Between Time and Space: Coordination of Articulator Movements in The Motor Cortex

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> [I]n English, the lateral tongue contraction . . . gives to those unaccustomed to this setting the impression that the tongue is somewhat tensed, but the Englishman is not aware of any tension and feels the tongue to be relaxed.[1]

Singing is the most complex human motor behavior involving the seemingly instantaneous coordination of more than 100 diverse muscles. The perceived spontaneous sound production requires precise control in a tight timing window at the level of milliseconds. The synchronous recruitment is a wonder of motor prediction, with calculations, signals, and even some muscle activity occurring prior to any onset of sound. In previous "Minding the Gap" columns, we have explored the cortical nature of both respiratory and glottal regulation during phonation.[2] The research reveals that the fine motor control required consolidates to areas of the sensorimotor cortex. By shifting to a centralized location for laryngeal, respiratory, and auditory pitch processing, the brain can rapidly coordinate and adapt to both feedforward and feedback inputs (Figure 1). In addition to coordinating pitch, the dorsal laryngeal motor cortex (dLMC) also serves as the auditory pitch processing center. Both laryngeal motor cortices, dorsal (dLMC) and ventral (vLMC), also balance the natural pressure changes at the glottis as we inhale and exhale. Separate from pitch and voicing, this is a specialized area to counter the natural declination as we phonate through a phrase (note: this is different from the term "maximum flow declination rate" or MDFR, which refers to the fastest airflow pressure drop possible in each vibratory cycle).[3] In other words, when the respiratory system is homeostatically balanced, all components of vocalization are driven from a small, localized area in the sensorimotor cortex.

Articulators are organized similarly. They are signaled in close proximity to other vocal elements in the sensorimotor cortex. Much of the complexity in our vocal abilities revolves around the incredibly diverse shapes created in our vocal tract giving rise to an endless array of sound permutations. The active articulators (lips, tongue, jaw, glottis, pharynx, and soft palate) are the primary players in generating these diverse configurations. In speech, the shapes generated by the vocal tract are interpreted as distinct phonemic elements that give rise to language. However, singing involves more extreme variations: wide-ranging pitches, rhythms, volume, and durations mean that

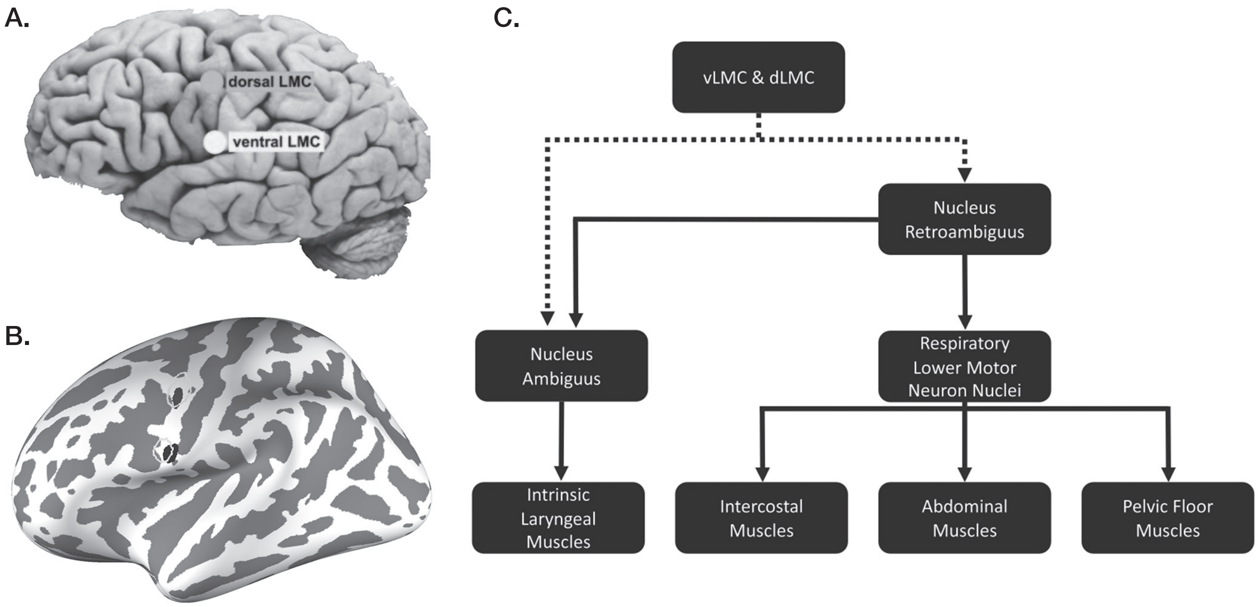

Figure 1. Cortical Consolidation in Phonation. The brain clusters motor and feedback functions for phonation in close proximity to facilitate coordination and speed. Some elements are far removed from their traditional sensorimotor locations in the brain, like auditory processing and respiration. A. Left hemisphere showing the locations of the vLMC and the dLMC (from Beylk, 2017). B. Combined data showing functional overlap from fMRI study of syllable auditory perception and covert vocalization (circle outlines) and areas that map speech motor function (solid circles) (from Rong et al., 2018 and Lu et al., 2021). C. Hierarchical organization of respiratory recruitment for phonation by the vLMC and dLMC (from Beylk, 2021).

these shapes must change to fit the context of a song rather than the accustomed linguistics. In other words, the brain is overriding preexisting signals to generate a new coordination that best suits the acoustics, flow of the music, and homeostasis within an individual.

As Honikman has noted, each language has a default neutral setting where all subsequent movements are generated.[4] A native speaker's linguistic profile dramatically influences the somatosensory system, and has just as much to do with the position of the speech articulators as it does with the sounds themselves. An English speaker's sense of a relaxed, neutral tongue makes a French speaker, whose neutral is different, feel tense and postured. The tongue can never be without any muscle action, because a floppy tongue would cause us to choke. Kerrie Obert has done incredible work in destigmatizing the term "tongue tension" in voice pedagogy:tension is required to create incredibly diverse palette of sounds. It is more about position than tension.[5]

In order to understand articulator signaling, we must first revisit the idea of prediction. When your brain decides to sing something, it relies on past experience to signal an appropriate motor pathway. Information from many parts of the brain feed into a pre-motor auditory signal which recruits the appropriate muscles for that particular sound.[6] As vocal learners, the auditory step is essential and a hallmark of the system. These predictive calculations are made rapidly at an unconscious level. However, pedagogically we can use tools such as audiation (hearing in one's head), affect, and intention to refine this predictive process.

Much of the brain's predictive information for singing comes from motor learning. But the motor learning field evolved using nonvocal systems (e.g., athletics), and not all elements are analogous. The vocal motor system is both unique and more complex than Schmidt's thesis, so qualifying and quantifying these differences is essential.[7] Articulator movement in the motor cortex is an outlier among motor systems. Thus, in order to design better protocols to maximize efficiency in singing, these distinctions must be both understood and incorporated. Otherwise, singers are either reinforcing

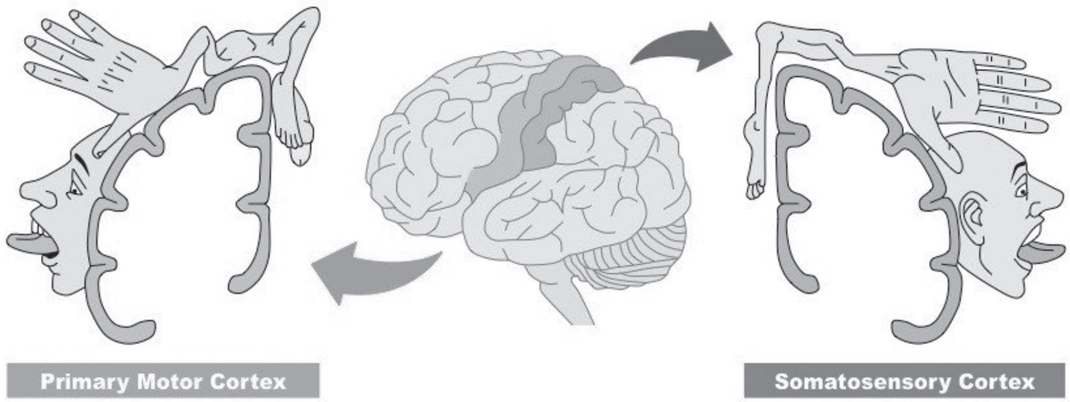

Figure 2. **Traditional Cortical Homunculus. In this model, each part has a corresponding location in the sensorimotor cortex. Areas for fine motor skills have more real estate due to the number of neurons and connections. The vocal motor system is not organized by location, but rather by temporal-spatial relationships. Additionally, cortical areas for respiration and auditory pitch processing consolidate with the laryngeal motor cortices for more efficient and rapid coordination (image source unknown).**

unhelpful habits, or performing unnecessary actions that have little bearing on the ultimate target. This favors a more context-dependent framework of voice pedagogy as opposed to the instrumental model. Exercises from the nonvocal world, like scales and arpeggios, have been appropriated by a motor system that is inherently different. To better imprint motor skills, singers will improve more rapidly if the learning process is targeted. Traditionally, lessons begin with warm ups with little direct reference to the music students are singing. Instead, it may be helpful to extract elements from a song and design vocalises around those structures to better serve the vocal motor pathway. Repertoire can offer variety and technical options on a par with standard exercises; creating customized patterns from phrases through inversions or permutations, changing dynamics, changing rhythms, adding staccato, coloratura, improvisation, etc., are more fruitful vocal explorations. The brain then receives more predictive targets for the task at hand. This is more helpful for the vocal motor system than an arbitrary vocal gesture.

Much of motor learning theory involves the idea of a homunculous (Figure 2). Simply stated, the brain executes movement of a particular part of the body from a particular part of the brain; for example, if one is learning to play piano, each finger has a "home" in the motor cortex that reproducibly fires a signal from that location. It is an easy to follow map of "part to place to action." However, the articulators in speech and singing are not arranged in that same manner. This was first observed in focal stimulation experiments conducted in 1937.[8] Unlike other muscles, when scientists would target areas representing articulators, focal stimulation could never generate any speech sounds.[9] When we vocalize, the tongue is not signaled from a singular "tongue" location in the motor cortex, but rather in association with other articulators to generate a specific sound target. Although the spatial organization of the speech sensorimotor cortex is laid out according to a somatotopic representation of the face and vocal tract, the functional areas are different.[10] Articulator representations appear to be interdigitated, overlapping, and fractured in their organization. In other words, cortical signaling is actually coupled to phoneme context, not the articulators themselves.[11]

Consonants occupy distinct regions of cortical state-space that are different from vowels, despite sharing articulators. They are clustered in the sensorimotor cortex such that consonant to vowel distances (C->V) were greater than C->C and V->V distances[12] This may be why it is easier to substitute one or the other—e.g., Raffi's "Apples and Bananas" (or "Ooples and Boo-noo-noos"), a North American children's song that plays with the vowels of words.[13] The verses replace most or all vowels with one given vowel sound. For example, vowels can be replaced by each of the long vowels sounds

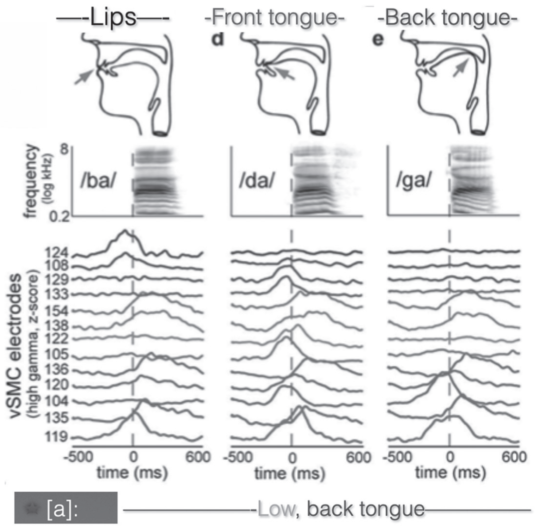

Figure 3. **Cortical signal of a consonant-vowel transition. Vowels are signaled in the vocal motor cortex based on context in a spatial-temporal fashion (image from Bouchard et al., 2013).**

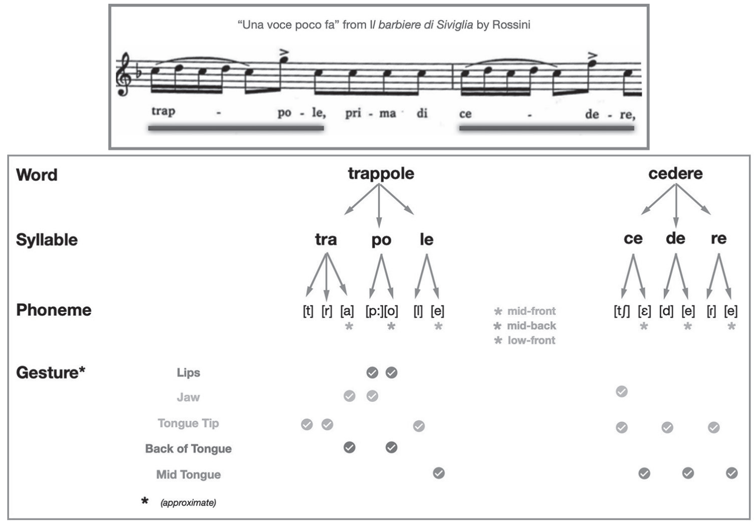

Figure 4. **Gesture complexity is variable within phonemes.**

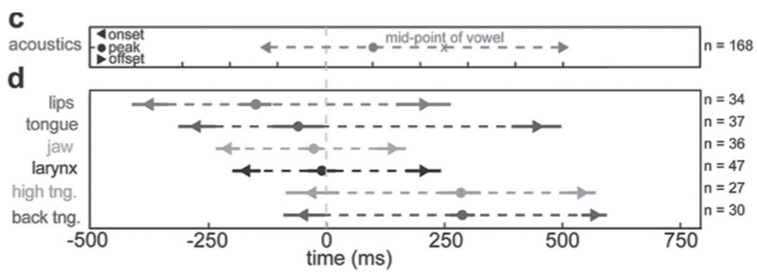

Figure 5. **Timing relationships between articulators is staggered (image from Bouchard et al., 2013).**

of ⟨a⟩ (/eɪ/), ⟨e⟩ (/iː/), ⟨i⟩ (/aɪ/), ⟨o⟩ (/oʊ/), and ⟨u⟩ (/uː/). However, it is more challenging to mix and match consonants and vowels in this kind of exercise given the cortical localizations. Context plays an essential role in signaling. Articulators are mapped according to spacial-temporal locations in the motor cortex. Sites are tuned to one articulator and then co-modulated by other articulators.[14] For example, the sounds [ba], [da], and [ga] show that there is no discrete motor signal for [a]: each unit has a different signal based on context (Figure 3). This means when practicing on vowels alone, it is also important to occasionally audiate them in context to truly represent the motor signaling. Like other predictive motor behaviors, the neural activity occurs before vocalization to maximize integration of complex motor commands. This points to a gestural theory of speech control over alternative acoustic or vocal tract geometry theories. These results are consistent with an underlying organization reflecting the construct of a phoneme. Because gestures can vary in complexity within a phoneme, it is important for singers to keep that in mind that not all phonemes are created equal in terms of ease (Figure 4).

There are also temporal considerations in the coordination of vocal motor signaling schema (Figure 5).[15] Like a conductor of an orchestra, the brain needs to cue elements in a specific order and relate each subsequent action based on the previous one in line. For articulators, it flows in the spatial order of the vocal tract starting with the lips. Interestingly, the laryngeal elements are signaled before the tongue elements. This all happens incredibly fast—too rapid to micromanage—but the order is interesting nonetheless.

We can apply all of these ideas pedagogically. Temporal, acoustic, stylistic, and linguistic elements contribute to the vocal palette and are considered in articulator calculations. Motor learning can be used to rewire vernacular pathways into context-dependent pathways, since articulator movements for speech do not always align with singing. Dynamics and pitch can impact articulator positions at the unconscious level as well as our language of origin. An understanding of

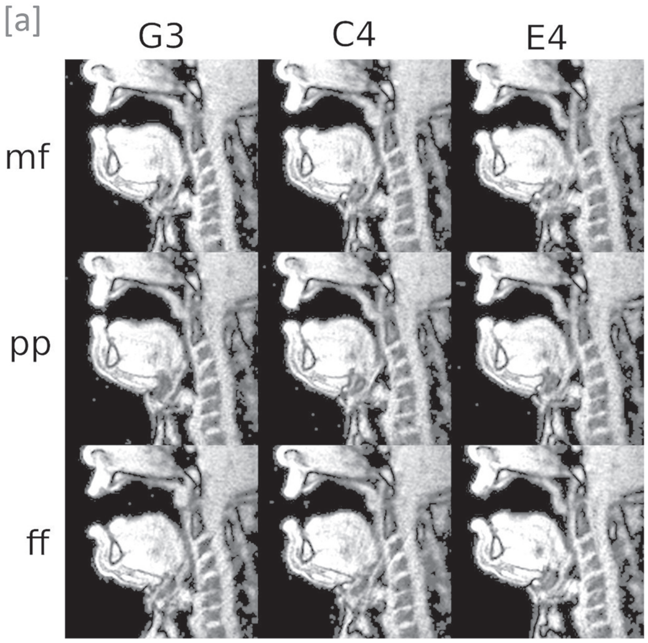

Figure 6. Impact of pitch and dynamics on articulator positions for [a] (image from Echternach et al., 2016).

articulatory settings ("linguistic neutral") can enhance efficiency of motor targets (Figure 6).[16] The spaces in between (e.g., before and after a phrase/word, during a breath) are also important for efficient articulation since we can prime the system with shapes such as lip rounding or under vowel based on acoustic targets.[17]

"What to think about when" is the holy grail when designing pedagogic strategies for both practice and performance. Vocal expertise via flexible predictive imprinting is achieved via motor learning. But motor learning in vocalization is unique given the distinct cortical mapping of the over 100 muscles necessary to execute a vocal task. Thus, to imprint efficient habits, practice requires reductionism and repetition which can automate movement in alignment with how the system is signaled. Mistakes, trial and error, and play are also a necessary part of motor learning. Rest between motor practice segments generates cognitive replay and is essential for consolidation of a skill.[18] A wide variety of pedagogic approaches can yield positive results; every teacher and student is unique so there is no one path to vocal ease. But since vocal ease is necessary for artistry, articulator efficiency is one element that can have a broad impact on a singer's success. Since the vocal system is functionally integrated, an acoustically optimized vocal tract via articulator movements will subsequently fuel efficiency at the vocal folds, which in turn facilitates respiratory flow. A suggested articulator practice strategy for singers and teachers is listed in Table 1. Understanding the cortical signaling of these mechanisms facilitates ease. Since the goal for all singers is freedom of the mechanism and agency in artistry, we can use this information to generate greater ease, making singers better faster.

TABLE 1. A Strategy for Achieving Articulator Efficiency.

Gestural Clustering of Phonemes.

- Sometimes we need to **dissect text** into its **component gestures** in order to have *efficiency of pronunciation*.
  - — In other words, ***not*** thinking about linguistic diction can make for better diction!
- This exercise is about creating the *shortest distance between points*:
  - — Play with **two words in a row** that have *complex consonant clusters* at the *end* of one and the *beginning* of another. Play with pronouncing that linkage until it becomes ONE unit in your brain, not a part of two different words.
  - — For example, Strauss's "An Die Nacht": *"Heilige Na***cht, St***erngeschloss'ner Himmelsfriede!"*
    - Try saying "**nacht Ste-**" over and over until it feels easy and like a unified gesture rather than parts of two words.
  - — Same goes for **vowels**:
    - e.g., "The Silver Aria" from *The Ballad of Baby Doe: "'T***i***s th***e** *m***oo***n that mints her silver."*
    - If you practice with an ***intention*** of the **lip rounding vowel** in *"moon"* WHILE singing *"Tis the,"* it will be a more efficient transition of articulators.
- **Practicing "the shortest distance between points"** is the goal for speed and efficiency.

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Heidi Moss Erickson received a dual biology and voice degree at Oberlin College, where she worked in the voice lab of Richard Miller. Her more than 20 year performing career spans both opera and concert repertoire, with a focus on new music. She received her graduate degree in biochemistry with an emphasis in neuroscience. Her postgraduate research on telomeres at Rockefeller University led to prestigious publications, including a landmark paper in *Cell*. Heidi teaches vocal physiology at the San Francisco Conservatory of Music and applied voice at UC Davis. In 2007 she came down with a rare CNVII nerve injury which resurrected her passion for how the brain controls singing. Her courses and lectures have been featured both nationally and internationally at conferences and universities. www.heidimosserickson.com

Beneath the waning moon I walk at night,
And muse on human life, for all around
Are dim uncertain shapes that cheat the sight,
And pitfalls lurk in shade along the ground,
And broken gleams of brightness, here and there,
Glance through, and leave unwarmed the
death-like air.

The trampled earth returns a sound of fear,
A hollow sound, as if I walked on tombs!
And lights, that tell of cheerful homes, appear
Far off, and die like hope amid the glooms.
A mournful wind across the landscape flies,
And the wide atmosphere is full of sighs.

And I, with faltering footsteps, journey on,
Watching the stars that roll the hours away,
Till the faint light that guides me now is gone,
And, like another life, the glorious day
Shall open o'er me from the empyreal height,
With warmth, and certainty, and boundless light.

William Cullen Bryant,
"The Journey of Life"