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Short Communication

Bilingualism increases neural response consistency and attentional control: Evidence for sensory and cognitive coupling

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ABSTRACT

Auditory processing is presumed to be influenced by cognitive processes – including attentional control – in a top-down manner. In bilinguals, activation of both languages during daily communication hones inhibitory skills, which subsequently bolster attentional control. We hypothesize that the heightened attentional demands of bilingual communication strengthens connections between cognitive (i.e., attentional control) and auditory processing, leading to greater across-trial consistency in the auditory evoked response (i.e., neural consistency) in bilinguals. To assess this, we collected passively-elicited auditory evoked responses to the syllable [da] in adolescent Spanish-English bilinguals and English monolinguals and separately obtained measures of attentional control and language ability. Bilinguals demonstrated enhanced attentional control and more consistent brainstem and cortical responses. In bilinguals, but not monolinguals, brainstem consistency tracked with language proficiency and attentional control. We interpret these enhancements in neural consistency as the outcome of strengthened attentional control that emerged from experience communicating in two languages.

1. Introduction

Every moment, our ears are bombarded with millions of bits of data that inform us about our acoustic environment. To best utilize this flood of information, the brain has developed ways to adaptively respond to sensory input (Engel, Fries, & Singer, 2001). One mechanism by which sensory signaling is improved is by cognitive (i.e., executive) functions biasing the encoding of contextually or behaviorally relevant signals over irrelevant ones. The executive functions that guide this selection are based in the frontal and parietal cortex (Miller & Cohen, 2001; Smith & Jonides, 1999; Weissman, Roberts, Visscher, & Woldorff, 2006) and exert their influence on sensory processing via top-down mechanisms (Bar et al., 2006; Hochstein & Ahissar, 2002) These top-down mechanisms enable the executive system to influence a variety of auditory processing tasks (see McLachlan & Wilson, 2010 for review), including focusing the "searchlight" on a target sound (Fritz, Elhilali, David, & Shamma, 2007; Luo, Wang, Kashani, & Yan, 2008).

The executive system follows a protracted maturational time course that extends through adolescence (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999; Spear, 2000). As evidenced by cognitive deficits in profoundly deaf children, development of the executive system may be shaped by sound-to-meaning connections made through auditory-based language experience (Conway, Pisoni, & Kronenberger, 2009). In further support of a link between language experience and executive function, in bilinguals, the mapping of sound-to-meaning connections across two languages can fine tune the ability to selectively attend to important stimuli and ignore irrelevant ones, an executive function called inhibitory control. (Bialystok, 2011; Blumenfeld & Marian, 2011; Carlson & Meltzoff, 2008; Soveri, Laine, Hamalainen, & Hugdahl, 2011). Given that bilingualism can improve attentional control abilities and that the executive system can influence sensory encoding via top-down signaling, we hypothesize that greater attentional control in bilinguals exerts a stronger influence on auditory processing enabling the bilingual auditory system to more effectively hone-in on the

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behaviorally-meaningful features of the incoming signal. We predict that this strengthened interaction between cognitive and sensory processing manifests as greater across-trial consistency in the far-field (i.e., scalp-recorded) population evoked response to sound for bilinguals relative to monolinguals (Hornickel & Kraus, 2013). To test this hypothesis, we compared bilingual and monolingual adolescents on their attentional control abilities and the consistency of their auditory cortical and brainstem evoked response potentials to a speech syllable evoked under passive listening conditions.

Auditory evoked cortical and subcortical responses, though obligatory, can be influenced via top-down signaling (Hairston, Letowski, & McDowell, 2013; Woldorff et al., 1993; Wu, Weissman, Roberts, & Woldorff, 2007). For example, the auditory cortex is sensitive to attentional state (Coch, Sanders, & Neville, 2005; Lutz, Slagter, Dunne, & Davidson, 2008; Näätänen, 1990; Winer, 2006; Woldorff et al., 1993; Wu et al., 2007) and is innervated by areas of the brain thought to be involved in directing attention (Gao & Suga, 2000; Huffman & Henson, 1990; Malmierca & Ryugo, 2011). Moreover, recent evidence suggests that the inferior colliculus, the primary generator of the auditory brainstem response to complex sounds (Chandrasekaran & Kraus, 2010; Skoe & Kraus, 2010) is also sensitive to the effects of attentional control (Hairston et al., 2013; Krizman, Marian, Shook, Skoe, & Kraus, 2012; Raizada & Poldrack, 2007; Rinne et al., 2008; Ruggles, Bharadwaj, & Shinn-Cunningham, 2011). This coupling between the executive system and the inferior colliculus, which is presumed to take place through the extensive network of efferent connections that link cortical to subcortical structures (Gao & Suga, 1998; Gao & Suga, 2000), can be measured by the auditory brainstem response to complex sounds (Kraus & Chandrasekaran, 2010).

The auditory brainstem response to complex sounds provides a neurophysiologic snapshot of how lifelong experience has re-wired the auditory system's automatic brainstem response to sound. For example, lifelong experiences such as native-language learning, bilingualism, and protracted music training leave their mark on auditory brainstem encoding (Krishnan et al., 2009; Krizman, Marian, et al., 2012; Musacchia et al., 2007). This type of experience-dependent plasticity is thought to arise via top-down mechanisms and can be observed even when the response is evoked under passive listening conditions (Kraus & Chandrasekaran, 2010). Thus, if second language experience hones attentional control, if attentional control strengthens neural consistency through top-down processes, and if subcortical and cortical auditory structures are sensitive to attentional control throughout life, then bilinguals by virtue of having better attentional control abilities, are predicted to have greater consistency in their auditory evoked cortical and brainstem response to speech sounds. This greater neural consistency should in turn relate to attentional control abilities in bilinguals. Moreover, if neural consistency, like attentional control, is shaped by language experience, then we further predict that greater proficiency across a bilingual's two languages would relate to more consistent neural responses, given that reading abilities (another linguistic skill) have been positively related to neural consistency (Centanni et al., 2013; Hornickel & Kraus, 2013).

2. Results

2.1. Summary of results

Bilingual adolescents had greater consistency in both their brainstem and cortical responses to the speech sound [da] than monolinguals. In both groups, cortical and brainstem consistency were highly related; however, in bilinguals, brainstem consistency, and not cortical consistency, tracked with attentional control and language proficiency.

2.2. Auditory Response Control (attentional control)

Bilinguals outperformed monolinguals on behavioral measures of attentional control ($F_{(1,54)} = 7.363$ $p = 0.009$), with bilinguals having a mean standard score (±1SE) of 84.37 ± 3.52 and monolinguals having a mean standard score of 69.19 ± 4.21.

2.3. Response consistency

Bilinguals demonstrated more consistent brainstem ($F_{(1,54)}$= 7.874, $p = 0.007$) and cortical ($F_{(1,54)}$=4.302, $p = 0.043$) responses to the syllable [da] compared to monolinguals (Fig. 1). For the bilinguals, the mean r-value was 0.769 ± 0.026 for the brainstem response consistency and 0.538 ± 0.033 for the cortical response consistency. Monolinguals had mean r-values of 0.675 ± 0.032 and 0.439 ± 0.039 for brainstem and cortical responses, respectively.

2.4. Relationships among attentional control, subcortical and cortical response consistency

For all participants, there was a strong correlation between the consistency of the cortical and brainstem responses ($r = 0.797$, $p < 0.0005$; Fig. 2). This was not seen when correlating the electrical activity recorded during the silence preceding each stimulus ($r = 0.225$, $p = 0.109$). Only bilinguals demonstrated a relationship between brainstem response consistency and Auditory Response (attentional) Control ($r = 0.418$, $p = 0.038$; Fig. 2) and language proficiency ($r = 0.479$, $p = 0.015$; Fig. 2), with more consistent responses linked to better attentional control and greater language proficiency. Monolinguals did not show a relationship between brainstem response consistency and Auditory Response Control ($r = 0.21$, $p = 0.314$) or language proficiency ($r = -0.092$, $p = 0.662$). There was no relationship between cortical response consistency and attentional control abilities for either group (bilinguals: $r = 0.308$, $p = 0.135$; monolinguals: $r = -0.252$, $p = 0.225$).

3. Discussion

We show that the bilingual auditory system processes sound in ways that are both different from and similar to the monolingual system. Specifically, we demonstrate that although both groups showed consistent cortical and subcortical responses, bilinguals had greater consistency in their neural responses relative to monolinguals. We also observed that consistency of the cortical and subcortical evoked responses was related in both monolinguals and bilinguals. However, specific to bilinguals was a relationship between subcortical response consistency and both attentional control abilities and language proficiency, while neither group showed a relationship between cortical response consistency and these abilities.

All participants demonstrated a relationship between cortical and brainstem consistency that was specific to the evoked responses (and not the preceding neural background activity), suggesting that consistency in processing sound, as indexed by auditory evoked potentials, is maintained throughout the auditory system. This synching of brainstem and cortical responses is argued to result from signaling between afferent and efferent auditory pathways which link the generators of these responses to facilitate encoding of the signal in a behaviorally-relevant manner (Gao & Suga, 2000; Huffman & Henson, 1990). However, given that both the cortical and subcortical responses were recorded