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

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Bilingualism Positively Predicts Mathematical Competence: Evidence from Two Large-Scale Studies

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Authors’ Note

The first and second authors contributed equally to this work.

Research highlights

- Using large-scale datasets, we examined the relation between bilingualism and math achievement.
- We found that bilingualism significantly predicted preschoolers’ math achievement.
- The positive predictability of bilingualism persisted from kindergarten through first grade.
- Bilingual advantages in executive functioning likely extends to mathematical achievement.

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.

Word count: 174

Bilingualism Positively Predicts Mathematical Competence:

Evidence from Two Large-Scale Studies

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 et al., 2015; 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, Pritchard, & Woodward, 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, 2011). 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 at 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 assessments that tap into mathematical reasoning and problem solving. Additionally, although several key variables—such as SES, race/ethnicity, and proficiency in the assessment language—could substantially affect bilinguals' mathematical achievements, previous studies did not control for those variables; also, the method used to approximate SES (e.g., the number of books at home) should be refined further. In view of these limitations, it is premature to draw definitive conclusions from previous studies. Given children's rapid brain development and cognitive maturation, methodologically rigorous large-scale studies are vital. Moreover, longitudinal research will be beneficial for investigating whether the relationship between bilingualism and mathematical attainment is reliable over time. In this study, therefore, we sought to examine the effect of bilingualism on mathematical achievement outcomes, using two existing large-scale longitudinal datasets.

In Study 1, we examined the relation between bilingualism and mathematical achievement in terms of emergent numeracy, mathematical reasoning, and applied problems. We compared bilingual and monolingual pre-kindergarteners aged 4-5 in terms of their mathematical abilities by analyzing a combined dataset from two major studies that were part of a large research project, the Multi-State Study of Pre-Kindergarten (hereafter called

“Multi-State”) and the State-Wide Early Education Programs (SWEEP), both of which were conducted by the National Center for Early Development and Learning (NCEDL) at the University of North Carolina at Chapel Hill.

In Study 2, we aimed to determine whether the predictability of bilingualism remains intact as bilingual kindergarteners progress to first grade. We also sought to identify whether bilingualism positively predicts performance on standardized mathematical assessments that are ecologically more relevant. To this end, we analyzed a new dataset from the Early Childhood Longitudinal Study: Kindergarten Class of 2010-11 (ECLS-K: 2011).

Building on evidence of bilingual advantages in executive functioning (e.g., Sorge et al., 2016; Yang & Yang, 2016), our primary hypothesis is that early bilingual experience will positively predict children’s mathematical learning when key demographic variables and proficiency in the assessment language (English) have been controlled for.

Study 1

We examined the potential relation between bilingualism and mathematical achievement outcomes among young children aged 4-5, using the Applied Problems subtest of the Woodcock-Johnson III Test of Achievement (Woodcock, McGrew, & Mather, 2001); two criterion-referenced tests of number identification and counting; and teachers’ reports on children’s mathematical reasoning skills. We hypothesized that if bilingual advantages in EF extend to their mathematics learning, bilingualism will be positively related to performance on the various tasks and teacher-reported reasoning skills.

In all of our analyses, we controlled for important demographic and language-related variables that have been shown to potentially affect children’s mathematical abilities: age Reilly, Neumann, & Andrews, 2015); gender, to control for the small but significant gender gap in mathematical achievement, potentially due to stereotype threat (e.g., Cimpian, Lubienski, Timmer, Makowski, & Miller, 2016; Picho & Schmader, 2017); household income and maternal education, which are important aspects of SES (e.g., Hackman, Gallop, Evans, & Farah, 2015); receptive vocabulary as an indicator of language proficiency (e.g., Kempert et al., 2011); and race/ethnicity to control for potential cultural influences on mathematical achievement (e.g., Guiso, Monte, Sapienza, & Zingales, 2008), as such influences have been shown to be a significant predictor of school achievement even after controlling for SES and parental education (e.g., Lubienski, 2002).

Methods

Data sources

A large-scale integrated dataset available from the Multi-State and SWEEP studies—which were differently referred to but collected by NCEDL as part of a large study, based on the same data-collection methods—was used to examine the link between bilingualism and mathematical achievement in children over a period of approximately 1 year.[1] Data collection for the Multi-State Study took place twice for the same participants during the fall and spring of the 2001-2002 school year in six states—California, Georgia, Illinois, Kentucky, New York, and Ohio—across 40 randomly chosen centers or schools in each state. These states were selected to maximize geographical diversity, program settings (public school or community setting), program intensity (full day vs. part day), and teachers' educational qualifications. Data collection for the SWEEP study also took place twice for the same participants during the fall and spring of the 2003-2004 school year in five states—Massachusetts, New Jersey, Texas, Washington, and Wisconsin. These states were selected to complement the states used in the Multi-State Study in terms of programs, funding models, and modes of service delivery; in each of these five states, 100 pre-kindergartens were randomly selected. Data from these two major studies were officially combined by NCEDL to provide more representative and comprehensive information on pre-kindergarteners in the US (Early et al., 2005). In total, 2,982 kindergarteners from 721 classrooms across 11 states participated in the two studies, in both the fall and spring of the relevant school year (for details, see Early et al., 2005).

Participants

Pre-kindergarteners (aged 4-5) participated in Wave 1 of the Multi-State and SWEEP studies during the fall of 2001 and 2003, respectively, and in Wave 2 of those studies during the spring of 2002 and 2004, respectively. To standardize the language of assessment across monolinguals and bilinguals, we selected children who had completed the English assessment battery. Children who were reported to speak Spanish at home and failed to pass the English proficiency test, as measured by the Preschool Language Assessment Scales (preLAS; Duncan & De Avila, 1998), were excluded from the study, since the Spanish assessment battery was administered to them instead of the English assessment battery.

Bilingualism was determined by the parents' report of their child's use of another language (other than English) as their home language, with Spanish as the majority (80%) followed by other languages, such as Chinese, Korean, and Vietnamese (20%). Overall, 2,566 kindergarteners participated in Wave 1 (monolingual = 2,060; bilingual = 506), and 2,577 kindergarteners in Wave 2 (monolingual = 2,060; bilingual = 517).[1] Table 1 summarizes participants' demographics and other characteristics.

Table 1. *Demographic and Other Characteristics of Bilingual and Monolingual Children Tested in Wave 1 and Wave 2*

	Wave 1 (Fall)		Wave 2 (Spring)	
	Bilinguals	Monolinguals	Bilinguals	Monolinguals
Age in years	4.61 (0.32)	4.63 (0.32)	5.04 (0.32)	5.06 (0.32)
Gender (% girls)	51.78	50.68	51.45	50.68
Household income[a]	5.82 (4.23)	7.78 (5.30)	5.84 (4.20)	7.78 (5.30)
Years of maternal education	12.21 (2.51)	13.00 (2.19)	12.11 (2.19)	13.00 (2.19)
Race/ Ethnicity				
White (%)	7.24	55.40	7.11	55.40
Hispanic (%)	68.01	7.61	69.37	7.61
Black (%)	4.63	24.24	4.55	24.24
Asian or multiracial (%)	20.12	12.76	18.97	12.76
Receptive vocabulary (PPVT)	86.86 (13.68)	95.68 (14.68)	88.85 (12.19)	98.33 (14.09)
Applied Problem subtest	95.41 (13.12)	99.06 (13.63)	97.30 (12.08)	99.61 (12.83)
Identifying Numbers task	5.01 (3.92)	4.62 (3.91)	7.05 (3.38)	6.83 (3.54)
Counting task	14.87 (9.54)	14.65 (9.98)	20.42 (11.49)	20.88 (12.11)
ARS–Mathematics	-	-	2.97 (1.07)	2.99 (1.05)

Note. *SD*s are shown in parentheses. Data were presented before multiple imputation. ARS–Mathematics = teacher-rated Academic Rating Scale–Mathematics.
[a] Household income was rated on a scale of 1 (less than $5,001) to 18 (more than $850,001), with intervals of $5,000.

Measures

Mathematical achievement. Four measures were used to assess mathematical achievement: the Applied Problems subtest of the Woodcock-Johnson III Test of Achievement (Woodcock et al., 2001); two criterion-referenced measures, Identifying Numbers and Counting; and the teacher-rated Academic Rating Scale–Mathematics (ARS–Mathematics; Early et al., 2005). Initial items on the Applied Problems subtest required children to apply simple mathematical concepts, while the majority of items required that they listen to the problem, recognize the mathematical procedure required, and perform the appropriate calculations (α_{fall} = .84, α_{spring} = .93). The measure is standardized with a mean of 100.

In the Identifying Numbers task, children were shown a sheet of numbers from 1 to 10 in random order and asked to identify as many numbers as possible, with a maximum score of 10. In the Counting task, children were asked to count and point, with a one-to-one correspondence, using picture cards of teddy bears. Performance on these two measures were used as indicators of emergent numeracy in young children (Gelman & Gallistel, 1986).

The teacher-reported ARS–Mathematics was only used in Wave 2 (α = .94) to assess a child's mathematical reasoning skills. Teachers compared each child to other students at the same grade level and rated him or her, using a 5-point scale, on seven mathematical skills: (a) sorting, classifying, and comparing mathematical materials using various rules and attributes; (b) ordering a group of objects; (c) demonstrated understanding of the relationship between quantities; (d) solving number problems using concrete objects; (e) demonstrated understanding of graphing activities; (f) using instruments accurately for measuring; and (g) using a variety of strategies to solve math problems.

Receptive vocabulary. The Peabody Picture Vocabulary Task–Third Edition (PPVT-III; Dunn & Dunn, 1997) primarily served to measure receptive vocabulary knowledge by asking children to select a picture from four options to match a word given by the experimenter. The PPVT–III is a standardized measure for assessing children's receptive vocabulary (α_{fall} = .96, α_{spring} = .96). However, given that PPVT performance is highly correlated with other intelligence measures, such as the Kaufman Brief Intelligence Test (r =.62 -.82), it was also used as an estimate of overall cognitive ability (Fantuzzo, McWayne, Perry, & Childs, 2004).

Data Analysis

We examined the relationship between bilingualism and mathematical achievement, as measured by the (a) Applied Problems subtest, (b) Number Identification task, (c) Counting task, and (d) teacher-reported ARS–Mathematics. For all measures, lower scores indicate poorer ability and higher scores indicate better ability. For both Wave 1 and Wave 2 data, we performed two ordinary least squares regression models for each criterion variable.

In the first model, bilingualism was included without covariates to provide estimates for a preliminary relation between bilingualism and mathematical achievement. In the second model, bilingualism was included as a predictor while taking into account crucial covariates that were entered into the model simultaneously—age at assessment; gender; household income; years of maternal education; receptive vocabulary in English, as measured by the PPVT-III; and race/ethnicity, to control for cultural influences on math achievement. Therefore, the second model provides estimates for the unique relationship between bilingualism and mathematical achievement outcomes while controlling for important covariates. Bilingualism was dummy coded to compare bilinguals with monolingual reference; thus, a positive beta coefficient suggests that bilinguals outperformed monolinguals on the relevant assessment. Similarly, sex was dummy coded with male as reference. Each race/ethnicity was dummy coded (e.g., Asian, 1 = yes, 0 = no) with white as reference. For missing data, multiple imputation was used to impute missing data in the predictor and covariates of critical interest. As recommended by Von Hippel (2007), we employed the multiple imputation, then deletion (MID) procedure, in which missing criterion variables were excluded from the analysis subsequent to the imputation. Collinearity statistics did not indicate multicollinearity.

Results

Receptive Vocabulary

The PPVT-III was used to measure receptive vocabulary and general cognitive ability in children (Fantuzz et al., 2004). Consistent with the literature (e.g., Luk et al., 2011), bilinguals had significantly smaller receptive vocabularies than monolinguals in Wave 1 ($M_{bilinguals}$ =86.9, $M_{monolinguals}$ =95.7) and Wave 2 ($M_{bilinguals}$ =88.9 $M_{monolinguals}$ = 98.3), *p*s < .001 (see Table 1).

The Applied Problems Subtest

When Model 1 did not control for key covariates of age, sex, household income, maternal education, receptive vocabulary, and race/ethnicity, we found that bilingualism negatively predicted scores on the Applied Problems subtest in both Wave 1 ($B = -3.47$, $SE = .81$, 95% CI [−5.07, −1.87], $t = -4.26$, $p < .001$) and Wave 2 ($B = -2.15$, $SE = .70$, 95% CI [−3.52, 0.77], $t = 3.06$, $p = .002$). Note that the negative beta coefficients suggest that bilingual children performed worse on the Applied Problems subtest than their monolingual counterparts.

However, these results were not sustained in Model 2, in which empirically important covariates were controlled for. The unique relationship in Model 2 showed that bilingualism positively predicted mathematical attainment. Further analysis showed that this beneficial effect of bilingualism was more pronounced in Wave 2 than in Wave 1. Bilingualism significantly predicted standardized scores on the Applied Problems subtest in Wave 1 ($B = 1.97$, $SE = .79$, 95% CI [0.42 – 3.53], $t = 2.49$, $p = .013$) and in Wave 2 ($B = 2.88$, $SE = .71$, 95% CI [1.50, 4.27], $t = 4.08$, $p < .001$). Overall, Model 2 explained 38.4% and 39% of variance in Applied Problem subtest in Wave 1 and Wave 2, respectively. Note that the positive beta coefficients in Model 2 suggest that bilingual children outperformed monolingual children on the Applied Problems subtest when critical covariates were controlled for. All covariates were significant in the model, all *p*s<.05, except for Hispanic and Asian ethnicity (see Table 2). These results support a unique positive relation between bilingualism and math achievement in pre-kindergarten children.

We performed the same analyses without excluding participants who had been administered the Spanish assessment battery instead of the English assessment battery (see Appendix A), and observed a pattern of results similar to those of the previous model.

Identifying Numbers and Counting tasks

Consistent with the results above, when key covariates were not controlled for in Model 1, bilingualism significantly predicted emergent numeracy in Wave 1, as measured by the Identifying Numbers task ($B = 0.53$, $SE = .23$, 95% CI [0.08, 0.98], $t = 2.32$, $p = .020$), but it did not predict performance on the Counting task ($B = 0.58$, $SE = .58$, 95% CI [−0.55, 1.71], $t = 1.00$, $p = .316$). In Wave 2, bilingualism predicted scores on neither the Identifying Numbers task ($B = 0.28$, $SE = .19$, 95% CI [−0.08, 0.65], $t = 1.53$, $p = .126$) nor Counting task ($B = -0.29$, $SE = .63$, 95% CI [−1.52, 0.95], $t = -0.46$, $p = .648$).

In contrast, when critical covariates were controlled for in Model 2, the unique relationship between bilingualism and emergent numeracy was more pronounced: We found that bilingualism emerged as a significant predictor of scores on both the Identifying Numbers task ($B = 1.63$, $SE = .23$, 95% CI [1.17, 2.09], $t = 6.97$, $p < .001$) and the Counting task ($B = 3.00$, $SE = .65$, 95% CI [1.72, 4.28], $t = 4.61$, $p < .001$) in Wave 1. Consistent results were obtained in Wave 2; bilingualism significantly predicted both the Identifying Numbers task ($B = 1.19$, $SE = .21$, 95% CI [0.77, 1.61], $t = 5.59$, $p < .001$) and the Counting task ($B = 2.40$, $SE = .74$, 95% CI [0.95, 3.85], $t = 3.24$, $p = .001$). These results support a unique link between bilingualism and emergent numeracy skills in pre-kindergarten children. Overall, Model 2 explained 27.5% and 19.4% of variance in the Identifying Numbers task in Wave 1 and Wave 2, respectively, and 17.5% and 18.4% of variance in the Counting task in Wave 1 and Wave 2, respectively.

ARS–Mathematics

Consistent with the results reported above, the use of covariates as control variables made a substantial difference in assessing the predictive role of bilingualism. When covariates were not controlled for in Model 1, bilingualism did not predict teacher-reported ARS–Mathematics in Wave 2 (B = −0.07, SE = .06, 95% CI [−0.18, 0.04], t = −1.29, p = .199). However, bilingualism significantly predicted teacher-reported ARS–Mathematics (B = 0.30, SE = .08, 95% CI [0.15, 0.46], t = 4.03, p < .001) when the host of covariates was taken into consideration; note that scores on the ARS–Mathematics were obtained only in Wave 2. This result suggests that bilingualism plays a unique role in children's metacognitive reasoning skills. Overall, Model 2 explained 14.6% of variance in teacher-reported ARS–Mathematics in Wave 2.

Table 2. *Ordinary Least Squares Regression Models of Mathematical Achievement in Wave 1 (Fall, 2001-2002) and Wave 2 (Spring, 2003-2004): NCEDL's Multi-State Study of Pre-Kindergarten and Study of State-Wide Early Education program (SWEEP)*

Variables	Wave 1 (Fall)			Wave 2 (Spring)			
	APS (*n*=2,295)	IN (n=2,295)	CT (n=2,276)	APS (n=2,435)	IN (n=2,439)	CT (n=2,435)	ARS−M (n=2,453)
Predictor							
Bilingualism	.053*	.152**	.110**	.087**	.132**	.077*	.125**
Covariates							
Age	−.078**	.280**	.226**	−.091**	.220**	.232**	.184**
Gender	.073**	.063**	.088**	.075**	.038*	.088**	.049*
Income	.089**	.136**	.110**	.081*	.111**	.156**	.068*
Maternal Education	.062*	.087**	.097**	.086**	.101**	.020	.098**
Receptive Vocabulary	.526**	.352**	.248**	.537**	.306**	.299**	.233**
Race/ Ethnicity							
Hispanic	−.045*	.017	.004	.000	.042*	.065*	−.062*
Black	−.053*	.147**	.136**	−.052*	.124**	.164**	−.003
Asian or multiracial	−.018	.078**	.036†	−.002	.061*	.068*	−.014

Note. Values reflect standardized coefficient estimates when the predictor and all covariates were entered in Model 2. Bilingualism was dummy coded with monolinguals as reference (i.e., bilinguals = 1, monolinguals = 0); gender was dummy coded with male as reference; and race/ ethnicity was dummy coded with white as reference. For all criteria, higher values reflect better performance. APS = Applied Problems Subtest of Woodcock-Johnson III Test of Achievement; IN = Identifying Numbers Task; CT = Counting Task; ARS–M = teacher-rated Academic Rating Scale–Mathematics. † $p < .01$, * $p < .05$, * $p < .001$.

Discussion

Using a large-scale dataset that integrates two identical studies conducted at two time points, we found a consistently unique relationship between bilingualism and mathematical attainment. When key covariates of demographic variables and language proficiency were controlled for, we found a positive relationship between bilingualism and mathematical achievement such that bilingualism positively predicted performance on tests of mathematical achievement, as measured by the Applied Numbers subtest; emergent numeracy, as measured by the Identifying Numbers and Counting tasks; and mathematical reasoning skills, as measured by the teacher-rated ARS–Mathematics. Our findings suggest that growing up with two languages is beneficial for the child's development of (a) emergent numeracy-related concepts, such as identifying numbers and counting; (b) the mathematical skills required to analyze and solve simple word problems; and (c) metacognitive arithmetic reasoning.

Despite our large sample size, however, we acknowledge that the study is limited, since we were unable to examine whether the beneficial effect of bilingualism on mathematical achievement continues into subsequent developmental stages when children progress to elementary school. Especially given that mathematics instruction and assessment become more formal, complex, and academically rigorous in elementary school, it is crucial to extend our findings to elementary school children, over longer periods and using valid standardized measures, to ensure that bilingualism's effect on mathematical attainment is robust. Moreover, since the measures of mathematical achievement in Study 1 were limited to assessing emergent numeracy, basic math skills, and arithmetic reasoning, they may not sufficiently reflect typical classroom math exercises, which cover a broader variety of content (e.g., algebra, geometry, and probability) and require the ability to integrate conceptual and procedural knowledge and problem-solving skills. Therefore, it is essential to identify the robustness of bilingualism in predicting mathematical achievement by using ecologically valid measures that mimic real-life math curricula. These areas were addressed in Study 2.

Study 2

To extend our findings from Study 1, we exploited a new large-scale public dataset from the ongoing Early Childhood Longitudinal Study: Kindergarten Class of 2010-11 (ECLS-K: 2011) conducted by the National Center for Education Statistics. This dataset is particularly useful, because it assesses children's mathematics skills longitudinally from kindergarten to the elementary grades. Also, it incorporates a well-validated mathematical assessment based on the 1996 National Assessment of Educational Progress Mathematics Framework, which was examined by an expert panel of educators (for details on sampling procedures and materials, see Tourangeau et al., 2015). Study 2 had two primary goals. First, we sought to determine whether the predictability of bilingualism is evident when kindergarteners progress to elementary school. Second, we aimed to examine whether the unique relation between bilingualism and mathematical achievement persists when students are tested with mathematical assessments that have high ecological validity and are similar to those typically used in actual classrooms.

Method

Data sources

We analyzed a public-use dataset of the ECLS-K: 2011 study, which tracked a nationally representative sample of approximately 18,200 children from diverse socioeconomic and racial/ethnic backgrounds over a longitudinal period from their entry into kindergarten through the first grade. The ECLS-K:2011 study offers comprehensive and reliable data that are useful for understanding children's development, learning, and experiences at school. We used data collected at the four time points currently available for Wave 1 (Fall 2010-11; Kindergarten Fall); Wave 2 (Spring 2010-11; Kindergarten Spring); Wave 3 (Fall 2011-2012; First Grade Fall); and Wave 4 (Spring 2011-2012; First Grade Spring).[3]

Participants

We excluded participants who had performed mathematical tasks in Spanish, due to their low English proficiency; in doing so, we standardized the language used for the battery of assessments. We also excluded participants who were reported to have been interrupted (e.g., by a fire drill or class) or disturbed (e.g., by noise or another person) during the assessment. Bilingualism was confirmed if children were reported to: (a) speak a language other than English at home, and (b) speak English at home or demonstrate sufficient basic English skills, as determined by their score (16 out of 20) on a language screener (i.e., the English version of the Preschool Language Assessment Scales). As a result, a total of 12,530 children participated in Wave 1 (Kindergarten Fall: monolingual = 11,144; bilingual = 1,386); 13,118 in Wave 2 (Kindergarten Spring: monolingual = 11,462; bilingual = 1,656); 3,577 in Wave 3 (First Grade Fall; monolingual = 2,886; bilingual = 691); and 9,862 in Wave 4 (First Grade Spring; monolingual = 8,447; bilingual = 1,415).[4] Bilingual participants spoke a variety of languages in addition to English, with Spanish as the majority followed by other languages, such as Chinese, Japanese, French, German, and Italian. Table 3 summarizes the main characteristics of both bilinguals and monolinguals across all four waves.

Table 3. *Characteristics of Bilinguals and Monolinguals across the Four Waves in the ECLS-K: 2011*

	Wave 1: Kindergarten Fall		Wave 2: Kindergarten Spring		Wave 3: First Grade Fall		Wave 4: First Grade Spring	
	Bilinguals	Monolinguals	Bilinguals	Monolinguals	Bilinguals	Monolinguals	Bilinguals	Monolinguals
Age in years	5.57 (0.36)	5.63 (0.37)	6.05 (0.37)	6.13 (0.37)	6.55 (0.36)	6.59 (0.28)	7.06 (0.36)	7.13 (0.37)
Sex (% girls)	50.76	49.15	51.00	48.57	50.51	47.19	49.79	48.49
Household income[a]	6.75 (4.53)	11.41 (5.41)	6.44 (4.51)	11.36 (5.43)	5.94 (4.09)	11.16 (5.57)	6.19 (4.17)	11.21 (5.49)
Maternal educational level[b,c]	3.23 (1.91)	4.86 (1.78)	3.10 (1.93)	4.85 (1.78)	3.04 (1.80)	4.90 (1.90)	3.08 (1.85)	4.94 (1.86)
Paternal educational level[b,c]	3.19 (2.03)	4.83 (1.88)	3.09 (2.07)	4.81 (1.89)	2.77 (1.80)	4.90 (2.01)	2.97 (1.98)	4.91 (2.01)
Race								
White	5.50	54.96	4.67	54.02	3.18	45.15	4.81	52.82
Hispanic	73.59	16.95	74.62	17.98	84.23	26.76	76.59	18.96
Black	4.05	15.60	3.57	14.77	1.16	14.53	3.47	14.84
Asian	14.83	5.91	15.38	6.69	9.84	6.08	13.65	6.63
Native Indians	0.43	1.01	0.36	0.97	0.43	2.09	0.28	1.19
Native Hawaiian	0.80	0.53	0.61	0.68	0.58	0.63	0.71	0.64
Multiracial	0.80	5.04	0.79	4.89	0.58	4.76	0.50	4.92
PreLAS	16.57 (2.74)	19.04 (2.08)	17.54 (2.48)	19.46 (2.13)	16.35 (3.95)	19.35 (1.59)	16.53 (4.11)	19.44 (1.49)
Mathematics assessment (IRT)	25.95 (10.13)	31.00 (10.78)	38.49 (10.96)	43.89 (11.39)	45.62 (12.48)	50.96 (13.40)	56.78 (12.96)	63.17 (13.33)
Mathematics assessment (Theta)	-0.87 (0.92)	−0.43 (0.88)	0.13 (0.76)	0.48 (0.76)	0.62 (0.78)	0.92 (0.82)	1.28 (0.80)	1.67 (0.85)

Note. *SD*s are shown in parentheses. Data were presented before multiple imputation

[a] Household income was rated on a scale of 1 (*less than $5,000*) to 18 (*more than $200,000*), with an interval of $5,000 from levels 1–15, of $25,000 on level 16, and of $100,000 on levels 17 and 18.

[b] Parental education level was rated on a scale of 1 (*none*) to 8 (*master's degree or higher*) in Wave 1 and Wave 2, and on a scale of 1 (*none*) to 9 (*doctorate or professional degree*) in Wave 3 and Wave 4.

Measures

Mathematical achievement. The measure of mathematics used in the ECLS study was designed to assess conceptual knowledge, procedural knowledge, and problem-solving skills. The measure consists of questions that assess (a) number sense, properties, and operations; (b) measurement; (c) geometry and spatial sense, (d) data analysis, statistics, and probability; and (e) patterns, algebra, and functions. Development of the measure was based on the Mathematics Framework of the 1996 National Assessment of Educational Progress. All items were examined by an expert panel of mathematics curriculum specialists for content and framework strand design, accuracy, nonambiguity of response options, and appropriate formatting (Tourangeau et al., 2015). Assessments took approximately 60 minutes to complete and were administered on an individual basis by trained and certified assessors. Responses were entered into a computer-assisted interviewing program.

Item Response Theory (IRT) was used to calculate each child's overall IRT scores, which were used to compare children's performance regardless of the specific items that had been administered to them. In the procedure, assessment items for math achievement were selected using a two-stage evaluation method to ensure that the measure would adequately measure children's mathematical knowledge and maximize the instrument's accuracy (while minimizing total administration time). Specifically, in the first stage, a set of routing items with a wide range of difficulty (low, medium, and high) was administered to all children; that is, in this stage, all children received similar mathematical questions. In the second stage, a set of items appropriate for the level of each child's math abilities, as demonstrated in the first stage, was administered; thus, children could receive different mathematical questions. Unlike other typical procedures, which consider only the number of correct or incorrect items, IRT procedures estimate the probability of each child's providing correct responses to items by taking into account (a) the pattern of each child's responses to administered items,

(b) the items' overall difficulty levels, (c) each item's ability to discriminate high achievers from low achievers, and (d) each item's "guess-ability," i.e., the probability of guessing the correct answer. The IRT procedure, therefore, can adjust for the possibility of a poorly performing child's correct guesses on difficult items.

Assessment scores computed by using the IRT procedure include theta scores and IRT-scale scores, which reflect children's latent math abilities more precisely than raw scores. Theta scores were obtained to estimate a child's mathematical ability, which is calculated based on his or her performance on the actual items administered. These scores represent a child's latent ability and are independent of the difficulty of assessment items. Theta scores are reported on a metric that ranges from −6 to 6, with lower scores indicating poorer performance and higher scores indicating better performance. The IRT-scale score is an estimate of the number of questions a child would have answered correctly if they were administered all the available test items: 96 unique questions in the first stage and three second-stage mathematics forms. The IRT-scale score was calculated based on each participant's theta score, and was used to predict each test item's probability that the participant would have gotten it correct. Subsequently, the overall IRT-scale score was calculated by summing the probabilities for all of the items fielded in every round (for more details, see Tourangeau et al., 2015).

English proficiency. Children's English proficiency was measured by the Preschool Language Assessment Scales (preLAS; Duncan & De Avila, 1998), which consists of the Simon Says task and the Art Show task. The Simon Says task requires children to follow simple and direct instructions spoken in English by the assessor. The Art Show task is a picture vocabulary assessment that tests children's expressive vocabulary. Using the conventional scoring method, total scores for the preLAS served as an index of English proficiency. Because the preLAS was assessed only at Waves 1 and 2, we used the score obtained at Wave 2 as a proxy for English proficiency for Waves 3 and 4.

Data Analysis

As in Study 1, we tested our hypothesis using ordinary least squares regression analysis in which bilingualism was used to predict each criterion variable, i.e., the IRT-scale scores and theta scores on mathematical assessments across the four waves. In Model 1, we examined the preliminary relationship between bilingualism and mathematical achievement without controlling for key covariates. In Model 2, we examined the unique relationship between bilingualism and mathematical achievement while controlling for the covariates of age at assessment, sex, household income, paternal and maternal education, and English proficiency (preLAS), which were entered simultaneously into the model. Bilingualism was dummy coded to compare bilinguals with monolingual references. Sex was dummy coded with male as reference. Since specific information on cultural orientation was not available in the dataset, we used race as a proxy to control for cultural influences on mathematical achievement (Chen & Stevenson, 1995). Each race was dummy coded (e.g., Asian, 1 = yes, 0 = no) with white as reference. Similar to Study 1, multiple imputation was used to impute missing values in predictor and covariates of critical interest with MID (Von Hippel, 2007).

Results

English Proficiency

Bilinguals had significantly lower English proficiency than monolinguals, as indicated by total scores on the preLAS in Wave 1 ($M_{\text{bilinguals}}$ =16.57, $M_{\text{monolinguals}}$ =19.04); Wave 2 ($M_{\text{bilinguals}}$ =14.91, $M_{\text{monolinguals}}$ =19.02); Wave 3 ($M_{\text{bilinguals}}$ =16.35, $M_{\text{monolinguals}}$ =19.35); and Wave 4 ($M_{\text{bilinguals}}$ =16.53, $M_{\text{monolinguals}}$ =19.44), ps < .001. Results are consistent with those of Study 1, suggesting that bilingualism, compared to monolingualism, is disadvantageous for English proficiency.

Mathematical Achievement

In Model 1, we examined the preliminary relationship between bilingualism and math achievement identified by IRT and theta scores without controlling for covariates. We found that bilingualism negatively predicted IRT scale scores in Wave 1 ($B = -5.05$, $SE = .31$, 95% CI [−5.36, −4.75], $t = -16.55$, $p < .001$); Wave 2 ($B = -5.40$, $SE = .30$, 95% CI [−5.98, −4.81], $t = 18.11$, $p < .001$); Wave 3 ($B = -5.35$, $SE = .56$, 95% CI [−6.45, −4.26], $t = -9.56$, $p < .001$); and Wave 4 ($B = -6.39$, $SE = .38$, 95% CI [−6.77, −6.01], $t = -16.74$, $p < .001$). Similarly, bilingualism also negatively predicted theta scores in Wave 1 ($B = -0.44$, $SE = .03$, 95% CI [−0.47, −0.42], $t = -17.37$, $p < .001$); Wave 2 ($B = -0.35$, $SE = .02$, 95% CI [−0.38, −0.31], $t = -17.30$, $p < .001$); Wave 3 ($B = -0.32$, $SE = .03$, 95% CI [−0.39, −0.25], $t = -9.28$, $p < .001$); and Wave 4 ($B = -0.39$, $SE = .02$, 95% CI [−0.42, −0.37], $t = -16.23$, $p < .001$). Negative beta coefficients suggest that bilingual children performed worse than monolingual children when key covariates were not taken into consideration.

In contrast, when covariates (age, sex, income, paternal and maternal education, race, and English proficiency) were controlled for in Model 2, we obtained strikingly different results. Bilingualism positively predicted IRT-scale scores across the four waves (see Table 4): Wave 1 ($B = 1.38$, $SE = .30$, 95% CI [0.79, 1.96], $t = 4.61$, $p < .001$); Wave 2 ($B = 1.54$, $SE = .32$, 95% CI [0.93, 2.16], $t = 4.90$, $p < .001$); Wave 3 ($B = 1.79$, $SE = .63$, 95% CI [0.55, 3.03], $t = 2.83$, $p = .005$); and Wave 4 ($B = 1.59$, $SE = .42$, 95% CI [0.78, 2.41], $t = 3.83$, $p < .001$). Overall, Model 2 explained 32.5%, 28.2%, 24.0%, and 25.4% of variance in the IRT-scale scores in Wave 1, Wave 2, Wave 3, and Wave 4, respectively. Similarly, bilingualism positively predicted theta scores in Wave 1 ($B = 0.13$, $SE = .02$, 95% CI [0.08, 0.18], $t = 5.36$, $p < .001$); Wave 2 ($B = 0.13$, $SE = .02$, 95% CI [0.09, 0.186], $t = 6.41$, p

< .001); Wave 3 (B = 0.13, SE = .04, 95% CI [0.05, 0.20], t = 3.26, p = .001); and Wave 4 (B = 0.11, SE = .03, 95% CI [0.06, 0.16], t = 4.27, $p < .001$). Model 2 explained 34.4%, 28.2%, 24.0%, and 25.4% of variance in theta scores in Wave 1, Wave 2, Wave 3, and Wave 4, respectively. Combined with the results of Study 1, our findings support the unique positive relationship between bilingualism and mathematics achievement (see Appendix B for analyses in which participants who failed the English proficiency test were not excluded, and thus were administered a Spanish assessment battery).

Table 4. *Ordinary Least Squares Regression Models of Mathematical Achievement across the Four Waves of the Early Childhood Longitudinal Study: Kindergarten Class of 2010-11*

Variables	Wave 1		Wave 2		Wave 3		Wave 4	
	IRT	Theta	IRT	Theta	IRT	Theta	IRT	Theta
	n = 12,477	*n* = 12,476	*n* = 13,087	*n* = 13,087	*n* = 3,574	*n* = 3,574	*n* = 9,850	*n* = 9,850
Predictor								
Bilingualism	.040**	.046**	.045**	.058**	.053*	.061*	.041**	.046**
Covariates								
Age	.226**	.217**	.192**	.181**	.196**	.198**	.132**	.136**
Sex	−.010	−.001	.002	.008	.005	.002	−.012	−.024*
Income	.156**	.153**	.155**	.149**	.151**	.151**	.154**	.150**
Maternal Education	.131**	.131**	.125**	.119**	.136**	.136**	.120**	.124**
Paternal Education	.115**	.099**	.091**	.079**	.086**	.085**	.086**	.092**
English Proficiency	.269**	.319**	.259**	.300**	.189**	.201**	.215**	.211**
Race								
Hispanic	−.007	−.005	−.018†	−.011	−.041*	−.036†	−.061**	−.057**
Black	−.076**	−.077**	−.105**	−.102**	−.100**	−.097**	−.152**	−.149**
Asian	.114**	.111**	.092**	.093**	.057**	.057**	.075**	.076**
Native Indians	−.032**	−.038**	−.024*	−.021*	−.032*	−.030*	−.031**	−.029*
Native Hawaiian	−.006	−.005	−.004	−.004	−.003	−.003	−.005	−.006
Multiracial	.010	.004	.003	.004	−.015	−.016	−.008	−.006

Note. Values reflect standardized coefficient estimates when both the predictor and covariates were entered in Model 2. Bilingualism was dummy coded with monolinguals as reference (i.e., bilinguals = 1, monolinguals = 0); sex was dummy coded with male as reference; and race was dummy coded with white as reference. In all of the criteria, higher values reflect better performance. † $p < .01$, * $p < .05$, ** $p < .001$.

Discussion

Using a new, large-scale longitudinal dataset, we found strong evidence that favors bilingualism in mathematical achievement. A positive relation between bilingualism and mathematical competence was evident across all four waves when important covariates were taken into account, which suggests that bilingual advantages are robust and persistent during the transition period from kindergarten to elementary school. Given that Study 2 tested older children using an ecologically valid measure of mathematics that closely resembles typical mathematics assessments in classroom settings, our results successfully extend Study 1. Together with the results of Study 1, our findings further support the continuing and positive relationship between bilingualism and children's mathematical performance on more challenging and advanced mathematical tests in kindergarten and early elementary grades.

General Discussion

Using two independent large-scale datasets, we found that bilingualism significantly predicted pre-kindergarteners' emergent numeracy, teacher-rated mathematical reasoning, and curriculum-based mathematical knowledge and problem-solving skills, especially when critical covariates were taken into consideration. We also found that the positive relationship between bilingualism and mathematical achievement endures through the transition period from kindergarten to elementary school. Building on the growing number of studies that support the close link between EFs and mathematical achievement (Bull & Scerif, 2001), our findings imply that bilingual advantages in executive functioning (e.g., Sorge et al., 2016; Yang & Yang, 2016; Yang et al., 2011) likely extend to mathematical achievement based on strong analytic reasoning, attentional focus, and problem-solving skills. Given that Marian et al. (2013) found similar bilingual advantages in math performance among bilingual students in the third, fourth, and fifth grades, our findings further suggest that the positive predictability of bilingualism in terms of mathematical competence is evident among even kindergarteners and first graders. These findings support Stocco and Prat's (2014) assertion that speaking two languages modulates the brain circuits associated with acquiring and applying rules, which are necessary for learning complex rule-based procedures in math curricula. Given that the majority of previous studies of bilingualism have focused on its effects on the development of EFs, our study opens a promising avenue for research on the impact of bilingualism on academic achievement.

We would also like to emphasize the importance of two covariates—SES and proficiency in the language of instruction—in studying the effect of bilingualism on mathematical word problems in particular. It is notable that we found different patterns of results depending on the control of covariates. Specifically, when covariates were disregarded, we found bilingual disadvantages in mathematical word problems (Study 1). When covariates were retained, however, we found the opposite. Our findings are not entirely new in this respect. Previous studies have noted the potential importance of SES and language competence in studying children's mathematical achievements (e.g., Aunio & Niemivirta, 2010). For instance, Byrnes and Wasik (2009) found that SES is an important antecedent factor for math achievement in kindergarteners and first and third graders. Similarly, Clarkson (1992) found that the quality of housing and the father's occupation—which are indices of SES—emerged as significant covariates that influenced children's performance on general math and word-problem tests.

Regarding the importance of language proficiency, Clarkson (1992) found that bilinguals with low language competence were at a disadvantage compared to either monolinguals or highly competent bilinguals. However, despite their low SES, bilinguals who had high competence in their primary language relatively outperformed monolinguals. In a similar vein, Kempert et al. (2011) stressed the critical importance of bilinguals' language proficiency for mathematical word problems. Vukovic and Lesaux (2013) also found strong evidence of a significant relationship between linguistic skills (i.e., phonological decoding and verbal analogies) and arithmetic performance and knowledge in children in the third grade. Given bilinguals' lower language proficiency relative to monolinguals, we would expect that bilinguals' low command of the instructional language would hinder their ability to understand and form an accurate mental representation of the problem at hand (Ní Ríordáin & O'Donoghue, 2009; Saalbach, Eckstein, Andri, Hobi, & Grabner, 2013). In view of this evidence, our findings of the positive relationship between bilingualism and children's mathematical achievement when crucial covariates of SES and language proficiency are taken into account suggest that bilingualism uniquely contributes to mathematical achievement.

Our study is not without limitations. First, given that the Multi-State and SWEEP studies were collected between the 2001-2002 and 2003-2004 school years, respectively, we note that our dataset is relatively outdated and thus our findings should be interpreted with caution. Second, as the Multi-State, SWEEP, and ECLS datasets contain limited information on language skills and development, our studies are unable to address how the complex nature of bilingual experiences relates to mathematical achievement. Future studies are warranted to examine this issue by administering various language assessments and acquiring more detailed information on bilingual profiles. Third, one might raise the validity issue of the teacher-rated Academic Rating Scale–Mathematics. Although we acknowledge the limitation of this measure, it is notable that our primary conclusion does not solely rely on teacher-reported abilities. By drawing on multiple mathematical assessments—the Applied Problems subtest of the Woodcock-Johnson III Test of Achievement, the Identifying Numbers Task, the Counting Task, and standardized mathematical assessments—we established convergent validity regarding the relationship between bilingualism and mathematical achievement. Fourth, although the dataset for Study 2 has a longitudinal structure, we did not focus on identifying group differences in intra-individual changes in mathematical achievements. Instead, our analyses focused on each time point to determine the reliability of the relationship between bilingualism and mathematical achievement. This was done due to a short interval (i.e., 1.5 years) between Wave 1and Wave 4, which is quite restrictive in finding longitudinal trajectories of changes in mathematical achievement. The literature on bilingualism has suggested that lifelong bilingual experiences are often necessary to observe any language-group differences in executive functions (e.g., Luk et al., 2011), especially when second-language acquisition occurs in a natural context (e.g., home). Nevertheless, the repeated-measures design still has advantages, since it allows us to examine the reliability of our results over time.

Another notable limitation is that we are still unclear about the causal relationship between bilingualism and mathematical achievement. Although the positive link between bilingualism and mathematical achievements is likely attributable to bilinguals' daily practice of speaking two languages, it is possible that a third variable accounts for the association observed in our study. For instance, children who have attained better mathematical abilities are smarter, and therefore better equipped and more motivated to acquire a second language (e.g., Li & Grant, 2015). We believe, however, that the latter is unlikely because during early childhood, bilingual acquisition is involuntary and not the result of voluntary behaviors or motivation. Recent empirical studies that employed longitudinal language-immersion training for monolinguals have accumulated convincing evidence regarding the direction of causality between bilingualism and cognitive advantages (Nicolay & Poncelet, 2015). Specifically, Woumans, Surmont, Struys, and Duyck (in press) found that monolingual children who had participated in bilingual immersion schooling showed significantly greater gains in intelligence than their monolingual counterparts; this suggests that bilingual training indeed facilitates children’s cognitive development. Taken together, although our findings suggest that bilingualism is conducive to mathematical achievement, a causal conclusion should be avoided due to the study’s correlational nature.

In conclusion, our study identified bilingualism as a new predictor that enhances children’s potential for mathematics. Future studies using longitudinal language-immersion programs will be essential to shed light on the causal mechanisms that underlie bilingual training, cognitive development in EFs, and math performance. Furthermore, additional research is needed to investigate the mediating role of diverse aspects of EFs and working memory in the relationship between bilingual advantages and mathematics achievement. It will also be critical to identify potential boundary conditions that delimit the association between bilingualism and math performance. Considering recent studies that suggest that various bilingual experiences—such as bilinguals’ disparate interactional contexts and their practice of language switching—modulate the cognitive consequences of bilingualism (Hartanto & Yang, 2016; Luk, De Sa, & Bialystok, 2011; Verreyt, Woumans, Vandelanotte, Szmalec, & Duyck, 2016; Yang, Hartanto, & Yang, 2016a; Yang, Hartanto, & Yang, 2016b), it is important that we understand how these various bilingual experiences influence bilingual advantages in mathematical abilities.

Footnotes

[1] The integrated dataset and materials of the Multi-State Study and SWEEP are available from the Inter-University Consortium for Political and Social Research (http://www.icpsr.umich.edu/icpsrweb/ICPSR/studies/34877).

[2] In Wave 2, 252 additional children were recruited to increase the size of participating classrooms that had fewer than four participating children and replace children who had disenrolled from those classrooms.

[3] The combined dataset and materials from the ECLS-K:2011 are available from the National Center for Education Statistics (http://nces.ed.gov/ecls/kindergarten2011.asp).

[4] The sample size in Wave 2 (Spring 2011) is larger than that of Wave 1 (Fall 2010) because ECLS investigators continued to recruit participants between fall and spring of the kindergarten year, and therefore additional students were eligible in Wave 2. Wave 3’s sample size (Fall First Grade) was the smallest, because the study was conducted on a subsample of approximately one-third of total participants.

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Appendix A

Summary of ordinary least squares regression models of mathematical achievement in Study 1 and Study 2 without standardizing the language used for the battery of assessments

Table A. *Ordinary Least Squares Regression Models of Mathematical Achievement Assessed by English or Spanish Batteries in Wave 1 (Fall, 2001-2002) and Wave 2 (Spring, 2003-2004): NCEDL's Multi-State Study of Pre-Kindergarten and Study of State-Wide Early Education Program (SWEEP)*

Variables	Wave 1 (Fall)			Wave 2 (Spring)			
	APS	IN	CT	APS	IN	CT	ARS−M
	(*n*=2,667)	(*n*=2,689)	(*n*=2,637)	(*n*=2,752)	(*n*=2,756)	(*n*=2,742)	(n=2,453)
Predictor							
Bilingualism	.067*	.141**	.082**	.139**	.131**	.071**	.113**
Covariates							
Age	−.083**	.267**	.221**	−.091**	.216**	.221**	.183**
Gender	.071**	.056**	.083**	.064**	.030†	.084**	.047*
Income	.087**	.137**	.113**	.085*	.119**	.163**	.066*
Maternal Education	.044*	.097**	.099**	.075**	.087**	.022	.097**
Receptive Vocabulary	.510**	.351**	.254**	.521**	.329**	.305**	.250**
Race/ Ethnicity							
Hispanic	−.216**	−.051*	−.048†	−.176**	−.011	.021*	−.023
Black	−.032†	.136**	.129**	−.035*	.123**	.155**	.001
Asian or multiracial	−.015	.074**	.041*	−.011	.057*	.063*	−.009

Note. Spanish assessment scores were used when participants were administered the Spanish assessment battery. Values reflect standardized coefficient estimates when the predictor and all covariates were entered in Model 2. Bilingualism was dummy coded, with monolinguals as reference (i.e., bilinguals = 1, monolinguals = 0); gender was dummy coded with male as reference; and race/ethnicity was dummy coded with white as reference. For all criteria, higher values reflect better performance. APS = Applied Problems Subtest of Woodcock-Johnson III Test of Achievement; IN = Identifying Numbers Task; CT = Counting Task; ARS–M = teacher-rated Academic Rating Scale–Mathematics. † $p < .01$, * $p < .05$, * $p < .001$.

Table B. *Ordinary Least Squares Regression Models of Mathematical Achievement Assessed by English or Spanish Batteries across the Four Waves of the Early Childhood Longitudinal Study: Kindergarten Class of 2010-11*

Variables	Wave 1		Wave 2		Wave 3		Wave 4	
	IRT	Theta	IRT	Theta	IRT	Theta	IRT	Theta
	n = 12,736	n = 12,735	n = 13,206	n = 1,3206	n = 3,622	n = 3,622	n = 9,892	n = 9,892
Predictor								
Bilingualism	.043**	.046**	.031**	.043**	.040*	.048*	.036*	.041**
Covariates								
Age	.230**	.221**	.200**	.190**	.196**	.197**	.132**	.136**
Sex	−.002	.010	.006	.012	.004	.001	−.012	−.025*
Income	.161**	.156**	.157**	.154**	.152**	.152**	.156**	.153**
Maternal Education	.139**	.136**	.135**	.130**	.141**	.139**	.121**	.125**
Paternal Education	.114**	.096**	.096**	.081**	.081**	.080**	.081**	.088**
English Proficiency	.247**	.316**	.195**	.230**	.196**	.188**	.214**	.210**
Race								
Hispanic	−.018†	−.013	−.025*	−.019†	−.043*	−.038†	−.060**	−.056**
Black	−.078**	−.076**	−.107**	−.104**	−.102**	−.098**	−.152**	−.149**
Asian	.096**	.093**	.076**	.076**	.054*	.055*	.075**	.076**
Native Indians	−.032**	−.037**	−.024*	−.022*	−.031*	−.029*	−.031**	−.029*
Native Hawaiian	−.008	−.007	−.006	−.006	−.005	−.005	−.006	−.007
Multiracial	.009	.004	.003	.004	−.015	−.016	−.008	−.005

Note. Spanish assessment scores were used when participants were administered the Spanish assessment battery. Due to the lack of assessment in Spanish language proficiency, only English proficiency was included as a covariate. Thus, results should be interpreted with caution, since language of instruction was not properly controlled for in participants who were administered the Spanish assessment battery. Values reflect standardized coefficient estimates when both the predictor and covariates were entered in Model 2. Participants were considered to have acquired English when they passed the English version of the Preschool Language Assessment Scales in at least one of the waves. Bilingualism was dummy coded with monolinguals as reference (i.e., bilinguals = 1, monolinguals = 0); sex was dummy coded with male as reference; and race was dummy coded with white as reference. In all of the criteria, higher values reflect better performance. † $p < .01$, * $p < .05$, ** $p < .001$.