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Approximate number system development in preschool: What factors predict change?

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ABSTRACT

A large body of work has developed over the last decade examining the relation between the approximate number system (ANS) and mathematical performance across a wide range of ages, but particularly for preschool-age children. Largely, the evidence is mixed and suggests that a small relation exists that is dependent on a number of child-related or measurement-related factors. In contrast, little work has focused on understanding the stability and predictors of the ANS. These issues were examined by assessing 113 preschool children in the fall and spring of the preschool year on mathematical and cognitive assessments. Mixed-effect regressions indicated fall ANS performance was the strong predictor of spring ANS performance, suggesting moderate stability of this variable during preschool. However, cardinality and response inhibition were also significant predictors, and school-level variance was high. These findings indicate that the ANS may not be as foundational for mathematics development as previously suggested.

1. Introduction

Given the growing recognition of the importance of early mathematics for later outcomes (Every Child a Chance Trust and KPMG, 2008; Williams, Clements, Oleinikova, & Tarvin, 2003), there has been a surge of recent research focusing on the pre-school and early school years to further understand the processes involved in mathematical development with the aim to inform interventions to improve mathematical achievement. A variety of domain-specific and domain-general factors have been identified as being related to, or predictive of, early mathematical skills. Domain-general cognitive factors such as working memory (Raghubar, Barnes, & Hecht, 2014) and executive functions more generally (Bull, Andrews Espy, & Wiebe, 2008; Clark, Prithard, & Woodward, 2010) are related to mathematical achievement in young children. In addition, domain-specific skills such as the approximate number system (ANS; Chen & Li, 2014), counting skills (Muldoon, Towse, Simms, Perra, & Menzies, 2013), calculation fluency (Cowan et al., 2011), and mathematical language use (Purpura & Reid, 2016) have been identified as being particularly important for mathematical achievement in young children. Among these domain-general and domain-specific factors that are related to early mathematical development, the ANS has seemed to receive a sizeable share of focus within the mathematical development research literature over the last decade. However, despite the focus on this factor, little is known regarding its stability during preschool and factors that may be related to its development. Thus, the focus of this study was to examine the within-year stability of the ANS during preschool and identify which, if any, domain-general and domain-specific factors predict children's acquisition of this skill.

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1.1. The approximate number system

The ANS is an analogue, approximate system believed to be innate and shared across children, adults, and a variety of animals (Brannon & Merritt, 2011). Data suggest that the ANS guides approximate manipulation of quantities, such as comparison, addition and subtraction of sets. A popular task used to measure the ANS is the non-symbolic comparison task, in which participants are asked to compare two sets of dots and indicate which set contains the larger quantity (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). A common finding from these studies is that accuracy and response time to the non-symbolic comparison task is dependent on the ratio between the two sets of quantities. Quantities that are similar (e.g. a ratio of 3:4) are more difficult to discriminate than quantities that are dissimilar (e.g. a ratio of 1:2; Chen & Li, 2014). This provides an indication of the signature of the ANS; it is ratio dependent. Developmental change is observed in the precision of the system, with 6-month-old infants being able to successfully discriminate sets with a 1:2 ratio (Lipton & Spelke, 2003; Xu & Spelke, 2000) through to adults who can successfully perform the task with 8:10 (Inglis, Attridge, Batchelor, & Gilmore, 2011) or even 9:10 ratios (Halberda & Feigenson, 2008; Pica et al., 2004). Yet, there is a surprising lack of reliability data for this task (particularly for younger children); this is unusual in cognitive and developmental psychology research. However, there appears to be evidence of reliability (Price, Palmer, Battista, & Ansari, 2012) and moderate stability over time (Clayton, Gilmore, & Inglis, 2015) in performance in non-symbolic comparison tasks in adults.

1.2. Relation of the ANS to mathematical development

Studies utilising non-symbolic comparison tasks have observed individual differences in the precision of the ANS and some studies have identified a significant relationship between ANS precision and either arithmetic skills or mathematical achievement more broadly (Bonny & Lourenco, 2012; Mazzocco, Feigenson, & Halberda, 2011; Purpura & Logan, 2015). Some intervention studies have also reported transfer from ANS training to arithmetic (Hyde, Khanum, & Spelke, 2013) and general mathematical achievement (Park & Brannon, 2013; Wilson, Dehaene, Dubois, & Fayol, 2009). However, there are mixed results (see De Smedt, Noël, Gilmore, & Ansari, 2013 for a review). Notably, a recent meta-analysis indicates that there is a small relation between the ANS and mathematical achievement (Chen & Li, 2014), but there may be a number of factors that account for this relation including executive functioning skills, school-level instruction, and language skills that are not consistently measured in prior work.

Thus, there is growing recognition that the relation between ANS and mathematical achievement may be more complex than has been previously suggested. In particular, there are differences in the observed relation between the ANS and mathematics performance between preschool and older children (Fazio, Bailey, Thompson, & Siegler, 2014), children and adults (Inglis et al., 2011), and across studies that either do or do not account for potential confounding variables (Gilmore et al., 2013). In addition, a recent systematic review has questioned the validity of ANS training study results due to publication bias, with citation analysis indicating that null results are not being published to same extent as positive findings (Szűcs & Myers, 2016). Thus it is essential to fully understand the factors that may be underpinning performance on the ANS task, especially if this construct will be targeted by intervention.

1.3. Limitations of previous work

Given the wealth of evidence examining the relation between the ANS and mathematical ability, there is a relative dearth of research specifically examining the construct of the ANS itself. Notably, few studies assess either (a) the relative stability of ANS performance across time or (b) factors that may predict performance on the ANS task over time. Even if these types of data have been collected, examination of the factors that predict ANS performance has not been a targeted research question (e.g., Soto-Calvo, Simmons, Willis, & Adams, 2015). These questions are critical to evaluate, and to better explain, why and under what conditions that ANS may be related to mathematics performance.

1.3.1. Longitudinal performance

Longitudinal data suggests that there is varying stability in the measurement of ANS over time in childhood. Specifically, Chu, Van Marle, and Geary (2016) observed a moderate correlation in ANS precision over one year in 3–5 year-olds ($r = 0.38$, $p < 0.001$). In addition, a study tracking 4½-year-olds over a 2½ year period observed that there were correlations between time-point to time-point (6 in total) ranging from $r = 0.18$ and $r = 0.34$ (all p's < 0.01; Toll, Van Viersen, Kroesbergen, & Van Luit, 2015). These low to moderate correlations suggest that either the construct being measured by ANS tasks may not be stable during this time period or there may simply be rapid development of performance on these tasks across these time periods. More work in assessing the stability of this construct in the preschool years is needed.

1.3.2. Predictors of the ANS

Understanding which factors predict the ANS may provide evidence to explain why inclusion of certain covariates affects the relation between the ANS numeracy performance. In fact, Moore, Van Marle, and Geary (2016) established that once numerous domain-specific and domain-general cognitive skills were accounted for, ANS precision was not a significant predictor of basic numerical performance both concurrently (at the beginning of preschool) or later in the academic year (at the end of preschool). In particular, cardinal number knowledge (Mussolin, Nys, Content, & Leybaert, 2014), mathematical language (Negen & Sarnecka, 2014; Purpura & Logan,2015), and executive functions, specifically response inhibition (Fuhs & McNeil, 2013), may be key predictors