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Research article

Speaking Two Languages Enhances an Auditory but Not a Visual Neural Marker of Cognitive Inhibition

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Abstract: The purpose of the present study was to replicate and extend our original findings of enhanced neural inhibitory control in bilinguals. We compared English monolinguals to Spanish/English bilinguals on a non-linguistic, auditory Go/NoGo task while recording event-related brain potentials. New to this study was the visual Go/NoGo task, which we included to investigate whether enhanced neural inhibition in bilinguals extends from the auditory to the visual modality. Results confirmed our original findings and revealed greater inhibition in bilinguals compared to monolinguals. As predicted, compared to monolinguals, bilinguals showed increased N2 amplitude during the auditory NoGo trials, which required inhibitory control, but no differences during the Go trials, which required a behavioral response and no inhibition. Interestingly, during the visual Go/NoGo task, event related brain potentials did not distinguish the two groups, and behavioral responses were similar between the groups regardless of task modality. Thus, only auditory trials that required inhibitory control revealed between-group differences indicative of greater neural inhibition in bilinguals. These results show that experience-dependent neural changes associated with bilingualism are specific to the auditory modality and that the N2 event-related brain potential is a sensitive marker of this plasticity.

Keywords: bilingualism; inhibition; event-related brain potentials; N2; executive function

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Abbreviations: Anterior cingulate cortex (ACC); Inhibitory Control (IC); Event related brain potential (ERP); Socioeconomic status (SES); Bilingual Verbal Ability Test (BVAT); Electroencephalogram (EEG); Reaction time (RT); Standard deviation (SD); Analysis of variance (ANOVA)

1. Introduction

Exciting new brain imaging studies reveal that the experience of being bilingual, and therefore constantly managing two languages, enhances brain structures and function and may even slow down or protect against brain deterioration associated with aging. For instance, studies directly link brain areas associated with language control, such as the anterior cingulate cortex (ACC), to executive control and reveal that bilinguals use this structure more efficiently and outperform monolinguals on ACC mediated, conflict monitoring tasks [1]. Other studies reveal that being bilingual protects against decreases in cerebral gray [2] and white matter 2013 [3], which is associated with normal aging. While less consistent, results of behavioral studies also suggest a bilingual advantage on tests of executive function [4–6].

One mechanism that links language control to enhanced executive control in bilinguals is the inhibitory control (IC) model [7], which explains that when bilinguals speak in one language, their other language is actively suppressed. Bialystok and Martin [8] propose that the same processes that inhibit one language when a bilingual speaks are used to solve non-linguistic, executive function tasks. In other words, the inhibition processes involved in suppressing a second language can cause long-lasting changes that transfer to other (non-language) executive control processes such as cognitive inhibition.

In support of this model, recent work from our laboratory directly linked bilingualism to a neural correlate of cognitive inhibition. Specifically, we revealed that relative to monolinguals, bilinguals show greater N2 amplitude in the event-related brain potential (ERP) during a non-linguistic, auditory Go/NoGo task, in the absence of behavioral differences [9]. ERPs are electrical potentials that are time-locked to a cognitive event and are generated by populations of neurons within milliseconds after event. Because of their temporal resolution, ERPs are considered the gold standard for observing neural activity across time. We measured the N2 ERP component (a negative going wave in 200–300 ms post-stimulus time window, with maximum amplitude over frontal-central sites) because it has been linked to non-motor, neural inhibition [10,11]. Results of our study revealed that compared to monolinguals, bilinguals showed enhanced N2 amplitude on tasks that required inhibitory control (NoGo task), but performance was similar between the groups on tasks that did not require inhibition (Go task).Moreover, second language proficiency scores were correlated with NoGo N2 amplitude, such that higher second language proficiency was associated with greater inhibition. To our knowledge this was the first and only study to directly link bilingualism to an ERP marker of cognitive inhibition and to suggest that inhibition in bilinguals is moderated by second language proficiency. In fact, one ERP study [12] comparing bilinguals and monolinguals on executive function tasks did not reveal greater inhibition in bilinguals or between-group reaction time (RT) differences. Their results are inconsistent with our findings and do not suggest better neural inhibition or an advantage on behavioral tasks in bilinguals. However, it is difficult to compare these studies because our task was a simple, non-linguistic, auditory task, while their tasks were more complex, visual tasks. Similarly, Luk et al. [13] found neither behavioral nor fMRI differences during a visual Go/NoGo task. Their findings showed that the same brain region mediates inhibitory control in bilinguals and monolinguals and no bilingual advantage. Differences between their findings and ours may be because their task was visual and our task was auditory. It is possible that inhibitory control in bilinguals is better developed in the auditory than in the visual modality since the experience of being bilingual relates directly to auditory as opposed to visual attention processes. Indeed, compared to monolinguals, dual-language speakers continuously “fine tune” their auditory system and are shown more efficient at automatically processing sounds [14].

Thus, the present study was developed 1) to replicate our original findings revealing enhanced inhibitory control in the auditory modality in bilinguals and 2) to clarify whether enhanced neural inhibition in bilinguals extends to the visual modality. Based on our previous results, we predicted that relative to monolinguals, bilinguals would show greater N2 amplitude during auditory NoGo trials and no differences during Go trials. We further predicted that, also consistent with our original work, greater neural inhibition (N2 amplitude) would be correlated with greater second language proficiency scores. With regard to the visual modality task, we speculated that because of the intrinsic link between the auditory system and language control, that inhibition in bilinguals would be better developed in the auditory compared to the visual modality and that the visual NoGo N2 amplitude would not distinguish bilinguals from monolinguals

2. Methods

2.1. Participants

Right-handed participants, 18–35 years of age, who spoke English (Monolingual Group) or Spanish and English (Bilingual Group) were recruited. Only participants with normal hearing and normal or corrected-to-normal vision participated. Participants were rejected if they had a history or a family history of neurologic or serious mental illness, or if they were taking medications that affect the EEG. Testing procedures were carried out according to a protocol approved by the Nova Southeastern University Institutional Review Board, and all participants read and signed a consent form prior to testing. Participants received a $30 gift card to compensate them for their time.

2.2. Questionnaires, neuropsychological tests, &ERP tasks

Edinburgh Handedness Inventory: This freely available self-report questionnaire was used to verify handedness; only right handed participants were recruited.

Background &language questionnaire: A background and language questionnaire, specifically developed for this study, was used to determine socioeconomic status (SES), parental education, country of birth of participants and their parents, first language spoken by participant, age of second language acquisition, frequency of Spanish language usage at home, work, school, and in social settings.

Oral vocabulary subtest of the Bilingual Verbal Ability Test [15]. The Oral Vocabulary subtest is one of three subtests that make up this standardized instrument used to assess English language proficiency and overall verbal ability in non-native English speakers. This test is administered in English to quantify English language proficiency. Items failed in English are administered in the person’s native language (this test is available in numerous languages including Spanish) and scores are combined to determine overall language ability. For our study, we administered the English version of the Oral Vocabulary subtest (synonyms and antonyms) to all participants and the Spanish version to all bilinguals to quantify English language proficiency in all participants and Spanish language proficiency in bilinguals.

Matrix Reasoning subtest of the Wechsler Adult Intelligence Scale-Fourth Edition [16]. This is a standardized and widely used subtest of nonverbal fluid intelligence, and was used to assess equivalence of general intelligence between the groups.

Auditory Go/NoGo ERP task: This task, which is the same task we employed in first study [9], consisted of four blocks of 50 trials for a total of 200 trials, and each trial consisted of two tones. The intra-trial interval between the onset of the first and second tone was 1200 ms and inter-trial interval was 1800 ms. High (1100 Hz) and low-pitch (1000 Hz) pure tones (40 ms duration, 5 ms rise and fall times; 70 dB SPL) were presented binaurally through headphones. The combination of low and high tones generated four different trials (High/High, N = 72; High/Low, N = 72; Low/High, N = 28; Low/Low, N = 28). Participants pressed the space-bar key on a computer keyboard with their right index finger in response to the second tone in a pair when two target stimuli (the high tone for all participants) were presented within a trial and withheld their response on all other trials. Trials in which the first tone was low (Low/High & Low/Low trials) and participants did not have to get ready to either respond (High/High tone trials) or withhold their response (High/Low tone trials) were not analyzed. Only the High/High tone trials (Go trials, N = 72) and the High/Low tone trials (NoGo trials, N = 72) were analyzed. RT and accuracy of responses to the second tone on Go and NoGo trials were recorded.

Visual Go/NoGo ERP task: The visual Go/NoGo task used the same format as the auditory Go/NoGo task, but the stimuli were presented on the center of a 23 inch computer monitor (HP Compaq LA2306x) and consisted of 40 ms duration, 4X3 inch white triangles and rectangles on a black background. Participants pressed the space-bar key in response to the second stimulus in a pair when two targets (the rectangle for all participants) were presented within a trial and withheld their response on all other trials. As in the auditory task, trials in which the first stimulus was not a target (Triangle/Rectangle, Triangle/Triangle) were not analyzed. Only the Rectangle/Rectangle trials (Go trials, N = 72) and the Rectangle/Triangle trials (NoGo trials, N = 72) were analyzed. RT and accuracy of responses to the second figure on Go and NoGo trials were recorded.

2.3. EEG recording

The ongoing electroencephalogram (EEG) was recorded using Psychlab EEG amplifying and recording equipment software (Contact Precision Instruments, Cambridge, MA) with a cap (Electro-Cap International, Eaton, OH) fitted with pure tin-cup electrodes placed in accordance with the 10–20 International System of electrode placement and referenced to the earlobes. The EEG was recorded from Fz, Cz, Pz, F3, F4, C3, C4 electrode locations. Two electrodes monitored ocular activity one placed above and the other on the outer canthus of the left eye. Electrode impedance was maintained at less than 5 kΩ. Low and high pass filters were set at 40 and 0.1 Hz, respectively, and a 60 Hz (50 dB/octave) notch filter was active. The EEG amplifier was set at a gain of 30,000 and the EEG sampling rate was 500 Hz. Data were analyzed offline using Psylab8 software (Contact Precision Instruments, Cambridge, MA). Trials contaminated with eye blinks exceeding ± 50 µV, were automatically rejected. The remaining trials were visually inspected and rejected if contaminated with excessive eye movement, muscle artifact, or alpha activity.

EEG activity of 1400 ms duration, including 140 ms pre-stimulus baseline was averaged to extract the ERP. The ERP in response to the second stimulus (auditory and visual) in Go and NoGo trials was extracted separately as was the ERP to the first tone in these trials. All trials were baseline (140 ms) corrected.

2.4. Procedure and design

After participants read and signed the consent form, the examiner administered the handedness inventory, background and language questionnaire, the Oral Vocabulary subtest of the BVAT in Spanish and/or English, and the Matrix Reasoning subtest. Participants were then fitted with the electrode cap and conductive gel was inserted into each electrode with a blunt needle. Earlobes and the skin around the left eye were abraded with skin-prepping cream before attaching the electrodes and inserting the conductive gel. Prior to starting the ERP task, participants were instructed to focus their eyes on an “X” in the center of the computer monitor positioned on a desk in front of the participant approximately 24 inches from the face. Participants were instructed to relax, to keep eye movement to a minimum, to place their right hand on the desk close to the computer key board, and to press the response key (space bar) with the right index finger as quickly as possible when targets were presented. The headphones were securely placed on the participant, and they were given 20 practice trials to familiarize themselves with the tones and the task. Participants were given brief breaks between blocks of trials to blink and to stretch. The auditory Go/NoGo task was followed by the visual Go/NoGo task. Prior to the start of the visual Go/NoGo task, the headphones were removed and participants were given 20 practice trials to familiarize themselves with the visual task. The EEG was not recorded during practice trials. Once participants completed the practice trials, EEG recording began. After completion of the ERP task, the cap was removed and participants were given the gift card.

3. Results

Statistical analyses were conducted using IBM SPSS version 20 for Windows. Level of significance was set at $\alpha < 0.05$, and two-tailed probabilities are reported unless otherwise specified. The Greenhouse-Geisser adjustment was used to compensate for any violations of the assumption of circularity and the adjusted p values and epsilon values (ε) are reported.

A total of 41 participants were tested, 19 English monolinguals and 22 Spanish/English bilinguals. Both language groups were matched on age, sex and years of education. A total of six participants did not generate usable EEG data, therefore, 35 participants (Monolinguals, $N = 17$; Bilinguals, $N = 18$) comprised the final sample. Moreover, some participants generated usable EEG data in one modality but not the other. For this reason, 26 participants (13 in each group) generated usable EEG data during the auditory task and 30 (15 in each group) during the visual task.

3.1. Demographic data

Bilinguals ($N = 18$) and Monolinguals ($N = 17$) were similar in age, male/female ratio, socioeconomic status, years of education, household income, and parental education. Table 1 lists means and standard deviations (SD) and results of between-group comparisons for age, sex ratios, education, household income, and parental education. All monolingual participants were born and raised in the United States and lived in monolingual households. Most bilingual participants (11/18) were born in Central or South America and all lived in the United States in bilingual households. The rest of the bilingual participants were born in the United States (6/18), one was born in Puerto Rico, and grew up in a bilingual household. Most bilinguals spoke Spanish before English (15/18), the mean age of second language acquisition was 6.22 (4.80). Two bilinguals learned their second language at age 9, one at age 13 and one at age 22. At school and work bilinguals spoke English almost exclusively.

Table 1. Demographic information, test scores, & reaction times by group.

Demographics	Monolingual group N = 17 Mean (SD)	Bilingual group N = 18 Mean (SD)	Significance test
Age	20.41 (2.40)	22.06 (3.80)	t(33) = 1.521, P = 0.138
Male/Female	4:13	5:13	
Education (yrs)	14.35 (1.22)	15.06 (1.26)	t(33) = 1.674, P = 0.104
Household Income	5.47 (1.81)[b]	4.88 (1.50)[c]	t(32) = 1.034, P = 0.309
Parental Education	3 (1.32)[d]	3.56 (1.15)[d]	t(33) = 1.329, P = 0.193
Neuropsychological test scores			
Matrix reasoning SS *	12.12 (3.26)	11.78 (1.83)	t(33) = 0.383, P = 0.704
BVAT (English)	33.18 (4.26)	31.28 (3.88)	t(33) = 1.308 P = 0.177
BVAT (Spanish)		26.39 (4.53)[a]	
Reaction time data			
Go Auditory trials RT	639.9 (178.7) n = 6	749.6 (312.6) n = 11	t(15) = 0.786, P = 0.444
Go Visual trials RT	552.28 (322.54)	778.27 (647.93)	t(28) = 1.209, P = 0.237

[a] Spanish BVAT scores < English BVAT scores t(17) = 4.586, P = 0.000); [b] 5 = \$41.000–60.000; [c] 4 = \$21.000–40.000; [d] 3 = Some college/technical school/AA; *SS = Scaled Scores have a mean of 10 and a SD of 3.

3.2. Neuropsychological data and reaction times in the auditory and visual tasks

Table 1 also shows means, SD, and results of between-group comparisons for neuropsychological tests and RT during the auditory and visual Go/NoGo task. As seen in Table 1, Bilinguals and Monolinguals performed similarly on the Matrix Reasoning subtest of the WAIS-IV and on the Oral Vocabulary subtest of the English BVAT. As expected, and consistent with our previous findings, Bilinguals obtained significantly higher scores on the English BVAT (their second language) than on the Spanish BVAT.

Mean RT on Go trials, both in the auditory and visual modalities, did not reveal group differences. Because of a technical error, we only collected auditory RT data on 17 participants (Monolinguals N = 6, Bilinguals N = 11). Errors of commission during NoGo trials were not analyzed because very few participants committed errors (pressed the response button) during these trials, and this occurred on no more than4 trials in the auditory task and 6 trials in the visual task (out of 72 trials in each modality).

3.3. ERP data

Mean N2 amplitude during Go and NoGo trials in the auditory and visual tasks was computed as the difference between N2 mean peak amplitude in the 236–316 ms time window and P3 mean peak in the 180–260 ms time window.

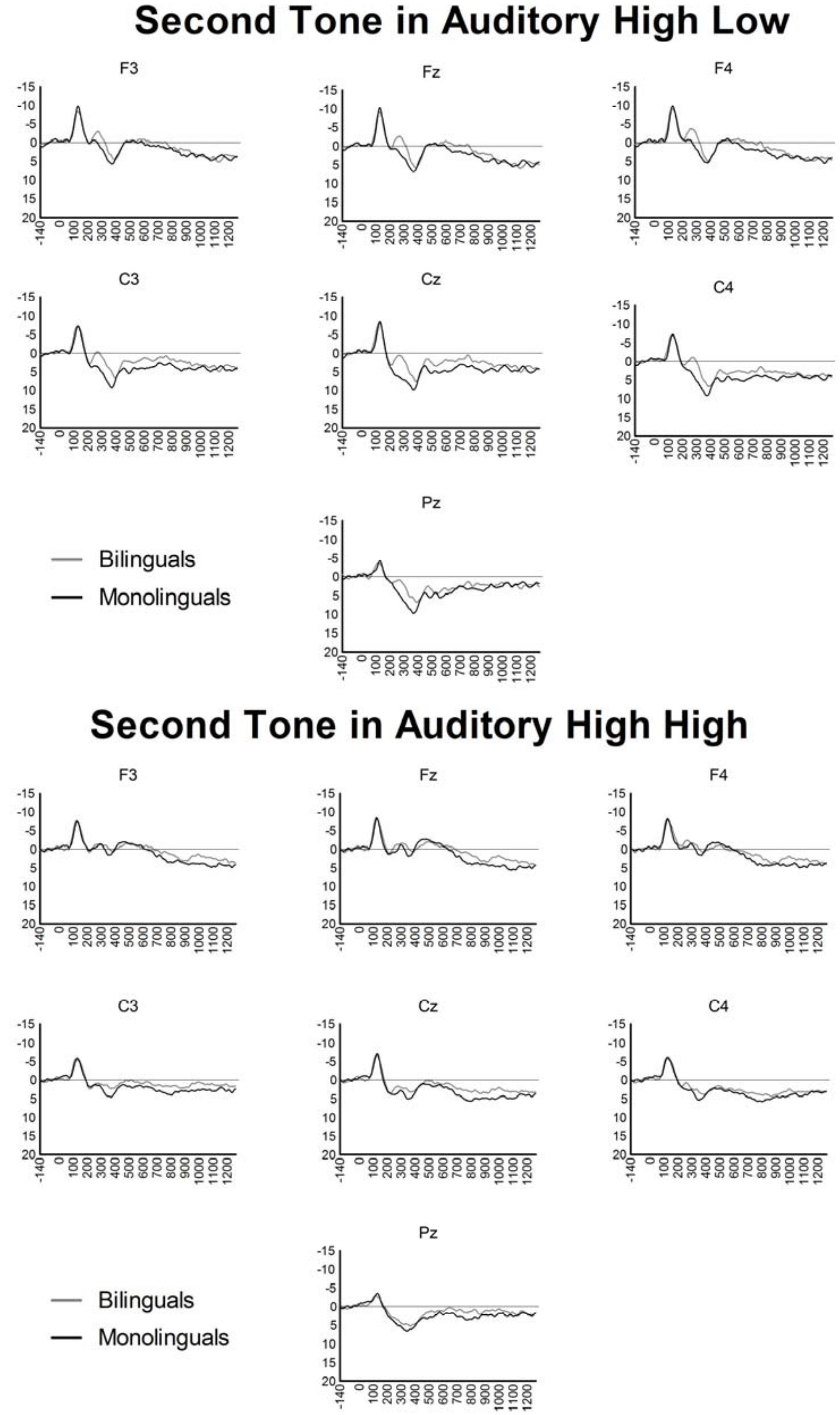


Figure 1. The auditory ERP to the second tone in the High/Low trials (NoGo trials) and in the High/High trials (Go trials) for each group at each electrode location.

3.3.1. Auditory N2

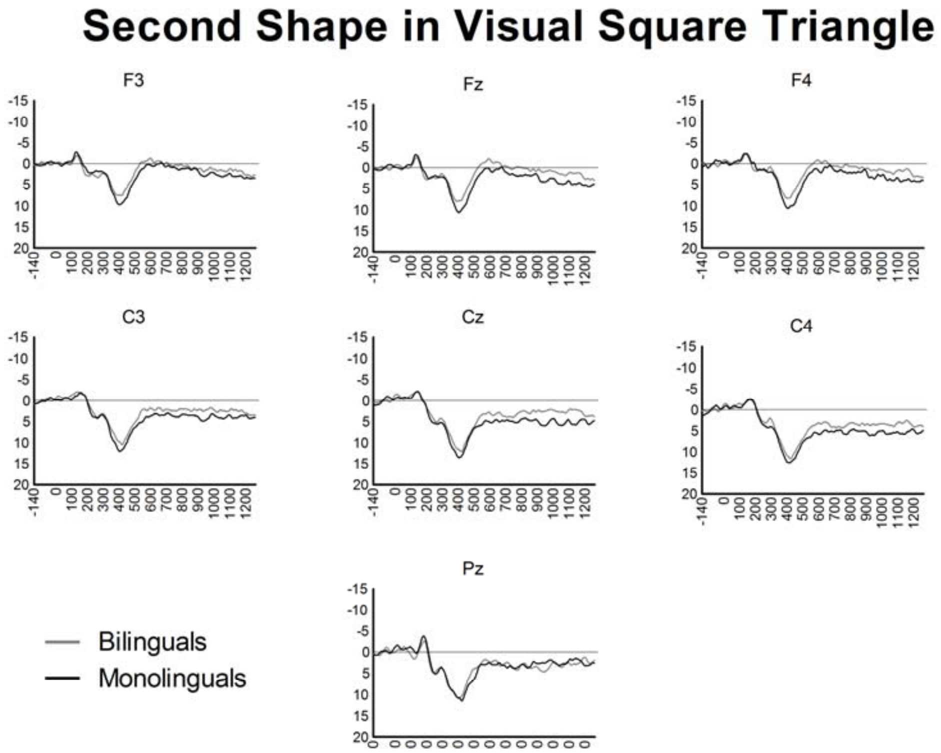
A Group (2) X Trial Type (2) X Electrode (7) repeated measures ANOVA on mean N2 amplitude revealed a Group X Trial type interaction *F*(1,24) = 6.951, *P* = 0.014, $\eta p^2 = 0.225$. Test of simple effects revealed a significantly more negative N2 amplitude for Bilinguals [*M* = -0.587(2.6)] than for Monolinguals [*M* = 1.845(3.01)] on NoGo trials *F*(1,24) = 5.906, *P* = 0.023, $\eta p^2 = 0.197$, Cohen's effect size value *d* = 0.863. Go-trial mean N2 amplitude did not distinguish the groups [Bilinguals, *M* = -0.396(2.02); Monolinguals, *M* = -0.045(1.86)] *F*(1,24)= 0.249, *P* = 0.622, $\eta p^2 = 0.010$, Cohen's effect size value *d* = 0.180. Neither the three-way interaction nor the main effect of trial was significant (all *P* values > 0.05). Figure1 shows the auditory ERP to the second tone in the High/Low trials (NoGo trials) and in the High/High trials (Go trials) for each group at each electrode location.

3.3.2. Visual N2

A Group (2) X Trial Type (2) X Electrode (7) repeated measures ANOVA on mean N2 amplitude revealed a main effect of trial type with NoGo trials showing greater N2 amplitude than the Go trials *F*(1,28) = 5.296, *P* = 0.029, $\eta p^2 = 0.159$ [Go trials, *M* = -1.29(0.552); NoGo trials *M* = -2.54(0.442)]. In contrast to the auditory ERP task, there was no Group by Trial type interaction, (*P* = 0.267). Similar to the auditory ERP task, the three-way interaction was not significant (*P* = 0.305). Figure 2 shows the visual ERP to the second shape in Square/Triangle trials (NoGo trials) and Square/Square trials (Go trials) for each group at each electrode location.

3.3.3. ERPs to the first stimulus in the auditory and visual modality

Statistical analyses on the N2 to the first stimulus did not reveal between group differences (all *P* values > 0.05). Figure 3 shows the ERPs to the first target stimulus in the auditory (High tone) and visual modality (Square shape) for each group at each electrode location. As seen in this figure, the two groups showed identical ERPs to the first target stimulus.



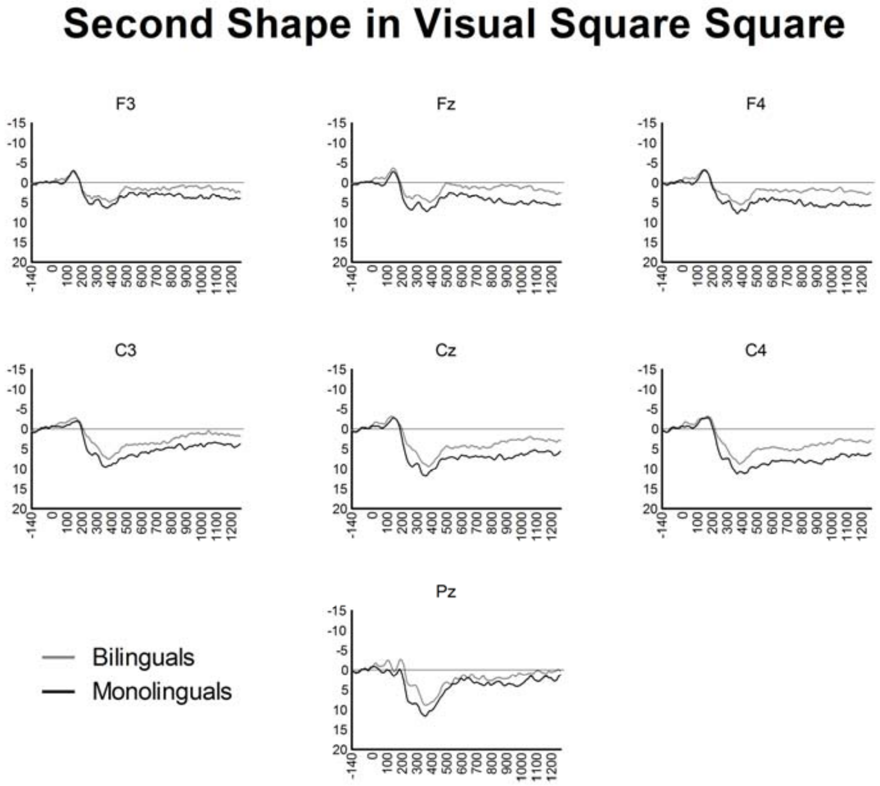
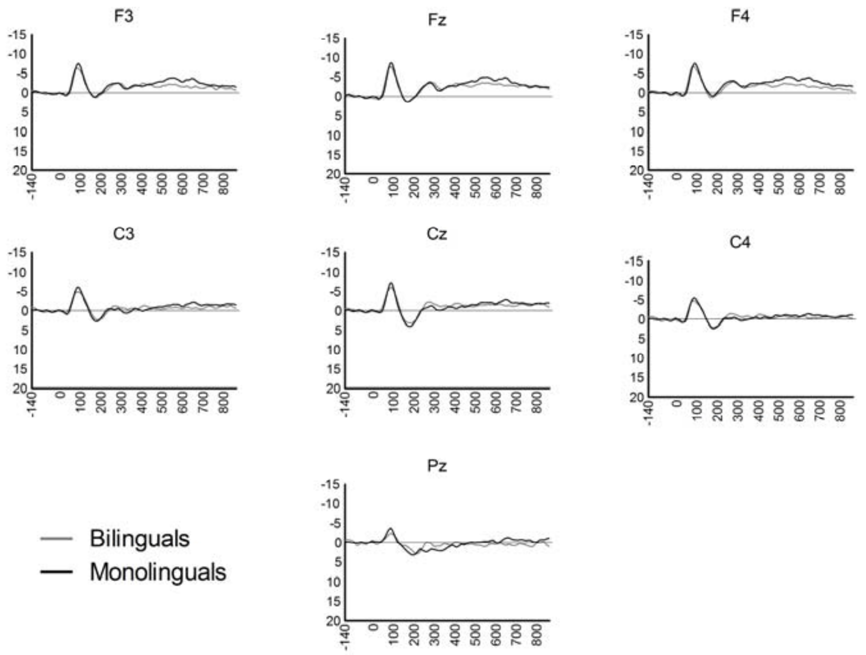
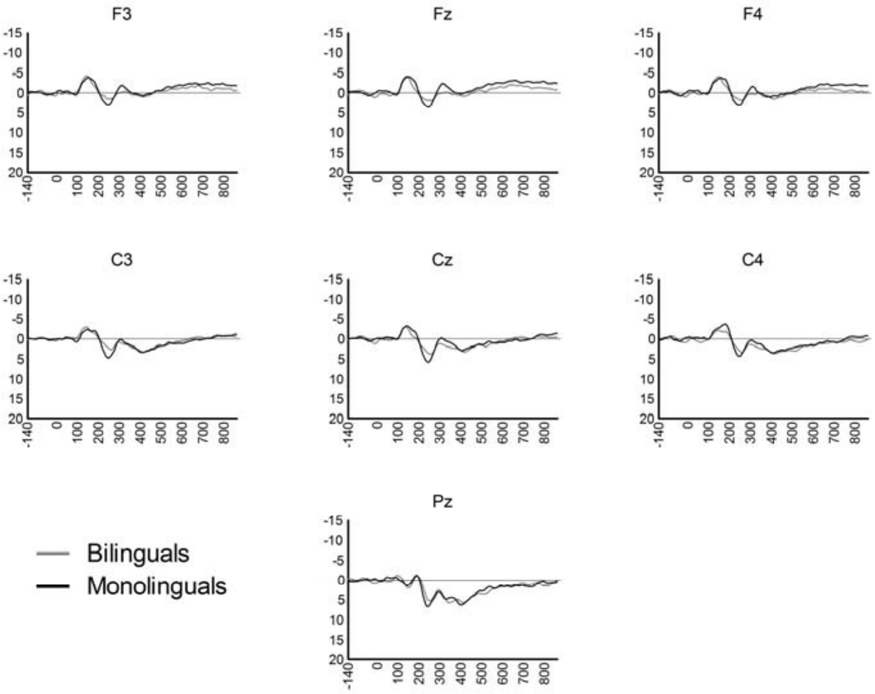


Figure 2. The visual ERP to the second shape in Square/Triangle trials (NoGo trials) and Square/Square trials (Go trials) for each group at each electrode location.



First Tone in Auditory (High)



First Shape in Visual (Square)

Figure 3. ERPs to the first target stimulus in the auditory (High tone) and visual modality (Square shape) for each group at each electrode location.

3.4. Correlation between inhibition and second language proficiency

To test the hypothesis that higher second language proficiency is correlated with greater neural inhibition, we correlated second language proficiency scores with NoGo N2 amplitude. Pearson correlations revealed that the strength of the relationship approached but did not reach statistical significance at electrode Cz (r = -0.436, P = 0.068) one-tailed probability. Other electrode locations did not approach significance (all P values > 0.10).

4. Discussion

This study replicates and extends our original findings of enhanced inhibitory control in bilinguals and reveals that controlling two languages in the brain refines cognitive inhibition in the auditory but not the visual modality. We measured the N2 ERP component as a marker of cognitive inhibition while participants performed an auditory and a visual Go/NoGo task. The first goal of this study was to replicate our original findings and our results confirmed that relative monolinguals, bilinguals exhibit greater N2 amplitude during the auditory NoGo trials. During the Go trials, however, neither the N2 amplitude nor RT distinguished the groups. An advantage of our study design is that we presented pairs of stimuli within each trial and thus were able to compare the groups on ERPs across three trial conditions: trials that required a motor response (second target stimulus in Go trials), trials that required inhibition of a motor response (second stimulus in NoGo trials), and on ERPs to passive target stimulus (first stimulus in Go and NoGo trials). Importantly, only trials that required inhibition in auditory modality revealed group differences. Demographic variables, neuropsychological test scores and RT did not account for our ERP findings because between-group comparisons of educational level, household income, parental education, scores on a test of nonverbal intelligence, on the English BVAT, and on RT were non-significant.

New to this study was the visual Go/NoGo task, which did not reveal between-group differences. This finding is consistent with other studies that employed visual tests of executive function to compare language groups [12,13]. Because we tested participants in both, auditory and visual modalities, we were able to determine that enhanced inhibition in bilinguals is modality specific and favors the auditory over the visual. Moreover, these findings are consistent with animal studies investigating the link between sensory plasticity and cortical inhibition [17,18]. Results are also consistent with ERP studies suggesting that NoGo N2 reflects modality specific inhibition [9,10]. If experience-dependent changes in inhibition processes occurred broadly, we would expect to see greater NoGo N2 amplitude across the two modalities in bilinguals compared to monolinguals, and this was not the case. Lastly, our results reveal that the N2 ERP component is a sensitive marker of neural inhibition and useful for distinguishing bilinguals and monolinguals.

One finding that we did not replicate was the correlation between second language proficiency scores and the auditory NoGo N2 amplitude. However, we did find the same trend here—higher language proficiency scores were correlated with greater inhibition (i.e., more negative N2 amplitude) but the strength of the relationship approached (P = 0.068), but did not reach statistical significance. Additionally, in our original study the strength of this relationship was strongest at electrode location F4 while in this study the highest association was found at electrode Cz. One difference between participants in the current study and our previous study is that in the original study, all participants learned their second language by age 6. In this study, two participants learned their second language by age 9, one by age 13, and another by age 22. We don’t know whether this difference in age of second language acquisition diminished the strength of the relationship between these two variables. Nevertheless, it is noteworthy that the relationship between second language proficiency and neural inhibition was in the predicted direction. Moreover, ERP studies show that NoGo N2 amplitude is greatest at frontal-central sites, which is consistent with our findings.

4.1. Limitations and future directions

While interesting, and contributing to our understanding of bilingualism and neural inhibition, these findings must be interpreted with caution because of small sample and because we only employed one ERP task. Studies that include multiple ERP tasks that require inhibition and greater sample size will strengthen understanding of inhibitory control and neural plasticity in bilinguals.

Overall, our study and others shed light on how experience-dependent dual language use contributes to long-term functional changes in neural plasticity. Our present and previous work shows that inhibition may be enhanced or refined through experience, but in a circumscribed manner. It appears within sensory domain that is most exercised in the practice of speaking two languages. It is tempting to think that this type of inhibition contributes to the widespread changes in cognitive performance and decreased cognitive decline with aging that is seen in bilinguals compared to monolinguals [19], but more work needs to be done to clearly link bilingualism, inhibition and aging especially, since inhibition is essential for successful interactions with the environment and is a key component of sensory gating [20]. Indeed, according to inhibition deficit model of aging, inhibitory processes are particularly likely to decline with age and age-related declines in cognitive control can be explained by decreases in inhibitory control over behaviors and thoughts [21,22]. Given that our N2 findings were observed in a relatively young group of participants, we are planning follow-up studies to test older dual-language adults in order to observe if 1) N2 inhibition effect observed here and in our previous work is more pronounced in an older bilingual population; 2) inhibition processes begin transfering across domains in older adults (i.e. to the visual domain); 3) if these neural changes are related to performance differences on an inhibitory task in older bilingual adults.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

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