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Research Report

Modality-independent neural mechanisms for novel phonetic processing

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ABSTRACT

The present study investigates whether the inferior frontal gyrus is activated for phonetic segmentation of both speech and sign. Early adult second language learners of Spanish and American Sign Language at the very beginning of instruction were tested on their ability to classify lexical items in each language based on their phonetic categories (i.e., initial segments or location parameter, respectively). Conjunction analyses indicated that left-lateralized inferior frontal gyrus (IFG), superior parietal lobule (SPL), and precuneus were activated for both languages. Common activation in the left IFG suggests a modality-independent mechanism for phonetic segmentation. Additionally, common activation in parietal regions suggests spatial preprocessing of audiovisual and manuovisual information for subsequent frontal recoding and mapping. Taken together, we propose that this frontoparietal network is involved in domain-general segmentation of either acoustic or visual signal that is important to novel phonetic segmentation.

1. Introduction

Our understanding of language processing has grown considerably since neuroimaging came to the forefront, and has been significantly refined by examining not only aural spoken languages but also manual sign languages. The study of sign languages contributes to a greater understanding of language universals and modality-independent and -dependent neurocognitive mechanisms (Poeppel et al., 2012; Sandler and Lillo-Martin, 2006). Today, we understand that the brain processes spoken and sign languages in many of the same ways (Emmorey et al., 2002; MacSweeney et al., 2008). A goal of the present study was to expand our understanding of modality-independent neural mechanisms for processing phonetic information of language. To do so, effective monolinguals (or very beginning second language learners) were examined in order to characterize the neural substrates of phonetic segmentation in novel languages across modalities.

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It has long been established that speech is segmented and processed in a left-lateralized network of frontal, temporal, and parietal areas (Geschwind, 1979). The neural processing of speech can be bifurcated into cortical streams through which speech is either mapped onto semantic (i.e., ventral stream) or articulatory (i.e., dorsal stream) representations (Hickok and Poeppel, 2004, 2007). Specifically, speech segmentation has been localized to prefrontal regions such as the inferior frontal gyrus (IFG; Burton et al., 2000; Zatorre et al., 1992, 1996).

There is a growing literature that suggests that Broca's area does not solely process linguistic information. Instead, Broca's area is involved in many higher-order, domain-general cognitive processes. For example, relationships between action sequence processing and the left IFG have been reported (Fazio et al., 2009; Clerget et al., 2009). These studies suggest that Broca's area is involved in the sequential and hierarchical processing of goal-directed movement. Additionally, Dominey et al. (2003) has proposed that language processing is in part predicated on the ability to extract and use sequential structure. Broca's area has also been implicated in other non-linguistic tasks, such as music processing. For instance, Tillmann et al. (2003) investigated the neural correlates of music processing in a priming study. Their imaging results indicated that there were higher levels of activation in the IFG for unrelated prime-target pairs, which is taken to mean that the IFG is involved in the processing and integration of sequential information over time (see also Fadiga et al., 2009 for a review).

Given evidence of IFG activation for both speech and nonspeech information, some have argued that the IFG is responsible for separating auditory stimuli for further processing and may not be specific to speech itself (Burton, 2009; LoCasto et al., 2004). Together, activation of prefrontal cortex for speech and nonspeech segmentation leads us to question whether the IFG may be responsible for multimodal integration. Perhaps the study of phonetic segmentation in different language modalities (i.e., sign versus spoken) can shed light on the modality-specificity of IFG activation.

American Sign Language (ASL) is a natural language that is primarily produced and perceived in a sensorimotor language modality (i.e., manual-visual) different from spoken languages. Sign languages, like other natural languages, possess all of the same linguistic characteristics of spoken language (e.g., phonology, morphology, syntax, semantics; Sandler and Lillo-Martin, 2006). ASL phonology includes at least three major phonetic parameters: handshape, movement, and location (Liddell and Johnson, 1989; Sandler, 1989; Brentari, 1998). Handshape is the configuration and the selected fingers and joints of the articulating hands during sign production. Movement is the directionality of the hands during sign production. Location is the place on the body where the sign is being articulated. Together, these three phonetic features must be combined in some manner in order to have a well-formed sign (Brentari, 1998). These parameters are analogous to those of spoken phonology where the features include voicing and place and manner of articulation, which describe the amount and, type of air flow constriction in the vocal tract. Given that the phonetic structure of sign languages diverges in modality from that of spoken languages, one might question the amodal nature of phonetic processing within the brain. However, cross-modal phonetic parameters are related to the perception of motor actions and therefore, overlap in processing may also be expected.

Numerous studies over the last two decades have shown that languages are processed similarly in the brain, regardless of language modality. For instance, multiple studies have shown that sign languages are processed in a left-lateralized language network, similar to that of spoken languages (Campbell et al., 2008; Corina et al., 1992; MacSweeney et al., 2008). Broca's (i.e., inferior frontal gyrus) and Wernicke's (i.e., posterior superior temporal gyrus) areas are activated for both sign and spoken language processing (Campbell et al., 2008; Emmorey, 2005; Emmorey et al., 2003; Emmorey et al., 2007; MacSweeney et al., 2002, 2006, 2008). Evidence from these same studies have found that deaf signers activate perisylvian areas, which are classically thought to be involved in auditory processing, when perceiving sign language. Additionally, studies have shown parietal (e.g., supramarginal gyrus, superior parietal lobule) activation for signs for both hearing and deaf signers (Emmorey et al., 2003; Emmorey, 2005; Capek et al., 2008). From these studies, the parietal lobe has been thought to combine spatial features that are essential to phonological processing in signed language for all signers (Mayberry et al., 2011). Together, these studies have shown a consistent pattern of activation for both spoken and sign languages in monolingual populations.

In the present study, we aimed to investigate whether prefrontal regions (e.g., inferior frontal gyrus) are responsible for amodal phonetic segmentation. Given evidence that the inferior frontal gyrus segments multimodal information, including speech, nonspeech, tones, music, actions, and signs, it is important to empirically test its amodal processing explicitly. Given that learners of a second language at the beginning level have little phonological (as well as grammatical) knowledge of the target language, like true monolinguals, they provide an interesting population to investigate phonetic segmentation. That is, they must learn to segment incoming linguistic information to form phonological categories (see Best and Tyler, 2007 for L2 phoneme category learning). Thus, we used absolute beginning learners of Spanish and American Sign Language from a larger longitudinal study to test the neural activation to words that differed based on their phonetic categories (i.e., initial phoneme or location parameter for Spanish and ASL, respectively) before they started to learn the language. In this way, we were able to investigate (1) whether phonetic segmentation of an unknown language elicited activation in prefrontal regions, and (2) whether similar patterns of activation were seen across languages in different modalities.

2. Results

2.1. Behavioral data

The accuracy data were analyzed using an analysis of variance (ANOVA) with Language (English vs. ASL vs. Spanish) as the within-subjects factor and Length of Instruction as a covariate. All subjects were analyzed because they were all