Learning and Individual Differences 61 (2018) 216–227

Contents lists available at ScienceDirect

Learning and Individual Differences

journal homepage: www.elsevier.com/locate/lindif

Bilingualism positively predicts mathematical competence: Evidence from two large-scale studies

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ARTICLE INFO

Keywords:
Bilingualism
Emergent numeracy
Mathematical reasoning
Math achievement
Standardized mathematical assessment

ABSTRACT

Although little is known about the link between bilingualism and mathematical achievement in children, the established link between executive functions (EFs) and mathematical achievement suggests that bilingualism—which has been shown to affect EFs—may positively predict math skills. Drawing on two large-scale datasets collected in the US—the Multi-State Study of Pre-Kindergarten and the State-Wide Early Education Programs (Study 1) and the Early Childhood Longitudinal Study (Study 2)—we examined the relation between bilingualism and mathematical achievement among preschoolers, kindergarteners, and first-grade students (ages 4–7), while controlling for key covariates of (a) demographic variables, such as age, gender, race/ethnicity, and socioeconomic status; and (b) language proficiency in the language used for instruction (English). In two studies, we found that bilingualism positively predicted teacher-rated mathematical reasoning, emergent numeracy skills, and test scores on either mathematical word problems or standardized mathematical assessments. Moreover, the positive relation between bilingualism and mathematical competence persisted through the transition period from kindergarten to first grade. Our results suggest that bilingualism is favorable for children's mathematical reasoning and problem-solving skills.

1. Introduction

Individual differences in executive functions (EFs)—a multifaceted construct of the general control processes of inhibition, updating, and shifting (Miyake et al., 2000)—have been linked to various key aspects of children's academic achievement (e.g., Bull, Espy, & Wiebe, 2008; Clark, Pritchard, & Woodward, 2010). Notably, EF skills have been shown to facilitate mathematical achievement (Clark et al., 2010; Lee, Ng, & Ng, 2009; Van der Ven, Kroesbergen, Boom, & Leseman, 2012). Thus, it is plausible that the factors that facilitate executive functioning may also confer benefits on mathematical achievement. In this regard, we sought to examine whether bilingualism, which has been demonstrated to modulate various aspects of EFs (for a review, see Bialystok, 2015, and Yang, Hartanto, & Yang, 2016a), predicts mathematical attainment for children's mathematical competence.

A large body of research suggests that speaking two languages on a regular basis confers benefits on EFs. Specifically, numerous studies in children have demonstrated, with relative consistency, that bilingual children outperformed their monolingual counterparts on a well-validated battery of EF tasks that assessed (a) inhibitory control, which is typically measured by the Simon Task (e.g., Antoniou, Grohmann, Kambanaros, & Katsos, 2016; Morales, Calvo, & Bialystok, 2013) or various types of flanker tasks (e.g., Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009), including the Attention Network Test (ANT; Yang, Yang, & Lust, 2011; Yang & Yang, 2016); (b) mental set-switching, as measured by the Dimensional Change Card Sort (DCCS; e.g., Bialystok & Martin, 2004; Carlson & Meltzoff, 2008) or variants of the color-shape task (e.g., Barac & Bialystok, 2012); and (c) working memory, as measured by complex span tasks such as the spatial working-memory task (e.g., Blom, Küntay, Messer, Verhagen, & Leseman, 2014; Sorge, Toplak, & Bialystok, 2016).

Although recent debates in the literature have questioned the existence of bilingual advantages in EF, especially among young adults (for a review, see Paap & Greenberg, 2013, and Paap, Johnson, & Sawi, 2015; for a review of studies on children and adults, see Hilchey & Klein, 2011), there is considerable evidence to suggest that bilingual advantages in EF are more evident among children than young adults (Yang & Yang, 2016). In support of this notion, brain-imaging studies in infants and young children have demonstrated that dual-language acquisition during early childhood facilitates the functioning of cortical and subcortical brain regions that are associated with EF (Arredondo, Hu, Satterfield, & Kovelman, 2016; Krizman, Skoe, & Kraus, 2015;

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https://doi.org/10.1016/j.lindif.2017.12.007
Received 20 October 2016; Received in revised form 17 October 2017; Accepted 9 December 2017

Ramírez, Ramírez, Clarke, Taulu, & Kuhl, 2016). Moreover, recent longitudinal studies have demonstrated that children's bilingual training significantly facilitates executive functioning. Specifically, both short-term second-language training of 4- to 6-year-olds (20 days; Janus, Lee, Moreno, & Bialystok, 2016) and a three-year second-language immersion program, which children began at the age of 5 (Nicolay & Poncelet, 2015), resulted in greater advantages in EF for participants than for their respective monolingual control groups (for similar results in an adult sample, see Bak, Long, Vega-Mendoza, & Sorace, 2016; see also Ramos, Fernández García, Antón, Casaponsa, & Duñabeitia, 2017, for null results in the elderly). Taken together, these findings suggest that acquiring two languages during childhood may lead to observable differences in executive functioning between bilingual and monolingual children (Moreno, Lee, Janus, & Bialystok, 2015; Sullivan, Janus, Moreno, Astheimer, & Bialytok, 2014).

Given the demonstrated bilingual advantages in EF in young children, a critical question is whether these advantages can be translated into significant benefits in learning mathematics, since mathematical problem solving requires strong analytic reasoning, concentration, and problem-solving skills, all of which are closely related to executive functioning (De Corte, 2004). For instance, young children's mathematical performance demands working memory, which allows them to mentally retain interim answers, while working out other parts (e.g., sums) of the problem (Cragg & Gilmore, 2014). Moreover, an ability to inhibit distracting information is necessary to apply and persist in the correct reasoning while suppressing incorrect principles. Shifting abilities are also critical when switching attention between different procedures (e.g., addition and subtraction) in solving complex mathematical problems. Consistent with this, the literature has documented the importance of EF in mathematical achievement (for a recent review, see Bull & Lee, 2014). Specifically, numerous studies suggest that not only updating (i.e., working memory), but also the inhibiting and shifting aspects of EF are essential for mathematical achievement (Bull & Scerif, 2001; Clark et al., 2010). Moreover, longitudinal studies suggest that the relationship between EF and mathematical achievement is not bidirectional; EF contributes to mathematical abilities, but mathematical abilities do not enhance EF (Bull et al., 2008; Clark et al., 2010). Not surprisingly, a self-regulation intervention that was designed to improve various aspects of executive functioning in young children from low-income families was shown to be effective in enhancing their performance on math tests (Goldin et al., 2014; Schmitt, McClelland, Tominey, & Acock, 2015). In view of this well-established link between EFs and math achievement, therefore, it is plausible that the bilingual advantages in EF that young children accrue through their challenging linguistic experiences should confer benefits on their mathematics abilities.

However, few studies have explored the link between bilingualism and mathematical achievement. For instance, Clarkson (1992) administered general mathematical and word-problem tests to sixth-grade Tok Pisin-English balanced bilinguals ($n = 232$) from five local schools in Lae, Papua New Guinea, and their English monolingual counterparts ($n = 69$) from two international schools in the same city. Clarkson found that bilinguals and monolinguals were comparable on math tests, even though most of the bilinguals' families were of lower socioeconomic status (SES). Ostensibly, this should have adversely affected bilingual children's overall academic achievement, since low-SES children have either limited or no access to resources that are critical for math achievement. For instance, it has been found that children from low-SES families are less likely to have access to learning materials and experiences, such as books, computers, or tutors for enrichment, which implies a disadvantageous and less nourishing environment for low-SES children's math achievement (e.g., Bradley & Corwyn, 2002; Bradley, Corwyn, McAdoo, & García Coll, 2001). Moreover, children from low-income families likely attend poor neighbourhood schools that are lacking in qualified teachers and well-equipped libraries, both of which can greatly facilitate students' mathematical understanding and abilities (e.g., Clotfelter, Ladd, & Vigdor, 2006).

More recently, Marian, Shook, and Schroeder (2013) examined the effect of bilingual education on mathematics achievement in students from the third ($n = 37$), fourth ($n = 19$), and fifth ($n = 19$) grades of a two-way immersion program that combined the majority language (English) with a minority language (Spanish). When bilingual students' scores were compared to those of monolingual students in the third ($n = 574$), fourth ($n = 579$), and fifth ($n = 624$) grades who were enrolled in mainstream classrooms, results demonstrated that the bilingual students outperformed their monolingual counterparts on the State Standards Achievement Test. However, it is noteworthy that when students from low SES families were excluded from the analyses, the relation between bilingualism and mathematical achievement was weakened; bilinguals' better performance on the mathematical assessment than monolinguals was evident only in third graders.

In a similar vein, a recent fMRI study by Stocco and Prat (2014) lends additional support to the notion that bilingualism facilitates mathematical abilities. The authors compared behavioral and brain data from bilingual adults with diverse language pairs ($n = 17$) to data from matched English monolinguals ($n = 14$). They found that bilinguals were significantly faster than monolinguals on tasks that required cognitive flexibility to combine simple arithmetic operations, which are typically embedded in mathematical problem solving. Moreover, bilinguals' better performance on the task was associated with greater modulation of neural activities in the basal ganglia, which are the brain circuits associated with learning and applying rules (Muhammad, Wallis, & Miller, 2006); selecting appropriate responses within a given time limit (Stocco, Lebiere, & Anderson, 2010); and manipulating information in working memory (Prat & Just, 2010). More recently, using a similar mathematical paradigm (a Rapid Instructed Task Learning), Becker, Prat, and Stocco (2016) observed that the anterior cingulate cortex, which plays a critical role in cognitive flexibility, had differential effects on the dorsolateral prefrontal cortex and striatum as a function of the language group (i.e., bilinguals or monolinguals). These results suggest that bilinguals and monolinguals employ different neural mechanisms for conflict monitoring while performing a novel mathematical task. In addition, Kempert, Saalbach, and Hardy (2011) emphasize the importance of bilinguals' language proficiency for mathematical word problems. When they compared 8-year-old German monolingual children ($n = 34$) with their Turkish-German bilingual counterparts ($n = 44$) while controlling for SES and cognitive and arithmetic abilities, monolinguals outperformed bilinguals on ordinary mathematical word problems, due to monolinguals' apparently greater language competence. However, bilingual children's disadvantages were diminished when word problems involved distractors that required attentional control. Notably, bilinguals' German proficiency was highly correlated with their performance on word problems with distractors; this suggests the importance of bilinguals' language proficiency for more demanding word problems. Taken together, these findings suggest that bilingual advantages in EF likely translate into benefits for mathematical abilities, despite potential adversities associated with either SES (Clarkson, 1992) or language proficiency (Kempert et al., 2011).

Despite the importance of this association between bilingualism and mathematical achievements, it has received little attention. Moreover, previous studies have often been constrained by notable limitations in methods and research design. Some studies, for instance, were largely underpowered due to small sample size. Most research focused on the upper elementary grades: Sixth-graders were tested in Clarkson's (1992) study, and third-graders in Kempert et al.'s (2011) study. As a result, little is known about kindergarteners or students in lower grades. In terms of mathematical assessments, previous studies have employed a single measurement—either mathematical word problems or a general mathematics test—despite the importance of gathering data from