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The relation between approximate number system and early arithmetic: The mediation role of numerical knowledge

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ABSTRACT

We investigated whether the approximate number system (ANS) was related to arithmetic among kindergartners and the mechanism underlying this possible relation. Specifically, we examined whether numerical knowledge mediated the possible relation between the ANS and arithmetic after controlling for potential confounding cognitive variables. Results showed that the ANS was moderately related with early arithmetic (r = .36–.37). After controlling for age, IQ, visual attention, working memory, visuospatial processing, and inhibition, numerical knowledge demonstrated a medium mediation effect (k^2 = .09) on the relation between the ANS and arithmetic. Our findings suggest the importance of the ANS in early arithmetic and support the numerical knowledge mediation hypothesis. That is, numerical knowledge plays a more important role than visuospatial processing and inhibition in explaining the relation between the ANS and early arithmetic. Implications of these findings for early arithmetic instructions are discussed.

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Introduction

Children learn and develop arithmetic skills during early childhood. Because of the hierarchical nature of mathematics skills, arithmetic serves as a foundation for developing increasingly advanced mathematical abilities (Ashcraft, 1992; Jensen & Whang, 1994; National Council of Teachers of Mathematics, 2006). Given the importance of arithmetic, it is critical to understand factors that contribute to early arithmetic development. During recent years, an increasing number of studies have examined the cognitive underpinnings of early arithmetic. One important cognitive skill is "number sense," which refers to a wide range of skills such as the ability to subitize (to perceive at a glance the number of items presented) and count, discriminate quantities, discern number patterns, and move flexibly between different numerical formats (Berch, 2005; Gersten, Jordan, & Flojo, 2005; Jordan et al., 2007; Kalchman, Moss, & Case, 2001). Number sense is often considered to support early arithmetic development and is a focus of early arithmetic intervention research (e.g., Hyde, Khanum, & Spelke, 2014) and early mathematics curricula (National Council of Teachers of Mathematics, 2006).

Approximate number system and early arithmetic

One central component of number sense is the approximate number system (ANS), the ability to quickly estimate the magnitude of a group of items (Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Gallistel, 2011). A typical measure of the ANS is to have children look at two arrays of dots and make a quick estimate about which pile has more dots. The ANS is active across the entire lifespan (Dehaene, 1997; Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Whalen, Gallistel, & Gelman, 1999) and is shown to support a primitive sense of numbers in human and animals (Brannon, Jordan, & Jones, 2010; Dehaene, 1997; Feigenson et al., 2004; Libertus & Brannon, 2009).

Because the ANS is an important component of number sense, it is often assumed to relate to arithmetic development. However, the findings on this relation are mixed. Some found that ANS acuity at preschool or early grades is significantly correlated with arithmetic or predicts arithmetic in later grades (e.g., Bonny & Lourenco, 2013; Gilmore, Attridge, De Smedt, & Inglis, 2014; Mazzocco, Feigenson, & Halberda, 2011), even after controlling for nonverbal IQ and verbal IQ (e.g., Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011). Some found that children identified with dyscalculia performed significantly worse on the ANS task than their age-matched typically developing peers (e.g., Piazza et al., 2010), suggesting that less accurate ANS representations are related to difficulty in arithmetic. In contrast, there are also many studies that failed to find a significant relationship between ANS acuity and arithmetic (e.g., De Smedt, Noël, Gilmore, & Ansari, 2013; Holloway & Ansari, 2009; Mundy & Gilmore, 2009; Vanbinst, Ghesquière, & De Smedt, 2012).

There are several plausible reasons for previous conflicting findings. One is the measurement of arithmetic. For example, some previous research measured arithmetic performance through comprehensive mathematics achievement tests, which often included not only arithmetic problems but also other types of mathematics problems (e.g., Bonny & Lourenco, 2013; Libertus et al., 2011; Mundy & Gilmore, 2009). This measurement issue may inflate or deflate the relation between the ANS and arithmetic. Another reason is that previous research was often based on a sample mixed with different age groups (e.g., 3–5 years, 5–11 years; Bonny & Lourenco, 2013; Gilmore et al., 2014; Holloway & Ansari, 2009; Mundy & Gilmore, 2009). Children of different ages, even during early childhood, may have varying mathematics learning experiences (Halberda & Feigenson, 2008), which may affect the relation between the ANS and arithmetic. Specifically, although the unidirectional causal relationship between the ANS and the acquisition of symbolic mathematics skills is still unclear, some researchers suggest that the ANS may be a stepping-stone for basic quantitative symbols learning and that once the ANS is used to bootstrap basic quantitative symbols learning, the learning of the explicit relations among these symbols could proceed independent of the ANS (e.g., Lyons & Beilock, 2011; van Marle, Chu, Li, & Geary, 2014). Thus, one aim of the current study was to investigate the relation between the ANS and arithmetic among kindergartners who have relatively few formal arithmetic learning experiences.

Theoretically, identification of variables that uniquely explain the relations between the ANS and variability in arithmetic provides necessary empirical support for theoretical explanations concerning