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Bilinguals at the "cocktail party": Dissociable neural activity in auditory–linguistic brain regions reveals neurobiological basis for nonnative listeners' speech-in-noise recognition deficits

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ABSTRACT

We examined a consistent deficit observed in bilinguals: poorer speech-in-noise (SIN) comprehension for their nonnative language. We recorded neuroelectric mismatch potentials in mono- and bi-lingual listeners in response to contrastive speech sounds in noise. Behaviorally, late bilinguals required ~10 dB more favorable signal-to-noise ratios to match monolinguals' SIN abilities. Source analysis of cortical activity demonstrated monotonic increase in response latency with noise in superior temporal gyrus (STG) for both groups, suggesting parallel degradation of speech representations in auditory cortex. Contrastively, we found differential speech encoding between groups within inferior frontal gyrus (IFG)—adjacent to Broca's area—where noise delays observed in nonnative listeners were offset in monolinguals. Notably, brain-behavior correspondences double dissociated between language groups: STG activation predicted bilinguals' SIN, whereas IFG activation predicted monolinguals' performance. We infer higher-order brain areas act compensatorily to enhance impoverished sensory representations but only when degraded speech recruits linguistic brain mechanisms downstream from initial auditory-sensory inputs.

1. Introduction

Bilingualism is an intrinsic part of modern culture. It is believed that nearly half the world is bilingual (Grosjean, 2010) and that in the U.S. alone, more than 20% of the population speaks multiple languages (U.S. Census Bureau, 2010). Indeed, increased demand for a multi-lingual society has influenced recent educational practice and public policy (Wiese & Garcia, 2010). Consequently, there is substantial interest in understanding how language experiences sculpt brain function and potentially enhance perceptual-cognitive skills (Bialystok, Craik, & Luk, 2012; Costa & Sebastian-Galles, 2014; Ressel et al., 2012).

By virtue of interacting with multiple languages, non-native speakers experience an enriched auditory–linguistic environment atypical of their monolingual peers. The joint activation of two competing language systems (Kim, Relkin, Lee, & Hirsch, 1997) forces bilinguals to regulate, manipulate, and suppress multiple streams of lexical information (Bialystok, 2009; Bialystok et al., 2012). As a consequence of managing two languages (Crinion et al., 2006), bilinguals develop more effective inhibitory control than their monolingual peers (Bialystok et al., 2012; Costa & Sebastian-Galles, 2014; Crinion et al., 2006; Krizman, Marian, Shook, Skoe, & Kraus, 2012). While usually more pronounced in late-onset bilinguals, the increased cognitive demands of bilingualism, in turn, yield physical (Ressel et al., 2012) and functional (Bialystok et al., 2012; Costa & Sebastian-Galles, 2014; Li, Legault, & Litcofsky, 2014) changes in brain networks that confer advantages in complex human behaviors including sustained attention, conflict monitoring, and executive functions (Bialystok, 2009; Bialystok et al., 2012; Krizman et al., 2012). Intriguingly, these behavioral benefits garnered through lifelong, early multilingual experience may act to boost "cognitive reserve" and ultimately postpone or even protect against cognitive decline over the lifespan (Bialystok, Craik, & Freedman, 2007; Craik, Bialystok, & Freedman, 2010; Gold, Johnson, & Powell, 2013; Kave, Eyal, Shorek, & Cohen-Mansfield, 2008). Indeed, early bilingualism is now linked to enriched perceptual abilities and protection against age-related decline in cognitive control.

The human brain is a limited capacity system whose neural resources are allocated according to the functional demands of the environment (Marois & Ivanoff, 2005). Moreover, experience-

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dependent plasticity is an inherently competitive process and plastic changes that produce beneficial behavioral adaptations are equally accompanied by those which hinder behaviors (i.e., "maladaptive" or "negative plasticity") (Kolb & Gibb, 2014; Mahncke et al., 2006). Thus, while it is clear that speaking multiple languages yields neural reorganization that influences perceptual-cognitive skills (Krizman et al., 2012; Ressel et al., 2012), bilinguals' gains in certain abilities may have detrimental consequences for other, equally important functions. Indeed, developmental studies reveal that bilinguals control a smaller vocabulary (Oller & Eilers, 2002) and show deficiencies in verbal fluency (Portocarrero, Burright, & Donovick, 2007) relative to their monolingual peers, providing evidence for neuroplastic tradeoffs. Here, we examined the neurobiological basis of another prominent and pervasive limitation of speaking multiple languages: bilinguals' poorer speech-in-noise (SIN) comprehension for their nonnative language (Hervais-Adelman, Pefkou, & Golestani, 2014; Rogers, Lister, Febo, Besing, & Abrams, 2006; Tabri, Smith, Chacra, & Pring, 2010; von Hapsburg, Champlin, & Shetty, 2004; Zhang, Stuart, & Swink, 2011). In the current study, we chose to examine *late-onset bilinguals* in order to maximize the possibility of identifying a neural correlate of nonnative listeners' SIN perception deficits. However, while speech in noise deficits are more prominent in late bilinguals, even relatively early bilinguals [i.e., second language (L2) onset prior to age 6] can show behavioral deficits in speech in noise listening (Rogers et al., 2006; Shepherd & Bent, 2014; Tabri et al., 2010).

Natural listening environments typically contain interferences (which can be both acoustic and linguistic in nature), making successful extraction of speech from noise a fundamental skill for effective communication. In this regard, understanding nonnative listeners' SIN recognition deficits is among the many broad and widespread interests to understand how human experiences influence auditory scene analysis and figure-ground perception (e.g., Alain, Zendel, Hutka, & Bidelman, 2014; Bidelman & Krishnan, 2010). Characterizing nonnative listeners' noise-exclusion deficits is particularly germane for understanding communication in modern classrooms, which are inherently noisy (Knecht, Nelson, Whitelaw, & Feth, 2002) and increasingly bilingual environments (Chin, Daysal, & Imberman, 2013). It also has important ramifications for establishing normative measures in nonnative speakers for speech testing in the audiology clinic.

To elucidate the neurobiological basis of nonnative listeners' SIN deficits, we recorded neuroelectric mismatch negativity (MMN) potentials in monolingual and late bilingual listeners in response to contrastive speech sounds presented in various levels of noise. The MMN is a scalp-recorded component of the auditory event-related potentials (ERP), indexing cortical registration of acoustic deviancy in the absence of attention or a behavioral engagement (Naatanen, Paavilainen, Rinne, & Alho, 2007). Previous studies have shown earlier latency mismatch activity is correlated with more accurate behavioral speech discrimination, indicating the response provides a neural correlate of speech perception abilities (e.g., Dehaene-Lambertz et al., 2005; Tremblay, Kraus, & McGee, 1998). A constellation of neural generators contributes to the MMN including sources in the superior temporal plane (bilateral auditory cortices) and frontal lobes (Giard, Perrin, Pernier, & Bouchet, 1990; Naatanen et al., 2007; Yago, Escera, Alho, & Giard, 2001). Both temporal and frontal MMN sources are thought to contribute to normal speech perception; sources in superior temporal gyrus (STG) are thought to play a role in initial sound analysis in auditory sensory cortex while those near inferior frontal gyrus (IFG) likely reflect higher-order (i.e., linguistic) analysis of speech information downstream (for review, see Myers, 2014). Relevant to the current report, previous studies have shown that inferior frontal sources (proximal to Broca's area and the insula) show particular sensitivity when listening to ambiguous or noise degraded speech (Diaz, Baus, Escera, Costa, & Sebastian-Galles, 2008; Du, Buchsbaum, Grady, & Alain, 2014).

Here, we applied distributed source analysis to these neural responses to evaluate cross-language and region-specific differences in the brain's differentiation of degraded speech. Comparing listeners' electrical brain responses to their perception allowed us to assess the degree to which different neural substrates (i.e., those subserving auditory sensory vs. linguistic processes) contribute to behavioral SIN abilities. We predicted parallel noise-related changes in both groups within auditory cortical regions, consistent with progressive masking of neural speech representations in sensory brain areas (e.g., Binder, Liebenthal, Possing, Medler, & Ward, 2004; Du et al., 2014; Eisner, McGettigan, Faulkner, Rosen, & Scott, 2010). Furthermore, we hypothesized monolinguals would show additional recruitment of frontal sources (cf. Diaz et al., 2008; Eisner et al., 2010). These findings would suggest that higher-order linguistic brain regions act in a compensatory manner to improve noise-degraded speech representations output from the sensory cortices in native (monolingual) but not nonnative (late bilingual) listeners.

2. Methods

2.1. Participants

Ten monolingual (Mono) and ten bilingual (Bi) young adult listeners (age range: 21–34 years) were recruited from the University of Memphis graduate student body to participate in the experiment. A language history questionnaire assessed linguistic background (Bidelman, Gandour, & Krishnan, 2011; Li, Sepanski, & Zhao, 2006). Monolinguals were native speakers of American English unfamiliar with a L2 of any kind. Bilingual participants were classified as late sequential bilinguals having not received formal instruction in English, on average, before age 10.1 ± 3.9 years. We chose to recruit late bilinguals to be consistent with previous work in this area (von Hapsburg et al., 2004; Zhang et al., 2011) and to maximize the possibility of identifying a neural correlate of the bilingual SIN deficit. However, it should be noted that even early bilinguals (i.e., L2 onset well before age 6) can show a behavioral disadvantage in speech in noise listening (Rogers et al., 2006; Shepherd & Bent, 2014; Tabri et al., 2010). All reported using their first language 46 ± 33% of their daily use. Self-reports of L2 language aptitude indicated that all were fluent in English reading, writing, speaking, and more critically, listening proficiency [1(very poor)–7(native-like) Likert scale; reading: 5.9(0.73); writing: 5.2(0.62); speaking: 5.2(0.62); listening: 5.7(0.94)]. We specifically recruited bilinguals with diverse language backgrounds (e.g., Spanish, Hindi, Korean, and Japanese) to increase external validity/generalizability of our study.

Participants were otherwise matched in right handedness [Mono: 73.8 ± 62%; Bi: 88 ± 19%; $t_{18} = 0.67$, $p = 0.49$] and formal education [Mono: 18.4 ± 1.8 years; Bi: 20 ± 2.3 years; $t_{18} = 1.73$, $p = 0.09$]. Musical training amplifies the auditory evoked potentials (Bidelman et al., 2011; Musacchia, Strait, & Kraus, 2008; Zendel & Alain, 2009) and improves SIN listening skills (Bidelman & Krishnan, 2010; Parbery-Clark, Skoe, Lam, & Kraus, 2009). Hence, all participants were required to have minimal ($\leqslant$3 years) formal musical training. Air conduction audiograms confirmed normal hearing (i.e., $\leqslant$25 dB HL) at octave frequencies (250–8000 Hz). Subjects reported no history of neuropsychiatric disorders. Each gave written informed consent in compliance with a protocol approved by the University of Memphis Institutional Review Board and were reimbursed monetarily for their time.