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Early Learning Shapes the Memory Networks for Arithmetic: Evidence From Brain Potentials in Bilinguals

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Abstract

Language and math are intertwined during children's learning of arithmetic concepts, but the importance of language in adult arithmetic processing is less clear. To determine whether early learning plays a critical role in the math-language connection in adults, we tested retrieval of simple multiplication in adult bilinguals who learned arithmetic in only one language. We measured electrophysiological and behavioral responses during correctness judgments for problems presented as digits or as number words in Spanish or English. Problems presented in the language in which participants learned arithmetic elicited larger, more graded, and qualitatively different brain responses than did problems presented in participants' other language, and these responses more closely resembled responses for digits, even when participants' other language was more dominant. These findings suggest that the memory networks for simple multiplication are established when arithmetic concepts are first learned and are independent of language dominance in adulthood.

Keywords

bilingualism; mathematical ability; evoked potentials; language; cognitive neuroscience

The acquisition of simple arithmetic is mediated by language (e.g., through the verbal rehearsal of multiplication tables). Accordingly, it has been argued that exact mathematical concepts, such as simple multiplication, are represented in a language-specific format (Dehaene, 1997). In bilinguals, this means that mathematical concepts are accessed more efficiently in the language in which the person learned simple arithmetic (language of arithmetic, or LA+) than in the person's other language (LA−; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Spelke & Tsivkin, 2001). However, factors such as language proficiency play an important role in bilingual language processing (Elston-Guttler, Paulmann, & Kotz, 2005; Moreno & Kutas, 2005; Weber-Fox, Davis, & Cuadrado, 2003), affecting the efficiency of retrieving and using words. By inference, language proficiency could similarly affect accessing and processing of language-dependent arithmetic concepts

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(Frenck-Mestre & Vaid, 1993). Thus, it is not clear to what extent the representations established in childhood determine the strength and relationships of arithmetic facts in adulthood and whether access to adult representations is dependent on the original language in which those facts were learned. In the study reported here, we took advantage of the bilingual brain to determine whether early learning plays a critical role in the math-language connection in adults.

The debate over the cognitive relationship between language and math (Campbell & Clark, 1988; Dehaene et al., 1999) focuses in part on the extent to which math is dissociable from other cognitive functions, including language (Cipolotti & Harskamp, 2001; Spelke & Tsivkin, 2001). Co-occurring impairments in math and language skills in neuropsychological patients and language-based development of number concepts in childhood (Dehaene & Cohen, 1991; Gelman & Butterworth, 2005; Gelman & Gallistel, 1978) allude to a relationship between these domains. This relationship is more obvious for mathematical concepts that rely on language-specific representations than for mathematical concepts that rely on abstract representations (e.g., multiplication tables versus approximate calculations;Delazer & Benke, 1997; Hittmair-Delazer, Sailer, & Benke, 1995; Spelke & Tsivkin, 2001).

Typically, both bilinguals and monolinguals learn arithmetic concepts, such as multiplication, once. The ability to separate learned mathematical facts from the language used to learn them can prove challenging in the healthy monolingual brain, in which words and arithmetic concepts have a one-to-one mapping. In contrast, the bilingual brain—with multiple mappings for the same concepts—provides an excellent resource for teasing apart the relationship between arithmetic and language (Dehaene et al., 1999; Frenck-Mestre & Vaid, 1993).

The sole model of bilingual arithmetic posits separate representations for arithmetic facts, one in each language and in each language-independent digit format (Campbell & Epp, 2004). There is some evidence from studies of bilinguals suggesting that concepts such as multiplication are intimately linked to LA+. Adult bilinguals trained on novel exact-number facts (e.g., base-6 addition) retrieve these facts more effectively in LA+ than in LA−, even when LA+ was not their preferred or first natural language (Dehaene et al., 1999; Spelke & Tsivkin, 2001). This finding implies that arithmetic facts should be represented in adults more strongly, or solely, in LA+. This hypothesis is in line with anecdotal reports from bilinguals who feel the need to count or perform simple arithmetic in their first language, even when communicating in the other (Dehaene, 1997).

A bilingual’s use of each language, however, is dynamic over a lifetime, and the language in which concepts were learned in childhood does not necessarily remain the language of preference in adulthood. The language that is more dominant or more frequently used changes based on a bilingual’s environment, beginning in early childhood (Kohnert, 2002; Linck, Kroll, & Sunderman, 2009). In many instances, the language of early education can become the less dominant language in adulthood (Bahrick, Hall, Goggin, Bahrick, & Berger, 1994). In the United States, for example, early education can take place in a language other than English for both immigrant populations (e.g., in English-as-a-second-language or dual-language programs) and native English speakers (e.g., language-immersion programs). Ultimately, dominance and proficiency in a language can affect language performance and modulate the underlying neural processes (Elston-Guttler et al., 2005; Moreno & Kutas, 2005). In the present study, we tested whether LA+ is the critical factor in representation and retrieval of arithmetic facts, or whether high proficiency or dominance in a language can change early representations of arithmetic concepts.

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Generally, the memory network for arithmetic within a language is thought to have extensive connections among arithmetic facts, similar to conceptual networks for other domains (Campbell & Clark, 1988; Niedeggen & Rösler, 1999; Stazyk, Ashcraft, & Hamann, 1982). Each operand in a multiplication problem, and the problem as a whole, can trigger a candidate set of solutions in the network through an automatic spread of activation. In turn, each possible solution is activated proportionally to the strength of its relation with the operands (e.g., the problem 2 × 3 not only triggers the solution 6, but also the numbers 4 and 9 more weakly as multiplication factors of each operand). In monolinguals, correctness judgments for simple multiplication problems are faster for correct solutions than for incorrect ones, and faster for incorrect solutions unrelated to either operand (e.g., 2 × 3 = 13) than for incorrect solutions related to either operand (e.g., 2 × 3 = 15, in which 15 is a factor of 3; Niedeggen & Rösler, 1999; Niedeggen, Rösler, & Jost, 1999). This relatedness effect is thought to reflect interference from potential solutions that are automatically activated when processing digits (Galfano, Rusconi, & Umilta, 2003; Niedeggen et al., 1999).

These effects of arithmetic correctness and relatedness are also observed in monolingual electrophysiological data, specifically on the N400 component, a negative-going event-related potential (ERP) peaking around 400 ms after stimulus onset. The N400 is thought to reflect the automatic spread of activation among representations of arithmetic facts (Niedeggen & Rösler, 1999). Similar to the N400 effect for semantically related versus unrelated words (Federmeier & Kutas, 1999a; Kutas & Hillyard, 1980), N400 amplitude is larger for unrelated than for related incorrect arithmetic solutions, with the smallest N400 amplitude observed for correct solutions (Niedeggen et al., 1999). The operand-solution relationship also modulates a late positive component (LPC), which shows larger positivity as the relationship between them becomes more distant. The LPC is thought to reflect more controlled processes than the N400 does (Coulson, King, & Kutas, 1998; Kolk & Chwilla, 2007; Wicha, Moreno, & Kutas, 2004).

The goal of this study was to determine whether LA+ establishes the quality and strength of representations for multiplication facts in adult bilinguals, and whether these representations are independent of natural language dominance. We addressed this question by measuring behavior (in a reaction time, RT, experiment) and brain electrical responses (in an ERP experiment) to multiplication-fact retrieval in adult bilinguals. From this data, we inferred the strength and interconnection of arithmetic fact representations in each language. We selected Spanish-English bilinguals who learned both languages early in childhood and who were proficient in both languages but learned arithmetic in only one. Critically, the specific language in which arithmetic was learned (Spanish or English) was independent of which language was more dominant.

If early learning determines the structure of representations for arithmetic facts, then even bilinguals who are proficient in both languages should show greater sensitivity (e.g., stronger modulation of the N400 amplitude to correct than incorrect solutions) and more extensive connectivity (e.g., gradation in N400 response across solutions based on relatedness of the solution and the operands) for multiplication problems presented in LA+ than in LA−. This relationship between the N400 response and problems presented in LA+ should be independent of language dominance. In contrast, if proficiency or general language dominance can override early-established memory traces for arithmetic facts encoded in LA+ under normal conditions (e.g., in typical bilingual adults who do not relearn arithmetic concepts in their other language), then the N400 effects should either be larger in the dominant than in the nondominant language, irrespective of the language used for learning math during childhood, or similar in both languages.

Method

Participants

Participants were healthy, right-handed, Spanish-English bilinguals exposed to Spanish from birth and English by age 15 (mean age of exposure = 7.1 years); none had math expertise. Of the 11 participants in the RT experiment (5 male, 6 female; mean age = 21.7 years, range = 20–23 years), 6 learned arithmetic in English, and 5 learned arithmetic in Spanish. Of the 22 participants in the ERP experiment (6 male, 16 female; mean age = 23.5 years, range = 19–32 years), 12 learned arithmetic in English, and 10 learned arithmetic in Spanish; 4 of the subjects in the ERP experiment also participated in the RT experiment.[1]

Language assessment

Language proficiency was assessed with two measures administered to each participant in both Spanish and English: the Boston Naming Test (BNT; Kaplan, Goodglass, and Weintraub, 1983) and the Verbal Fluency Test (VFT; Benton, Hamsher, and Sivan, 1994; Rey & Benton, 1992; Table 1). On the BNT, participants were presented with 60 line drawings one at a time, and they had to name the items pictured in English and Spanish. On the VFT, participants named words from three semantic categories and from three categories of words starting with a specific letter (English: *f*, *a*, and *s*; Spanish: *p*, *t*, and *m*). Relative dominance of the participants' two languages (scores in English minus scores in Spanish) varied across participants. Although this variance was small, it was sufficient to allow us to use relative dominance as a regressor for ERP effects. Relative dominance was correlated between the BNT and the VFT ($r = .65$, $p = .001$); the BNT score was used as a regression factor. All analyses compared scores in LA+ with scores in LA−, collapsed across languages. Participants also reported the daily frequency with which they used each language.

Stimuli and procedure

Stimuli were simple multiplication problems printed in white text centered on a black background. Stimuli appeared on a 19-in. CRT monitor positioned approximately 1 m from the participant. Each trial sequence began with a 1-s fixation marker, followed by the first operand, which appeared for 350 ms. After a 250-ms blank interstimulus interval, the second operand appeared for 350 ms, followed by a 150-ms blank interstimulus interval. The solution then appeared for 350 ms. The problems were presented with no symbols (e.g., "2 3 6").

Participants sat in a dimly lit sound-attenuating chamber. In the behavioral experiment, participants made a speeded correctness judgment at the solution onset. In the ERP experiment, a question mark appeared 1 s after solution onset (to ensure movement artifacts did not appear in the ERP) to cue a delayed correctness judgment. Judgments of whether the solution presented was correct or incorrect were made using two different fingers of the right hand on two keyboard keys, counterbalanced for order across participants.

Problems appeared as digits and as lowercase words in Spanish and English (see Table S1 in the Supplemental Material). The solution could be correct, incorrect but related to one of the operands (e.g., "2 3 15," in which 15 is a factor of 3), or incorrect but unrelated to one of the operands (e.g., "2 3 13"). Number words were matched for lexical frequency across languages (Davies, 2002; see Table S2 in the Supplemental Material). Naturally, there were more syllables for Spanish than for English words, $F(1, 11) = 32.51$, $p < .001$, $\eta^2 = .74$;

[1]All analyses were performed with and without these 4 subjects, and the same pattern of effects was observed in both cases (for more details, see ERP Analyses Excluding 4 Participants from Behavioral Study in the Supplemental Material available online).

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however, in comparing responses in LA+ with responses in LA−, we collapsed Spanish and English items across participants, controlling for effects of syllable length. There were no significant differences in length or frequency across solution types (correct, related, or unrelated) in either language.

In total, there were 288 trials consisting of 96 trials per format (digits, LA+, LA−). Forty-eight of the 96 trials presented correct solutions, and the other 48 presented incorrect solutions. Across each of the 48 trials, 24 presented solutions related to one of the operands, and 24 presented solutions unrelated to one of the operands. These 288 trials were divided into three blocks and pseudorandomized. Problems were never presented twice consecutively; there were no more than three consecutive correct or incorrect items or items in the same format.

Electroencephalogram (EEG) recording and analysis

Continuous EEGs were recorded from 26 scalp electrodes placed in a geodesic array with the left mastoid as a reference. Recordings were obtained using SA Instrumentation bio-amplifiers and band-pass filtered from 0.01 to 100 Hz at a sampling rate of 250 Hz. Impedances were kept below 5kΩ. Free electrodes recorded blinks, horizontal eye movements, and left and right mastoid processes as references. Trials with eye or other artifacts were removed (there was roughly equal data loss across conditions). Data were rereferenced to the average mastoids. An analysis of variance (ANOVA) showed a significant interaction between correctness (2 levels), format (3 levels), and electrode (26 levels), $F(50, 1050) = 2.38$, $p = .043$, $\eta^2 = .10$; thus, 20 representative electrodes were selected for further analyses to capture this interaction. These electrodes were grouped in four regions of interest determined by anteriority (anterior-posterior) and hemisphere (left-right; see Fig. 1a). Mean amplitude (relative to a 100-ms prestimulus baseline) was measured in each condition from the onset of the solution.

Latency band calculation

ERPs for digits peaked earlier than ERPs for words; thus, latency bands were calculated for amplitude analyses using fractional area latency for the N400 (Handy, 2005) and baseline onset latency for the LPC (see Latency Band Calculation in the Supplemental Material). Time windows selected for amplitude analyses for the N400 were 290 to 390 ms for digits and 330 to 430 ms for words; for the LPC, the time window between 450 and 850 ms was selected for digits, and the time window between 500 and 900 ms was selected for words.

Results

RT experiment

Accuracy in judging the correctness of multiplication solutions was high (.972). There were no significant differences in the number of errors across formats (digits, LA+, and LA−) or between incorrect and correct solutions; there was a trend for fewer errors for unrelated incorrect solutions (.013) than for related incorrect solutions (.038), $F(2, 20) = 2.45$, $p = .1$. An ANOVA was conducted on trials responded to accurately.

Table 2 shows mean RTs for the behavioral experiment. Responses were slower for incorrect than for correct solutions in LA+, $t(10) = 6.1$, $p = .001$, and in digits, $t(10) = 4.07$, $p = .002$, but not in LA−, $t(10) = 0.7$, $p = .45$. Further, there was a Format (LA+, LA−, digits) × Correctness (correct, incorrect) interaction: $F(2, 20) = 3.43$, $p = .05$, $\eta^2 = .26$. Solutions presented in LA− elicited slower correct responses, $t(10) = 2.75$, $p = .02$, but equal incorrect responses compared with solutions presented in LA+, $t(10) = 0.5$, $p = .6$. Responses were slower for incorrect solutions related to the operands than for incorrect solutions unrelated to the operands, $F(1, 10) = 6.06$, $p = .033$, $\eta^2 = .38$; no interaction was observed between relatedness and format, $p > .9$. No other contrasts were significant.

ERP experiment

Accuracy for delayed judgments of the correctness of multiplication solutions was high (.98). A 3 (solution: correct, related incorrect, unrelated incorrect) × 3 (format) ANOVA showed a main effect of solution, $F(2, 42) = 10.83$, $p = .001$, $\eta^2 = .34$: There were fewer errors for unrelated incorrect solutions (.007) compared with correct solutions (.027), $F(1, 21) = 17.83$, $p = .001$, $\eta^2 = .46$, and related incorrect solutions (.032), $F(1, 21) = 14.85$, $p = .001$, $\eta^2 = .41$. Effects of format and the interaction of format and solution were not significant, $F(2, 42) = 0.7$, $p = .4$, and $F(2, 42) = 0.93$, $p = .4$, respectively. As in the RT experiment, delayed correctness judgments revealed a main effect of solution, $F(2, 42) = 5.26$, $p = .01$, with slower responses for related incorrect solutions (600.9 ms) than for unrelated incorrect solutions (555.6 ms), $F(1, 21) = 6.08$, $p = .02$, and for correct solutions (537.2 ms), $F(1, 21) = 6.33$, $p = .02$. The direction of effects for both immediate and delayed responses was consistent with the direction of effects in previous findings. All ERP analyses were performed on trials with accurate responses, and only significant effects are reported here ($p < .05$, Greenhouse-Geisser corrected where appropriate).

Correctness as an index of activation strength: N400 amplitude differences across formats

To test the activation strengths within each format, we analyzed the ERPs for correct and incorrect solutions (collapsed across relatedness) in a 2 (correctness: correct, incorrect) × 3 (format: digit, LA+, LA−) × 2 (anteriority: anterior, posterior) × 2 (hemisphere: left, right) × 5 (levels of electrode) ANOVA. N400 amplitude was modulated by correctness in all three formats, $F(1, 21) = 89.43$, $p < .001$, $\eta^2 = .81$ (Figs. 1b and 2). An interaction between correctness and format, $F(1, 21) = 5.1$, $p = .035$, $\eta^2 = .19$, was due to LA− trials eliciting a smaller N400 effect across the scalp compared with LA+ trials and at posterior sites compared with digits. There was also a three-way interaction between correctness, format, and anteriority: $F(1, 21) = 13.6$, $p = .001$, $\eta^2 = .39$. Critically, the correctness effects in LA+ and LA− did not correlate with language dominance (Figs. 3a and 3b). Correctness effects in LA−, but not in LA+, were positively correlated with frequency of daily use of each language (Figs. 3c and 3d).[2] This difference between languages implies weaker overall activation for arithmetic concepts in LA− than in LA+.

Relatedness as an index of complexity: gradation of N400 amplitude across solutions

To test the connections between concepts in each language, we compared the ERPs for related and unrelated incorrect solutions by format in a 2 (relatedness: related, unrelated) × 3 (format) × 2 (anteriority) × 2 (hemisphere) × 5 (levels of electrode) ANOVA. Larger N400 amplitudes were observed at right posterior electrodes for unrelated than for related incorrect solutions, both for LA+, $F(1, 21) = 5.75$, $p = .026$, $\eta^2 = .21$, and for digits, $F(1, 21) = 8.2$, $p = .009$, $\eta^2 = .28$ (Figs. 1c and 2). In contrast, the absence of an N400 relatedness effect in LA−, $F(1, 21) = 0.15$, $p = .69$, reflects a gross categorization of correct and incorrect responses. The relatedness effects in LA+ and LA− did not depend on relative language proficiency (LA+: $r = −.02$, n.s., LA−: $r = −.16$, n.s.) or frequency of language use (LA+: $r = −.38$, n.s., LA−: $r = .037$, n.s.), which indicates that the connections between arithmetic concepts do not change with general language use (see Fig. S1 in the Supplemental Material).

[2]We assumed that the frequency of language use includes frequency of hearing and verbalizing math concepts.

LPC amplitude differences across solutions and formats

The LPC was modulated by correctness (correct, incorrect), $F(1, 21) = 5.47$, $p = .029$, $\eta^2 = .21$; the lack of a significant interaction between correctness and format (digits, LA+, LA−) indicated that this was true in all three formats: $F(2, 42) = 1.8$, $p = .2$. The LPC was also modulated by relatedness (related, unrelated), $F(1, 21) = 0.07$, $p = .7$, but there was a significant interaction between relatedness and format, $F(2, 42) = 3.51$, $p = .05$, $\eta^2 = .14$ (Fig. 2); relatedness affected the LPC only in LA−. The results reveal qualitative differences between processing of LA− solutions and processing of LA+ and digit solutions; these differences were indiscernible from RTs alone. No other contrasts were significant.

Effects of correctness and relatedness as a way of comparing language formats

For digits, larger effects of correctness and relatedness were observed for individuals for whom LA+ was the dominant language for everyday use than for individuals for whom LA− was the dominant language for everyday use[3] (correctness: $r = -.47$, $p = .037$; relatedness: $r = -.58$; $p = .007$; see Fig. S2 in the Supplemental Material and Fig. 4).[4] The size of the correctness and relatedness effects for digits did not correlate significantly with the percentage of daily use of either language. These findings provide further evidence for differences in representation for arithmetic concepts based on the LA+ in childhood.

Discussion

The goal of the present study was to determine whether early learning plays a critical role in the organization of arithmetic memory in adults. Using bilinguals who learned arithmetic in only one of their proficient languages, we measured behavioral and electrophysiological responses while participants judged the correctness of simple multiplication problems. The problems were presented as digits or as words in either language, and the solution was correct, incorrect but related to the operands, or incorrect but unrelated to the operands.

As expected, faster RTs were observed for correct solutions, followed by unrelated then related incorrect solutions. Similarly, the N400 amplitude was larger for incorrect than for correct solutions, and larger for unrelated than related solutions. These findings are consistent with the notion of a graded spread of activation among concepts based on their relation to the multiplication problem. This effect was larger for problems presented in LA+ and as digits than for problems presented in LA−, which suggests weaker activation in LA−. In addition, access to related concepts in LA− was qualitatively different, as indexed by the LPC relatedness effect, compared with the more automatic N400 effect for LA+ and digits. Critically, the effects of correctness and relatedness for LA+ and LA− were not affected by language dominance or high proficiency in LA−.

Finally, a positive correlation between dominance in LA+ and the size of the N400 correctness effect for digits provides additional support for the importance of LA+ in establishing the memory network for multiplication facts. Overall, our findings suggest that arithmetic is differentially represented in each language in the bilingual brain and that these

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[3]These findings should be interpreted with caution in light of the debate over the necessity of a verbal code for processing digits (Campbell & Clark, 1988; Dehaene & Cohen, 1995; McCloskey, Marcuso, & Whetstone, 1992). Scalp distributions for both the effects of correctness and relatedness on the N400 showed that words elicited a more widely distributed N400 response than digits did; the Format × Correctness × Anteriority and Format × Relatedness × Anteriority × Hemisphere interactions were both significant, $F(2, 42) = 10.4$, $p < .001$, $\eta^2 = .33$, and $F(2, 42) = 8.48$, $p = .008$, $\eta^2 = .29$, respectively (Fig. 1c). This finding suggests that words and digits rely on overlapping but nonidentical neural activity. In addition, latencies were 40 ms shorter for digits than for words (290–390 ms and 330–430 ms, respectively), $F(2, 42) = 16.26$, $p < .001$, $\eta^2 = .44$ (Fig. 1b), whereas the opposite would be expected if digits required additional decoding and mapping than words did. These results suggest that arithmetic facts presented as digits can be processed without obligatory access to a verbal code.

[4]For these analyses, only 20 participants were included because of missing scores on the BNT.

representations are established during early learning and maintained into adulthood independently of natural language dominance.

These findings clarify the role of arithmetic representations in both bilinguals and monolinguals. The size of the N400 amplitude is thought to be inversely related to the strength of activation of arithmetic facts (Niedeggen & Rösler, 1999; Niedeggen et al., 1999). Therefore, the smaller N400 correctness effect for LA− than for LA+ and for digits—and the lack of a behavioral correctness effect—suggests weaker spread of activation from operands to solutions. Previous studies have shown that digits automatically activate a network of related concepts, including multipliers, even when multiplication facts are irrelevant to the task (Galfano et al., 2003; LeFevre, Bisanz, & Mrkonjic, 1988). The N400 relatedness effect we found for digits supports these findings. In addition, by inference, the same automatic activation of related concepts occurs in LA+ but not in LA−, indicating that connections between related operands and solutions are not as well established in LA−.

In addition to providing strong evidence for the importance of early learning, our data downplay the role of language dominance for arithmetic fact retrieval in fluent bilinguals. If proficiency could strengthen or reorganize the network in LA−, then results for our bilinguals who had similar proficiency in LA− and LA+ or greater proficiency in LA− than in LA+ should have shown this reorganization. Instead, LA− remained the weaker and less connected of the two languages. Moreover, problems presented in LA− shared less similarity in the pattern of effects with problems presented in the digit format than problems presented in LA+ did, which suggests qualitatively different processing. A higher percentage of daily use of LA− did increase the efficacy of discriminating correct and incorrect solutions, but still did not lead to an N400 relatedness effect. It is possible that the representations in LA− could become more like the representations in LA+ if pushed to the extreme (e.g., in bilinguals with very low proficiency or infrequent use of LA+) or if these concepts are relearned explicitly or implicitly in LA−. We are addressing these possibilities in ongoing research.

The absence of an N400 relatedness effect in LA− alludes to a gross categorization of correct and incorrect solutions in this language. Also, unlike solutions in LA+ and for digits, related solutions in LA− elicited larger late-positive amplitudes than unrelated solutions did. This indicates that this information is accessed, but on a later time scale and perhaps through more controlled processes (Coulson et al., 1998; Kolk & Chwilla, 2007; Wicha et al., 2004), such as translation into a more dominant format. The behavioral data show no difference in timing between languages for related or unrelated incorrect solutions (Table 2), even though a delay in processing problems presented in LA− due to translation would be expected. Alternatively, these effects in LA− could be due to implicit or automatic activation of a more dominant format (Kroll, Bobb, Misra, & Guo, 2008; Thierry & Wu, 2007).

Still, implicit activation of LA+ could explain the weaker correctness effects in LA−, but not the qualitative shift of a relatedness effect from the N400 to the LPC. Another possibility is that all formats require access to a concept-level representation (McCloskey, Marcuso, & Whetstone, 1992) and that LA− requires more effortful, controlled access than digits and LA + do. In either case, our data demonstrate that solutions to simple multiplication problems are less available and retrieved with more effort in LA− than in LA+.

An important remaining question is whether the effect of LA+ is specific to arithmetic or whether it can apply to any concept learned. There is evidence to suggest that exact number facts, such as simple multiplication problems, may be indeed treated uniquely (Dehaene et al., 1999; Spelke & Tsivkin, 2001; Zhou et al., 2009). It may be the method of learning such abstract concepts or the concepts themselves that make the reliance on LA+ so important.

Although it is known that factors such as age of acquisition and proficiency modulate access to meaningful words in a language, it is not known whether the semantic networks for other concepts have finer connections that make them more accessible and sensitive to relatedness in LA+ than in LA−.

In sum, our results show that arithmetic facts are organized into strong associative memory networks for problems presented in LA+ and digit formats, with a weaker network for problems presented in LA−. Problems presented in LA− displayed quantitatively and qualitatively different patterns of effects compared with problems presented in LA+ and digit formats. Though frequency of language use changed overall processing efficiency in LA−, it did not strengthen the spread of activation to related concepts. Finally, high LA− proficiency or LA− dominance (when LA+ was the weaker natural language) did not change the networks for arithmetic in either language. Thus, a connection between language and math is established at the time of learning and maintained into adulthood independently of natural language dominance. This finding may have important implications for teaching and testing young bilinguals, and it highlights the idea that bilinguals should not be treated as two monolinguals in one brain (Grosjean, 1989).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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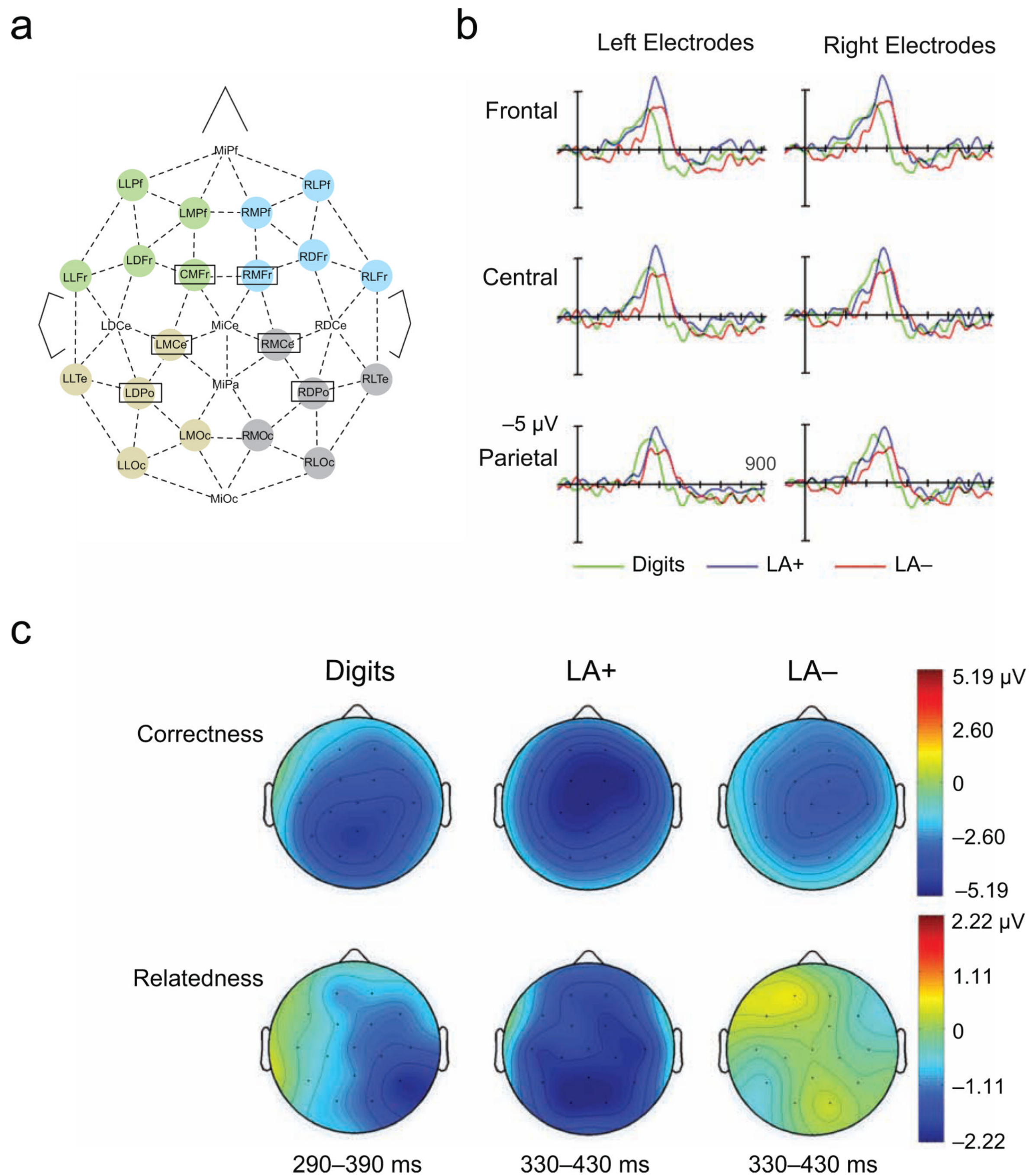

Fig. 1.

Results of the event-related potential (ERP) experiment. The illustration in (a) shows the location of the 26 electrodes in a geodesic array (for an explanation of these labels, see Federmeier & Kutas, 1999b). Rectangles identify the six representative electrodes for which waveforms are shown in this figure, and color coding shows the four regions of interest used in statistical analysis. Grand-average difference ERPs (b) from the six representative electrodes illustrate the N400 correctness effect for multiplication problems presented in three formats: digits, the language participants used to learn arithmetic (LA+), and participants' other language (LA−). The N400 correctness effect was calculated by subtracting the N400 amplitude on all trials that presented the correct solution from the

N400 amplitude on all trials that presented the incorrect solution. Spline-interpolated isovoltage maps (c) show the topographic distribution of the mean N400 correctness effect (top row) and mean N400 relatedness effect (bottom row) for the three formats. The N400 relatedness effect was calculated by subtracting the N400 amplitude on trials that presented solutions related to the operands from the N400 amplitude on trials that presented solutions unrelated to the operands.

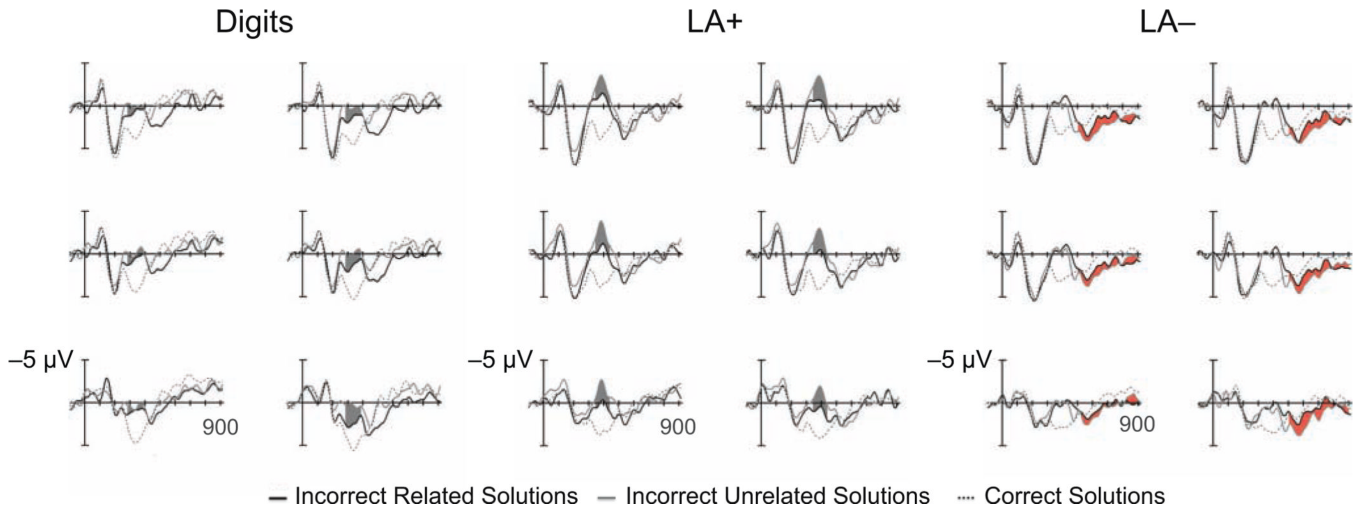

Fig. 2.
Sample grand-average difference event-related potentials for six representative electrodes for trials that presented correct solutions, trials that presented incorrect solutions related to the operands, and trials that presented incorrect solutions unrelated to the operands in three formats: digits, the language participants used to learn arithmetic (LA+), and participants' other language (LA−). Red shading shows the N400 effect; gray shading shows the late-positive-component effect.

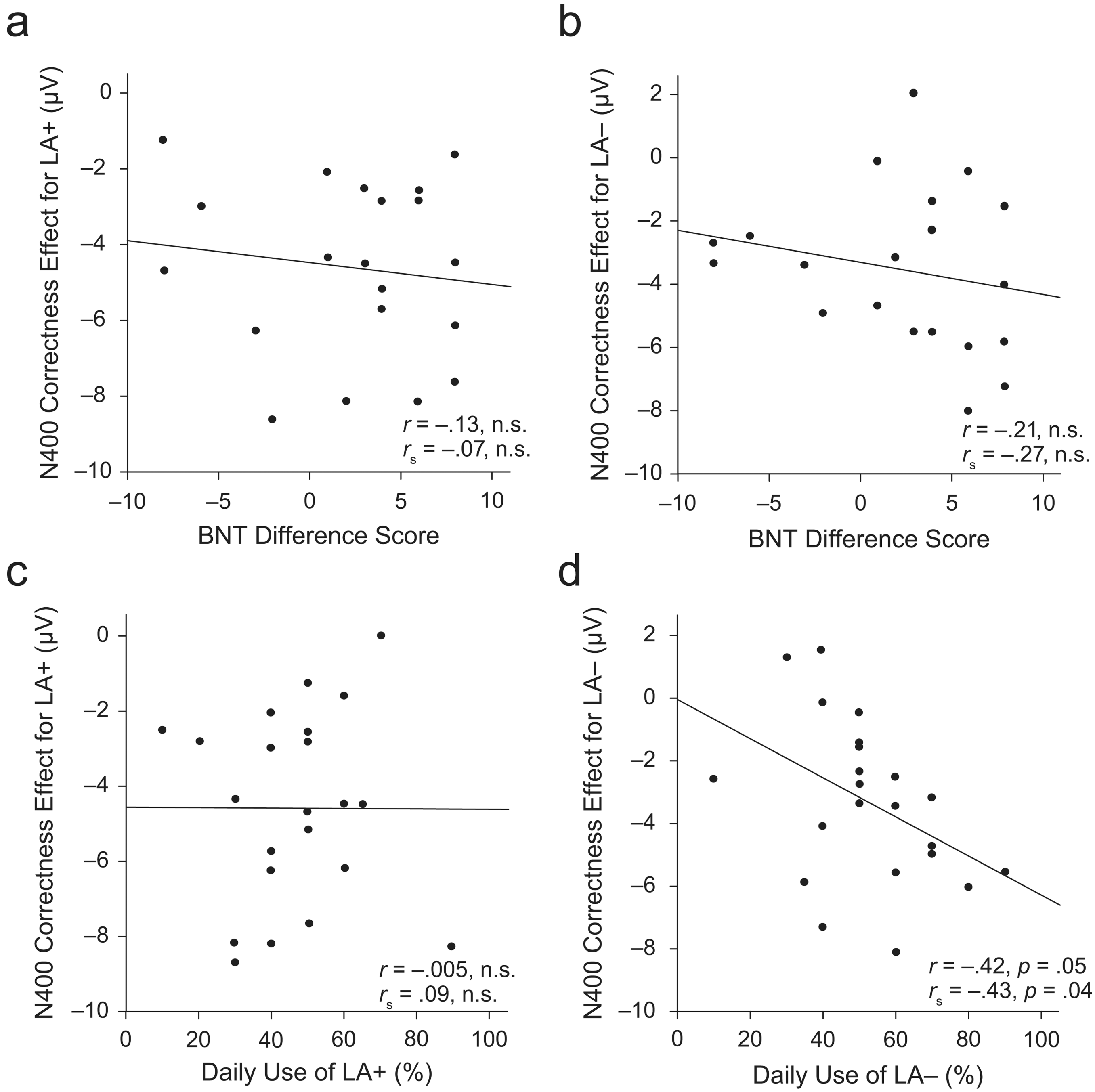

Fig. 3. Scatter plots (with best-fitting linear regression lines) showing N400 correctness effects in bilinguals solving multiplication problems. The N400 effect was calculated by subtracting the N400 amplitude on trials that presented the correct solution from the N400 amplitude on trials that presented the incorrect solution. The left column (a, c) shows effects when the problems were presented in the language in which participants learned arithmetic (LA+), and the right column (b, d) shows effects the problems were presented in participants' other language (LA−). The N400 effect is shown as a function of difference score on the Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 1983) in the top row. Difference scores were calculated by subtracting BNT scores in the LA− from BNT scores in the LA+. The N400 effect is shown as a function of the self-reported percentage of daily use of each language in the bottom row

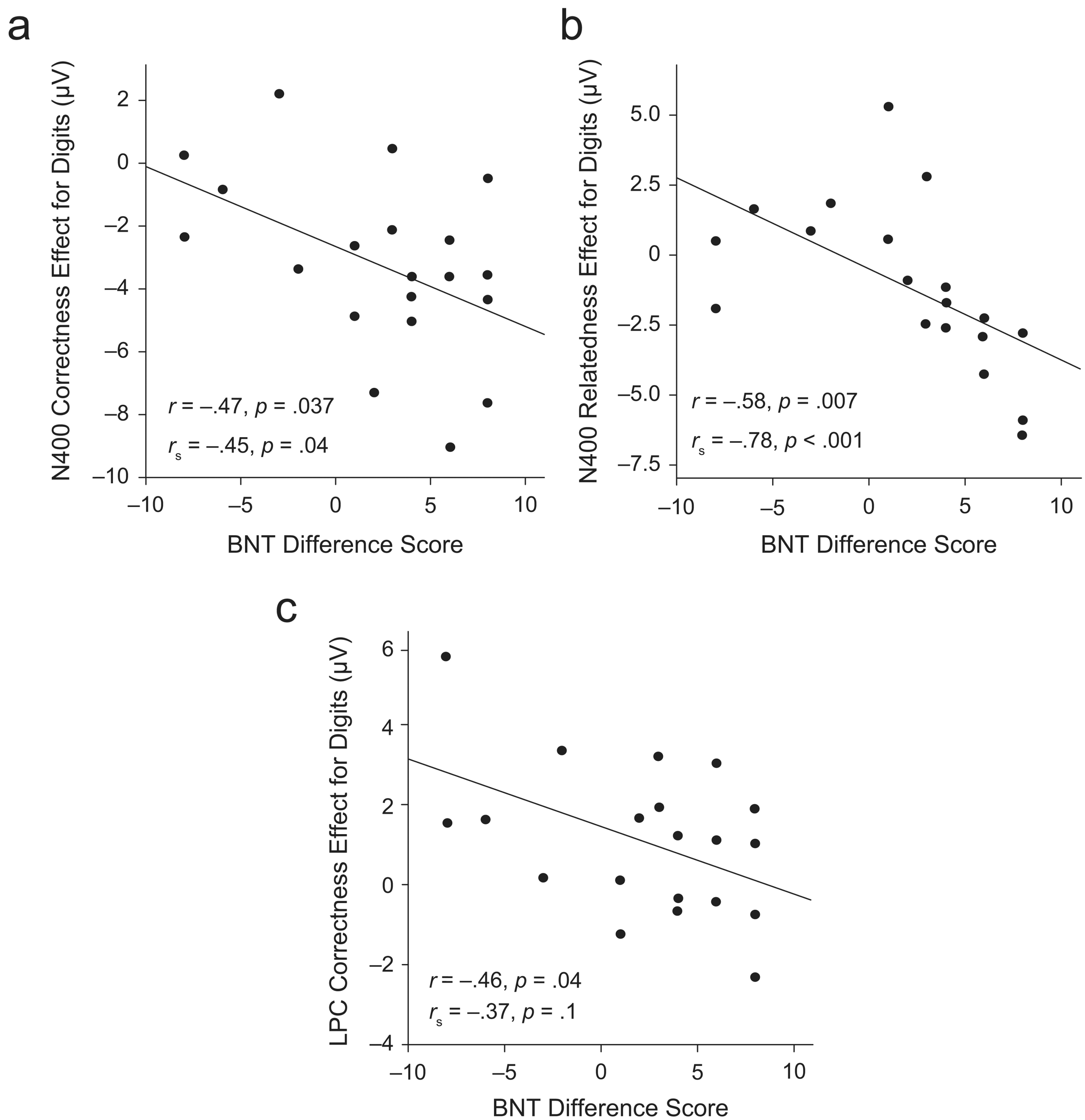

Fig. 4.

Scatter plots (with best-fitting linear regression lines) showing event-related potential effects in bilinguals solving multiplication problems presented in digit form. The N400 correctness effect (a) was calculated by subtracting the N400 amplitude on trials that presented the correct solution from the N400 amplitude on trials that presented the incorrect solution. The N400 relatedness effect (b) was calculated by subtracting the N400 amplitude on trials that presented solutions related to the operands from the N400 amplitude on trials that presented solutions unrelated to the operands. The late-positive-component (LPC) correctness effect (c) was calculated by subtracting the LPC amplitude on trials that presented the correct solution from the LPC amplitude on trials that presented the incorrect solution. The three effects are shown as a function of difference score on the Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 1983), which was calculated by subtracting BNT score in the language a participant used to learn arithmetic from BNT score in the participant's other language.

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Table 1

Language-Assessment Results for the Two Groups in the Event-Related Potential Experiment

	Mean BNT score		Difference	Mean VFT score		Self-reported percentage of daily use	
LA+	**Spanish**	**English**	**BNT score**	**Spanish valign="bottom"**	**English valign="bottom"**	**Spanish valign="bottom"**	**English valign="bottom"**
English (*n* = 12)	45.00	46.90	1.90	11.80	11.89	43.89	53.89
Spanish (*n* = 10)	49.80	47.00	2.80	16.02	13.27	41.25	58.75

Note: The maximum possible score on the Boston Naming Test (BNT; Kaplan, Goodglass, & Weintraub, 1983) is 60. Difference BNT scores were calculated by subtracting scores on tests given in the language in which bilinguals learned arithmetic (LA+) from scores on tests given in bilinguals' other language (LA−). Because of missing data, the means for BNT scores for English speakers include only 10 participants. For the Verbal Fluency Test (VFT; Benton, Hamsher, & Sivan, 1994; Rey & Benton, 1992), participants named words from three semantic categories and from three categories of words starting with a specific letter (English: *f*, *a*, and *s*; Spanish: *p*, *t*, and *m*).

Table 2

Mean Reaction Times (in Milliseconds) for the Behavioral Experiment ($N = 11$)

	Correctness			Relatedness		
Stimulus format	Correct solutions	Incorrect solutions	Difference	Related incorrect solutions	Unrelated incorrect solutions	Difference
Digit	611.37 (33.34)	700.72 (33.57)	89.35**	709.72 (35.42)	691.73 (35.43)	17.99*
LA+	639.64 (32.20)	722.18 (38.64)	82.54**	736.95 (46.06)	707.42 (35.34)	29.53*
LA−	697.84 (41.11)	714.68 (37.22)	16.84	735.82 (42.13)	693.55 (46.44)	42.27*

Note: Standard errors of the mean are given in parentheses. The same stimuli were used in the event-related potential experiment.

* $p < .05$.

** $p < .001$.