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# Does growth rate in spatial ability matter in predicting early arithmetic competence?

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ABSTRACT

There is a well-established relation between overall level of spatial ability and mathematics competence: people who are stronger in the former perform better on tests of the latter. However, does the rate of growth in spatial ability also matter? This longitudinal study of Chinese children (aged three to six) demonstrated that growth rate in spatial perception during the preschool years significantly predicted arithmetic competence at the end of preschool. This effect was over and above the overall levels of spatial perception and spatial reasoning and the level and rate of growth in phonological awareness. The findings highlight the need to provide spatial learning opportunities for preschoolers whose rate of growth in this skill is slower than that of their peers.



## 1. Introduction

It has recently been advocated that spatial learning be integrated into the mathematics curriculum (National Council of Teachers of Mathematics, 2010; Newcombe, 2013). The assumption underlying this recommendation is that spatial ability will aid the learning of mathematics, such that improvements in the former will strengthen competence in the latter. Accordingly, not only overall achievement, but rate of growth, in spatial ability should affect subsequent mathematical competence. However, despite a growing body of research into the importance of overall level (Barnes et al., 2011; Geary, 2011; Gunderson, Ramirez, Beilock, & Levine, 2012), little work has been done to explore whether differences in the rate of growth in spatial ability are predictive of subsequent mathematical skill. In addition, evidence about the space-mathematics relation usually comes from studies of primary and secondary school students and from assessments of higher-level mathematics that contain explicit spatial content such as geometry (e.g., Shea, Lubinski, & Benbow, 2001). It is less clear whether this connection exists with domains that emerge during the preschool years and are less overtly spatial, such as number and arithmetic. In this longitudinal study of Chinese preschoolers, we examine whether, and if so to what extent, skill level in spatial perception (an important spatial ability) at the start of preschool, and its growth rate over time, contribute to arithmetic competence as measured at the end of preschool.

Several theories have been proposed to explain the relation between spatial ability and arithmetic skill. For example, one theory that focuses on the mental process of arithmetic problem solving posits that some students use diagrams and visual-spatial images to process arithmetic information (Krutetskii, 1976; Presmeg, 1986). It is found that use of spatial imagery is related to success in arithmetic problem solving (Boonen, van der Schoot, van Wesel, de Vries, & Jolles, 2013; Hegarty & Kozhevnikov, 1999). In another theory, Dehaene argues that there is a spatial representation of numbers along a mental number line (Dehaene, Bossini, & Giraux, 1993). In support for this theory, studies show that people are faster to identify smaller numbers with their left hand and larger numbers with their right hand (i.e., the SNARC effect) starting in early childhood and continuing into adulthood (Dehaene et al., 1993; Hoffmann, Hornung, Martin, & Schiltz, 2013). Further, spatial ability may aid the construction of a part-whole concept, which Resnick (1992) considers to be the foundation for a deep understanding of number and arithmetic. According to the

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Gestalt principles of visual perception (e.g., spatial proximity and similarity; see Rock, 1993), people tend to partition a collection of objects into spatially distinct groups. This experience provides a basis for children to reason analogically about the relations between numerical symbols (e.g., if a collection of eight objects can be partitioned into two groups, so might be the number 8). In support for this theory, Manches and O'Malley (2016), using an additive composition task, show that young children who use spatially manipulatable materials (i.e., physical objects) can identify more solutions and display more conceptually developed strategies than their counterparts who use pictorial materials that cannot be spatially manipulated. Finally, people represent small quantities using a spatial tracking process in that the rapid enumeration of small sets (up to 3–4 items), a process called subitizing, is driven by a spatial individuation process that uses pointers to track object location (Noles, Scholl, & Mitroff, 2005).

Most researchers agree that spatial ability is not a unitary construct. Linn and Petersen (1985; see also Mix & Cheng, 2012) distinguish three types, namely spatial perception (identifying spatial relations among task components in spite of distracting information, such as identifying an object whose orientation is different from the others), mental rotation (mentally rotating a 2- or 3-D object), and spatial visualization (carrying out complicated, multi-step manipulations, often analytical, of spatial information; distinguished from the other two types by the use of multiple solution strategies). These types overlap substantially and may all involve visuospatial working memory (Loring-Meier & Halpern, 1999).

Earlier studies linking these spatial abilities to arithmetic focus mainly on primary and secondary school students (see Friedman, 1992 for a meta-analysis). Their results generally indicate that spatial ability correlates modestly with arithmetic outcomes. Moreover, the space-arithmetic correlation is lower for spatial perception than for the other two subtypes. Friedman even argues that simple tasks of spatial perception, as compared to tasks of mental rotation and spatial visualization, are not considered spatial reasoning (i.e., imagining of spatial transformations) and thus have the least in common with the process of arithmetic problem solving (e.g., operations).

Presumably because of these earlier findings, more recent research, which focuses increasingly on younger children, emphasizes how mental rotation (Casey, Dearing, Dulaney, Heyman, & Springer, 2014; Gunderson et al., 2012) and spatial visualization (Barnes et al., 2011; Zhang et al., 2014) contribute to early grasp of arithmetic. This research suggests that spatial ability predicts early numerical and arithmetic competence; however, it largely ignores the role of spatial perception.

Spatial perception is a basic spatial function that does not involve transformation or manipulation. Unlike tests of spatial visualization and mental rotation where many 4-5-year-olds perform at chance level (Dean & Harvey, 1979), standard tests of spatial perception (see Method) are often simpler and can be understood more easily by them and even younger children (Lin et al., 2012). The ability to perceive spatial relations (e.g., orientation) can be observed in newborns and continues to develop through early childhood (Spelke, 2000). Moreover, young children's development of spatial perception is accompanied by considerable individual variations (McBride-Chang & Kail, 2002). It thus seems that early childhood is a crucial stage of life for children's development of spatial perception ability.

In a recent study, we assessed spatial perception ability in a sample of Chinese 4-year-olds and examined its relation with their arithmetic competence one year later (Zhang & Lin, 2015). We found that spatial perception was predictive of various measures of arithmetic outcomes. However, given the vital role of mental rotation and spatial visualization in arithmetic competence (Barnes et al., 2011; Casey et al., 2014; Gunderson et al., 2012; Zhang et al., 2014), we do not know whether or not the contribution of spatial perception is independent of mental rotation and spatial visualization.

Moreover, studies relating space to arithmetic, while informative, are almost exclusively limited to examining point estimates of these relations. Although data on a certain spatial ability gathered at a single point in time can be used to predict arithmetic competence, such data may be misleading. Take, for example, two children who have the same level of spatial perception ability at three years of age. Using observed spatial perception at three years to predict later arithmetic would lead us to predict identical performance in arithmetic word problems at the end of preschool. However, we might wonder what would happen if one of the children was growing his or her spatial ability more rapidly than the other: Would the former have higher arithmetic competence at the end of preschool than the latter? In this case, examining the rate of growth in spatial ability would be useful in answering this question. Importantly, spatial ability improves substantially throughout childhood, and children vary widely in the rate at which their spatial ability grows (Spelke, 2000); however, prior studies have rarely assessed spatial ability in multiple time points and have seldom examined the linkage between the growth trajectory of spatial ability and later arithmetic competence.

The rate of growth in spatial ability may contain crucial information about children's potential in spatial learning and development. Learning potential was first introduced by Vygotsky (1930–1934/1978) to account for the concept of Zone of Proximal Development (ZPD). ZPD, or learning potential, is defined as the gap (i.e., growth) between current and potential capability after learning with assistance from an adult or a more capable peer. Vygotsky argues that a complete profile of intellectual ability must include both static measures of existing skills, or current capability, and dynamic measures of developing skills, or learning potential. Beginning with this argument, discussions of intelligence or cognitive functioning have emphasized defining it as either a “fixed and immutable” capacity or as learning potential (Sternberg & Grigorenko, 2002). Some theorists (e.g., Feuerstein, Feuerstein, Falik, & Rand, 2002) further suggest that a learning phase be included in the assessment of cognitive functioning to distinguish between “gainers” who show significant growth after learning (i.e., high learning potential) and “non-gainers” who do not (i.e., low learning potential). Although a child who has higher learning potential in a certain domain is more likely to have higher capability in that domain later on, learning potential differs from not only current capability but also potential capability. In Day, Engelhardt, Maxwell, and Bolig's (1997) study, for example, 4- to 5-year-old children took pretests, were trained, and took posttests on a series of spatial (block design) tasks. They found that learning potential scores (i.e., growth) predicted posttest scores over and above pretest scores. Moreover, their factor analysis showed that these scores correlated with one another only at moderate levels and were clearly distinguished into three factors. These findings suggest that learning potential and current/potential capability should be regarded as domain specific rather than as global traits.

Recently, Feuerstein, Falik, and Feuerstein (2013) contend that learning potential may reflect neural plasticity. In support for this notion, research in the field of developmental cognitive neuroscience has shown that working memory capacity and its *change* or *growth* are related to differential genetic basis and brain activities (see Klingberg, 2014 for a review of 20 years of research with mice, monkeys, and human subjects using genetics, functional magnetic resonance imaging [fMRI], electroencephalopathy [EEG], and positron emission tomography [PET]). Whereas working memory