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Linking language, visual-spatial, and executive function skills to number competence in very young Chinese children

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ABSTRACT

Early number competence is highly predictive of later mathematics achievement. The present study aims to examine how fundamental domain-general skills, including language, visual-spatial, and executive functions, together relate to early acquisition of numbers among very young children. A total of 109 Chinese children, aged approximately three years, in Hong Kong were tested individually on their number competence, receptive vocabulary, knowledge of written letters, rapid automatized naming, spatial perception, and behavioral executive skills. The results showed that vocabulary, letter knowledge, spatial perception, and executive skills all made a unique contribution to number competence. The findings add to the literature by documenting the critical importance of spatial perception and written language for early number learning. They also suggest that language, visual-spatial, and executive skills provide the building blocks for children's number acquisition at a very young age.

1. Introduction

Children vary substantially in their understanding of numbers and number relations at very young ages (Starkey & Klein, 2008). Because this early number competence is highly predictive of later academic achievement (Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009), it is vital to identify factors associated with number learning. A growing body of studies suggests that basic domain-general skills, such as language, visual-spatial, and executive functions, provide the building blocks for this process (LeFevre et al., 2010; Noël, 2009; Purpura & Ganley, 2014; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). Little research, however, has examined how these skills together relate to number competence, especially among very young children. Furthermore, most prior work has been carried out in Euro-American settings, with only limited research in Chinese societies. In the present study, we assess the relations of oral and written language, visual-spatial, and executive function skills with number competence among 3-year-old Chinese children.

1.1. Early number development

Research over the past three decades suggests that preschoolers have a considerable body of number competencies (Fuson, 1988; Gelman & Gallistel, 1978; Ginsburg, 1977). Number competencies refer to ability to count numbers in the correct order, grasp counting principles (e.g., cardinality: the last number of a set indicates the total number of objects), apprehend the relations between numbers (e.g., 7 is more than 5), and join and separate sets (e.g., 1 and 3 makes 4, and 4 take away 1 is 3). These competencies are in contrast to the abstract concepts (e.g., commutative law of addition: $m+n=n+m$) and calculations that children acquire primarily through formal teaching (Jordan et al., 2009).

Aspects of number competencies develop over time. Oral counting begins at around two years of age and evolves from an initial acquisition phase of learning the conventional number word sequence to an elaboration phase of decomposing this sequence into separate words (Fuson, 1988). Different parts of the number sequence (e.g., "one, two, three" versus "eight, nine, ten") may be in different phases of development at the same time, and it takes several years to acquire and elaborate the sequence. During the acquisition phase, children begin to use the number sequence to count objects (Fuson, 1988). As early as two and a half years of age, children can discover the cardinality principle (Gelman & Gallistel, 1978). The counting principles are acquired over several years, such that most six-year-olds apply these principles when they enumerate a set of objects.

Children can understand numerical relations, such as the precedence relation between number words, as they learn the number sequence at very young ages (Fuson, 1988). For example, when asked what comes after a number such as five, some two-year-olds

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can start with one and count up to the number: "one, two, three, four, five—oh, six." By six years of age, children typically can automatically state the number after a given number without counting from one (Baroody & Wilkins, 1999).

Even before schooling, many children are interested in how to read numerals (Baroody & Wilkins, 1999). This is the first step toward formal mathematical knowledge. Learning to read numerals depends on how often children are exposed to them in the environment, but it also requires children's ability to construct mental images of the symbols and distinguish among them (Baroody & Wilkins, 1999). Preschoolers also have some calculation abilities before they comprehend formal expressions such as $2+3=?$. As early as two years of age, children can solve addition problems involving sums of three or less (Klein & Starkey, 1988), and preschoolers as young as three years of age can perform simple addition and subtraction involving larger numbers when both verbal labels and physical referents are provided (Starkey & Gelman, 1982).

1.2. The role of domain-general skills in number competence

The acquisition of number competencies involving words and symbols at a young age provides a foundation for later academic achievement (Duncan et al., 2007; Jordan et al., 2009). Thus, it is warranted to examine the factors associated with number competence. Most researchers agree that early number learning relies heavily upon basic domain-general processes such as visual-spatial and language (Dehaene, 2011; Mix & Sandhofer, 2007). Dehaene posits that a language-dominant area (the left angular gyrus) and a space-dominant area (the posterior superior parietal lobule) in the brain, alongside a quantity-dominant area (the intraparietal sulcus), are involved in numerical processing. Mix and Sandhofer even argue that number development can be explained solely in terms of domain-general processes such as visual-spatial (e.g., processing contour length) and language (e.g., naming). Finally, executive functions, which include a variety of top–down mental processes that help children focus attention, resist distractions, and follow directions, are another general skill set that is often highlighted in relation to number competence in the literature (Bull & Lee, 2014). Consequently, the focus of the present study is on three sets of domain-general skills, namely language, visual-spatial, and executive functions, that may be crucial for number learning. Before the details of the study are described, a review of studies of the relations from these domain-general skills to number competence will be considered.

1.2.1. Language skills and number competence

Language skills refer to the ability to understand and use an acquired oral and written language. In the literature, language-impaired children are found to be at particular risk for difficulties with basic numeracy (Koponen, Mononen, Räsänen, & Ahonen, 2006). For example, Fazio (1994) showed that 4–5-year-old children with specific language impairment had difficulties with rote counting, displayed a limited repertoire of number terms, and miscounted sets of objects. These findings suggest that language skills may play an important role in numerical development.

Because vocabulary deficits are a defining characteristic of language impairment, some investigators are interested in the relation of vocabulary with number competence. LeFevre et al. (2010) posit that receptive vocabulary reflects children's ability to acquire vocabulary in the number system (i.e., word names for numbers). They found that receptive vocabulary at ages 4–5 years was associated with a variety of number competencies, including number recognition, order, and magnitude comparison, measured concurrently or two years later. Negen and Sarnecka (2012) propose that children's development of general vocabulary (e.g., nouns) helps them pick out the referents of number words (e.g., children hearing "two rabbits" are better able to figure out what "two" means if they already understand the word rabbit(s)). They further showed that both receptive and expressive vocabulary was related to number–word knowledge in children aged between 30 and 60 months.

Prior studies linking language to numerical development focused almost exclusively on children's ability to understand oral language. To understand the Arabic number system, children must have the ability to map oral sounds to the written symbols (Brizuela, 2004; Neumann, Hood, Ford, & Neumann, 2013). It is possible that children's early exposure to written language symbols (letters, characters etc.), where they are provided with experience of mapping sounds to the symbols, facilitates their ability to use and manipulate other written symbols, such as Arabic digits. In support of this notion, Purpura, Hume, Sims, and Lonigan (2011) showed that 3- to 5-year-old children's print knowledge was associated with their numeracy competence one year later. Zhang et al. (2014) found that children's knowledge of Finnish written letters at age six predicted their growth trajectory of competence in written arithmetic from ages 7 to 10. More recently, both oral and written language skills were found to have distinct relations with young children's acquisition of numbers (Purpura & Napoli, 2015) and arithmetic calculations (Zhang & Lin, 2015). Indeed, neuroimaging research has shown that the left mid-fusiform area, often referred to as 'the visual word form area' (VWFA) and located in the language-dominant cortex, is involved in processing Arabic digits (Arsalidou & Taylor, 2011). From an evolutionary perspective, the VWFA is initially involved in object recognition and later on evolves and is recruited to serve an analogous function in recognizing written symbols (e.g., letters, numbers; Lervåg & Hulme, 2009). Hence, there is good reason to believe that written symbolic skills are crucial for learning Arabic digits and acquiring number competence.

Recently, rapid automatized naming (RAN) has been noted in the literature in relation to number competence. RAN is often viewed as a global measure of processing speed or a specific measure of phonological processing speed. Recent evidence suggests that RAN taps the integrity of the VWFA and the areas involved in phonological retrieval and production (Lervåg & Hulme, 2009). If this is true, RAN may capture the speed of processing both oral and written language and, consequently, should be related to number competence such as counting and number recognition. Empirically, Koponen et al. (2006) found that RAN was related to counting in preschool children, and Cirino (2011) showed that RAN was associated with number recognition in kindergarten children. Because some researchers argue that RAN and number competence are associated because numbers are used as stimuli in RAN tasks (Landerl, Bevan, & Butterworth, 2004), in this study we use objects as stimuli.

1.2.2. Visual-spatial skills and number competence

Visual-spatial skills, which refer to the ability to understand the visual-spatial relations among objects, are essential for numerical understanding. It has long been suggested that there is a spatial representation of number magnitude along a mental number line in the human mind (Dehaene, Dupoux, & Mehler, 1990). Siegler and Booth (2004) demonstrate that this spatial representation develops from a logarithmically-compressed form to a linear form; such development involves refinement of the spacing of numbers along the number line. Moreover, Siegler and Booth further found that the use of linear representation was related to children's numerical and arithmetic acquisition, indicating that visual-spatial skills may play a crucial role in early number learning.

Visual-spatial skills are not a unitary construct. Linn and Petersen's (1985) meta-analysis distinguishes three types, namely spatial perception (i.e., identifying spatial relations among task