Neuroscience Letters 585 (2015) 48–53

Contents lists available at ScienceDirect

Neuroscience Letters

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

Neural processing of speech in children is influenced by extent of bilingual experience

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HIGHLIGHTS

- Auditory neural function reflects a child's bilingual experience.
- Neural consistency and spectral encoding track with amount of bilingual experience.
- Bilingualism enhances auditory processing of select acoustic aspects of speech.

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form 30 October 2014
Accepted 7 November 2014
Available online 13 November 2014

Keywords:
Auditory
Brainstem
Bilingual experience
Fundamental frequency
Neural consistency

ABSTRACT

Language experience fine-tunes how the auditory system processes sound. Bilinguals, relative to monolinguals, have more robust evoked responses to speech that manifest as stronger neural encoding of the fundamental frequency (F0) and greater across-trial consistency. However, it is unknown whether such enhancements increase with increasing second language experience. We predict that F0 amplitude and neural consistency scale with dual-language experience during childhood, such that more years of bilingual experience leads to more robust F0 encoding and greater neural consistency. To test this hypothesis, we recorded auditory brainstem responses to the synthesized syllables 'ba' and 'ga' in two groups of bilingual children who were matched for age at test (8.4 ± 0.67 years) but differed in their age of second language acquisition. One group learned English and Spanish simultaneously from birth ($n = 13$), while the second group learned the two languages sequentially ($n = 15$), spending on average their first four years as monolingual Spanish speakers. We find that simultaneous bilinguals have a larger F0 response to 'ba' and 'ga' and a more consistent response to 'ba' compared to sequential bilinguals and we demonstrate that these neural enhancements track with years of bilingual experience. These findings support the notion that bilingualism enhances subcortical auditory processing.

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1. Introduction

Acquisition of a second language enhances how sound is processed both cortically [19] and subcortically [14]. While bilingualism's influence on cortical areas has been extensively evaluated [see [5] for a review] its effects on subcortical auditory processing is a recent topic. Assessments of subcortical processing have revealed that bilingual adolescents demonstrate greater across-trial neural consistency and encode the fundamental frequency (F0) of speech more robustly than monolinguals [14] ; however,

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http://dx.doi.org/10.1016/j.neulet.2014.11.011
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whether the degree of these enhancements is dependent on the extent of second language experience is unknown. The subcortical auditory response of newborns is not biased to the native language of their parents [10], but young adults show enhanced subcortical processing of native language features [10,13], implicating an emergence of spoken-language dependent tuning of the auditory brainstem during childhood. Therefore, we hypothesize that second language learning during childhood leads to additional structural and/or functional changes in the neural circuitry underlying auditory communication, with the amount of plasticity being commensurate with the amount of bilingual experience. This leads to the prediction that among age-matched bilinguals, the encoding of the F0 of speech and the consistency of the response will be greater in children who learned their second language earlier in life. To test this prediction, the current study compared F0 encoding strength and response consistency across two groups of bilingual children who differed in their age of second language acquisition.

2. Methods

2.1. Participants

Electrophysiological responses to the synthesized syllables 'ba' and 'ga' were collected in 27 school-aged children (8.4 ± 0.67 years, 17 female) recruited from Los Angeles, California. All children were Spanish–English bilinguals and all but four were from low socioeconomic backgrounds as measured by maternal education, which has previously been used as a reliable index of socioeconomic status in children [26,28] (high-school or less: $n = 23$; some college or beyond: $n = 4$). Two sequential bilinguals were born outside the United States (Honduras, Mexico) and moved to the U.S. at age 3. All participants had normal hearing (≤20 dB HL at octaves ranging from 125 Hz to 8000 Hz, ANSI, 2009) and normal click-evoked auditory brainstem responses based on lab-internal normative data [25] (80 dB SPL, 31.1/s). All participants had normal IQ (simultaneous = 102.83 ± 12.7, sequential = 96.67 ± 12.2, $t = 1.278$, $p = 0.213$, Wechsler Abbreviated Scale of Intelligence, WASI), were right-handed, and had no reported diagnosis of language, learning, neurological or attention impairment. Parental ratings of language proficiency and language exposure have previously been found to be reliable measures of a child's first and second language experience [3,8]; and so, parental ratings were used in the current study. Based on these parental reports, all participants were rated to be highly proficient in speaking and understanding Spanish and English on a scale of 1 (lowest)–10 (highest).

Using standard grouping criteria to define the participants as simultaneous or sequential bilinguals [e.g., see [2,24]], the children were divided into two groups based on the parental report of when the child began learning English. The simultaneous group ($n = 13$, 10 female, age 8.36 ± 0.53 years, bilingual experience 8.3 ± 0.64 years) comprised children exposed to both English and Spanish in the home since birth. Children in the sequential group ($n = 15$, 7 female, age 8.44 ± 0.79 years, bilingual experience 4.24 ± 1.1 years) were exposed to Spanish since birth but did not begin learning English until pre-school or Kindergarten (mean age of English exposure = 4.1 years). For each child, extent of bilingual experience was quantified by subtracting the child's age of English acquisition from age at test. Parent ratings of English and Spanish proficiency were matched between the simultaneous and sequential groups (English: simultaneous = 9.88 ± 0.3, sequential = 9.50 ± 0.9, $t = 1.603$, $p = 0.121$; Spanish: simultaneous = 7.80 ± 2.0, sequential = 7.80 ± 2.3, $t = -0.038$, $p = 0.97$). The two groups were sex- ($t(26) = 1.656$, $p = 0.110$) and age-matched ($t(26) = -0.332$, $p = 0.742$), however, given their influence on the cABR [15,25] all analyses were run co-varying for both factors. Prior to testing, all participants provided English informed assent and parents gave informed consent in their preferred language. All procedures were approved by the Internal Review Board of Northwestern University.

2.2. Stimuli

The syllables 'ba' and 'ga' were synthesized with a Klatt-based synthesizer (Klatt). Each syllable is 170 ms, consisting of an initial stop-consonant burst followed by a 50 ms transition between the burst and sustained vowel. During the transition the first, second, and third formants linearly change (F1 = 400–720 Hz; F2(ba) = 900–1240 Hz; F2(ga) = 2480–1240 Hz; F3 = 2580–2500 Hz) while the fundamental frequency (F0), fourth, fifth, and sixth formants remain level (F0 = 100 Hz, F4 = 3300 Hz; F5 = 3750 Hz; F6 = 4900 Hz). The F0 and formants are constant during the vowel (50–170 ms). These syllables were constructed to be neither Spanish-like nor English-like, but to minimally differ in the acoustic properties that distinguish them as 'ba' or 'ga' (i.e., F2 trajectory during the transition). These phonemes were chosen because they are present in both Spanish and English [32] allowing us to focus on how bilingual experience modulates the processing of sounds that are common to both languages. Moreover, we selected two syllables, instead of just one, to assess the generalizability of the bilingual neural enhancement across stimuli.

2.3. Electrophysiological recording

Subcortical electrophysiological responses (i.e., cABRs) were recorded using the SmartEP cABR module (Intelligent Hearing Systems). During the recording, the child sat in a comfortable chair and watched a movie in English on a portable DVD player (Sony Corporation, Minato, Tokyo, Japan). cABRs were collected using three Ag/AgCl electrodes applied in a vertical montage (CZ – active, right ear – reference, forehead – ground). Stimuli were presented in alternating blocks (i.e., 'ba', 'ga', 'ba', 'ga' or 'ga', 'ba', 'ga', 'ba') to the participant's right ear through an insert earphone at 4.35 Hz (60 ms interstimulus interval) and 80 dB SPL. The left ear remained unoccluded so the participant could hear the movie soundtrack at a level that did not mask the stimulus (<40 dB SPL). For each stimulus, 6000 responses were collected over two 3000-trial blocks (1500 of each stimulus polarity). Responses were digitized at 13,333 Hz, and filtered from 50–3000 Hz (6 dB/octave roll off). Epoching (−40 ms to 190 ms), artifact rejection (±35 μV), and averaging were performed on-line.

2.4. Analyses

2.4.1. Spectral encoding

In MATLAB (Mathworks, Inc.) a fast-Fourier transform was performed for the formant transition (20–60 ms) and steady-state response (60–180 ms) from which average spectral amplitudes were calculated over 40 Hz wide frequency bins, centered on the stimulus F0 (100 Hz) and harmonics H2–H10 (200–1000 Hz). A composite of harmonic amplitude was calculated by averaging H2–H10 [22]. Spectral amplitudes over the formant transition and vowel were analyzed using a 2 (language group: simultaneous, sequential) *x* 2 (stimulus: 'ba', 'ga') *x* 2 (frequency range: F0, harmonics) repeated measures ANOVA covarying for sex and age (RMANCOVA). Significant interactions were explored using independent-samples *t*-tests.

2.4.2. Response consistency

Consistency was calculated for each stimulus over the formant transition (20–60 ms) and vowel (60–180 ms) by correlating an average of the first 3000 trials (i.e., block 1) to an average of

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