Sensorimotor Integration in the Dorsal Speech Processing Stream via Directed Beta-Band Interactions

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Abstract

Speech processing relies on dorsal stream brain circuitry linking speech sounds with their articulatory representations (Hickok & Poeppel, 2007). We investigated sensorimotor integration along the dorsal stream by measuring frequency-specific directed connectivity between auditory and frontoparietal brain regions during a categorical speech perception task. Beta-band (13-29Hz) interactions between auditory and sensorimotor cortex related to perceptual behaviour, including when participants' articulatory configuration was mechanically perturbed. These findings advance the neurophysiology of sensorimotor integration in speech perception.

Keywords: speech perception; sensorimotor integration; dorsal stream; MEG

Introduction

The motor theory of speech perception proposes that speech sounds are recognized according to their underlying articulatory representations (Liberman & Mattingly, 1985). The dorsal speech processing stream is hypothesized to support such sensorimotor integration: white-matter tracts connecting auditory and frontoparietal brain areas subserve *repetition*—the auditory-motor transformation of speech sounds into their respective articulatory representations (Baboyan et al., 2021).

Neurophysiologically, auditory and motor brain systems interact through coupled neural oscillations (Bedford et al., 2025), which mediate predictive auditory processing via top–down signalling in the beta frequency range (12-29Hz ; Arnal et al., 2015; Morillon & Baillet, 2017). When listening to speech sounds, motor cortex is somatotopically activated according to the heard phoneme's place of articulation (Pulvermüller et al., 2006); and differential modulation of beta power between clear and ambiguous speech sound responses predicts listeners' ability to distinguish perceptual categories (Bidelman, 2015).

We propose that oscillatory interactions along the dorsal stream are involved in mapping speech sounds to articulatory representations, thus facilitating phonetic perception. We investigated directed functional connectivity during a categorical speech perception task performed with and without articulatory perturbation. We posited that auditory-dorsal signalling in the beta band correlates with task performance and is altered by speech-relevant articulatory perturbations.

Methods

We recorded MEG from healthy adults (*N* = 18) both while at rest and as they listened to and classified speech sounds. The stimuli consisted of a 9-step acoustic continuum synthesized between vowels /u/ (small lip area) and /œ/ (large lip area). The task was performed twice: once normally (baseline), and once with a 2.5 cm plastic tube held between the lips (liptube). This perturbation aimed to mimic the postural configuration and orofacial somatosensory feedback associated with articulation of the more opened vowel, inducing biased vowel production (Ménard et al., 2016) and perception (Ménard et al., 2023) accordingly.

MEG sensor data were co-registered to each participants' T1-weighted MRI before reconstructing cortical sources via minimum-norm imaging with *Brainstorm*. We first analyzed undirected, whole-brain connectivity with bilateral auditory cortices during task and rest (baseline condition only) using imaginary coherence. Next, we computed bidirectional phase-transfer entropy (PTE) between primary auditory cortices and ipsilateral dorsal stream regions of interest (ROI) comprising: inferior frontal gyrus (IFG), dorsal premotor (PMd), ventral primary motor (M1v) and somatosensory (S1v) cortices and the Sylvian parietotemporal area (SPT). We then derived a single directed measure per ROI (dPTE) whose sign reflected the preferred direction of neurophysiological influence:

$$dPTE(x) = \frac{PTE(x \to A1) - PTE(A1 \to x)}{PTE(x \to A1) + PTE(A1 \to x)} - .5$$

Task-based PTE was calculated from both conditions on a single-trial basis: examining 500-ms epochs immediately before and after sound onset. Stimulus-related changes in dPTE were assessed by subtracting pre- from post-dPTE.

Results

We contrasted imaginary coherence maps between task and rest using one-tailed paired samples t-tests, which highlighted several frontoparietal regions manifesting enhanced broadband phase synchrony with the auditory cortex when listening to speech sounds (Figure 1).

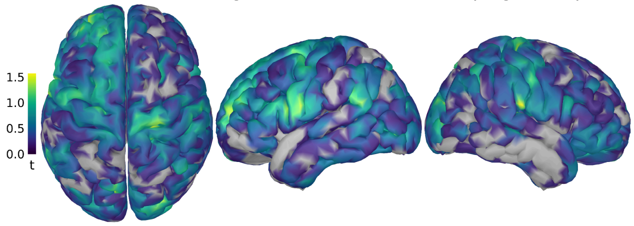

Figure 1: Broadband speech-enhanced connectivity with auditory cortex ($p < .05$, uncorrected), averaged across frequencies from 2-59 Hz.

Directed phase-transfer entropy revealed frequency-specific influence along the auditory dorsal stream: with predominant bottom-up interactions in the alpha band, and top-down in delta, theta and beta bands (Figure 2).

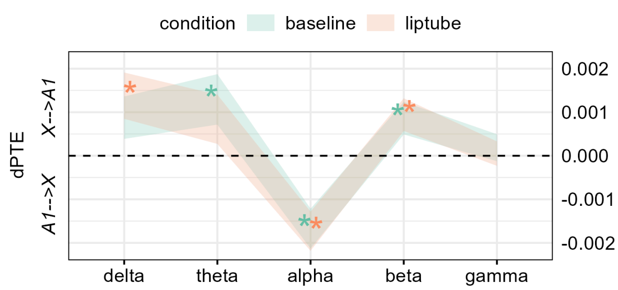

Figure 2: Directed influence between auditory cortex and dorsal stream regions. Asterisks denote significantly non-zero (i.e. directional) PTE ($p < .05$).

Response times increased for ambiguous tokens near the middle of the acoustic continuum (Figure 3), correlating with stimulus-related dPTE in the IFG ($r = -0.210$, $p = 0.007$) and S1v ($r = 0.206$, $p = 0.009$).

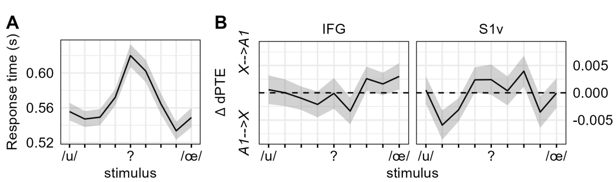

Figure 3: Stimulus response time (A) and dPTE' (B).

Articulatory perturbation inversed the direction of pre-stimulus beta-band information flow with left M1v: those with bottom-up dPTE at baseline tended more towards top-down with the liptube, and vice versa (Figure 4A). Baseline beta-band dPTE values predicted perceptual changes imposed by the liptube in the left S1v ($r = .588$, $p = .010$) and M1v ($r = .538$, $p = .0212$): bottom-up dPTE increased the likelihood of perceiving ambiguous sounds as /œ/, and top-down dPTE decreased it (Figure 4B).

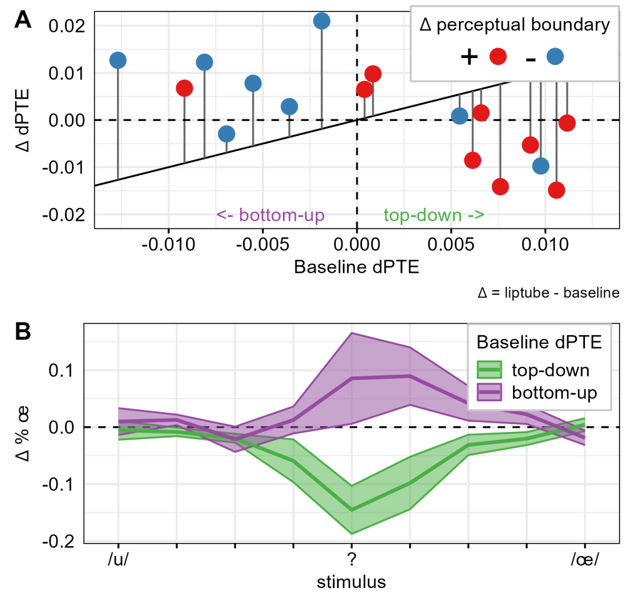

Figure 4: Effects of the articulatory perturbation on ventral primary motor dPTE (A) and perception (B).

Discussion

Using a task engaging phonetic processing, we reveal the dynamics of auditory dorsal stream connectivity during speech perception. We show that directed beta-band interactions track phonetic ambiguity, and are sensitive to altered orofacial configuration, ultimately predicting the perceptual changes imposed by this articulatory perturbation.
These findings emphasize that the neural auditory-dorsal pathway is involved in the articulatory transformation of speech sounds, and suggest a neurophysiological circuit mechanism for sensorimotor integration in speech perception supported by neural oscillations.

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