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New approaches to the neural basis of speech sound processing: introduction to special section on brain and speech

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Standard approaches to understanding the neural basis of speech and language have focused on identifying brain areas responsible for very broad aspects of representation and processing. The initial observations by Broca and Wernicke (the left inferior frontal lobe is responsible for expression, the left posterior superior temporal lobe for comprehension) are being further elaborated, largely based on the increasing connection of neurolinguistics to linguistic theory and psycholinguistic work. Much research over the last 30 years has sought to refine the ideas by attributing more specific aspects of language function to different brain areas. For example, it has been argued that Broca's area is responsible for syntactic processing and Wernicke's area for semantic processing. Overall, this research program has been led by the concept of 'spatial representation of function' and comes to conclusions of the sort 'phonology is mediated by areas x and y, semantics is mediated by area z,' and so on.

The successes of this line of research notwithstanding, it is worth bearing in mind that the granularity of analysis is still rather coarse—the units of analysis are entire areas of study, such as phonology or semantics. Current research on cognitive neuroscience of speech and language builds on previous findings by further specifying the functional neuroanatomy but, crucially, aims to go *beyond questions of localization.* In particular, current work attempts (i) to work with theoretically motivated 'elementary units' of analysis (e.g., feature, morpheme, root, etc.); (ii) to be computationally explicit; and (iii) to connect with neurophysiologically identified mechanisms.

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Speech processing: the articulatory-perceptual interface

The cognitive neuroscience research on speech processing discussed in these papers builds on the notion that the language system consists (at least) of a central computational core that interfaces with several input/output systems. The most common input-output (sensory-motor) interface is the auditory speech system, although the computational system interfaces with visual (i.e., written text, sign) and tactile (Braille) inputs and outputs as well.

Until recently, the neural basis of speech perception was primarily studied from the perspective of neuropsychological deficit-lesion data. The established view, articulated in most textbooks on neuroscience, neurology, or neuropsychology, rehearses the classical viewpoint, roughly arguing that speech perception is a left-hemisphere process. This view, although perhaps right, is theoretically underspecified and empirically weak. Moreover, it is disconnected from contemporary neuroscience as well as speech research.

In the last ten years, the development of the functional recording techniques (PET, fMRI, MEG, high-density EEG) has changed the empirical landscape considerably. The papers collected in this issue illustrate how the various techniques employed in research on the cognitive neuroscience of speech, coupled with the increased sensitivity to speech research and theory, are converging to yield a more theoretically motivated, computationally tractable, and biologically realistic model of the neural basis of speech.

The papers below provide evidence from different techniques, the overall result of which is a new view of the functional anatomy and physiology of speech. In particular, *Phillips* argues on the basis of electrophysiological (EEG, MEG) and developmental data that it is critical to maintain different levels of representation and analysis (acoustics, phonetics, and phonology); in addition, he distinguishes two developmental models that aim to specify how the learner builds his or her phonetic repertoire. Consistent with Phillips' position, *Poeppel* suggests on the basis of word deafness deficit-lesion data that speech perception is functionally segregated from general auditory object recognition; further it is argued that the primary cortical substrate for speech perception is not lateralized, and that the bilateral architecture provides a way to analyze the signal on multiple time scales. *Buchsbaum, Hickok, and Humphries* provide new fMRI evidence that identifies a cortical area that appears to be involved in the acoustic-to-articulatory transformation. Finally, *Burton* discusses PET and fMRI data that suggest that several anterior areas (usually lumped together as Broca's area) are differentially sensitive to different types of speech segmentation tasks. The view she develops constrains the anatomic model we aim to develop as well as which types of computation different areas may mediate.

The model that emerges based on the integration of hemodynamic, electrophysiological, and neuropsychological data (Fig. 1) has the following properties: (1) The primary substrate to construct sound-based representations of speech is in the *bilateral* superior temporal cortex (Buchsbaum, Hickok, and Humphries; Poeppel). (2) These areas must be construed such that they maintain the differentiation between different levels of representation and analysis, specifically acoustics, phonetics, and phonology (Phillips, Poeppel). (3) Sound-based representations interface in task-dependent ways with other systems. In particular, the acoustic-phonetic-articulatory "coordinate transformation" occurs in a dorsal pathway (Buchsbaum, Hickok, and Humphries, Burton); a second pathway interfaces with lexical

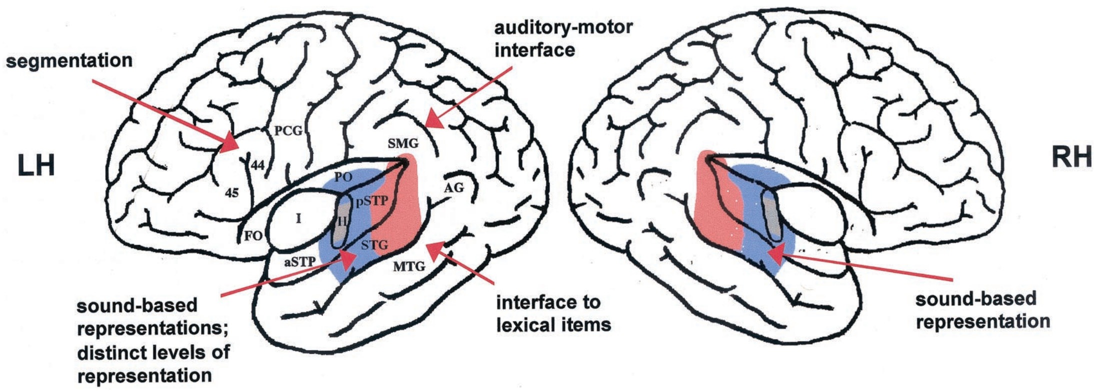

Fig. 1. Left and right lateral view of cortex with the auditory areas unfolded for expository purposes. 44/45 - Broca's area, PCG - precentral gyrus, SMG - supramarginal gyrus, AG - angular gyrus, FO - frontal operculum, I - insula, H - Heschl's gyrus, PO - parietal operculum, a(p)STP - anterior (posterior) superior temporal plane, STG - superior temporal gyrus, MTG - middle temporal gyrus.

semantic systems (not discussed in any paper here). (4) Anterior cortical regions play a central role in very specific *perceptual* speech segmentation tasks (Burton).

In the context of this model future research can now ask a number of questions about the representations and processes germane to speech sound processing. For example, there is a theoretically unifying property, namely the notion of feature. Features in the context of speech are theoretically well motivated, there is new cognitive neuroscience evidence to support their relevance in auditory cortex, and production is best described making use of features. Insofar as the concept of feature motivates the properties of a model such as that outlined here, the concept ties many of the results together—and gives them theoretical bite. Other ideas that can be fruitfully addressed in the present context include the relevance of different levels of representation, the promise of analysis-by-synthesis approaches in speech perception, the extent to which task specificity conditions the functional architecture, and whether there are coordinate transformations in speech analysis.