Published in final edited form as:

Mind Brain Educ. 2024 August ; 18(3): 373–381. doi:10.1111/mbe.12386.

Arithmetic in the Bilingual Brain: Language of Learning and Language Experience Effects on Simple Arithmetic in Children and Adults

Vanessa R. Cerda,
Nicole Y. Wicha
Department of Neuroscience, Developmental and Regenerative Biology, University of Texas at San Antonio,

Abstract

In 2020, 21.5% of US preschoolers spoke a language other than English at home. These children transition into English-speaking classrooms in different ways, often handling foundational concepts in two languages. Critically, some knowledge may be dependent on the language learning. For instance, both bilingual children and adults typically prefer, and exhibit higher performance on arithmetic in the language in which they learned math (LA+) compared with their other language (LA−). The typical interpretation is that arithmetic facts are accessed from memory more efficiently or solely in LA+. However, recent research suggests that bilingual arithmetic is not restricted to one language in memory, and that language experience plays an important role in performance. Moreover, evidence suggests children and adults process arithmetic fundamentally differently. Thus, bilingual arithmetic memory may manifest differently across the life span. This review outlines evidence to date at the intersection between the brain basis of bilingualism, arithmetic processing, and development.

REPRESENTATION OF SIMPLE ARITHMETIC IN MEMORY

As the bilingual population continues to grow worldwide, it is increasingly important to understand how the bilingual brain processes foundational concepts in education. As a case in point, bilinguals are often faster and more accurate at performing arithmetic in one language than the other. These performance differences may reflect language-specific memory established during early learning. However, the way bilinguals use their languages is dynamic and variable, both across individuals and over a lifetime. In fact, recent evidence

---

Address correspondence to Nicole Y. Wicha, Department of Neuroscience, Developmental and Regenerative Biology, University of Texas at San Antonio, 1 UTSA Circle, San Antonio, TX 78249; vanessa.cerda.2@utsa.edu.

CONFLICT OF INTEREST
The authors have stated explicitly that there are no conflicts of interest in connection with this paper.

INFORMED CONSENT
Please refer to the individual studies included in this review for statements of informed consent.
ANIMAL RIGHTS
Studies on animal models were not included in this review.

suggests that increased language proficiency or frequency of use can mitigate language differences observed for arithmetic processing (Cerda, Grenier, & Wicha, 2019; Cerda, Montufar Soria, & Wicha, 2022; Martinez-Lincoln, Cortinas, & Wicha, 2015; Tamamaki, 1993). This review examines how bilinguals learn and process arithmetic in each of their languages and makes direct comparisons between what is known about bilingual arithmetic processing in adults and the limited work in the developing brain. A consistent theme is whether bilinguals show a language bias for arithmetic, and what the cognitive and neural mechanisms are to support arithmetic in the bilingual brain during development and beyond.

Simple arithmetic facts, like multiplication tables, are typically learned through verbal rehearsal in early childhood until they become overlearned concepts in long-term memory. As the facts are learned, it is thought that the problems and correct solutions are stored in memory as a network of associated concepts, and efficient retrieval from this network leads to better arithmetic performance (Ashcraft, 1987, 1992; Campbell & Graham, 1985). Bilinguals often develop a preference for the language in which they learned the facts, referred to herein as LA+ (i.e., language of arithmetic learning, see Cerda et al., 2019, 2022; Cerda, Flaugher, Montufar Soria, & Wicha, 2023; Martinez-Lincoln et al., 2015; Salillas & Wicha, 2012). This preference can persist into adulthood with better performance in LA+ over the other language, or LA− (Dewaele, 2007; Vaid & Menon, 2000). Whether this preference is based on early learning or a function of habit is still debated.

Most models of bilingual language propose a shared set of conceptual representations across languages (Dijkstra & van Heuven, 2002; Shook & Marian, 2013), with a few exceptions (e.g., Pavlenko & Driagina, 2007). Arithmetic facts represent exact math concepts and do not have different language-specific meanings, for example, 2 × 4 is always 8 regardless of the language. Therefore, similar to the bulk of words in a language, arithmetic facts may be part of language-specific lexicons that represent a common set of concepts. Models of arithmetic generally propose a common conceptual store for arithmetic facts, often referred to as a magnitude code, where the meaning of these facts resides. However, how each language accesses this meaning is different across models.

The Encoding Complex Model, or ECM (Campbell, 1994; Campbell & Clark, 1992; Campbell & Epp, 2004; Campbell, Kanz, & Xue, 1999) suggests that separate arithmetic memory representations exist for each format in which problems can appear (e.g., Arabic Digits or number words across languages). Critically, the efficiency of accessing these format-specific representations is dependent on experience. As arithmetic facts are most commonly encountered as Arabic digits (i.e., $2 \times 4 = 8$), access to arithmetic facts in this format is most efficient, followed by the preferred language for arithmetic, and the nonpreferred language. In turn, ECM suggests that bilinguals engage similar cognitive processes for arithmetic across languages, namely access to the facts from language-specific memory stores with retrieval efficiency dependent on experience using the facts in each language.

However, ECM does not explicitly address whether arithmetic facts engage typical language networks. As an extension of the ECM, the bilingual encoding complex model (BECM; Bernardo, 2001) postulates that factors like language proficiency or length of number words may influence the strength of the associative links between problems and solutions within the format-specific memory representations proposed in the ECM. This idea is in line with evidence from the general bilingualism literature, where age of acquisition and language proficiency can modulate the degree of overlap in the brain areas activated for each of a bilingual’s languages (Hernandez, Martinez, & Kohnert, 2000; Kim, Relkin, Lee, & Hirsch, 1997). Additionally, age of acquisition and vocabulary proficiency affect the speed at which bilinguals can integrate words into a semantic context during sentence reading (Moreno & Kutas, 2005). Additionally, the BECM points out that a bilingual’s preferred language for arithmetic is not limited to their native language if they have more experience with math in their non-native language.

Another leading math cognition model, the Triple Code Model (TCM) (Dehaene, 1992; Dehaene & Cohen, 1995, 1997), proposes that there are three mental codes for numbers (i.e., visual Arabic numbers, auditory verbal words, and analog magnitude representations) and that all numerical processes are assigned to only one prespecified code. Thus, subjects must switch mentally depending on the type of mathematical process they are engaging in. Specifically, the TCM states that “multiplication facts are just part of a learned lexicon of verbal associations” (Dehaene, 1992, p. 34), where arithmetic facts must be transcoded into an “auditory verbal code” (Dehaene & Cohen, 1995). For monolingual individuals, these verbal associations would by default be in the language in which the math concepts were learned. Additionally, TCM proposes that arithmetic fact retrieval involves language areas not specific to numbers, including classic language areas of the left hemisphere (Dehaene & Cohen, 1995). However, a limitation of TCM is that it does not explicitly address bilingual arithmetic. TCM proponents have implied that bilinguals have a single representation of arithmetic facts in the language of original learning (Spelke & Tsivkin, 2001). By inference, bilinguals should engage in separate cognitive processes for simple arithmetic across languages: direct retrieval in the language used for learning and translation in other languages.

Spelke and Tsivkin (2001) suggested that bilinguals can have a representation of math facts in other languages, but only if they explicitly relearn the facts. Moreover, the authors suggest that because the math facts can be relearned, “at least in the case of arithmetic, children may not need great facility with a language in order to use that language as a medium of representation” (p. 80). This idea seems to separate arithmetic processing from language ability entirely. Given that arithmetic facts are a closed and highly controlled set of memorized concepts, they might be learned and retrieved in a second language without strong (or perhaps any) fluency in that language.

To address these competing perspectives, we first consider the overwhelming majority of behavioral and neuroimaging evidence from bilingual adults. Next, we consider how interpretations of the cognitive processes adults engage for arithmetic processing have been reinterpreted over time and what the reinterpretation means for adult bilingual arithmetic processing. Finally, we present the limited research that has helped inform bilingual arithmetic in bilingual children and make comparisons with adult work.

EARLY INVESTIGATIONS OF A LANGUAGE BIAS FOR ARITHMETIC

In a seminal bilingual arithmetic study, Marsh and Maki (1976) found that when bilinguals were asked to add or subtract a series of Arabic numerals, they were faster at producing solutions in their LA+, regardless of their fluency in that language. One explanation the authors proposed was that language differences might arise from translation from the nonpreferred language to the preferred language. Subsequent studies helped shape a clearer idea of the underlying cognitive processes that might be influencing the language differences.

To promote explicit engagement of each language, McClain and Huang (1982) had bilinguals solve addition problems presented as spoken number words with an increasing number of operands. Solutions were produced consistently faster in LA+ with response times increasing at equivalent rates in both languages as the number of operands increased, suggesting that there is an overall advantage in producing the solutions in the LA+. However, the authors did not find evidence of an interaction between language and number of operands. The authors argued that this reflected encoding/responding rather than translation or calculation, which would have incrementally slowed the weaker language as the number of operands increased. Notably, this LA+ advantage occurred in blocks that included trials in both languages, and disappeared in blocks presented in each language separately, suggesting that the well-established cost of language switching may partially account for this performance difference across languages (Gade, Declerck, Philipp, Rey-Mermet, & Koch, 2021).

Frenck-Mestre and Vaid (1993) later demonstrated that these language of learning effects observed in production tasks could also be measured in arithmetic verification tasks. Bilinguals verified the correctness of addition and multiplication problems presented as either Arabic digits or written number words in their native language English (also LA+) and later-learned second language French (LA−). Participants were fastest at verifying digit problems, followed by LA+ and then LA−. In a follow-up experiment, incorrect items were designed to elicit “cross-operation interference” between multiplication and addition problems (i.e., $7 \times 5 = 12$; $7 + 5 = 35$). Participants were only sensitive to cross-operation interference in their LA+. The authors interpreted this as evidence for language-sensitive automatic spread of activation in a network of problem–solution associations, which is in line with a model like ECM.

Campbell et al. (1999) originally proposed ECM based on findings from Chinese–English bilinguals who have four representations of arithmetic problems. Participants solved addition and multiplication problems presented as Arabic or Mandarin numerals and were cued to produce the solutions in either Chinese (LA+) or English (LA−). Response times were faster in Chinese than English, where English was at an even greater disadvantage when problems were presented as Mandarin numerals. The authors suggested that this interaction between problem format and language could be explained by language-specific representations that were differentially accessible based on notation. They also concluded that their Chinese–English bilinguals had memory representations in both languages, but the English store was weakly developed.

Based on these early behavioral studies, an LA+ advantage, in the form of faster production or verification, may be driven overall by more efficient language processing or more robust spread of activation in LA+, but not likely translation. In the following decades, several studies, including those using a combination of behavioral and neuroimaging techniques to help elucidate the brain basis of bilingual arithmetic, have examined the role of language-specific memory and language experience on bilingual arithmetic facts more closely.

BEHAVIORAL AND NEUROIMAGING EVIDENCE SUPPORTING LANGUAGE-SPECIFIC MEMORY

Dehaene, Spelke, Pinel, Stanescu, and Tsivkin (1999) and Spelke and Tsivkin (2001) performed a series of experiments in which Russian–English bilinguals were taught sets of exact or approximate sums in only one language. For exact problems, participants selected the correct sum from two choices, and for approximate problems, they selected a close approximation. Bilinguals performed faster in the language of training when tested on exact problems, regardless of whether it was in Russian (LA+) or English. In contrast, approximate additions were performed equivalently in both languages. This suggests that only verbally rehearsed exact arithmetic facts are stored in a language-dependent manner, whereas approximate arithmetic is not language dependent. In fact, Spelke and Tsivkin (2001) also observed that the exact number of facts more broadly (e.g., recalling facts about ages, event durations, or distances) can be language-specific even in non-math contexts.

Indeed, the Dehaene et al. (1999) neuroimaging results in these bilingual adults revealed that exact arithmetic engaged the left cingulate and left angular gyrus, which are part of a language network thought to be involved in language-dependent coding. Approximate arithmetic engaged various frontal and visuo-spatial areas not typically implicated in language processing. Both the behavioral and neuroimaging results have been replicated in subsequent bilingual arithmetic studies (Kraut & Pixner, 2020; Spelke & Tsivkin, 2001; Venkatraman, Siong, Chee, & Ansari, 2006).

More recently, Kraut and Pixner (2020) tested native speakers of German, who learned English as a second language after learning basic arithmetic. Adult participants practiced simple multiplication facts either exclusively in German, exclusively in English, or in both languages. After completing the practice, participants verified the correctness of written number word multiplication problems in both languages. Performance in German was fastest regardless of the language used for practice, reflecting the strong influence of the original language used to learn the problems. Additionally, practicing problems in German resulted in equivalent improvements for both German and English test performance. However, practicing problems in English improved English test performance significantly more than performance in German. The authors concluded that arithmetic fact knowledge that is primarily gained in one language does not automatically transfer to another language. Moreover, they argued that “facts need to be learned in the language one wants to retrieve them in” (p. 11), echoing ideas from TCM (Dehaene, 1992; Dehaene et al., 1999; Dehaene & Cohen, 1995, 1997; Spelke & Tsivkin, 2001).

Together, these studies suggest that arithmetic facts might be represented only in the language of original learning. However, the studies discussed above investigated bilinguals who learned a second language later in life, typically after learning simple arithmetic, and as a result were likely more proficient or dominant in their L1 (LA+). The bilinguals in Dehaene et al. (1999) and Spelke and Tsivkin (2001) learned English at the age of 15 on average, which would be considered late learners of L2. Kraut and Pixner (2020) included German speakers who learned English relatively early (~8 years old), yet they were dominant in German. As discussed next, these factors of language experience can affect performance on arithmetic tasks.

EVIDENCE SUPPORTING EFFECTS OF LANGUAGE EXPERIENCE ON ARITHMETIC

Behavioral Evidence

The role of language experience in arithmetic was first noted by Tamamaki (1993) in direct response to the seminal bilingual arithmetic studies mentioned above. Unlike Tamamaki, the original bilingual arithmetic studies did not account for critical language factors, or inferred language proficiency from self-report. Tamamaki directly examined how L2 proficiency influenced performance in native speakers of Japanese who learned English (L2) at different stages of adulthood, resulting in varying proficiency in L2. When asked to produce the solutions to multioperand addition and subtraction problems, bilinguals with lower proficiency in English (L2) performed better in Japanese (L1). However, bilinguals with high English proficiency performed virtually identical across languages. These results suggest that language experience can modulate the advantage of the language of learning.

Indeed, a recent meta-analysis of 38 behavioral studies using a variety of tasks, including arithmetic verification, calculation, and number naming, reveals an important role for language experience in bilingual arithmetic (Garcia, Faghihi, Raola, & Vaid, 2021). Reinforcing Tamamaki’s observations, lower L2 proficiency typically leads to larger differences in performance across languages on arithmetic tasks, while bilinguals with higher L2 proficiency tend not to show performance differences across languages. Additionally, when the first-learned language is also the language of learning for math (i.e., L1 = LA+), the effects of language on arithmetic performance are more pronounced. This suggests that a bilingual’s language experience can affect arithmetic performance in adulthood, an idea not originally considered by the TCM.

Neuroimaging Evidence

Event-related potential (ERP) studies have been useful in understanding the time course of arithmetic processing more generally and have found additional evidence that the arithmetic language bias is influenced by a bilingual’s language history. Seminal studies measuring ERPs in mono-linguals asked participants to verify the correctness of simple multiplication problems presented as sequential Arabic digits (Niedeggen & Rösler, 1999; Niedeggen, Rösler, & Jost, 1999). ERPs time-locked to the presentation of proposed solutions revealed that correct problems elicited a less negative amplitude compared with incorrect problems. Originally,[1] this ERP response was interpreted as a modulation of the N400 component

(Kutas & Hillyard, 1980), which is an index of the current activation of meaningful information in memory (for review, see Federmeier & Kutas, 2001; Kutas & Federmeier, 2011).

Following these seminal studies, Salillas and Wicha (2012) conducted the first bilingual ERP study examining the role of language on multiplication verification in adulthood. Spanish–English bilinguals were presented with single-digit multiplication problems as written words in their LA+ and LA−. Both languages elicited modulations of the N400, with smaller negative amplitude for correct than incorrect solutions, suggesting a similar cognitive process in both languages, namely access to semantic memory. However, the size of the N400 effect was smaller in LA−, suggesting less efficient memory retrieval. Moreover, self-reported increased use of LA− correlated with larger N400 effects in LA−, suggesting that access to arithmetic facts might be dependent on language experience, in line with ECM.

Martinez-Lincoln et al. (2015) tested this possibility directly by comparing bilingual teachers who had experience teaching in either their LA+ or LA−. Teachers who taught in their LA+ elicited larger N400 effects in their LA+ than LA−, replicating Salillas and Wicha (2012). However, teachers who taught in their LA− elicited equivalent amplitude, scalp distribution, and timing of the N400 effect in both languages. The authors concluded that increased experience using LA− for math, as in bilingual elementary school teaching, can mitigate the advantage of LA+.

COGNITIVE PROCESSES INVOLVED IN ADULT BILINGUAL ARITHMETIC VERIFICATION

Subsequent to the aforementioned ERP studies, it was discovered that the ERP response to arithmetic verification is not always an N400 (Dickson et al., 2018; Dickson & Federmeier, 2017; Dickson & Wicha, 2019; Grenier, Dickson, Sparks, & Wicha, 2020; Jasinski & Coch, 2012). Indeed, recent findings from monolingual adults suggest a reinterpretation of the original Niedeggen & Rösler, (1999) findings from an N400 to a P300 (Dickson & Federmeier, 2017; Dickson & Wicha, 2019; Jasinski & Coch, 2012). This P300 is thought to reflect categorizing the solutions as targets (correct) and nontargets (incorrect) rather than accessing semantic memory, and is acquired through years of practice (or over-rehearsal), with children showing an N400 through early childhood (Grenier et al., 2020). However, adults can engage in semantic-level processes depending on task demands (Dickson et al., 2018; Dickson & Wicha, 2019), for example, when multiplication problems are presented as written words, as in Salillas and Wicha (2012).

Given that the ERP response in adults is influenced by task demands, Cerda et al. (2022) reexamined the effect of language on multiplication verification in bilingual adults. They carefully controlled for previous experimental manipulations that may have impacted both the ERP response and the presence of an LA+ bias. Specifically, differences in reading fluency across languages (as in Martinez-Lincoln et al., 2015; Salillas & Wicha, 2012) or asymmetric language switching costs when problems are presented in both languages during a block of trials (as in McClain & Huang, 1982) could have introduced potential confounds in interpreting the source of language effects. To avoid these confounds, Cerda et al. (2022) presented the multiplication problems as spoken number words with each language presented in separate blocks. The authors measured ERPs and performance in balanced Spanish–English bilingual adults. They observed P300 modulations that were equivalent in timing, distribution, and size in both languages, contrasting the LA+ advantage observed in Salillas and Wicha (2012). This suggests that balanced adult bilinguals can efficiently categorize arithmetic problems in both languages.

In fact, it is only under limited circumstances that adult balanced bilinguals show differences in processing arithmetic across languages, such as when producing the solution (Cerda et al., 2023) or for more challengingproblems. Cerda et al. (2023) found that balanced bilinguals verify large multiplication problems (e.g., 8 × 7 = 56) less efficiently in LA− than in LA+ (as indexed by the P300) only when the task requires immediate speeded verification of the multiplication solutions. Similarly, Van Rinsveld and others (Lotus Lin et al., 2019; Van Rinsveld et al., 2015, 2017) have reported more robust language differences in their brain and behavioral data for complex addition problems involving two-digit operands than simple problems involving single-digit operands.

Solving these more complex problems is thought to engage cognitive processes that are less dependent on language (Dehaene, Piazza, Pinel, & Cohen, 2003). However, these studies suggest that language differences may arise for complex problems because of other factors. For example, a second language may recruit additional resources for number manipulation, including activating visual representations of numbers (Van Rinsveld et al., 2017) or translating less familiar two-digit operands into a stronger language (Lotus Lin et al., 2019). Critically, these processes are secondary to accessing the arithmetic facts from memory, which seems to be equivalent across languages in balanced bilinguals (Cerda et al., 2022).

Together, these ERP studies suggest that adult bilinguals verify arithmetic facts using the same cognitive processes in both languages, whether they engage semantic memory (Martinez-Lincoln et al., 2015; Salillas & Wicha, 2012) or categorize problems as correct or incorrect (Cerda et al., 2022). Critically, the presence of a language bias for arithmetic varies with language experience and task demands and may reflect processing differences that are not specific to math.

BILINGUAL ARITHMETIC AND DEVELOPMENT

A critical deficiency of both models of arithmetic, ECM and TCM, is that they are based primarily on research with adults. Both behavioral and neuroimaging studies suggest that children shift from less efficient procedural to more efficient retrieval strategies when mastering arithmetic (Geary, 1994; Prado, Mutreja, & Booth, 2014; Siegler, 1996). Yet, even children with strong math fluency process arithmetic differently than adults (Grenier et al., 2020). Consequently, models based on adult arithmetic might not apply to children. We turn now to the limited research on arithmetic in bilingual children. LA+ does not impact all types of arithmetic in the same way, with processing dependent on the type of arithmetic concept being tested and the age of the students (Bermejo, Ester, & Morales, 2021). We focus on simple arithmetic facts that are more likely to develop language-specific memories (Dehaene & Cohen, 1995). Similar to adults, questions revolve around the potential for a language bias, as well as the cognitive and neural mechanisms that support arithmetic in each language.

A processing advantage for LA+ has been observed in two studies with bilingual high school students. Bernardo (2001) tested students whose first language was Filipino, but used English as the primary language of school instruction. Consistent with adults, verifying single-digit addition problems was fastest when presented as Arabic digits, followed by spoken words in English or the LA+, and slowest for words in Filipino. A distance effect, where incorrect trials were rejected faster when the presented solutions were a numerically larger distance from the correct solution, was observed for digits and English words, but not Filipino. Bernardo (2001) interpreted this as evidence for a more refined and efficient memory network in LA+, even when the other language (Filipino) is proficiently used outside of school.

Bernardo’s findings contrast with Saalbach, Eckstein, Andri, Hobi, and Grabner (2013) who demonstrated that language proficiency in LA− can affect processing. Swiss–German high school students (15–17 years old) attending a German–French bilingual school underwent multiple days (3 or 4) of training on complex arithmetic problems in one of their languages. They then solved problems in the language of training or switched languages. In both languages, problems were solved faster and more accurately when trained than untrained, and language switching incurred a cost on both response times and accuracy. However, this switching cost was asymmetrical across languages. Switching to the less dominant and less frequently used language (French) produced slower processing times than switching to the dominant language (German). The authors argued that this asymmetry is specific to unbalanced bilinguals who might rely more on their dominant language for encoding new arithmetic facts, regardless of the LA+, perhaps consistent with initial reliance on L1 to access words in lower proficiency L2 during early language learning (Chen & Leung, 1989; Kroll & Sholl, 1992). However, faster responses in German may simply reflect that relatively short training cannot overcome weaker overall language proficiency in producing responses in L2.

Perhaps it is not surprising to find a similar LA+ advantage in high school students and young adults. However, younger bilingual children might show more or less of a language bias. The first neuroimaging study investigating bilingual arithmetic in 7- to 11-year-olds examined the effect of LA+ in proficient French–Dutch bilinguals (Mondt et al., 2011). Lying in an MRI scanner, children verified simple arithmetic problems presented as Arabic digits while thinking in either their home language or their schooling language, which were always different. Performance was equivalent in both the home and schooling languages. However, children using their home language showed increased activation of the visuomotor occipitofrontal network in the left hemisphere, which the authors interpreted as engaging greater reliance on working memory and visual–attentional resources than the language of schooling. Similar to prior adult behavioral studies (Kraut & Pixner, 2020; Spelke & Tsivkin, 2001), they concluded that knowledge acquired in LA+ does not transfer to the other language, making retrieval in LA− more effortful.

However, one limitation of this study was that the task only indirectly engaged one language while presenting problems as Arabic digits. Cerda et al. (2019) recently tested this question more directly in balanced early Spanish–English bilingual children similar in age to Mondt et al. (2011). Children verified the correctness of simple arithmetic problems presented as spoken number words in each language while ERPs were recorded. Children were faster and more accurate at verifying correct than incorrect problems. This correctness effect was larger in LA+ than LA−. However, the ERPs revealed modulations of the N400 with no differences in the size, timing, or distribution of the effect across languages. This equivalent N400 effect suggests that bilingual children engage in semantic-level processes in both languages. Therefore, at least in balanced bilingual children, differences in performance across languages were not driven by differences in access to multiplication facts in semantic memory, and were likely due instead to downstream decision or response-related processes. Moreover, this suggests that bilingual children do not need to learn math facts in both of their languages to achieve equivalent fluency, as has been suggested previously (Kraut & Pixner, 2020; Spelke & Tsivkin, 2001).

In fact, although children and adults elicit different ERP responses, an N400 and P300 respectively (Cerda et al., 2022; Dickson et al., 2018; Dickson & Wicha, 2019; Grenier et al., 2020), balanced bilinguals at either age engage similar processes across their languages for arithmetic verification. Specifically, adults rely on more superficial categorization processes, whereas children access semantic memory to retrieve the arithmetic facts (Grenier et al., 2020). Therefore, it is unclear if arithmetic processing in children would be affected by similar language factors as in adults. Indeed, it may be more important to ensure that bilingual children maintain fluency in both of their languages to help mitigate a language bias for arithmetic.

In a review outlining bilingual mathematics learning, Moschkovich (2006) questioned whether the subtle millisecond differences reported in previous psycholinguistic studies would even appear in natural classroom settings at all, especially if bilinguals are allowed to choose the language in which they perform arithmetic. Moschkovich (2006) argues that switching between languages occurs naturally for bilinguals during mathematical thinking and discourse, and should not be viewed as a deficiency or sign of “semilin-gualism.” This argument suggests that bilinguals might not necessarily lack mathematical competence across languages, but instead simply struggle to convey their knowledge in a weaker language.

Moreover, LA+ is not always the favored language, even when there is a bias. Bernardo and Calleja (2005) found that bilingual children favor their native language, rather than LA+, when solving word problems. They concluded that this difference in performance was driven by the fact that students’ native language was also their more proficient language, supporting the idea that other factors of a bilingual’s background play a role in mathematics learning aside from the language of instruction. A focus on other aspects of math cognition, like word problems, may reflect the real-world consequences of a language bias for arithmetic processing.

CONCLUSIONS

Bilingual arithmetic studies with adults suggest that language factors play an important role in simple arithmetic processing. It is possible that the language bias for arithmetic reflects differences in language experience, rather than language-specific memory based on early learning. Studies that argued for language-specific representations of math facts tested bilinguals who were dominant in their native language, with less fluency in their second language. In those studies, it was suggested that bilinguals relied on direct retrieval in their stronger language, whereas weaker languages relied on more effortful processes for arithmetic (e.g., Kraut & Pixner, 2020; Spelke & Tsivkin, 2001). In contrast, evidence from more fluent or early bilingual adults suggests that a language bias for simple arithmetic can be mitigated with increased experience with a language for arithmetic (e.g., Martinez-Lincoln et al., 2015). The way that language factors seem to influence the language bias for arithmetic mirrors hypotheses from the bilingualism literature more broadly, where second language learners might initially rely on their native language to access concepts in that weaker language. As fluency in a second language increases, direct conceptual links can be created within memory, decreasing the reliance on the native language (Kroll & de Groot, 2020).

Importantly, predictions constructed primarily from adults may not entirely apply for young bilingual children, given that recent evidence has shown that adults and children engage in distinct cognitive processes for arithmetic (Grenier et al., 2020). Bilingual children are an understudied population, especially in the arithmetic literature. With bilingual education becoming increasingly commonplace, it is critical to understand the dynamics between bilingualism and early arithmetic learning to inform the best practices in the classroom. Increased collaboration between bilingualism, math cognition, and education research is essential in understanding the real-world implications of a language bias for arithmetic. This includes determining whether or not bilinguals should be encouraged to choose the language in which they perform mathematics in the classroom. Additionally, it is important to understand to what extent bilingual research on simple arithmetic processing extends to more complex mathematics like word problems that inherently rely on language skill, especially as they are commonly used to assess math ability.

Overall, the evidence suggests that the bilingual brain is dynamic and flexible even when processing arithmetic, in contrast to the strict belief that early arithmetic learning was the sole driver of language differences. Bilingualism presents many advantages that outweigh any potential challenges of managing two languages for learning. Models of bilingual arithmetic processing would benefit from including specific predictions based on bilinguals' language factors and considering arithmetic learning in the developing brain. Research in this domain will push the field toward a more refined and holistic understanding of bilingual cognition and arithmetic processing and, in turn, inform the best practices for arithmetic learning in the classroom.

REFERENCES

Ashcraft MH (1987) Children's Knowledge of Simple Arithmetic: A Developmental Model and Simulation. In Bisanz J, Brainerd CJ, Kail R (Eds.), Formal Methods in Developmental Psychology. Springer Series in Cognitive Development. New York: Springer. 10.1007/978-1-4612-4694-7_9

Ashcraft MH (1992). Cognitive arithmetic: A review of data and theory. Cognition, 44(1–2), 75–106. 10.1016/0010-0277(92)90051-I [PubMed: 1511587]

Bermejo V, Ester P, & Morales I (2021). How the language of instruction influences mathematical thinking development in the first years of bilingual schoolers. Frontiers in Psychology, 12. 10.3389/fpsyg.2021.533141

Bernardo ABI (2001). Asymmetric activation of number codes in bilinguals: Further evidence for the encoding complex model of number processing. Memory & Cognition, 29(7), 968–976. [PubMed: 11820756]

Bernardo ABI, & Calleja MO (2005). The effects of stating problems in bilingual students' first and second languages on solving mathematical word problems. The Journal of Genetic Psychology, 166(1), 117–129. 10.3200/GNTP.166.1.117-129 [PubMed: 15782681]

Campbell JID (1994). Architectures for numerical cognition. Cognition, 53(1), 1–44. 10.1016/0010-0277(94)90075-2 [PubMed: 7988104]

Campbell JID, & Clark JM (1992). Cognitive number processing: An encoding-complex perspective. Advances in Psychology, 91, 457–491. 10.1016/S0166-4115(08)60894-8

Campbell JID, & Epp LJ (2004). An encoding-complex approach to numerical cognition in Chinese-English bilinguals. Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale, 58(4), 229–244. 10.1037/h0087447 [PubMed: 15648727]

Campbell JID, & Graham DJ (1985). Mental multiplication skill: Structure, process, and acquisition. Canadian Journal of Psychology, 39(2), 338–366.

Campbell JID, Kanz C, & Xue Q (1999). Number processing in Chinese-English bilinguals. Mathematical Cognition, 5, 1–39.

Cerda VR, Flaugher TG, Montufar Soria P, & Wicha NYY (2023). Bilingual problem size effect: An ERP study of multiplication verification and production in two languages. Translational Issues in Psychological Science. 10.1037/tps0000361

Cerda VR, Grenier AE, & Wicha NYY (2019). Bilingual children access multiplication facts from semantic memory equivalently across languages: Evidence from the N400. Brain and Language, 198, 104679. 10.1016/j.bandl.2019.104679 [PubMed: 31445417]

Cerda VR, Montufar Soria P, & Wicha NY (2022). Reevaluating the language of learning advantage in bilingual arithmetic: An ERP study on spoken multiplication verification. Brain Sciences, 12(5), 532. 10.3390/brainsci12050532 [PubMed: 35624920]

Chen H, & Leung Y (1989). Patterns of lexical processing in a nonnative language. Journal of Experimental Psychology: Learning, Memory, and Cognition, 15(2), 316–325. 10.1037/0278-7393.15.2.316

Dehaene S (1992). Varieties of numerical abilities. Cognition, 44(1–2), 1–42. 10.1016/0010-0277(92)90049-N [PubMed: 1511583]

Dehaene S, & Cohen L (1995). Towards an anatomical and functional model of number processing. Mathematical Cognition, 1, 83–120.

Dehaene S, & Cohen L (1997). Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic. Cortex, 33, 219–250. [PubMed: 9220256]

Dehaene S, Piazza M, Pinel P, & Cohen L (2003). Three parietal circuits for number processing. Cognitive Neuropsychology, 20(3), 487–506. [PubMed: 20957581]

Dehaene S, Spelke E, Pinel P, Stanescu R, & Tsivkin S (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. Science, 284(5416), 970–974. 10.1126/science.284.5416.970 [PubMed: 10320379]

Dewaele JM (2007). Multilinguals' language choice for mental calculation. Intercultural Pragmatics, 4(3), 343–376. 10.1515/IP.2007.017

Dickson DS, Cerda VR, Beavers RN, Ruiz A, Castaneda R, & Wicha NYY (2018). When 2 × 4 is meaningful: The N400 and P300 reveal operand format effects in multiplication verification. Psychophysiology, 2017, e13212. 10.1111/psyp.13212

Dickson DS, & Federmeier KD (2017). The language of arithmetic across the hemispheres: An event-related potential investigation. Brain Research, 1662, 46–56. 10.1016/j.brainres.2017.02.019 [PubMed: 28237544]

Dickson DS, & Wicha NYY (2019). P300 amplitude and latency reflect arithmetic skill: An ERP study of the problem size effect. Biological Psychology, 148, 107745. 10.1016/j.biopsycho.2019.107745 [PubMed: 31470071]

Dijkstra T, & van Heuven WJB (2002). The architecture of the bilingual word recognition system: From identification to decision. *Bilingualism*: Language and Cognition, 5(3), 175–197. 10.1017/S1366728902003012

Federmeier KD, & Kutas M (2001). Meaning and modality: Influences of context, semantic memory organization, and perceptual predictability on picture processing. Journal of Experimental Psychology: Learning Memory and Cognition, 27(1), 202–224. 10.1037//027I7//0278-7393.27.1.202 [PubMed: 11204098]

Frenck-Mestre C, & Vaid J (1993). Activation of number facts in bilinguals. Memory & Cognition, 21(6), 809–818. 10.3758/BF03202748 [PubMed: 8289658]

Gade M, Declerck M, Philipp AM, Rey-Mermet A, & Koch I (2021). Assessing the evidence for asymmetrical switch costs and reversed language dominance effects – A meta-analysis. Journal of Cognition, 4(1), 55. 10.5334/joc.186 [PubMed: 34611575]

Garcia O, Faghihi N, Raola AR, & Vaid J (2021). Factors influencing bilinguals' speed and accuracy of number judgments across languages: A meta-analytic review. Journal of Memory and Language, 118(2), 104211.

Geary DC (1994) Children's mathematical development: Research and practical applications. Washington, DC: American Psychological Association. 10.1037/10163-000

Grenier AE, Dickson DS, Sparks CS, & Wicha NYY (2020). Meaning to multiply: Electrophysiological evidence that children and adults treat multiplication facts differently. Developmental Cognitive Neuroscience, 46, 100873. 10.1016/j.dcn.2020.100873 [PubMed: 33129033]

Hernandez AE, Martinez A, & Kohnert K (2000). In search of the language switch: An fMRI study of picture naming in Spanish–English bilinguals. Brain and Language, 73(3), 421–431. 10.1006/brln.1999.2278 [PubMed: 10860563]

Jasinski EC, & Coch D (2012). ERPs across arithmetic operations in a delayed answer verification task. Psychophysiology, 49(7), 943–958. 10.1111/j.1469-8986.2012.01378.x [PubMed: 22563982]

Kim KHS, Relkin NR, Lee K-M, & Hirsch J (1997). Distinct cortical areas associated with native and second languages. Nature, 388(6638), 171–174. 10.1038/40623 [PubMed: 9217156]

Kraut C, & Pixner S (2020). Bilingual adults practicing multiplication tables – Looking into bilingual arithmetic learning. International Journal of Bilingual Education and Bilingualism, 25(5), 1825–1837. 10.1080/13670050.2020.1810204

Kroll JF, & de Groot AMB (2020). Lexical and conceptual memory in the bilingual: Mapping form to meaning in two languages. In Wei L (Ed.), The bilingualism reader. London, UK: Routledge. 10.4324/9781003060406

Kroll JF, & Sholl A (1992). Lexical memory in novice bilinguals: The role of concepts in retrieving second language words. In Harris RJ (Ed.), Cognitive processing in bilinguals. (Vol. 83, pp. 191–204). London, UK: Elsevier.

Kutas M, & Federmeier KD (2011). Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP). Annual Review of Psychology, 62(1), 621–647. 10.1146/annurev.psych.093008.131123

Kutas M, & Hillyard SA (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. Science, 207(4427), 203–205. [PubMed: 7350657]

Lin J-FL, Imada T, & Kuhl PK (2019). Neuroplasticity, bilingualism, and mental mathematics: A behavior-MEG study. Brain and Cognition, 134, 122–134. 10.1016/j.bandc.2019.03.006 [PubMed: 30975509]

Marsh LG, & Maki RH (1976). Efficiency of arithmetic operations in bilinguals as a function of language. Memory & Cognition, 4(4), 459–464. 10.3758/BF03213203 [PubMed: 21287388]

Martinez-Lincoln A, Cortinas C, & Wicha NYY (2015). Arithmetic memory networks established in childhood are changed by experience in adulthood. Neuroscience Letters, 584, 325–330. 10.1016/j.neulet.2014.11.010 [PubMed: 25445361]

McClain L, & Huang JY (1982). Speed of simple arithmetic in bilinguals. Memory & Cognition, 10(6), 591–596.

Mondt K, Struys E, Van den Noort M, Balériaux D, Metens T, Paquier P, … Denolin V (2011). Neural differences in bilingual Children's arithmetic processing depending on language of instruction. Mind, Brain, and Education, 5(2), 79–88. 10.1111/j.1751-228X.2011.01113.x

Moreno EM, & Kutas M (2005). Processing semantic anomalies in two languages: An electrophysiological exploration in both languages of Spanish–English bilinguals. Cognitive Brain Research, 22(2), 205–220. 10.1016/j.cogbrainres.2004.08.010 [PubMed: 15653294]

Moschkovich J (2006). Using two languages when learning mathematics. Educational Studies in Mathematics, 64(2), 121–144. 10.1007/s10649-005-9005-1

Niedeggen M, & Rösler F (1999). N400 effects reflect activation spread during retrieval of arithmetic facts. Psychological Science, 10, 271–276. 10.1111/1467-9280.00149

Niedeggen M, Rösler F, & Jost K (1999). Processing of incongruous mental calculation problems: Evidence for an arithmetic N400 effect. Psychophysiology, 36(3), 307–324. 10.1017/S0048577299980149 [PubMed: 10352554]

Pavlenko A, & Driagina V (2007). Russian emotion vocabulary in American learners? Narratives. The Modern Language Journal, 91(2), 213–234. 10.1111/j.1540-4781.2007.00541.x

Prado J, Mutreja R, & Booth JR (2014). Developmental dissociation in the neural responses to simple multiplication and subtraction problems. Developmental Science, 17(4), 537–552. [PubMed: 25089323]

Saalbach H, Eckstein D, Andri N, Hobi R, & Grabner RH (2013). When language of instruction and language of application differ: Cognitive costs of bilingual mathematics learning. Learning and Instruction, 26, 36–44. 10.1016/j.learninstruc.2013.01.002

Salillas E, & Wicha NYY (2012). Early learning shapes the memory networks for arithmetic: Evidence from brain potentials in bilinguals. Psychological Science, 23(7), 745–755. 10.1177/0956797612446347 [PubMed: 22707225]

Shook A, & Marian V (2013). The bilingual language interaction network for comprehension of speech. Bilingualism: Language and Cognition, 16(2), 304–324.

Siegler RS (1996) Emerging minds. New York: Oxford University Press. 10.1093/oso/9780195077872.001.0001

Spelke ES, & Tsivkin S (2001). Language and number: A bilingual training study. Cognition, 78(1), 45–88. 10.1016/S0010-0277(00)00108-6 [PubMed: 11062322]

Tamamaki K (1993). Language dominance in bilinguals' arithmetic operations according to their language use. Language Learning, 43(2), 239–261.

Vaid J, & Menon R (2000). Correlates of bilinguals' preferred language for mental computations. Spanish Applied Linguistics, 4, 325–342.

Van Rinsveld A, Brunner M, Landerl K, Schiltz C, & Ugen S (2015). The relation between language and arithmetic in bilinguals: insights from different stages of language acquisition. Frontiers in Psychology, 6. 10.3389/fpsyg.2015.00265

Van Rinsveld A, Dricot L, Guillaume M, Rossion B, & Schiltz C (2017). Mental arithmetic in the bilingual brain: Language matters. Neuropsychologia, 101, 17–29. 10.1016/j.neuropsychologia.2017.05.009 [PubMed: 28495598]

Venkatraman V, Siong SC, Chee MWL, & Ansari D (2006). Effect of language switching on arithmetic: A bilingual fMRI study. Journal of Cognitive Neuroscience, 81(1), 64–74.