# THE EFFECTS OF BILINGUALISM ON SPEECH EVOKED BRAINSTEM RESPONSES RECORDED IN QUIET AND IN NOISE

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## Résumé

L'objectif principal de cette étude était d'évaluer l'effet de l'enrichissement sensoriel, tel que le bilinguisme, sur le traitement auditif sous-cortical, dans deux types de conditions d'écoute : dans le silence et dans le bruit. Plus spécifiquement, le but de cette étude était d'identifier des marqueurs biologiques neuronaux, au niveau du tronc cérébral, qui distinguent les bilingues des monolingues. Quarante et un adultes âgés de 18 à 25 ans ont participé à l'étude: 19 monolingues et 22 bilingues. Leur maîtrise de la langue a été évaluée à l'aide d'un questionnaire LEAP (*Language Experience and Proficiency*). Les potentiels évoqués auditifs du tronc cérébral (PÉATC) ont été enregistrés en utilisant des stimuli de clics et des stimuli verbaux (/da/), dans le silence ainsi que dans le bruit (stimuli verbaux seulement). Aucunes différences significatives n'ont été observées entre les deux groupes avec les PÉATC enregistrés par les clics. Les ondes transitoires évoquées par les stimuli verbaux (V, C) et les latences de la région périodique (D et F) étaient plus longues pour le groupe monolingue que pour le groupe bilingue. La réponse soutenue en fréquence (*frequency following response*) F0 et F1 des PÉATC verbaux était similaire pour les deux groupes dans le silence et dans le bruit. Les résultats suggèrent que, les monolingues ont besoin de plus du temps pour traiter les stimuli verbaux que les bilingues. Très tôt dans le système auditif, on constate que le traitement neuronal de leurs réponses aux stimuli verbaux en absence ou présence de bruit semble moins robuste que celui des adultes maîtrisant les deux langues. Le bilinguisme pourrait stimuler les capacités de traitement automatique du son du système auditif de manière à améliorer son efficacité. De surcroît, cette étude confirme le potentiel d'utilisation des PÉATC en réponse à des sons de parole en tant qu'outil clinique pour la détection de marqueur biologique.

**Mots clefs :** potentiels évoqués auditifs sous-corticaux; potentiels évoqués auditifs du tronc cérébral avec stimuli verbaux; bilinguisme; plasticité dépendant de l'expérience; enrichissement sensoriel

## Abstract

The main objective of the present study was to investigate the effect of sensory enrichment, such as bilingualism, on the subcortical processing in quiet and adverse listening conditions such as in the presence of noise. More specifically, the aim of this investigation was to identify some neural biomarkers at brainstem level distinguishing bilinguals from monolinguals. Forty-one 18- to 25-year-old adults participated in the study: 19 monolinguals and 22 bilinguals. Their language fluency was assessed with the Language Experience and Proficiency (LEAP) questionnaire. Auditory Brainstem Responses (ABRs) were recorded using click and speech /da/ stimuli in quiet and also in noise for the latter. No significant differences between the two groups were observed for click-evoked ABR. The speech-evoked ABR transient waves (V, C) and the periodic region (D and F) latencies were longer for the monolinguals compared to the bilingual group. The Frequency Following Responses (F0 and F1) of the speech-evoked ABR were similar for the two groups in quiet and in noise. Results suggested that monolinguals need more time to process speech stimuli than their bilingual peers. Early in the auditory system, the neural responses related to speech processing in the absence or the presence of background noise seem to be less resilient when compared to those of adults who are fluent in two languages. Bilingualism could stimulate the automatic sound processing abilities of the auditory system in a way that makes it highly efficient. Furthermore, this study demonstrated the applications of speech-ABR and its potential usefulness as a clinical biomarker.

**Keywords:** sub-cortical auditory evoked potentials, speech-ABR, bilingualism, experience-dependent plasticity; sensory enrichment

## 1 Introduction

Early life experiences and adversity have a powerful impact on the developing brain and influence on brain function [1-4]. Personal development and long life experience alter the brain's physical structure and shape its neural networks, allowing it to adapt to its environment [1-3, 5]. Neuronal plasticity is the idea that neural pathways can be strengthened through repetitive use [6]. Markham et al. (2004) [7] reported that experience-dependant plasticity is a dynamic interaction between one's environment (nurture) and the biological make-up of one's brain (nature).

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Experience-dependent plasticity is affected by how individuals adapt to the demands of their environment leading to reorganization of the brain at the cellular level [7].

The interaction between subcortical and cortical processes allows modifications of our perceptual system, changing how external sensory information is perceived [8, 9]. The cerebral plasticity is particularly evident in individuals who are in constant contact with auditory-enriched environments, such as musicians [10, 11], speakers of tonal languages [12, 13], children with rigorous auditory training [14] and bilinguals [15, 16]. Krizman et al. 2014 [16] recorded subcortical neurophysiological responses to speech sound in 14-year-old high school Spanish-English bilinguals and English monolinguals. The stimuli taken were the consonant-vowel (CV) phoneme /da/ of 170 ms in quiet and background noise which consisted of multi-talker babble. Krizman et al. (2014) [16] illustrated that in bilingual adolescents the efferent neural pathways that connect the executive system of the frontal cortex with the subcortical auditory system are more efficient than in monolinguals. The efferent pathways appear to optimize the perception and encoding of auditory stimuli based on what the auditory system is receiving from the environment [15, 16]. By using speech auditory evoked response, Krizman et al. (2012) [15] found that there exists a relationship between enriched linguistic environments - such as a bilingual environment in contrast to a monolingual environment - and the neural response of the auditory system. Although cortical and subcortical auditory evoked responses were present in both monolingual and bilingual groups, the two evoked potentials of the bilinguals were more pronounced (e.g., larger amplitude) than in the monolingual cohort [15, 16]. Moreover, in contrast to those who acquired a second language at a later stage, bilinguals from birth showed better encoding of the fundamental frequency of speech sounds /ba/ and /ga/ [17].

The speech-auditory brainstem response, Speech-ABR, is utilized as an objective tool to observe how subcortical structures of the auditory pathway encode speech sounds [9, 18, 19]. The chosen phonemes (e.g., /da/) are found in the majority of languages and no one group has a greater advantage over the other in processing that sound ([9]. When plotted on a time-amplitude domain, its peak amplitudes and latencies correspond with the acoustic features of its evoking acoustic stimulus [9, 18, 19]. Speech-ABR would provide an objective index of the brainstem and midbrain's representation of complex sounds [9, 18, 19].

The present study aims to determine whether subcortical neural biomarkers would distinguish between bilingual Canadian young adults who experience a linguistic environment composed of two or sometimes more languages, and monolinguals. For the current investigation, we hypothesized that bilingual adults exhibit more efficient auditory processing capacities in quiet and noisy conditions compared to monolinguals as has been observed in Krizman et al.'s study with high school children (2014) [16].

## 2 Materials and Method

All procedures were approved by the Office of Research Ethics and Integrity at the University of Ottawa. Participants provided informed consent before the experiments.

### 2.1 Participants

Forty-one 18-to-25-year-old students were divided into two experimental groups based on answers to the Language Experience and Proficiency (LEAP) [20] questionnaire as well as oral expression with native speakers: 19 monolinguals (mean 22.8 yrs, standard deviation (SD) 1.4, 11 females) and 22 bilinguals (mean 23.1 yrs, SD 0.79, 19 females). A hearing screening test was conducted to ensure that participant's hearing sensitivity was within normal limits (thresholds < 20 dB HL) between 250 Hz to 8000 Hz. Although more females were recruited than males in the present study, the two groups were matched in sex, age and hearing threshold.

### 2.2 Questionnaire

The participants' linguistic capabilities and environment were evaluated by the LEAP questionnaire, available in either the English or French (Marian, Blumenfeld, and Kaushanskaya, 2007) [20]. Participants responded to the questionnaire using a subjective rating scale from zero to ten, and provided information on the daily use of their spoken language (i.e. the proportion of each language spoken) and the age of language acquisition and fluency. The responses to the questions of language proficiency were evaluated to identify bilingual participants. Participants who rated their proficiency and fluency greater than six and spoke two languages were placed in the bilingual group. The participants in the monolingual group spoke either French or English. The bilingual group spoke both French and English.

### 2.3 Electrophysiology

#### Preparation

The electrophysiological protocols were run using both click and speech ABR. The BioMAP® software in the Biologic Navigator Pro System (Natus Medical Inc.) was used to collect and analyze the recordings. Participants were prepared for the electrophysiological testing by having three contact zones scrubbed with an abrasive gel and alcohol swaps. The data was recorded with an active electrode placed at the vertex and the reference placed on the right ear. The forehead acts as the ground. An intra-auricular earphone (EARLINK 3B) was placed into the participant's right ear. The impedance of each electrode was less than 5 kΩ and the impedance difference between the electrodes was never greater than 2kΩ.

#### ABR with click stimulus

Click-evoked ABR was conducted on all participants across both groups. Rarefaction 100 µsec clicks were presented to the right ear at an intensity of 80 dB peak SPL and were bandpass filtered on-line from 100 to 1500 Hz. The rate of presentation was 13.3 clicks/s. A block of 1500 artifact free sweeps was recorded. The entire procedure was presented a second time and the data collapsed across the two blocks (total of 3000 artifact free sweeps).

### Data acquisition of speech ABR with and without competitive noise

The speech ABR was recorded to a 40 ms custom speech /da/ syllable from Bio-Logic software (Figure 1). The stimulus consisted of five formants with a transition between the consonant [d] and the vowel [a] [9, 21]. After the initial 5 ms, the fundamental frequency (F0) transitioned from 103 to 121 Hz between 0 and 35 ms, and reached 121.2 Hz between 35 ms and 40 ms [9, 21]. The stimulus was presented to the right ear at a rate of 10.9 stimuli per second at 80 dB SPL with an alternating polarity. The phoneme was presented in both quiet and noise conditions. In the latter, the phoneme was presented in continuous white noise with a signal-to-noise-ratio (SNR) of +10 dB. A total of 2000 artifact free stimuli were collected in each condition. The stimuli were presented a second time (i.e., the averages were based on 4000 artifact free presentations) and averaged using a 85.33 ms (including a 15-ms pre-stimulus time window). The responses were amplified 100,000 times, and were bandpass filtered on-line from 100 to 2000 Hz. Artifacts were rejected online at ± 23 µV and did not exceed 10% of the total number of sweeps. In all conditions, participants were asked to remain calm and relaxed, and the lights inside the audiological cabin were dimmed.

### Data processing

Data processing and averaging were performed usingBioMAP® software in the Biologic Navigator Pro System. The two recorded waveforms (4000 sweeps) were weighted average. The weighted response was compared with normative template during analysis. All waves of the click and speech-ABR were identified and marked manually by three independent experienced scorers. Click-ABR waves were replicated twice and visually marked as waves I, III and V. The speech ABR waves (responses) consist of onset peaks labelled as A and V, a consonant–vowel transition peak C, and an offset wave O. In addition, three sustained frequency following response (FFR) waves D, E and F were observed. These responses were thus quantified in the speech-ABR weighted average waveforms.

In addition to the temporal analysis (Figure 2), spectral analysis, F0 and F1, (Figure 3) was performed on the sustained portion of the speech-ABR using the Brainstem Toolbox [9] under MATLAB v.8.1 (MathWorks, Natick, MA). Fast Fourier Transform (FFT) analysis of the response was performed, with zero padding, over the period of 11.4–40.5 ms to evaluate the spectral composition of the response. The magnitudes of frequency representation over the stimulus F0 (103–121 Hz) and F1 (454–720 Hz), were measured by taking the average of the amplitudes over the specified frequency ranges.

### Statistical analysis

All statistical analyses were completed using IBM SPSS Statistics V24. Dependent measures included timing (i.e., the latencies in ms for waves V, A, C, D, E, F and O of the speech-ABR and the peak latency for peaks I, III and V of the click ABR), magnitude (the amplitudes of the waves) and the spectral representation (i.e., F0 and F1). For each dependent measure, ANOVA analyses of variance were used for the group factor (monolinguals, bilinguals) in the two conditions (quiet vs. noise). In all cases, p-values reflect two-tailed tests. Levene’s test was used to ensure homogeneity of variance for all measures.

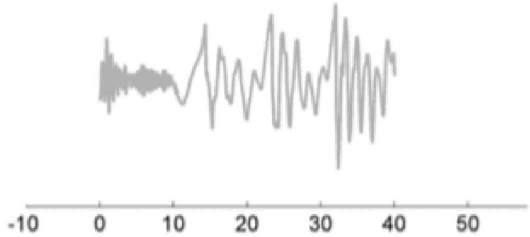

**Figure 1.** Time-domain representation of a 40 ms custom speech stimulus /da/.

## 3 Results

No significant differences were observed between the groups for ABR wave latencies (p≥ 0.05) and amplitudes (p≥ 0.05) in response to click stimuli.

### 3.1 Speech ABR

Figures 2 and 3 illustrate the grand average responses to speech stimuli in the two groups recorded in two conditions. Tables 1 and 2 show the latency and amplitude values for the speech ABR in the two groups of participants measured in two testing conditions.

### Neural Timing (Latency)

Significant condition (with and without noise) effects were observed for all the waves (V, A, C, D, E, F and O). Longer latencies were observed in the noisy condition than in the quiet condition. The group factor (bilingual or monolingual) was significant for the V, C, D and F waves. Significant longer latencies were observed in monolinguals than in bilinguals. The interaction between condition X group factors was significant only for the wave C: [F (1, 39) = 7.5, p = 0.009, ηp2 =0.16] (see Table 1). An analysis of simple effects for this significant interaction indicated that longer latency was observed in monolinguals when the stimulus was presented in +10 signal to noise ratio. Wave C latency was longer in monolinguals (mean 20.39, SD= 1.3 ms) than bilinguals: (mean 19.04, SD = .85 ms), [t (18) = 5.05, p = 0 .000].

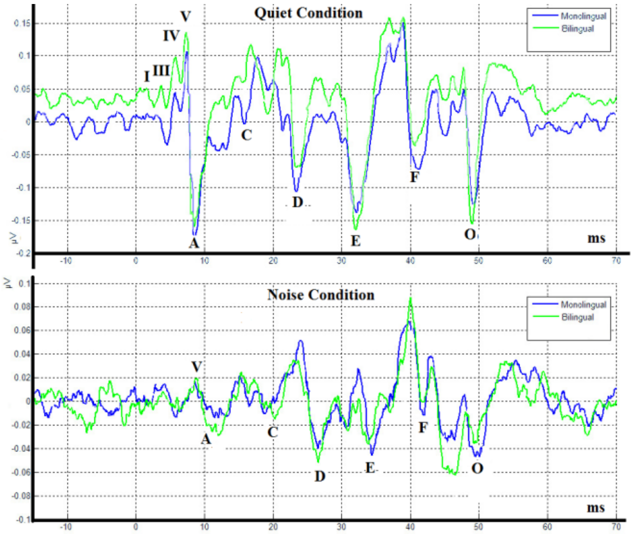

**Figure 2:** Grand average of subcortical responses (Speech-ABR) obtained from the two groups: monolinguals (blue) and bilinguals (green) recorded in quiet and in noise.

### Neural magnitude (amplitude)

Regarding the amplitude value, significant effects were onlyobserved for the main condition factor for all of the waves except wave C (see Table 2). Wave amplitude was larger in quiet than in noise. No significant effect was observed for the main group factor or for the interaction between group and condition factor except for the wave E: [F (1, 39) = 4.2, p = 0.04, ηp2 =0.096] (see Table 2).

### Spectral analysis

The amplitudes of the FFR are shown in Figure 3 and Table 2 along with their statistical significance. ANOVA results revealed a significant difference only for the main condition factor F0: [F (1, 38) = 62.8, p = 0.0001, ηp2 =0.62] and F1: [F (1, 38) = 72.76, p = 0.0001, ηp2 =0.66] (see Table 2). However, results revealed no significant differences between the groups or an interaction between groups and condition (p > 0.05 in all cases, see Table 2). T-tests for the condition factor revealed that the F0 and F1 amplitudes were larger in quiet than in noise.

**Table 1:** Results of a two-way, repeated-measures ANOVA, as a function of condition (noise and no noise) and group (monolingual, bilingual), for the mean latencies of waves V, A, C, D, E, F, O.

| | | Latency | | | | |
|---|---|---|---|---|---|---|
| | | **df (between group)** | **df (within group)** | **F** | ***p*** | **SE** |
| **Condition** | **V** | 1 | 39 | 45.7 | 0.001 | 0.54 |
| | **A** | 1 | 39 | 87.9 | 0.001 | 0.69 |
| | **C** | 1 | 39 | 41.1 | 0.001 | 0.51 |
| | **D** | 1 | 39 | 149 | 0.001 | 0.79 |
| | **E** | 1 | 39 | 96.7 | 0.001 | 0.7 |
| | **F** | 1 | 39 | 75.8 | 0.001 | 0.7 |
| | **O** | 1 | 39 | 30.8 | 0.001 | 0.44 |
| **Group x Condition** | **V** | 1 | 39 | 3.6 | 0.07 | 0.08 |
| | **A** | 1 | 39 | 0.68 | 0.42 | 0.02 |
| | **C** | 1 | 39 | 7.5 | 0.009 | 0.16 |
| | **D** | 1 | 39 | 1.45 | 0.24 | 0.04 |
| | **E** | 1 | 39 | 3.1 | 0.08 | 0.07 |
| | **F** | 1 | 39 | 0.91 | 0.35 | 0.02 |
| | **O** | 1 | 39 | 0.49 | 0.49 | 0.01 |
| **Group** | **V** | 1 | 39 | 4.4 | 0.04 | 0.10 |
| | **A** | 1 | 39 | 1.63 | 0.21 | 0.04 |
| | **C** | 1 | 39 | 4.19 | 0.04 | 0.1 |
| | **D** | 1 | 39 | 9.4 | 0.004 | 0.2 |
| | **E** | 1 | 39 | 2.33 | 0.14 | 0.06 |
| | **F** | 1 | 39 | 3.9 | 0.05 | 0.09 |
| | **O** | 1 | 39 | 2.1 | 0.15 | 0.05 |

**Table-2:** Results of a two-way, repeated-measures ANOVA, as a function of condition (noise and no noise) and group (monolingual, bilingual), for the mean amplitudes of waves V, A, C, D, E, F, O, VA complex and spectral magnitude.

| Amplitude | | | | | | |
|---|---|---|---|---|---|---|
| | | **df (between group)** | **df (within group)** | **F** | ***p*** | **SE** |
| **Condition** | **V** | 1 | 39 | 99.9 | 0.001 | 0.7 |
| | **A** | 1 | 39 | 143.3 | 0.001 | 0.8 |
| | **C** | 1 | 39 | 2.13 | 0.15 | 0.05 |
| | **D** | 1 | 39 | 14.9 | 0.001 | 0.28 |
| | **E** | 1 | 39 | 163.8 | 0.001 | 0.81 |
| | **F** | 1 | 39 | 19.33 | 0.001 | 0.3 |
| | **O** | 1 | 39 | 54 | 0.001 | 0.6 |
| | **F0 amp: 103–121 Hz** | 1 | 38 | 62.8 | 0.001 | 0.62 |
| | **F1 amp: 454–719 Hz** | 1 | 38 | 72.8 | 0.001 | 0.66 |
| **Condition X Group** | **V** | 1 | 39 | 0.08 | 0.78 | 0.002 |
| | **A** | 1 | 39 | 0.93 | 0.34 | 0.02 |
| | **C** | 1 | 39 | 1.8 | 0.18 | 0.04 |
| | **D** | 1 | 39 | 0.43 | 0.5 | 0.01 |
| | **E** | 1 | 39 | 4.2 | 0.04 | 0.096 |
| | **F** | 1 | 39 | 0.1 | 0.76 | 0.002 |
| | **O** | 1 | 39 | 4.07 | 0.05 | 0.09 |
| | **F0 amp: 103–121 Hz** | 1 | 38 | 2.13 | 0.7 | 0.004 |
| | **F1 amp: 454–719 Hz** | 1 | 38 | 0.6 | 0.45 | 0.015 |
| **Group** | **V** | 1 | 39 | 0.08 | 0.78 | 0.002 |
| | **A** | 1 | 39 | 1.4 | 0.24 | 0.035 |
| | **C** | 1 | 39 | 1.3 | 0.26 | 0.033 |
| | **D** | 1 | 39 | 0.29 | 0.6 | 0.007 |
| | **E** | 1 | 39 | 3.7 | 0.06 | 0.087 |
| | **F** | 1 | 39 | 0.5 | 0.5 | 0.012 |
| | **O** | 1 | 39 | 3.3 | 0.08 | 0.08 |
| | **F0 amp: 103–121 Hz** | 1 | 39 | 0.5 | 0.48 | 0.013 |
| | **F1 amp: 454–719 Hz** | 1 | 39 | 3.2 | 0.08 | 0.077 |

## 4 Discussion

The aim of the current study was to compare neural responses of subcortical auditory potentials in both a quiet and a noisy listening environment using two groups of adults, monolingual speakers and bilingual speakers, who have an enriched sensory experience. Several neural biomarkers of speech-ABR were more sensitive, enabling us to distinguish between the two groups. In fact, the temporal analysis of the neural onset (wave V), the consonant transition (Wave C) and the harmonic region (D, F) responses showed longer latencies among the monolingual group compared to their bilingual peers. This would suggest that the wave's latency could be considered as a neural biomarker distinguishing the two groups. Moreover, when speech stimuli were presented in noise, the processing of the transition between consonant /d/ to /a/ required a longer time in monolinguals than bilinguals.

Part of the difficulty in perceiving stop consonants, such as /d/ in noisy situations, is the rapid production and the relatively low-amplitude transient features of speech [22]. Generally, increased peak latencies could be an indicative of a disruption of the encoding process [23-

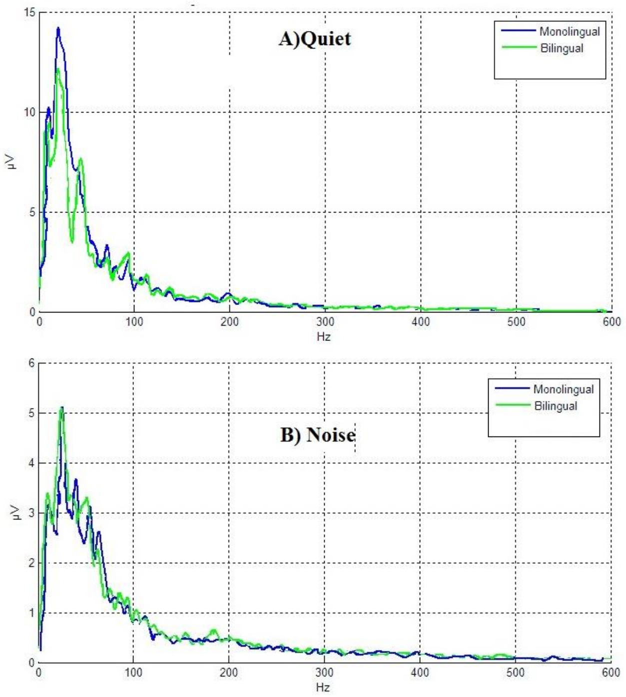

**Figure 3:** Grand average of fundamental frequency of subcortical responses of monolinguals (blue) and bilinguals (green) recorded in quiet (A) and in noise (B).

25]. Longer latencies have been observed in a number of clinical conditions, including specific language impairment, auditory processing disorder and hearing loss [23, 24, 26]. Although no clinical condition was observed in the monolingual participants, being bilingual could add extra advantages to the central auditory processing. In other words, enhanced experience in two languages could stimulate the automatic sound processing abilities of the auditory system in a way that make it highly efficient in regular and in challenging listening conditions.

It should be emphasized that a large change in the speech-ABR morphology of the waves was noted when comparing the noisy listening condition to the quiet condition in the two groups; waves with smaller amplitude and longer latency were observed in the noisy condition. The loss of the robust nature of the signal translates to an overall reduction of the amplitude peaks as well as increased latencies [8, 15]. A reduction in the amplitude of the response might serve as a manifestation of less efficient system processing [25]. Although the morphology of the neural responses obtained in noise was generally degraded in all participants, monolinguals demonstrated delayed neural subcortical encoding of transition of speech sound in the presence of background noise. The presence of background noise appears to greatly affect the coding of the stimulus in the monolingual group and to a lesser extent the bilingual group. The timing delays calculated for monolinguals contribute to the idea that individuals living in an enriched environment are better equipped to detect relevant sound characteristics more rapidly. Language experience in bilinguals limited the degradative effects of noise on neural timing in response to the formant transition of a speech syllable.

Although some studies have observed a deficit in speech-in-noise comprehension in bilinguals [27, 28], these studies assessed the non-native language in the bilinguals, and not the native or dominant language. Bilingual listeners have better speech-in-noise performance in their native rather than their non-native language [29].

Contrary to Krizman et al. (2012, 2014) [15, 16], none of the groups were found to have a fundamental frequency (F0) that was encoded more robustly than the others, in silent or noisy conditions. In noise, since vowels are less affected than consonants, the FFR is less degraded than the onset and the transition response [19]. A major difference between the onset and FFRs (F0 and F1) measured in this study was that neural encoding of onset features was delayed in the monolingual group, whereas the sustained FFR amplitude remained relatively similar in two groups. FFR refers to the later portion of the response evoked by the harmonic vowel structure of the stimulus [14]. The addition of ipsilateral noise predominately affected the latency of the several responses and also resulted in a reduction of the amplitude for all waves, as previously mentioned [14, 19]. The difference between the present study and Krizman et al.'s 2012 and 2014 studies could be explained, in part, by the differences in methodology and the method of analysis. Krizman et al. (2012; 2014) [15, 16] chose a 170 ms long stimulus and they studied the F0 after 50 ms of formant transition from /d/ to the FFR of /a/. In our case, /da/ was 40 ms long, with a 35 ms FFR. This may have potentially prevented the present study from finding any differences in the representation of F0 between the two groups. Moreover, no transient analysis had been performed for the first 50 ms of the stimuli in Krizman et al.'s 2012 and 2014 studies [15, 16]. Using a 40 ms stimulus, 7 distinct subcortical waves could be identified which is not the case with 170 ms. In terms of clinical application, Audiologists would be more familiar with speech ABR recorded with a 40 ms stimulus (due to similarities with click-ABR waves) than with a 170 ms stimulus. To be able to translate research findings to the clinical setting; 40 ms stimulus would be more suitable for clinical Audiologists seeking to identify neural biomarkers in clinical populations.

Though very little in the literature makes reference to the stimulus-encoding abilities of bilinguals using speech-ABR (with 40 ms /da/) in quiet and/or in noise, bilinguals could encode the auditory stimulus more efficiently due to enhancements of cognitive processes [16,17]. Krizman et al. (2012) [15] found that through experience-dependant plasticity, cortical regions of the brain that are responsible for processing language and executive control undergo modifications that lead to these enhancements. Therefore, bilinguals benefit from better inhibitory control, allowing them to better discriminate the characteristics of the desired stimulus, even if when the latter is presented in conjunction with an unrelated and disturbing signal, such as noise [15].

## Limitations of the study

The participants in our study's bilingual group were not all bilingual to the same level of proficiency. It is difficult to ensure that second-language speakers have similar levels of language competency and frequency of utilization, which can be explained by the fact that there are many tools available to measure bilingualism. Each tool measures a specific capacity, and the literature does not clearly and/or accurately describe which tools were used to classify the relationship between levels of bilingualism based on individual proficiency. In addition, we did not take prior musical training into consideration. Since the effects of musical training on auditory processing are well known, this may have had an impact. Behavioral measures (such as the speech-in-noise test) could have been used for comparing behavioral and electrophysiological responses. Taken together, these limitations may affect the probative strength of the results in our study.

### Future direction and clinical application

The speech-evoked ABR may be used as a tool to objectively measure and quantify the effects of noise, and may shed light on why some people have more difficulty in noise than others. Investigation of auditory evoked potentials in a population having specific difficulties understanding speech in background noise, such as children with auditory processing disorders, older adults, and individuals with sensory hearing loss shows excessive difficulty in noisy listening situations [30, 31]. Since Audiologists regularly use click-ABR in their clinical practice, this study supports the feasibility of using 40 ms /da/ to record Speech ABR in clinical setting.

## 5 Conclusion

Individuals speaking two or more languages are examples of lifelong acoustic exposure that may have an effect on the brain's functional organization. The results from this study show enriched language experience can lead to more efficient subcortical processing. ABR recorded with 40 ms /da/ provides an objective, multidimensional measure of sound encoding that could be different and/or abnormal in some individuals with different life experience or in clinical populations. This technique helps observe and might evaluate the effects of auditory activities and auditory processing and could serve as a sensitive biomarker.

## Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors are grateful to the participants who invested considerable time and effort to participate in this research project. We are very grateful to Dominique Côté, Émilie McClinton and Pamela-Lara Soueidan for their assistance in the execution of the first phase of the research project.

All authors contributed to this work. A.K. designed experiments, analyzed data, provided statistical analysis and wrote the paper; J.T. and G.Ch. performed experiments, collected and analyzed data, and contributed to the first draft of the paper. All authors discussed the results and implications and commented on the manuscript at all stages.

## References

[1] J. Crinion, R. Turner, A. Grogan, T. Hanakawa, U. Noppeney, J. T. Devlin, T. Aso, S. Urayama, H. Fukuyama, K. Stockton, K. Usui, D. W. Green, and C. J. Price. Language control in the bilingual brain. Science, 312 :5779, 1537-1540, 2006.

[2] G. Garbin, A. Sanjuan, C. Forn, J. C. Bustamante, A. Rodríguez-Pujadas, V. Belloch, M. Hernandez, A. Costa, and C. Ávila. Bridging language and attention: brain basis of the impact of bilingualismon cognitive control. Neuroimage, 53 :4, 1272-1278, 2010.

[3] C. A. Nelson. Neural Plasticity and human development: the role of experience in sculping memory system. Dev Sci, 3 :2, 115-136, 2000.

[4] T. Ohnishi, H. Matsuda, T. Asada, M. Aruga, M. Hirakata, M. Nishikawa, A. Katoh, and E. Imabavashi. Functional anatomy of musical perception in musicians. Cereb Cortex, 11 :8, 754-760, 2001.

[5] T. J. Fria, and W. J. Doyle. Maturation of the Auditory Brain Stem Response (ABR): Additional Perspectives. Ear Hear, 5 :6, 361–365, 1984.

[6] J. A. Kleim, and T. A. Jones. Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. J Speech Lang Hear Res, 51 :1, S225-S239, 2008.

[7] J. A. Markham, and W. T. Greenough. Experience-driven brain plasticity: beyond the synapse. Neuron Glia Biol, 1 :4, 351-363, 2004.

[8] N. Kraus, E. Skoe, A. Parbery-Clark, and R. Ashley. Experience-induced malleability in neural encoding of pitch, timbre, and timing: Implications for language and music. Ann N Y Acad Sci, 1169, 543–557, 2009.

[9] E. Skoe, and N. Kraus. Auditory brainstem response to complex sounds: a tutorial. Ear Hear, 31 :3, 302–324, 2010.

[10] G. Musacchia, M. Sams, E. Skoe, and N. Kraus. Musicians have enhanced subcortical auditory and audiovisual processing of speech and music. Proc Natl Acad Sci U S A, 104 :40, 15894-15898, 2007.

[11] H. K. Sanju, and P. Kumar. Enhanced auditory evoked potentials in musicians: A review of recent findings. J Otol, 11 :2, 63-72, 2016.

[12] G.M. Bidelman, J. T. Gandour, and A. Krishnan. Musicians and tone language speakers share enhanced brainstem encoding but not perceptual benefits for musical pitch. Brain Cogn, 77 :1, 1-10, 2011.

[13] A. Krishnan, Y. Xu, J. Gandour, and P. Cariani. Encoding of pitch in the human brainstem is sensitive to language experience. Brain Res Cogn Brain Res, 25, 161–168, 2005.

[14] N. M. Russo, T. G. Nicol, S. G. Zecker, E. A. Hayes, and N. Kraus. Auditory training improves neural timing in the human brainstem. Behav Brain Res, 156:1, 95-103, 2005.

[15] J. Krizman, V. Marian, A. Shook, E. Skoe, and N. Kraus. Subcortical encoding of sound is enhanced in bilinguals and relates to executive function advantages. Proc Natl Acad Sci U S A, 109:20, 7877–7881, 2012.

[16] J. Krizman, E. Skoe, V. Marian, and N. Kraus. Bilingualism increases neural response consistency and attentional control: Evidence for sensory and cognitive coupling. Brain Lang, 128: 1, 34–40, 2014.

[17] J. Krizman, J. Slater, E. Skoe, V. Marian, and N. Kraus. Neural processing of speech in children is influenced by extent of bilingual experience. Neurosci Lett, 585, 48–53, 2015.

[18] B. Chandrasekaran, and N. Kraus. The scalp-recorded brainstem response to speech: Neural origins and plasticity. Psychophysiology, 47 :2, 236–246, 2010.

[19] N. Russo, T. Nicol, G. Musacchia, and N. Kraus. Brainstem responses to speech syllables. Clin Neurophysiol, 115 :9, 2021–2030, 2004.

[20] V. Marian, H. K. Blumenfeld, and M. Kaushanskaya, M. The Language Experience and Proficiency Questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. J Speech Lang Hear Res, 50 :4, 940-967, 2007.

[21] B. Wible, T. Nicol and N. Kraus, N. Correlation between brainstem and cortical auditory processes in normal and language-impaired children. Brain, 128, 417–423, 2005.

[22] J. Brandt and J.J. Rosen. Auditory Phonemic Perception in Dyslexia-Categorical Identification and Discrimination of Stop Consonants. Brain Lang, 9 : 324-337, 1980.

[23] A. Koravand, B. Jutras, and M. Lassonde. Abnormalities in cortical auditory responses in children with central auditory processing disorder. Neuroscience, 346, 135-148, 2017.

[24] A. Koravand, R. Al Osman, V. Rivest, and C. Poulin. Speech-evoked auditory brainstem responses in children with hearing loss. Int J Pediatr Otorhinolaryngol, 99, 24–29, 2017.

[25] S. J. Luck. An introduction to the event-related potential technique. Cambridge: MIT Press, 2005.

[26] M. Basu, A. Krishnan, and C. Weber-Fox. Brainstem correlates of temporal auditory processing in children with specific language impairment. Dev Sci, 13 :1, 77–91, 2010.

[27] G. M. Bidelman, and L. Dexter. Bilinguals at the ‘‘cocktail party’’: Dissociable neural activity in auditory–linguistic brain regions reveals neurobiological basis for nonnative listeners’ speech-in-noise recognition deficits. Brain Lang, 143, 32–41, 2015.

[28] L. L. Mendel, and H. Widner. Speech perception in noise for bilingual listeners with normal hearing. Int J Audiol, 55 :2, 126-134, 2016.

[29] A. Hervais-Adelman, M. Pefkou, and N. Golestani. Bilingual speech-in-noise: Neural bases of semantic context use in the native language. Brain Lang, 132, 1–6, 2014.

[30] S. Kochkin. MarkeTrak V: “Why my hearing aids are in the drawer”: The consumers’ perspective. Hear J, 53 :2, 34-41, 2000.

[31] B. Moore. Speech processing for the hearing-impaired: Successes, failures, and implications for speech mechanisms. Speech Commun, 41 :1, 81-91, 2003.