Specialization of posterior prefrontal cortex: segmentation or something else?

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ABSTRACT

One of the challenges for cognitive neuroscience is to identify functional roles of brain regions involved in complex decision-making phonological tasks. The Chinese language provides an optimal window for investigating extraction of segmental and suprasegmental units. The aim of this fMRI study is to elucidate neural mechanisms involved in extraction of Chinese consonants, rhymes, and tones in non-minimal and minimal pairs. Triplets of minimal or non-minimal pairs of Chinese monosyllables were constructed to compare consonants, rhymes, and tones. Ten Chinese and English subjects were asked to selectively attend to intrasyllabic components of the target syllables and make discrimination judgments. In comparison to the English group, the Chinese group showed increased activation in the left posterior prefrontal cortex (PFC) when processing consonants, rhymes, or tones, no matter the stimulus type, minimal or non-minimal. Comparisons of non-minimal to minimal pairs within the Chinese group revealed activation of areas outside of the left posterior PFC for consonants and rhymes; for tones, bilateral activation in anterior and posterior prefrontal regions, and in predominantly left-sided inferior parietal regions. Comparisons of consonants, rhymes, and tones within stimulus type (minimal, non-minimal) show left posterior prefrontal activation for rhymes in the Chinese group, tones in the English group. These findings support the notion of an attention-modulated neural network underlying different aspects of phonological processing.

1. INTRODUCTION

Overt segmentation requires that there are a number of differences in the segments of paired speech stimuli (*non-minimal* pairs). In non-minimal pairs, subjects must separate the individual sounds from the whole stimulus in order to make a discrimination judgment. In *minimal* pairs, a subject's judgment can be based on simple acoustic similarity. The optimal test of the overt segmentation hypothesis requires that non-minimal pairs (e.g., ***d**ip-**t**omb* pairs) be compared directly to minimal pairs (e.g., ***d**ip-**t**ip* pairs). It has been demonstrated that non-minimal pairs activate a posterior and superior subregion of left inferior PFC, whereas minimal pairs do not [1].

The Chinese (Mandarin) language provides an optimal window for investigating segmentation of intrasyllabic units because of its status as a tone language. In addition to consonants (21) and rhymes (37), Chinese (Mandarin) has four lexical tones: e.g., *ma*^{1} 'mother', *ma*^{2} 'hemp', *ma*^{3} 'horse', *ma*^{4} 'scold').

The specific aim of this functional magnetic resonance imaging (fMRI) study is to elucidate neural mechanisms involved in extraction of Chinese consonants, rhymes, and tones. The use of minimal and non-minimal pairs permits us to test directly extraction of phonetic information associated with all three intrasyllabic units. Chinese and English listeners are asked to make phonetic discrimination judgments of Chinese consonant, rhymes, and tones.

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2. MATERIALS AND METHODS

Subjects

Ten adult Chinese and English right-handed speakers were closely matched in age and years of formal education. All subjects gave informed consent in compliance with a protocol approved by the Institutional Review Board of Indiana University Purdue University Indianapolis and Clarian Health.

Stimuli

Triplets of monosyllabic, Chinese morphemes were constructed to allow for overt comparison of intrasyllabic units - consonant (C), rhyme (R), tone (T). The target syllables for comparison, which occurred in the first and last positions, were either minimal or non-minimal pairs for Chinese consonants, rhymes, and tones (see Table 1). Three sets of triplets were made up of minimal pairs, one for each intrasyllabic unit ($C_{minimal}$, $R_{minimal}$, $T_{minimal}$). Similarly, another three sets were made up of non-minimal pairs ($C_{non\text{-}minimal}$, $R_{non\text{-}minimal}$, $T_{non\text{-}minimal}$). The intervening syllable differed from the first and last in C, R, and T.

	Minimal Pair	Response
	chai^4 heng^2 **ch**ai^4	same
Consonant	**m**ang^1 you^2 **f**ang^1	different
	b**o**^{2} liu^4 b**o**^{2}	same
Rhyme	r**ong**^{2} lei^4 r**eng**^{2}	different
	huo$^{\mathbf{2}}$ pian^4 huo$^{\mathbf{2}}$	same
Tone	shao$^{\mathbf{2}}$ dong^1 shao$^{\mathbf{4}}$	different
	Non-minimal Pair	Response
	chai^4 heng^2 **ch**a^1	same
Consonant	**m**ang^1 you^2 **r**en^4	different
	b**o**^{2} liu^4 p**o**^{3}	same
Rhyme	r**ong**^{2} lei^4 d**eng**^{3}	different
	huo$^{\mathbf{2}}$ pian^4 ke$^{\mathbf{2}}$	same
Tone	shao$^{\mathbf{2}}$ dong^1 fang$^{\mathbf{4}}$	different

Table 1. Triplets of minimal and non-minimal pairs.

Speech stimuli for the consonant, rhyme, and tone tasks were identical in phonetic structure for both minimal and non-minimal pairs. Corresponding triplets of non-speech hums (H) were created (*Praat*) for the passive listening baseline tasks by resynthesizing the natural speech stimuli.. The non-speech stimuli effectively held spectral information constant, while preserving duration and fundamental frequency properties of the speech stimuli.

Tasks

In active tasks, subjects were required to direct their attention to the *first* and *last* target syllables of each triplet, and make discrimination judgments of consonants, rhymes, or tones, ignoring the intervening syllable. They were asked to press a button to indicate their same/different judgment during a 2 s response interval following each triplet. In the passive control task, they were asked to listen passively to non-speech stimuli.

Imaging Protocol

Scanning was done on a 1.5T Signa GE LX Horizon scanner (Waukesha, WI) equipped with birdcage transmit-receive radiofrequency head coils. Gradient-echo EPI images were acquired with a repetition time/echo time 2 s/50 ms. High-resolution, anatomic images were acquired in 124 contiguous axial slices using a 3D Spoiled-Grass sequence for purposes of anatomic localization and co-registration.

Imaging Analysis

Individual anatomic images and single-subject interpolated activation maps were projected into a standardized stereotaxic coordinate system, summed pixel-by-pixel, combined into within-group activation maps, and displayed on anatomic images from a representative subject. Stereotaxic location of activation peaks and extent of activation were identified by drawing regions of interest around activation foci at a Student's *t*-statistic threshold (1-tailed, uncorrected).

3. RESULTS

Between-Group Comparisons

Tasks (consonant, rhyme, tone) by minimal pairs

A comparison of $C_{minimal}$, $R_{minimal}$, and $T_{minimal}$ to passive listening revealed significant increases of activation in frontal, temporal, and parietal regions predominantly in the left hemisphere (LH) in the Chinese group relative to the English group (tables & figures are omitted due to space limitations). In the frontal lobe, a common peak of activation was observed across tasks in left posterior PFC. Temporal lobe activity was restricted to the left posterior

middle temporal gyrus (MTG) across tasks. Parietal lobe foci were restricted to the LH.

Tasks (consonant, rhyme, tone) by non-minimal pairs

A comparison of $C_{non\text{-}minimal}$, $R_{non\text{-}minimal}$, and $T_{non\text{-}minimal}$ relative to passive listening also revealed significant increases of activation in frontal, temporal, and parietal regions predominantly in the LH in the Chinese group relative to the English group. In the frontal lobe, the left anterolateral MFG was activated in common across tasks. Posterior prefrontal foci were predominantly left-sided across tasks. In the temporal lobe, the left posterior MTG was activated across tasks. In the parietal lobe, peak foci were located near the banks of the intraparietal sulcus.

Within-Group Comparisons

Non-minimal vs. minimal pairs by task (consonant, rhyme, tone)

A comparison of $C_{non\text{-}minimal}$ relative to $C_{minimal}$ showed significant increases of activation in the left inferior parietal region in the Chinese group only. In $R_{non\text{-}minimal}$ minus $R_{minimal}$, an activation focus in the right IFG was centered in the pars triangularis. Activation in anterior regions of the MFG occurred bilaterally.

A comparison of $T_{non\text{-}minimal}$ relative to $T_{minimal}$ showed significant increases of activation in frontal and parietal regions in both groups. Anterior prefrontal activations occurred bilaterally in the Chinese group, but were lateralized to the right hemisphere (RH) in the English group. Posterior prefrontal activations occurred in dorsal aspects of the inferior frontal gyrus bilaterally for the Chinese group. For the English group, posterior prefrontal activation foci also occurred bilaterally, more extensively in the RH. In the parietal lobe, activity was predominantly left-sided in the Chinese group, bilateral in the English group.

Consonant vs. rhyme vs. tone tasks by stimulus type (minimal, non-minimal)

In the Chinese group, a comparison of $R_{non\text{-}minimal}$ relative to either $C_{non\text{-}minimal}$ or $T_{non\text{-}minimal}$ revealed activation foci in the left posterior MFG, extending ventrally into the inferior frontal sulcus. When comparing $R_{minimal}$ to $T_{minimal}$, the focus was located more ventrally in the posterodorsal inferior frontal gyrus. No other direct contrasts of tasks by stimulus type revealed any areas of significant activation for the Chinese group.

In the English group, a comparison of $T_{non\text{-}minimal}$ relative to $C_{non\text{-}minimal}$ or $R_{non\text{-}minimal}$ revealed activation bilaterally in the posterior MFG and inferior parietal lobule. The posterior prefrontal activation was much more extensive in the RH.

4. DISCUSSSION

The major point of our findings is that extraction of phonetic information can only be fully understood by re-conceptualizing this phonological process as one that recruits multiple brain regions across cortex *in addition to* the left posterior PFC. The phonological elements or processes themselves are not in question, but rather how they are implemented in the human brain. The mapping of such phonological processes cannot be mapped onto single brain regions. Indeed, all language processing in real time is mediated by attention and memory processes associated with task demands. Phonology is no exception. By re-directing our focus to the interaction between attention/memory and phonology, we can now begin to see how brain activation associated with phonological processing might vary in degree as a function of language-specific parameters.

In direct between-group comparisons, the Chinese group displays activation of the left posterior PFC when processing consonants, rhymes, or tones, no matter the stimulus type, minimal or non-minimal. Contrary to fact, the segmentation hypothesis would predict prefrontal activation for non-minimal pairs only. Neither can it account for the language effect for minimal pairs. If listeners' judgments are based on acoustic information exclusively, there should be no language effect.

In within-group comparisons, the Chinese group fails to display activation of the left posterior PFC for either consonants ($C_{non\text{-}minimal}$ minus $C_{minimal}$) or rhymes ($R_{non\text{-}minimal}$ minus $R_{minimal}$). For tones ($T_{non\text{-}minimal}$ minus $T_{minimal}$), on the other hand, activation in the posterior PFC is bilateral. This unique effect for tonal processing is likely

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due to an increase in subvocal rehearsal due to late arrival of tonal information. A speeded-response task may exaggerate the computational demands of extracting tonal information from non-minimal pairs. The bilateral activation in the posterior PFC may reflect engagement of pitch processing mechanisms.

For the Chinese group, rhymes induce greater activation in the left posterior PFC as compared to consonants and tones in non-minimal pairs. Indeed, regardless of stimulus type, it is always the rhyme that shows increased activity relative to other intrasyllabic constituents. This activity presumably reflects demands of articulatory coding and subvocal rehearsal. Differences in acoustic characteristics of intrasyllabic components as well as abstract characteristics of the Mandarin syllable appear to be relevant. For the English group, tones show increased bilateral activity in the posterior PFC relative to consonants or rhymes in non-minimal pairs. These crosslinguistic differences in comparisons of intrasyllabic units reflect differences in listeners' processing strategies consistent with their language background [2-4].

It is claimed that activity in the left posterior PFC is modulated by attentional and memory constraints, and that these constraints may be related to internal, structural units of the Mandarin syllable. Segmentation is better thought of as an epiphenomenon that results from extraction of phonetic information from syllable structure within the context of task demands. Chinese listeners show more activity for tones in non-minimal pairs as compared to minimal primarily because of their processing relationship to the rhyme [5] and constraints of verbal working memory. Due to the small number of tones and their close connection to the rhyme, less subvocal rehearsal may be required for tones in the left posterior PFC in minimal pairs relative to non-minimal. A direct comparison of syllable-internal units reveals that rhyme judgments evoke more activity in the left posterior PFC than either consonant or tone across stimulus types. More subvocal rehearsal for rhymes than consonants may be due to the longer duration of rhymes, their co-occurrence restrictions with consonants, as well as to their numerical preponderance. Rhymes may elicit more subvocal rehearsal than tones because of their numerical preponderance and earlier accessibility in working memory.

In conclusion, the present fMRI study demonstrates that theoretical linguistic constructs can only be meaningfully interpreted in the context of specific task demands associated with attention and verbal working memory. They cannot be explained by focusing on a single brain region. Instead of attributing segmentation to posterior PFC, our findings are the first to demonstrate how anterior PFC regions play a crucial role in distinguishing between non-minimal and minimal pairs.

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