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The Cortical Computations Underlying Feedback Control in Vocal Production

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Abstract

Recent neurophysiological studies of speaking are beginning to elucidate the neural mechanisms underlying auditory feedback processing during vocalizations. Here we review how research findings impact our state feedback control (SFC) model of speech motor control. We will discuss the evidence for cortical computations that compare incoming feedback with predictions derived from motor efference copy. We will also review observations from auditory feedback perturbation studies that demonstrate clear evidence for a state estimate correction process, which drives compensatory motor behavioral responses. While there is compelling support for cortical computations in the SFC model, there are still several outstanding questions that await resolution by future neural investigations.

INTRODUCTION

When we speak we also hear ourselves. This auditory feedback is not only critical for speech learning and maintenance, but also for the online control of everyday speech. When sensory feedback is altered, we make immediate corrective adjustments to our speech to compensate for those changes. A speaker moves the articulators of his/her vocal tract (i.e., the lungs, larynx, tongue, jaw, and lips) so that an acoustic output is generated that is interpreted by a listener as the words the speaker intended to convey. In this review, we will focus on the prominent role of auditory feedback in speaking. For a number of years, we have explained this role using a model of speech motor control based on state feedback control (SFC) [1–11]

The SFC model explains a range of behavioral phenomena concerning speaking [9, 12], and other proposed models of speech production [13–20] can be described as special cases of SFC [21, 22]. Since its development, considerable new discoveries have been made about the neural substrate of auditory feedback processing during speaking. In this article, we consider how the findings from these recent studies impact our model.

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In our model (Fig 1), when a speaker is prompted to produce a speech sound, higher frontal cortex (IFG) responds by activating several speech control networks, including activating a speech motor control network (blue arrow in fig 1). This cortical network operates via state feedback control (SFC): During articulation, vPMC maintains a running estimate of the current articulatory state (orange in fig 1); this state carries multimodal information about current lip position, tongue body position, formant 1 (F1), formant 2 (F2), and any other parameter the CNS has learned is important to monitor for achieving correct production of the speech sound. M1 generates articulatory controls based on this state estimate, using a state feedback control law (state fb ctrl law in fig 1) that keeps the vocal tract tracking a desired state trajectory (e.g., one that produces the desired speech sound). The estimate of articulatory state is continually refined as articulation proceeds, with incoming sensory feedback from the vocal tract (both somatosensory and auditory feedback) being compared with feedforward sensory predictions (green arrows), generating feedback corrections (red arrows) to the state estimate. In turn, M1 makes use of the updated state estimate to generate further controls that move the estimated state closer to the desired articulatory state trajectory. This process continues until state trajectory generating the speech sound has been fully produced.

Our SFC model is derived from the general state feedback control framework used in optimal feedback control (OFC) models of motor behavior [5, 6, 10, 23, 24]. In this framework, control relies on state estimates furnished by recursive Bayesian filtering: motor efference copy and the previous state estimate determine a prior distribution of predicted next states, and this prior is then updated via Bayes rule using the likelihood of the current sensory feedback. This general form of Bayesian filtering lacks a direct comparison between incoming and predicted sensory feedback, which is notable because feedback comparison is the part of our SFC model's state correction process that allows our model to account for many of our empirical findings. Under linear Gaussian assumptions, however, the Bayesian filtering process reduces to exactly the feedback-comparison-based state correction process found in our SFC model [25].

In the sections that follow we consider what recent neural investigations tell us about how speaking is controlled, and how they impact our SFC model of speaking. We will conclude with brief discussion of some questions about our model that remain unresolved.

Neural evidence for auditory feedback processing during speaking

A crucial window onto the control of speaking (or indeed any motor task) is found in examinations of the role of sensory feedback in the process. For speaking, the processing of auditory feedback is particularly important, because the most proximal goal of speaking is to create sounds. If done correctly, a listener will interpret meaning from these sounds. Thus, the feedback that a speaker can use to most directly monitor the correctness of his/her speech output comes via auditory input. It is not surprising, therefore, that studies have found a variety of neural phenomena indicating that speakers actively monitor their auditory feedback and modulate their ongoing speech motor output based on this feedback [26–43].

Speaking-Induced Suppression (SIS)—One of the first of the neurophysiological phenomena found associated with auditory feedback processing during speech was the phenomenon of Speaking-induced suppression (SIS): the response of a subject's auditory cortices to his/her own self-produced speech is significantly smaller than the response seen when the subject passively re-listens to playback of the same speech (see Figure 2). This effect, which we call speaking-induced suppression (SIS), has been seen using positron emission tomography (PET) [44–46], electroencephalography (EEG) [47, 48], and magnetoencephalography (MEG) [49–54]. An analog of the SIS effect has also been seen in non-human primates [55–57]. MEG experiments have shown that the SIS effect is only minimally explained by a general suppression of auditory cortex during speaking and that this suppression is not happening in the more peripheral parts of the CNS [52]. They have also shown that the observed suppression goes away if the subject's feedback is altered to mismatch his/her expectations [52, 53], as is consistent with some of the PET study findings.

These results are well accounted for by the hypothesized feedback comparison operation at the heart of our SFC model. The onset of speech is predicted from efference copy of motor output in the speaking condition, generating small prediction errors and a small auditory response. On the other hand, in the absence of an onset prediction, the same speech onset generates a large prediction error and a large auditory response during passive listening.

Subsequent to these initial studies, more recent studies have refined this SFC account of SIS. First, studies examining high-gamma responses using direct recordings with electrocorticography (ECoG) have found that SIS is not seen across areas of auditory cortex, but instead is localized to specific subsets of auditory responsive electrodes [58–60]. This cortical response heterogeneity contrasts greatly with the clear SIS effects seen in the M100 evoked response. These results suggest the reasonable possibility that not all areas of auditory cortex are devoted to processing auditory feedback for guiding speech motor control, or, equivalently, that SIS may be a marker of what specific areas of auditory cortex do process feedback for speech motor control.

Second, SIS varies with the natural trial-to-trial variability in repeated vowel productions[61]. Vowel productions whose initial formants deviated most from the median production showed the least SIS and those closest to the median production showed the most SIS. This pattern of “SIS falloff” was consistent with a feedback prediction representing the median production but not variations around this median. This suggested there are limits on the precision of the efference copy-derived predictions hypothesized in SFC to account for SIS, either because the mapping from motor commands to auditory expectations is imprecise, or because the sources of the noise generating the observed production variability are further downstream of the motor cortical outputs presumed to drive efference copy-based sensory predictions. Results of another recent study based on ECoG are consistent with this last point. Bouchard et al. found that, after coarticulatory effects were removed from the audio data, activity in sensorimotor cortex was able to predict a significant fraction of the trial-to-trial variance in vowel productions, but this fraction was modest, suggesting that cortical activity variation is not the only influence on vowel production variability [62].

The results of the Niziolek et al. study also provided indirect evidence for the action of auditory feedback control during speaking. In addition to being associated with less SIS, it was also found that those vowel productions deviating most from the median production underwent a process of “centering” after speech onset. That is, after speech onset, the formant tracks of these productions converged towards the formant tracks of the median production. Furthermore, it was found that, across subjects, this centering of deviating productions was significantly related to those productions’ reduced SIS [61].

Speech Perturbation Response Enhancement (SPRE)—More direct evidence of a role for auditory feedback processing in speaking can be seen in behavioral experiments where speakers compensate for artificial perturbations in their auditory feedback during speaking. Such compensatory responses have been seen in response to perturbations of speech amplitude [30, 31], and vowel formants [32, 33, 63], but the compensatory responses to perturbations of pitch (the so-called “pitch perturbation reflex”) have been the most thoroughly studied, both behaviorally [29, 42, 64–66] as well as in neurophysiological investigations [58, 67–70]. Like the studies of SIS, many of the neural investigations of pitch compensation have been based on evoked responses. In these studies, subjects phonated a steady pitch, and at some point in this phonation, the pitch of their audio feedback was suddenly shifted up or down. Using either EEG [67] or MEG [69], the auditory cortical response to this sudden pitch perturbation was recorded and compared with the auditory response recorded during passive listening to playback of the pitch-perturbed feedback. These studies found that, compared with passive listening, the auditory response to the perturbation during active phonation (speaking) was enhanced, which we call Speech Perturbation Response Enhancement (SPRE) (see Figure 2). This effect differed from SIS in several important ways. It had the opposite polarity of the SIS response (i.e., it was a response enhancement, not a response suppression), and it was principally seen not in the 100ms post onset peak of the evoked response (M100/N1), but instead in the later part of the response (M200/P2).

These characteristics can be accounted for in the SFC model. First, the model posits that SPRE does not arise from any speak/listen difference in the generation of auditory prediction errors. The model assumes that during speaking, the CNS predicts what it will hear based on efference copy of vocal motor commands which, in this case, are maintaining a steady pitch. The model assumes that during passive listening, the CNS predicts it will continue to hear what it has been hearing: a steady pitch. Thus, in both the speak and listen conditions, the prediction is the same (a steady pitch). As a result, onset of the perturbation generates the same size auditory prediction error in both conditions.

But the model also posits that auditory prediction errors are then passed back to higher auditory cortex (red arrow from A1 to vSMG/pSTS in Figure 1), where they are used to correct the current state estimate (red box labeled “state corr auditory” in Figure 1). Here is where the model posits a speak/listen difference. There is a gain associated with this state correction process (called the Kalman gain [1, 2, 71, 72]) that determines how strongly auditory prediction errors drive state corrections. This gain is set to reflect how correlated auditory feedback variations are with changes in the true articulatory state. During speaking, the CNS can indirectly estimate this correlation from the correlation between auditory

feedback and somatosensory feedback (i.e., it can use somatosensory feedback as a noisy measure of the true articulatory state). The CNS then sets the state correction gain using this estimate. But during passive listening, there is no measure of the true articulatory state to correlate with auditory input. In this case, we posit that, without any way to estimate it, the CNS conservatively assumes a low value for the correlation, and sets the state correction gain correspondingly low. This lower gain means that, for the same size auditory prediction error, smaller state corrections are generated during listening than during speaking. In other words, during speaking, there is an enhanced state correction response to the perturbation (SPRE), which we would see reflected not in early (100ms post-perturbation) activity related to auditory prediction errors, but instead in the later activity of higher auditory cortex where state corrections are generated. It is therefore not surprising that the SPRE effect is seen not in M100/N1 responses, but instead in the later M200/P2 responses [67, 69]. Also consistent with this is evidence from the MEG study of SPRE showing that the effect is strongest in higher levels of temporal cortex [69].

In these initial investigations of SPRE, the effect is seen as a dominant feature of the evoked response to the pitch perturbation, but in subsequent investigations based on ECoG [58, 70], the reflection of the effect in high gamma power changes was seen to be more complicated. Not all electrode sites exhibited SPRE, and of those sites that did exhibit SPRE, many of them did not express SIS. In addition, several of the sites expressing SIS did not also express SPRE. The fact that not all sites showed SPRE is easily explained as reflecting the fact that not all areas of auditory cortex are devoted to feedback control of speaking, and the sites showing SIS but not SPRE can also be accounted for in the SFC model where the feedback comparison operation that generates SIS is separate from the state correction operation that generates SPRE. However, the model does predict that since the feedback comparison operation feeds into the state correction operation, all sites expressing SPRE should also express SIS. That this is not the case is a challenge for our original SFC formulation (and for the many models that are variants of SFC), and suggests the possibility that some state corrections could be based on feedback comparison operations that use predictions not derived from efference copy, thus don't express SIS.

Regardless of these variations of SPRE/SIS characteristics, our SFC model predicts that the SPRE should be most directly associated with feedback control of speaking, and indeed the Chang et al. study found evidence that this is the case. SPRE (as measured by the difference between speaking and listening responses to the pitch perturbation) was correlated with compensation across trials and SPRE significantly predicted the amount of compensation, whereas SIS did not [58]. SFC model predicts this: The SPRE expressing part of the model (state correction) is dependent on the state correction gain, while the SIS part (feedback comparison) is not. The state correction gain is postulated to be dynamically estimated on-line, so it varies a bit from trial to trial in the experiment. That trial-to-trial variability is expressed not in the SIS part of the model, but instead in the activity of the SPRE-expressing part, as well as in the downstream compensatory motor responses driven by the state correction.

More recent studies have elaborated our picture of the neural correlates of the pitch perturbation reflex, and these have, in turn, helped to elaborate further the details of our SFC

model. A recent study used magnetoencephalographic imaging (MEGI) to look at the high gamma responses to the pitch perturbation, and found that the dominant response to the perturbation was in the right hemisphere, in premotor cortex and the supramarginal gyrus [73]. Further, the study found that this right hemisphere activity was linked to the left via a dynamically changing pattern of functional connectivity. This result is consistent with that seen in a prior study of responses to formant perturbations [33] that also found right hemisphere involvement in perturbation responses. Taken together, these results imply that our SFC model has a neural substrate that is distributed between the two hemispheres, with the MEGI data suggesting that the early responding left hemisphere primarily detects feedback prediction mismatches, while the later responding right hemisphere is more involved in generating state corrections from the feedback prediction errors.

Unresolved questions about the SFC model—In sum, our SFC model accounts for much of what has been recently learned about the neural substrate of auditory feedback processing in speaking. Nevertheless, there remain several unresolved issues concerning the structure of the model and its neural instantiation. Central to the model are the motor-to-sensory mappings used to generate feedback predictions from speech motor activity. However little is known about the nature or neural substrate of these mappings, or the neural mechanisms by which their outputs are compared with incoming feedback. Are the mappings represented in frontal areas like vPMC, or instead in sensory areas like pSTG and SII? For each sense modality, is there a single mapping that's shared in the production of all speech sounds, or are there separate mappings for each speech sound's production? Recent ECoG studies show great differences in how speech features are organized in sensorimotor cortex [74] and auditory cortex [75] which may be difficult to reconcile with a single shared mapping. There are also studies showing that altering the audiomotor mapping in one word's production doesn't generalize to other words [39], suggesting individual mappings. If this were the case, then different words' productions might be controlled by separate SFC-based speech motor control networks (see Fig 1). Another issue concerns the structure of the SFC model. Recent ECoG studies and stimulation studies have also found a blurring of the distinction between primary motor (M1) and sensory (S1) areas around the central sulcus [74], suggesting a tight coupling between the two areas. This suggests the possibility of a control hierarchy, where M1 and S1 function as a low-level controller of articulatory movements, which in turn is controlled by a higher level SFC-based speech motor control network integrating both somatosensory and auditory feedback [20, 76]. These issues must be resolved in future investigations of the neural substrate of speech motor control.

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BOX 1-MAIN CONCEPTS

1. In the state feedback control (SFC) model, speaking is controlled using a running estimate of the current vocal tract state; this estimate is updated by comparing incoming sensory feedback with feedback predictions derived from motor efference copy.
2. The SFC model explains why auditory cortex is suppressed when listening to one's own speech (speaking-induced suppression, or SIS) but enhanced when a feedback perturbation is perceived during speaking (speech perturbation response enhancement, or SPRE).
3. The degree of suppression in SIS is reduced in utterance productions that deviate from the median production, implying that the accuracy of feedback predictions derived from motor efference copy is limited.
4. When auditory feedback is perturbed, the activity of areas in auditory cortex that express SPRE is more correlated with behavioral compensation than activity in other auditory areas; this result is predicted by the SFC model.

UNRESOLVED QUESTIONS

1. What are the neural mechanisms by which incoming sensory feedback is compared with feedback predictions?
2. What is the nature and neural substrate of the motor-to-sensory mappings required for SFC?
3. Is there neural evidence for a hierarchical organization of the speech motor control networks postulated by SFC?

HIGHLIGHTS (Houde and Chang)

1. State feedback control (SFC) model is described for speech motor control.
2. SFC explains auditory suppression/enhancement depending on motor predictions.
3. SFC confirmed by auditory-driven vocal compensation during feedback perturbation.

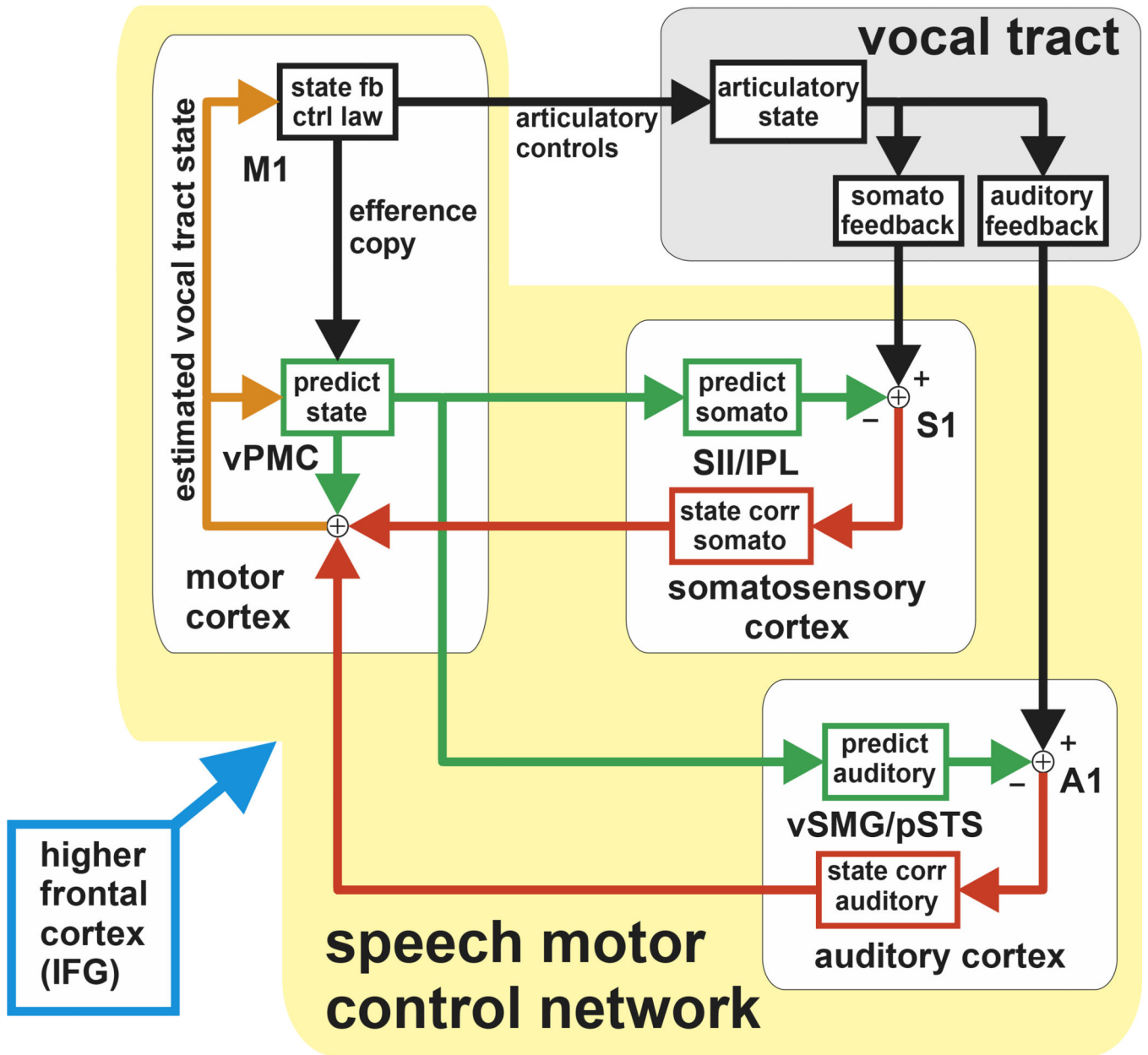


Figure 1. A model of speech motor control based on state feedback control (SFC). In the model, articulatory controls sent to the vocal tract from M1 are based on an estimate of the current vocal tract state (orange arrows) that is maintained by an interaction between vPMC and the sensory cortices. In this interaction, feedback predictions (green arrows) are compared with incoming feedback (black arrows), generating corrections to the state estimate (red arrows). See text for details.

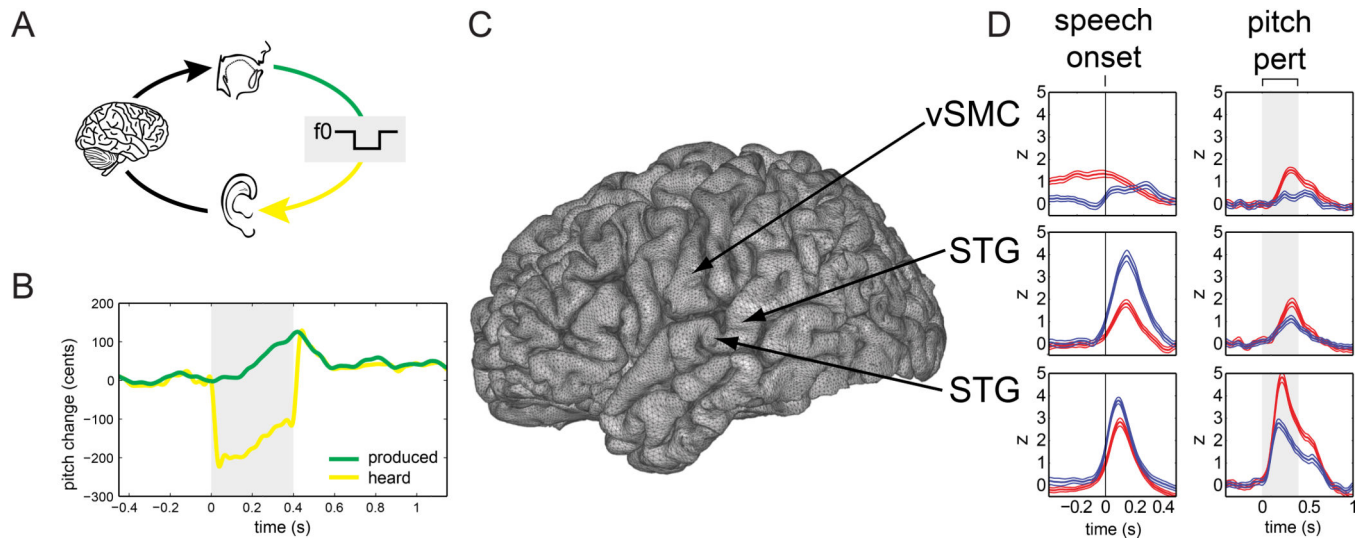


Figure 2. Examples of SIS and SPRE during pitch perturbation of vocalization. (a) A DSP shifted the pitch of subjects' vocalizations (green line) and delivered this auditory feedback (yellow line) to subjects' earphones. (b) Pitch track of an example trial. The green line shows the pitch recorded by the microphone (produced) and the yellow line shows the pitch delivered to the earphones (heard). Shaded region shows time interval when DSP shifted pitch by 200 cents (1/6 octave). (c) Location of three electrodes on the cortical surface. (d) High-gamma line plots for each electrode in the speak (red) and listen (blue) conditions, with vertical lines in the left column of plots representing speech onset (where SIS [speak response < listen response] is observed) and shaded regions in the right column of plots representing perturbation onset and offset (where SPRE [speak response > listen response] is observed). Adapted from Chang et al., PNAS 2011.