Neuroscience Letters 584 (2015) 325–330

Contents lists available at ScienceDirect

Neuroscience Letters

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

Short communication

Arithmetic memory networks established in childhood are changed by experience in adulthood

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HIGHLIGHTS

- A bilingual's language of learning (LA+) shows an advantage for arithmetic facts.
- N400 congruity effect was measured for simple multiplication in bilingual teachers.
- LA+ teachers maintained an LA+ advantage over their other language (LA–).
- Teaching in LA– results in similar brain activity for LA+ and LA–.
- Experience in adulthood can diminish the LA– disadvantage.

ARTICLE INFO

Article history:
Received 25 August 2014
Received in revised form 6 November 2014
Accepted 9 November 2014
Available online 13 November 2014

Keywords:
Multiplication
Bilingualism
Event-related potentials
N400
LPC

ABSTRACT

Adult bilinguals show stronger access to multiplication tables when using the language in which they learned arithmetic during childhood (LA+) than the other language (LA–), implying language-specific encoding of math facts. However, most bilinguals use LA+ throughout their life, confounding the impact of encoding and use. We tested if using arithmetic facts in LA– could reduce this LA– disadvantage. We measured event related brain potentials while bilingual teachers judged the correctness of multiplication problems in each of their languages. Critically, each teacher taught arithmetic in either LA+ or LA–. Earlier N400 peak latency was observed in both groups for the teaching than non-teaching language, showing more efficient access to these facts with use. LA+ teachers maintained an LA+ advantage, while LA– teachers showed equivalent N400 congruency effects (for incorrect versus correct solutions) in both languages. LA– teachers also showed a late positive component that may reflect conflict monitoring between their LA+ and a strong LA–. Thus, the LA– disadvantage for exact arithmetic established in early bilingual education can be mitigated by later use of LA–.

1. Introduction

Verbally rehearsing arithmetic facts, like multiplication tables, leads to encoding, and retrieving these facts as language representations [6]. How well these facts are represented in verbal memory predicts long-term mathematical competence [10]. For bilinguals, the language in which they learned arithmetic (LA+) often shows better access to arithmetic facts than their other language (LA–) [6,9,18,26,28]. This advantage for the LA+ persists into adulthood, seemingly uninfluenced by language proficiency [26]. By implication, bilinguals may be at a disadvantage when performing arithmetic in their LA– (e.g., taking standardized tests in LA–), creating a dilemma for parents and educators of bilingual children. Twenty percent of U.S. children speak English as a second language, making it critical to determine how this LA– disadvantage can be mitigated. Here, we tested if frequent use of LA–, in adult bilinguals who naturally use one language for simple arithmetic more than the other, could reduce or eliminate the LA– disadvantage for multiplication facts.

Memory networks for single digit multiplication (e.g., $2 \times 3 = 6$) are formed in childhood, when these concepts are learned through rote memorization, linking operands with their solutions, and other arithmetic concepts within the network [4]. Time to solve a problem or judge the correctness of a multiplication solution acts as a measure of the connectivity between facts in the network [2,4,24]. Bilinguals typically learn arithmetic in one language, and often

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http://dx.doi.org/10.1016/j.neulet.2014.11.010
0304-3940/

report preferring to use this language for retrieving arithmetic facts [18]. Moreover, these facts appear to be accessed preferentially in the language of learning [9,26,28][e.g., [9,26,28]]. For example, Spelke and Tsivkin [28] taught bilingual adults new arithmetic facts in one language, and observed that these facts were retrieved more accurately in the training language than their other language [28]. Similarly, Bernardo [3] showed that bilingual high-school students performed better on arithmetic in their language of schooling even though it was not their native language. Salillas and Wicha [26] reported that this LA+ advantage persists into adulthood, independent of general language proficiency in LA–. That is LA+ seemed to have an advantage over LA– even when LA– was the more proficient language.

These findings suggest format-, or language-, specific encoding of arithmetic facts that influences processing across the lifespan. Moreover, although reading fluency and vocabulary size influence math achievement [see review [1]], arithmetic fact retrieval may be insensitive to these factors. However, these studies potentially confounded the impact of encoding and use, given that most bilinguals continue to use LA+ throughout their life. In fact, Salillas and Wicha [26] observed that bilinguals who used LA– more often showed better access to multiplication facts in LA–. Thus, encoding may not be the only factor driving the LA+ advantage.

Experience, loosely defined here as frequent use of information to perform a task, is known to cause neuronal reorganization and changes in behavioral patterns in bilinguals [7,19,20]. Here, we tested if experience using LA– for arithmetic, without explicit training of multiplications in LA–, can reduce or eliminate the LA– disadvantage. We measured performance on simple multiplications in LA+ and LA– in bilinguals who naturally used these facts more in one language than the other, namely, bilingual elementary school teachers. This population allowed us to tease apart frequency of use and initial learning, since half of the sample taught primarily in LA+ and the other half in LA–. We hypothesized that if the LA– disadvantage were irreversible, then the disadvantage would be observed in both groups, independent of teaching experience. If, however, experience using LA– mitigates the disadvantage, then LA– would be disadvantaged only in the LA+ teaching group.

The current study was adapted from Salillas and Wicha [26]. Simple multiplication problems were presented one operand at a time, with a solution that was either correct or not ($3 \times 2 = 6$ versus $3 \times 2 = 7$). Each number was presented as a word in English (e.g., three two six) or Spanish (e.g., *tres dos seis*). While the teachers judged the correctness of each multiplication, we recorded accuracy, delayed response time, and event related potentials (ERPs) to solution onset.

ERPs are a direct measure of electrical brain activity that has been used to study arithmetic fact retrieval [11,23–26]. We focused on the N400, a negative-going wave that peaks around 400 ms post-stimulus onset, and a subsequent positive-going wave, the late positive component (LPC). The N400, first observed to language stimuli [16], is modulated by the predictability or semantic fit of a word in its preceding context (e.g., a sentence) [reviewed by [15]]. The worse the semantic fit is the larger the N400 amplitude is relative to a more contextually probable target [e.g., he spread the warm bread with socks; [16]]. That is smaller N400 amplitude reflects easier access to the information in memory. An equivalent N400 effect has been observed for simple arithmetic problems [11,23,25,26], with striking similarity in timing and morphology to the linguistic N400 [8,23,24]. The arithmetic N400 shows increased negative amplitude for incorrect than correct solutions, reflecting automatic spread of activation in the memory network from operand to solution [24,26]. Subsequent to the N400, a positive deflection has been observed in some cases with larger positive amplitude for incorrect than correct multiplication solutions [23,26]. A late positive component (LPC), called a P600 when it is related to processing linguistic structure [[14], see also [27] for arithmetic structure P600], has been observed to a variety of linguistic stimuli, from language translations to unexpected endings on jokes [5,20]. Less well understood than the N400, the LPC may reflect more controlled processing or reprocessing of information [14]. In arithmetic, the LPC is likely related to cognitive load or conflict in processing a problem. Conflict in resolving incorrect solutions may occur between the strong encoded LA+ and LA– in stages of controlled processing (LPC), especially for individuals with a stronger representation of LA– [29].

We predicted that teaching would strengthen access to arithmetic facts in that language, which would be indexed by larger N400 effects compared to the other language. The difference between N400 amplitude to correct and incorrect solutions should be larger for LA+ than LA– for LA+ teachers (learn = teach), but equivalent across languages for LA– teachers (learn $\neq$ teach). In addition, the LPC should be larger for LA– than LA+ teachers, because competition will be greater between the learned language (LA+) and teaching language (LA–) when LA– is used more frequently.

2. Material and methods

2.1. Participants

Participants were 14 (11 female) healthy elementary school teachers (mean age 37.43 years, range 27–48 years).[1] All participants' first language (L1) was also their language of learning arithmetic (LA+). All participants actively taught or had extensive recent experience teaching arithmetic (mean 9.21 years; range 1–12 years). Half of the participants taught primarily in LA+ (learn = teach) and half in LA– (learn $\neq$ teach). Critically, the years of teaching in LA– were significantly different between groups ($t = 4.408$, $p < 0.001$).

All participants were fluent in English and Spanish, with 9.07 years as the mean age of exposure (AOE) to the second language (L2) (range 0–27 years[2]; L2 was Spanish for 2 participants[3] and English for all others). Language proficiency was assessed using the Boston Naming Test [BNT; [12]], sections of the Woodcock Language Proficiency Test (i.e., picture vocabulary, oral vocabulary, and verbal analogies) in English and Spanish [32], and an adapted LEAP-Q questionnaire [17]. A percentile score (RPI) was obtained for the Woodcock data using the BVAT [22] scoring system. The groups differed in percent language use for both LA+ ($t = -2.93$, $p = 0.013$) and LA– ($t = 2.93$, $p = 0.013$), consistent with increased daily use of the teaching language. The groups were equivalent on all other measures: BNT LA+ ($t = -2.05$, $p = 0.063$; mean: LA+ teachers = 50.43, LA– teachers = 42.29); BNT LA– ($t = 0.87$, $p = 0.404$; mean: LA+ teachers = 41.71, LA– teachers = 45.29); BVAT LA+ ($t = -2.02$, $p = 0.066$; mean RPI: LA+ teachers = 89.29, LA– teachers = 73.00); BVAT LA– ($t = -1.61$, $p = 0.133$; mean RPI: LA+ teachers = 81.43, LA– teachers = 61.71).

[1] Two LA– participants were left-handed, but results did not change when data was analyzed without the participants. Therefore, they were included in analysis given the challenge in finding qualified participants. Two additional participants were excluded because their LA+ was not their L1.

[2] One L2-AOE outlier (age 27) did not change significance of correlations (AOE with teaching language, $p = 0.576$ and with non-teaching language, $p = 0.580$) or ANOVAs (group × congruency × teaching language × hemisphere: $p = 0.008$), and was included in analyses.

[3] One LA+ teacher and one LA– teacher with Spanish L2 did not change the pattern of results when excluded/included.