots), and number order. These findings were in line with the authors' hypothesis that working memory would be related to that subset of early math skills that are more complex and require multiple steps; in contrast, working memory was not related to more basic skills such as rote verbal counting, one-to-one counting (counting sets of objects), number identification, and simple story problems without extraneous information (e.g., "Johnny had one cookie and his mother gave him one more cookie. How many cookies does he have now?").

In one longitudinal study that compared the neurocognitive preschool predictors of later academic achievement in math and reading, visual working memory assessed during preschool was found to predict growth specific to math achievement in the early school

grades (Bull, Espy, & Wiebe, 2008). Visual-spatial working memory appears to support the ability of young children to solve non-symbolic arithmetic problems such as the type described above in which items are added to or subtracted from a hidden set of objects (Levine et al., 1992; Rasmussen & Bisanz, 2005). To solve these problems, it has been suggested that preschoolers use mental models or nonverbal representations of the mathematical situation involving transformation on number when adding to or subtracting from sets of objects (Bisanz et al., 2005). By first grade, however, visual-spatial working memory was no longer a significant predictor of these same nonverbal math problems, perhaps signaling a switch to the use of verbal rather than visual-spatial codes during problem solving (Bisanz et al., 2005).

A recent meta-analysis by Peng and colleagues (2015) has helped to specify the relation between math and working memory as well as potential moderators of this relation. This meta-analysis revealed that the relation between math and working memory was not impacted by domain of working memory; that is, verbal, visual-spatial, or numerical working memory. However, different types of math skills were found to draw on working memory resources to different degrees: Whole number calculations and word problem solving showed the strongest relation with working memory whereas geometry showed the weakest relation with working memory. Importantly, the relation between working memory and mathematics was stronger among individuals with MLD and a co-occurring disorder, such as attention-deficit/hyperactivity disorder, Turner syndrome, or velo-cardio-facial syndrome, compared to typically developing individuals or individuals with specific MLD alone. It may be that individuals with a co-occurring disorder demonstrate significant impairments in neurocognitive processes (such as working memory), which in turn, further impacts mathematical development.

In summary, working memory is an important predictor of several early numeracy skills including cardinality, set comparison, number order, and non-symbolic arithmetic (Bisanz et al., 2005; Purpura & Ganley, 2014). The continued importance of working memory for later mathematics achievement at school-age is demonstrated for a number of math skills at school age most notably calculation and word problem solving skills (Peng et al., 2015). Furthermore, relationships between working memory and school-aged math skills appear to be particularly strong for children with math difficulties in the context of comorbid neurodevelopmental disorders (Peng et al., 2015).

Language

Language is a strong predictor of several early numeracy skills including number identification, cardinality, number comparison, number order, and story problems (LeFevre et al., 2010; Purpura & Ganley, 2014), but not verbal counting, one-to-one counting, subitizing (Purpura & Ganley, 2014) and non-symbolic arithmetic (LeFevre et al., 2010). That children's language skills are related to many though not all aspects of early numeracy is not surprising considering that most early numeracy skills require children to know number names; connect number names with specific quantities and written numerals; connect written numerals with quantities; connect number names, quantities, and written numerals; and demonstrate an understanding of comparative terms such as "more", "less",

and “equal to”. Consequently, language may play a key role in the acquisition of new knowledge and the integration of that knowledge with prior knowledge. Moreover, language may play a critical role in the integration of early numeracy skills and formal mathematical learning.

Phonological awareness, a specific type of language-based ability that is strongly related to the acquisition of reading, refers to the ability to encode, access, and manipulate speech sounds within words. Phonological awareness, more so than measures of vocabulary or word meaning, tap the *quality* of lexical representations (perhaps because they require fine distinctions between phonological representations such as cat vs. car or cat vs. rat) and is related to young children’s sequential counting skills (Barnes et al., 2011; Koponen, Salmi, Eklund, & Aro, 2013; Krajewski & Schneider, 2009; Soto-Calvo, Simmons, Willis, & Adams 2015). A longitudinal study conducted by Krajewski and Schnieder (2009) followed children from preschool to third grade and examined the relation of phonological awareness to the development of early numeracy skills. Findings indicated that phonological awareness assessed in preschool was differentially related to the development of early numeracy skills. Phonological awareness predicted individual differences in learning the number sequence; but not individual differences on tasks where the number sequence is mapped onto quantity (e.g., deciding which of two number words represented “more” or “less”; matching quantities to the corresponding Arabic numerals and vice versa). Along these lines, Soto-Calvo and colleagues (2015) found that phonological awareness assessed in the first year of pre-kindergarten (at 4 years, 8 months on average) no longer predicted sequential counting skills 14-months later after including the autoregressor (sequential counting skills from the previous year). If a cognitive predictor remains significant when autoregressor effects are controlled, it can be concluded that the cognitive predictor predicts growth in the outcome measure. In this case, phonological awareness influenced sequential counting at school entry but not growth in sequential counting during the first year of schooling, suggesting that while phonological awareness is related to early counting, it is no longer a unique predictor of counting later in development.

Taken together, the evidence collected to date suggests that the quality of language-based representations, tapped by measures of phonological awareness, is important for acquisition of the counting sequence and may be less relevant for the formation of higher-order mathematical competencies. Moreover, the role of phonological awareness in learning the counting sequence may be rather circumscribed: Phonological awareness may influence the rate at which children acquire the first few number words, but later extension of the number sequence may depend to a greater extent on other conceptual factors, such as knowledge of the base 10 (Soto-Calvo et al., 2015). For example, it is likely that conceptual number knowledge, rather than phonological awareness is important for understanding that 20 follows 19 and comes before 21.

In addition to the quality of language representations and their role in early counting, there has been a more recent focus on the language of mathematics itself and how mathematical language is related to math achievement in both very young and older children. There is recent evidence to suggest that mathematical language is an important predictor of early mathematical performance among preschool-aged children even when accounting for other

cognitive processes, such as executive functioning, general vocabulary knowledge, and rapid automatized naming (Purpura & Logan, 2015; Purpura & Reid, 2016). Examples of math-specific language for preschoolers include comparative (e.g., “take away”, “more”, “less”) and spatial (e.g., “nearest”, “far away”, “under”) terms (Purpura & Logan, 2015). The importance of general language and mathematical language to early math development brings up strong consideration of children who are English language learners and/or from families of lower socioeconomic status (SES), as these children have both less word knowledge including mathematically-relevant vocabulary and are at greater risk for early math difficulties. For example, among 6–9 year-old native English-speaking and English language learners from low SES families, language ability was found to predict gains in some areas of math such as data analysis/probability and geometry but not in other areas such as algebra or arithmetic, suggesting that language ability is not directly involved in learning how to manipulate quantities and execute algorithms but is involved in how children learn to make meaning of mathematical content (Vukovic & Lesaux, 2013). Moreover, the relation between language ability and math concepts was similar for both English language learners and their native English speaking peers, though this relation was somewhat more pronounced for English language learners.

In sum, recent evidence suggests that mathematical language, may be particularly important even for preschool children’s mathematical competence. The link between math language and early numeracy skills is likely due to the fact that understanding math-specific terms (e.g., more, fewer) is inherently necessary for the completion of basic mathematical tasks (Purpura, Hume, Sims, & Lonigan 2011). Despite its importance for early numeracy skill development, math specific vocabulary assessments are currently not available, though they are being developed.

Finger Skills

A variety of finger skills have been linked to early numeracy and math achievement in the preschool and early school grades. Fingers act as a support to a number of early numeracy skills such as reciting the numerical chain (Sato & Lalain, 2008), understanding the cardinal meaning of number words (Butterworth, 1999), establishing one-to-one correspondence by pointing to each object when counting (Gallistel & Gelman, 1992), and keeping track of counted items in mental calculations (Geary, 2005). Such findings have been used to argue for common neural representations of fingers and numbers because of their functional developmental connections through use of fingers to count and calculate (e.g., Butterworth, 1999). Fine motor skills involved in finger counting and pointing may also help children compensate for limited working memory capacity by avoiding having to internally store a mental representation of each counted object (Alibali & DiRusso, 1999). Finger gnosis assessed at 5 years of age was found to be a powerful predictor of numerical ability up to three years later (Fayol, Barrouillet, & Marinthe, 1998). Among school-aged children, finger localization/gnosis has been shown to predict performance on standard mathematical tests, including number system knowledge and calculation (Noel, 2005; Penner-Wilger et al., 2007) as well as tasks tapping numerical representations, such as number-line estimation and magnitude comparison (Penner-Wilger et al., 2008). Moreover, training in finger identification in first grade was associated with improvements in mathematical tasks

including representation of numerosities with fingers, processing Arabic digits, and quantification (Gracia-Bafalluy & Noel, 2008).

Although we have mainly considered the predictive value of early number-specific and general neurocognitive abilities for early numeracy and later math achievement, a few more recent studies have attempted to address which number-specific and general neurocognitive abilities uniquely predict which early and later math skills by including a range of potential predictors in their studies (e.g. Bailey, Watts, Littlefield, & Geary, 2014; Purpura & Logan, 2015). In our longitudinal studies of SBM (Barnes et al., 2011), for example, the ability to detect counting errors, to count orally, and to perform nonverbal arithmetic problems at 60 months of age was best predicted by a combination of 36-month early number knowledge (as measured by the first few items on the TEMA) and neurocognitive factors (e.g., visual spatial, fine motor, and language abilities). Although the combination of predictors varied somewhat for counting and nonverbal arithmetic, the factors that predicted early numeracy in children at high risk for MLD (the children with SBM) were the same as those that predicted early numeracy in the typically developing control group. We also asked whether later math achievement at 9–10 years of age (multi-digit calculation, math fluency, math problem solving) is best predicted by early numeracy at 60 months (oral counting, detection of counting errors, nonverbal or nonsymbolic arithmetic), early neurocognitive abilities assessed at 36 and 60 months of age (visual working memory, phonological abilities, finger skills), or a combination of the two (Barnes et al., 2014; Barnes & Raghubar, 2016; in press). For complex calculation at 9–10 years of age, phonological awareness and working memory were significant longitudinal predictors along with non-symbolic arithmetic. These findings suggest that preschool working memory and language abilities are important developmental precursors of later math calculation ability, but also that there is developmental continuity in the ability to manipulate number because the ability to add and subtract non-symbolic representations of number in the preschool years predicted the ability to add and subtract multi-digit numbers at school-age. For mixed math problem solving, working memory was the only significant longitudinal predictor, again underlining the importance of working memory abilities for solving novel quantitative problems (Fuchs et al., 2016; Geary, 2013). For single-digit arithmetic fluency, only counting knowledge (detection of counting errors) was a significant predictor suggesting that a number-specific developmental precursor - counting knowledge - is an important early determinant of later math fact acquisition.

Taken together, both early general neurocognitive skills and number-specific skills appear to be important for the acquisition of preschool numeracy skills as well as for later school-age math achievement. Given the importance of early numeracy skills and early neurocognitive abilities to later math learning and performance, these findings have implications for assessment and intervention during the preschool years, which we discuss following a brief description of early math skills in neurodevelopmental disorders.

Mathematical Development in Children with Neurodevelopmental Disorders.

Neurodevelopmental disorders stemming from congenital, genetic, traumatic, or acquired origins are often associated with difficulties in academic achievement. Although these disorders may be associated with difficulties in both math and reading, specific or more

severe difficulties tend to be associated with *math* more so than reading (e.g., Fragile X, SBM, traumatic brain injury, very low birth weight). We have argued that this is the case because math is not a unitary skill and several neurocognitive systems are likely involved in math learning and performance (Barnes & Raghubar, 2014). As such, neurological insults or disorders that affect brain development can be expected to affect one or more of the neurocognitive systems that has been implicated in one or more mathematical skills/ domains. Although a review of mathematical learning and performance in children with neurodevelopmental disorders is beyond the scope of this review, in this section, we provide a brief description of early numeracy skills in two high incidence clinical populations associated with math difficulties; namely, children with low birth weight and Fragile X syndrome. Although there is increased incidence of math disability in these populations, mathematical development and its neurocognitive correlates are considerably less well studied than in children with SBM. For these populations, we limit our description to what is known about *early* numeracy and/or how their difficulties in early numeracy are related to later MLD.

Similar to SBM, children with very low birth weight or very preterm birth have higher rates of MLD than normal birth weight term-born children (reviewed in Taylor, Espy, & Anderson, 2009). As a group, preterm children demonstrate difficulties in formal mathematical skills at school-age, assessed using standardized tests or measures. However, there is limited information on early numeracy skill development and basic numerical processing in this population (Simms, Cragg, Gilmore, Marlow, & Johnson, 2013). Available information indicates that young children with low birth weight performed less well than their peers or national normative standards on measures of early numerical skills (e.g., classifying, sorting, comparing, and counting of objects; Aarnoudse-Moens, Oosterlaan, Duivenvoorden, van Goudoever, & Weisglas-Kuperus 2011) and number identification and sequencing (Pritchard et al., 2009). Similarly, very preterm 6-year-olds performed less well than their term-born peers on measures of symbolic magnitude comparison (i.e., determining which of two Arabic numerals is larger – 7 vs 9) and explicit number knowledge (i.e., counting, seriation, matching dots to numerals, Arabic numeral reading and writing), though 8-year-old very preterm children performed as well as their peers on these basic skills (Guarini et al., 2013). As such, findings suggest that very preterm children acquire these foundational skills but at a slower rate than their peers. However, this does not exclude that preterm children might remain behind their full-term peers at 8 years of age in more complex or formal mathematical skills.

Fragile X syndrome is a genetic condition that is associated with poor math performance and the prevalence of MLD among girls with Fragile X exceeds that in the general population during and beyond the primary school years (Mazzocco, 1998; 2001). Given that Fragile X syndrome affects females less severely than males, with only approximately 50% of females having intellectual disability compared to nearly all males, research on MLD in this population has typically involved only females without MLD. Kindergarten-aged girls with Fragile X syndrome demonstrate age-appropriate mastery of rote counting skills (e.g. counting by ones) and number recognition, but have more difficulty than their same-age peers with aspects of applied counting such as using one-to-one correspondence when counting to identify the *n*th item in a set (e.g. identifying the 5th item in a set) (Murphy,

Mazzocco, Gerner, & Henry, 2006). Difficulties with applied counting have been observed to extend into the third grade among girls with Fragile X syndrome (Mazzocco, Bhatia, & Lesniak-Karpiak, 2006). Fifth grade girls with Fragile X syndrome continued to demonstrate difficulties with counting principles at a higher rate than their typically developing peers, and demonstrated decreased accuracy on a problem verification task assessing number facts (e.g., $4 + 5 = 9$ or $2 \times 2 = 10$; Right or Wrong?) and number knowledge (e.g., $200 - 150 = 300$?), and complex calculation (Murphy & Mazzocco, 2008).

Children with neurodevelopmental disorders often demonstrate neurocognitive difficulties that are predictive of early numeracy acquisition and later math achievement. Children with very preterm birth (Litt et al., 2010; Taylor et al., 2000) and Fragile X syndrome (Mazzocco, Quintero, Murphy, & McCloskey, 2016) demonstrate difficulties with visual-spatial skills and working memory for example which have been shown to be related to mathematical achievement in these populations. Of importance is the suggestion that there may be particularly strong relationships between math achievement and neurocognitive skills such as working memory (Peng et al., 2015) in individuals with MLD and a co-occurring neurodevelopmental disorder.

Overall, relatively little research has been conducted specifically with young children with neurodevelopmental disorders to explore early numeracy development and relations to later math achievement. Similar to children at risk for math difficulties, children with neurodevelopmental disorders including SBM, Fragile X syndrome, and low birth weight exhibit difficulties with early numeracy skills, which are discernable at young age. These early difficulties have important implications for later math achievement. Given that children with neurodevelopmental disorders demonstrate deficits in core neurocognitive skills and early numeracy difficulties they are at particular risk for later math difficulties. Because math risk can be discerned at an early age in these neurodevelopmental disorders as well as in children without neurodevelopmental disorders, the implications for assessment and early intervention are clear; first, risk for later MLD can be assessed in the preschool years, and this also opens the possibility for early intervention. We turn now to a fuller discussion of assessment and intervention strategies to promote early numeracy development.

Implications for Early Assessment and Intervention

Early Assessment

Direct assessment of early numeracy skills is important in young children given their strong association with later mathematical achievement. Assessment of early math skills should include measures of numerical symbol knowledge such as number identification based on numerals and arrays, and counting emphasizing cardinality and ordinality (Merkley & Ansari, 2016). Given findings of developmental continuity in preschool non-symbolic arithmetic and later symbolic arithmetic, manipulation of non-symbolic number should also be part of early math assessment. These types of early numeracy skills are assessed separately in research-based studies, but are not currently available as separate normative based tests. However, there are some standardized measures of math that are suitable for preschool children and which contain some of these types of items. One advantage of one of these, the Test of Early Mathematics Ability – Third Edition (TEMA-3; Ginsburg &

Baroody, 2003), is that it was created based on theory and empirical studies of mathematical development so that it contains items that tap early numeracy skills that correspond to the sequence in which such skills are typically acquired; it is suitable for assessing numeracy very early - from 36 months of age and contains an adequate sampling of early numeracy skills at this early entry point; and it explicitly measures the early numeracy skills shown to be important for later mathematics, such as counting (ordinal and cardinal knowledge), number identification, non-symbolic arithmetic, and understanding of rudimentary mathematical words such as “more”.

Brief screening instruments for assessing risk for reading difficulties in the preschool years are now available (e.g., Test of Preschool Early Literacy or TOPEL; Lonigan, Wagner, Torgesen, & Rashotte, 2007), and similar brief, reliable and easy to score screening instruments for preschool math are in the process of being standardized (e.g., Preschool Early Numeracy Skills Screener-Brief or PENS-B; Purpura, Reid, Eiland, & Baroody, 2015). Although mathematically relevant vocabulary (e.g., more, less, take away, nearest, under, equals) is important in the preschool and early school years such math-specific vocabulary measures do not currently exist, although they are being developed. Other aspects of mathematics such as early spatial sense and geometry, early informal measurement skills, and so forth, are not yet well-represented in standardized math assessments suitable for preschool children.

Including an assessment of neurocognitive processes has not been shown to improve the validity or reliability of diagnosis of learning disabilities (Miciak, Fletcher, Stuebing, Vaughn, & Tolar, 2014). In recent diagnostic schemes such as DSM-5, testing of neurocognitive processes is considered to be largely unnecessary for diagnosing a learning disability and to increase assessment burden without improving diagnosis (reviewed in Barnes, Raghubar, & Martinez-Lincoln, in press; Tannock, 2013). However, we suggest that there is a role for the assessment of a small set of neurocognitive abilities among preschool-aged children at risk for MLD. Assessment of neurocognitive difficulties in preschoolers may be of particular importance for assessing risk for MLD because: 1) As the review above shows, difficulties in working memory and language early in development are powerful risk factors for poor development of preschool numeracy skills, and, in longitudinal research, for later MLD; and 2) Assessment of early math skills alone may be misleading for some young children who have had limited exposure to early numeracy concepts in the home or their preschool care settings making assessment of early math for these children possibly less reliable and valid than it is for older children. Thus for preschool children, we recommend a dual approach where both early numeracy skills as well as key neurocognitive abilities are assessed to determine risk for MLD.

Early Intervention

Mathematical concepts and procedures can be instructed in young children, and this is true for both typically developing preschool and kindergarten children and preschoolers and kindergarteners identified as at risk for mathematical difficulties (Barnes et al., 2016; Toll & Van Luit, 2012; van de Rijt, & van Luit, 1998), though the extent of transfer to later, formal math skills remains a matter for debate, particularly for children at significant risk for MLD.

It is beyond the scope of this paper to review early numeracy interventions. Therefore, we present a sampling of various early interventions that may hold promise for very young children who are at risk for later math difficulties.

The Building Blocks Intervention (Clements & Samara, 2007) has been shown to increase the mathematics knowledge of preschoolers from low-income communities more than “business as usual curricula”. This intervention stems from developing math around children’s everyday activities. Educational goals included developing competence in two foundational domains: 1) number concepts and arithmetic operations; and 2) spatial and geometric concepts and processes. Additionally, some studies report promising results using numerical games to improve early numeracy skills. For example, Siegler and Ramani (2008) conducted a series of studies examining the utility of an intervention based on a linear board game with squares labeled 1 through 10 for four, 15-minute sessions across a two-week time period among 4-year-olds from low-income families. Large effects on children’s early numeracy skills were observed, including improvements in number line estimation, counting, numerical magnitude comparison, and numeral identification (Ramani & Siegler, 2008; Siegler & Ramani, 2008), which are aspects of early numeracy that are related to later mathematical achievement. One thing to keep in mind is that these early interventions have been conducted with children who may be considered to be at heightened risk due to low SES and who enter preschool with low math knowledge. However, they are not specifically designed to address the needs of children who continue to have difficulties with math learning once a research-based curriculum is in place.

More intensive interventions for preschool children at high risk for later learning disabilities are just beginning to be tested for effectiveness (for reading see Lonigan & Phillips, 2016). In a randomized controlled trial, we have tested the effectiveness of a tutorial-based mathematics intervention for preschool children who scored at a very low level on a preschool math screening measure compared to their other low-income peers (Barnes et al., 2016). This intensive tutorial-based mathematics intervention focused largely on numbers and operations and early spatial sense and geometry. The intervention began with direct instruction in very rudimentary symbolic (e.g., counting to 3) and non-symbolic (e.g., non-symbolic arithmetic with small set sizes such as $2 + 1$) number skills and proceeded in a sequential fashion from these foundational mathematics activities to more complex preschool math activities. There were significant medium sized effects on a broad assessment of early mathematics ability and small, but significant effects on a standardized measure of early math ability (TEMA-3). Because one of the sites had a more supportive Tier 1 early numeracy program than the other, we could also see the effect of combining a highly supportive mathematics instruction at the classroom level with a more intensive higher tier of early math instruction. The children who received intensive math instruction through their Tier 1 classroom curriculum and through the tutorial program had the best math outcomes (Barnes et al., 2016). These results suggest that early interventions for children at highest risk for later MLD are most effective when they include a strong classroom-based program in combination with additional higher tiers of math instruction. We also suggest that in the absence of evidence to the contrary, early math interventions with evidence of efficacy for young children without neurodevelopmental disorders may also be useful for young children at risk for MLD with neurodevelopmental disorders. This has been

shown to be the case for adolescents with SBM who demonstrated gains in mathematical problem solving after instruction with a math word problem solving intervention originally designed for children with MLD and no neurodevelopmental disorder (Coughlin & Montague, 2011).

Given the relationship between neurocognitive skills and mathematical learning and achievement, it begs the question of whether children with strengths versus weaknesses in specific neurocognitive domains may derive varying levels of benefit from different types of math intervention. One such study (Toll & van Luit, 2013) examined the effects of an early math intervention in children with poor early numeracy skills accompanied by either very low or adequately developed working memory. Both groups were found to benefit from the math intervention, however, children with higher verbal working memory at the beginning of the intervention benefitted more from the intervention, suggesting that underlying neurocognitive factors may moderate training or intervention effectiveness. Similarly, recent intervention studies with school-aged children have found that working memory level moderates intervention effects (Fuchs et al., 2014; Swanson, 2014). Swanson (2014) found that third grade children at risk for math difficulties with relatively higher working memory were more likely to benefit from strategy training in a word problem solving intervention whereas children with lower working memory may have had their already low cognitive resources overtaxed by strategy training. Fuchs and colleagues (2014) found that fourth graders with very weak working memory learned fractions better with conceptual activities whereas students with more adequate, though still low, working memory learned fractions with fluency activities, meant to build automaticity.

These studies have focused on math-specific treatments and measured whether general neurocognitive processes (i.e., working memory) moderate treatment effects. Other studies have examined the effect of training math-related neurocognitive processes such as working memory and examining transfer of cognitive training to math performance. The premise for such interventions is that given the prominence of general neurocognitive skills such as working memory in predicting math performance, improvements in neurocognitive functioning (i.e. training working memory) may also lead to improved math performance. For the most part, interventions targeting working memory demonstrate improvements in working memory (though maintenance is an issue as is transfer to other related cognitive domains), with limited transfer to math performance (reviewed in Melby-Lervag & Hulme, 2012; Melby-Lervag, Redick, & Hulme, 2016).

Another recent class of studies have examined the effect of interventions that *combine* training of math-specific and general neurocognitive processes. Studies that compare the effectiveness of number-specific training alone (e.g., counting training) or a combination of the two (e.g., with simultaneous working memory training) on early numeracy skills in typically developing children, show that number-specific training appears to produce the greatest improvements (Kroesbergen et al., 2012; Kytala et al., 2015). This was also found to be the case in the tutorial-based math intervention study discussed above for very low performing preschool children (Barnes et al., 2016). In this study, attention training combined with the math intervention did not produce any added benefit for mathematics learning than the same math intervention alone; however, similar to many other studies that

just employ cognitive training with preschool children, the attention intervention was remarkably non-intensive in comparison to the typical number-specific math interventions that have been designed and tested for children with or at risk for MLD.

At the present time, findings are consistent with the idea that specific training of early numeracy skills is not only effective, but also more effective in improving early numerical performance than training of general neurocognitive processes in typically developing preschool children and in preschool children at high risk for MLD. Nor is there convincing evidence thus far that combined math-specific and neurocognitive intervention are more beneficial than math-specific interventions alone. It is interesting to note that we know much more about issues around scope and sequence of content and dosage (how much treatment is needed at what level of intensity and for how long) for specific math interventions than we do for training of neurocognitive processes such as attention and working memory. We suggest that further basic research is needed to test whether there are any benefits of combining neurocognitive training with math interventions. For example, such studies would ideally test whether effects of such combined interventions vary as a function of variables such as: 1) *when* the cognitive training is provided, for example, prior to math instruction or concurrent with it, at very young versus older ages etc; 2) the *intensity* and *scheduling* of training, such as the dosage of cognitive training and whether that training involves massed versus distributed practice; and 3) the *nature* of neurocognitive training, for example, whether cognitive training uses materials that are devoid of mathematical content or whether cognitive training is more strongly integrated with the mathematical intervention.

In sum, given the current state of evidence, early number-specific interventions are recommended for young children at risk for MLD. There is not enough evidence to recommend either general neurocognitive interventions or combined number-specific and general neurocognitive interventions for preschool children at risk for MLD.

Conclusions

In this review we have defined early numeracy skills, emphasized their association with later math achievement, and identified neurocognitive correlates of early numeracy and math achievement. We have done this, highlighting our longitudinal work with children with SBM, a congenital disorder diagnosed in utero and associated with increased risk of MLD at school-age. Our work along with other longitudinal studies indicates that children who are at risk for MLD demonstrate difficulties with numeracy very early in development, as evidenced by early difficulties in oral counting and counting knowledge, and imprecise representations and transformations on quantity. We argued that the association between early numeracy skills and formal mathematics learning warrants assessment of early numeracy skills, particularly those assessing symbolic number knowledge. A number of neurocognitive processes are related to early numeracy development, namely working memory and language. In school-aged children, assessment of neurocognitive processes offers limited utility for diagnosing MLD. However, among preschool-aged children poor working memory and/or low language abilities place children at increased risk for difficulties in acquiring early numeracy skills, with significant negative implications for later formal math learning and achievement. Knowledge of weaknesses in specific neurocognitive

processes may lead to instructional modifications of research-based math interventions that reduce working memory burden or provide direct instruction in basic mathematical vocabulary. However, given the lack of evidence for the efficacy of training of specific neurocognitive processes for early math learning, such neurocognitive training is not recommended for improving early numeracy in young children at risk for math learning difficulties.

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