What Garcia Got Right: Understanding Cortical Signaling of the Glottis

Heidi Moss Erickson

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> The pupil . . . should draw in breath slowly, and then produce the sounds by a neat, resolute articulation of the glottis . . . Care however must be taken to attend to the pitch of the sound at once on the note itself, and not to slur up to it, or feel for it . . .
>
> The glottis is prepared for articulation by closing it . . . [1]

PHONATION IS A WONDER of physics and physiology. In reductionist terms, the mechanics can be viewed as a valve system. The streaming airflow from the lungs passes through a dynamic and complex structure, constantly changing aperture and configuration. The effect impacts both the pressure and speed of the air (Figure 1). [2] The vocal tract symbiotically interacts with these waves, shaping and refining the sound to give rise to our unique voices. The nuance of this is extraordinary; as we sing and speak the vocal fold configuration is constantly changing in length and degree of contact under pressure conditions that are not always predictable. Yet the folds remain remarkably diligent in their ability to maintain equilibrium throughout these rapid changes. This is unlike other respiratory behaviors that have far less variation at the glottis. Without such discipline of the mechanism, we would not be capable of getting stability in any sound. Large, distal muscles of respiration are not designed to regulate such nuance at the millisecond level.[3] So it is left to the larynx and vocal folds to balance the source vibrations of the system.

The present installment of "Minding the Gap" addresses how the brain controls this valve element at the center of our instrument: the intricate behaviors of the glottis. As we learned in the earlier column on songbirds, we came to possess this intricate system through convergent evolution.[4] Only a few species, as vocal learners, have the ability to flexibly control pitch. Humans are the only primates with this capacity, and our brains are more akin to a songbird's than a chimpanzee's.[5] The ability arose serendipitously whereby the motor pathway for our limbs duplicated, migrated, and then coupled to the vocal system.[6] The hallmark of this duplication features the laryngeal motor cortex, which directs the action of our larynx and vocal folds. Humans have two: a ventral laryngeal motor cortex (vLMC), which is shared by our primate cousins, and a dorsal laryngeal motor cortex (dLMC), which is not (Figure 2a).[7] We are the only one of our species who possess a dLMC. It is located at a distance from the vLMC in the cortical homunculus (Figure 2b). This feature has consequence: When motor elements are close, they can couple both physically and functionally.[8] This saves time; when neurons

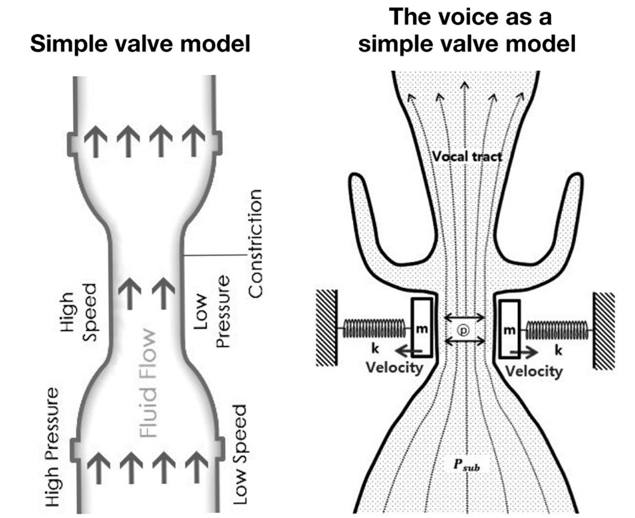
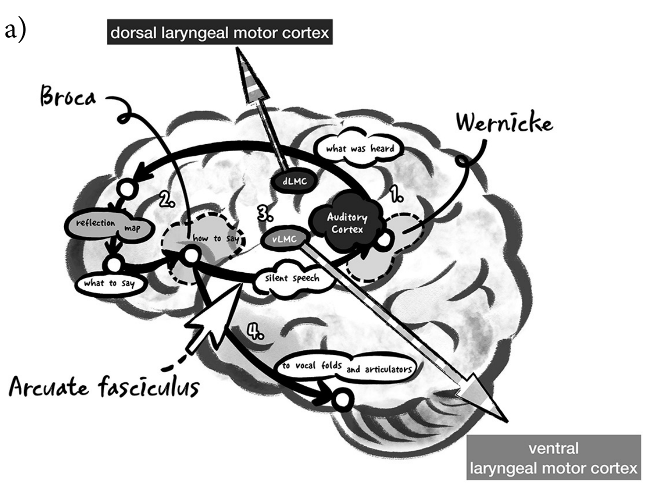


Figure 1. **Comparison of a simple valve system (Venturi) with the physics of the glottis. (Image of the valve from www.wassertec.co.za/explanation-venturi-effect-applications/ and the image of the voice is from Myung-cheol Park, "Understanding the Multi-Mass Model and Sound Generation of Vocal Fold Oscillation." Prime Archives in Physical Sciences. Vide Leaf, Hyderabad, 2020.)**

are closer, signals do not need to travel as far to send messages. The duplication element places the dLMC adjacent to the terminal parts of our limbs—elements involved in nonvocal communicative gestures—rather than its laryngeal counterpart, the vLMC. The fact that two facets of laryngeal function are separated in the motor cortex is striking. Recent research from the Chang lab at UCSF has parsed out the functional differences in the vLMC versus dLMC in great detail.[9] This data can be extracted and interpreted to facilitate targeted pedagogic approaches in singing.

The ability to learn new sounds, mimic, and modify both pitch and acoustics in order to produce complex vocalizations is a hallmark of vocal learners. This facility is not only useful for singing, but it is also the essential component to convey meaning in speech. Prosody gives tonal information about the content of a sentence, and certain stresses can dramatically change meaning for a listener.[10] When we emphasize a word, the stress and pitch are altered to indicate its importance. Therefore, regarding pitch, singing is an extreme version of what we already do naturally. Coordination in both types of vocalization requires extremely fast motor functions with an impressive array of nuance and adaptation. Conversations flow without any thought of mechanics, and singing also requires real-time adaptation to changing circumstances. Slight variations in tempo, room acoustics, or even the internal state of the singer, like fatigue or anxiety, can shift the motor system to adapt quickly. The brain is deft at these tasks and organizes the



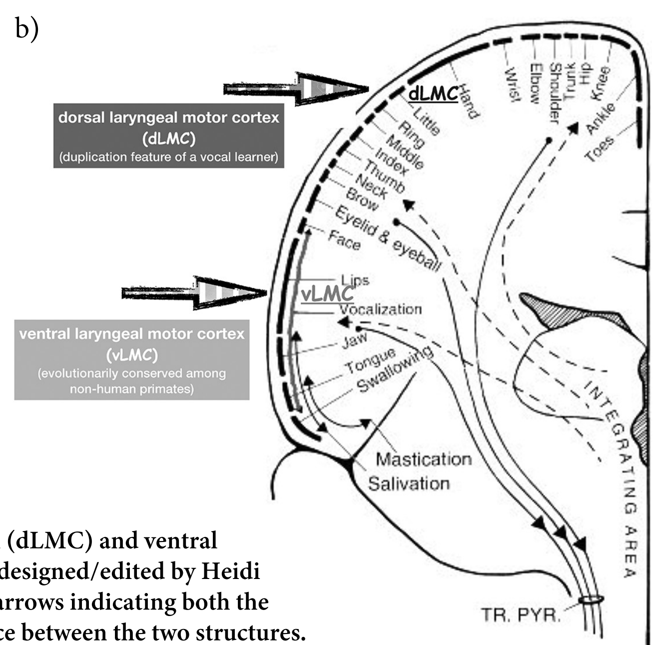


Figure 2. **a) Human vocal learning pathway indicating the dorsal (dLMC) and ventral (vLMC) laryngeal motor areas. (Image created by Kang Kang and designed/edited by Heidi Moss Erickson.); b) Close up of the cortical homunculus with the arrows indicating both the dorsal and the ventral laryngeal motor corticies. Notice the distance between the two structures. (Basic image from Simonyan, 2014 with added elements from Heidi Moss Erickson.)**

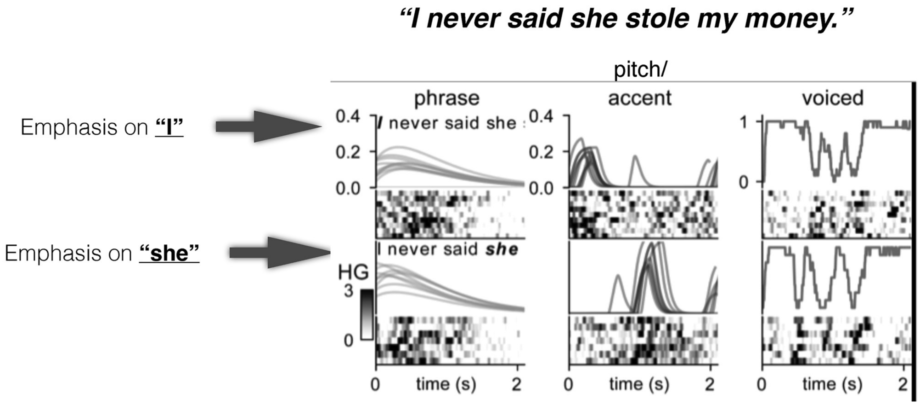


Figure 3. Images show two different representations of phrase (declination rate), pitch/accent, and voicing (fold contact) when a speaker emphasizes different words in the sentence, "I never said she stole my money." The lines show the degree of event over time and the black and gray squares indicate cortical firing data. (Image is adapted Figure 2B-D from Chang 2018.)

more than 100 muscles required for vocalization with great precision. To parse out these complex functions, research has shown that our brains process voicing (bringing the folds together to phonate), phrasing (the maintenance of equilibrium as the lung pressure changes through the phrase), and pitch changes differently (Figure 3), with each component having a unique motor pathway.[11] Using direct measurements on the surface of the brain during speech and singing, a detailed cortical map was obtained that elucidated the separable regions for voicing, pitch, and phrasing.[12] It revealed that different functions mapped to the two separated locations of the laryngeal motor cortex: voicing and phrasing were predominantly signaled in the vLMC and pitch modulation (via fine-tuning of fold configurations) executed exclusively by the dLMC.

There are additional differences regarding timing and location for vocal motor signals in speech and singing (Figure 4). The dLMC can be divided into two parts, posterior and anterior. Pitch signals from the anterior dLMC happen early in singing, prior to the acoustic onset. However, in speech, pitch fires from the posterior portion of the dLMC simultaneously with the onset.[13] Singing also shares some of this posterior dLMC pitch signaling after the acoustic onset. But the key point is that in singing, the brain signals pitch ahead of time, prior to any acoustic onset and without any feedback. Thus, the importance of the audiation step, particularly for pitch, cannot be overstated. Additionally, voicing (vLMC) signals precede breath signals: intention of phrase, pitch, dynamics, and homeostatic state will dictate the kind of breath, not vice versa.[14] While we are singing, the folds take on the job of regulating

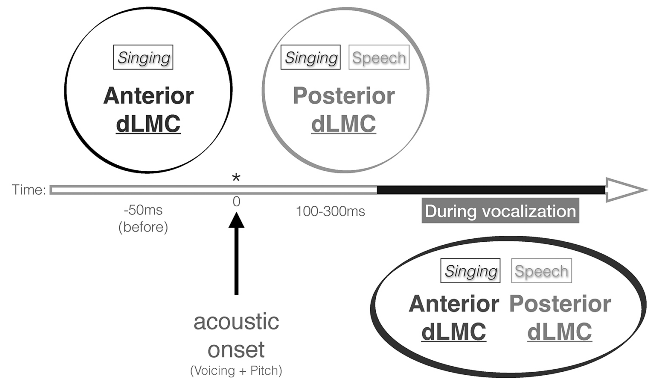


Figure 4. Timeline of dLMC signaling for both speech and singing. (Image created by Heidi Moss Erickson based on Chang 2018.)

airflow, adapting to any shift in pressure dynamics or homeostasis by adjusting accordingly to maintain the status quo. Although these signals and actions occur at the millisecond level, and are thus imperceptible at a conscious level, the order is nonetheless important to understand. We can capitalize on this knowledge to optimize these steps.

Another unique feature of the dLMC is its auditory feedback function. The auditory cortex is suppressed during speech and singing.[15] We often notice that we sound different to ourselves on recordings, and the reasons are multifaceted—e.g., pressure waves having to loop back to the ear, internal vibrations, etc.— but the role of a diminished auditory cortex is also important. The unique transfer of function from a sensory to motor area is unusual; however, this feature has been observed previously in the vocal system. For example, areas of the speech motor cortex can be active during listening,[16] more active during auditory pitch discrimination,[17] and when planning to repeat a melody.[18] Inhibition of the dLMC results in the inability to discriminate pitches pointing to its unique role in both motor and auditory response properties.[19] Evolutionarily this makes sense given the importance of vocalization, especially to communicate danger where a rapid feedback loop is necessary; a millisecond can be the difference between life or death. Proximity of the motor area to the auditory feedback loop for pitch ensures rapid coordination. Thus, execution of pitch has both feedback and feedforward mechanisms. However, the sensitivity of the dLMC's auditory feedback role is solely related to pitch elements, so other components of sound—e.g., voicing, timbre, and dynamics— are not as prominent when we are hearing ourselves as we speak or sing.

Anecdotally, we can learn something about laryngeal representations in the brain from individuals who stutter.[20] This speech fluency disorder is characterized by a white matter deficit in the vLMC (basically meaning there is less signaling power). [21] But strikingly, stutterers have the preserved ability to sing even though their speech prosody is disrupted.[22] This implies speech and singing prioritize dominance of dLMC vs. vLMC differently; for example, singing might recruit more dLMC involvement, while speaking may rely more heavily on vLMC networks. Taken together, these ideas strongly support functional segregation of the dual cortical larynx representations and that singing and speech have important differences to consider.

APPLICATIONS TO VOICE PEDAGOGY

The idea that these functions are segregated in the brain allows us to better design singing strategies around each component. Thus, Garcia was correct (and ahead of his time) when he advised to "produce the sounds by a neat, resolute articulation of the glottis," and described "the glottis is prepared for articulation by closing." He thus separated that action from his next directive, "care however must be taken to attend to the pitch of the sound at once on the note itself." The *coupe de glotte* exercises (literally "shock of the glottis," and later termed by Miller and others as the "attack") derived from these ideas were in fashion for many years, although given the harshness of the language, closure wasn't always initiated in a healthy manner by singers who took these directives literally. The neuroscience shows a much more nuanced closure that doesn't even need to be sensed, just a mental signal for coming together prior to the pitch signal: no "attack" or "shock" necessary. Pedagogically, however, we can use this idea to "fret" notes that may be harder to target: by gently bringing the folds together (first by gently saying "uh oh" in a whisper or mentally attending to a gentle closure), then staying in a semi-closed state while thinking a pitch, a singer can find the note more reproducibly. This intending of glottal closure while auditing pitch is critical for singing: the glottis can remain "on deck" or "fretted" in an appropriate laryngeal configuration ahead of the onset to make the vocal gesture easier and more equilibrated. This strategy is most obvious for onsets, but we can also integrate these concepts with more complex intervals, phrases, or registration shifts. The idea is to first imprint the folds before adding other layers of complexity. For example, the brain can toggle between two notes of a challenging interval to find the optimal equilibrium. There is no "up and down" in the neural mechanism for vocalization; that is a construct of written music and not how the brain perceives frequency to signal the voice. A pitch change is actually viewed as an accent to allow something to stand out from the rest. The key is for the brain to sense a gesture of pitches rather than two separate events, so the voicing remains equilibrated and easy to maintain from the vLMC perspective, but can be facile in the pitch change signal from the dLMC. Once the equilibrium is established, voicing a phrase is one continuous gesture while pitch changes are signaled independently by the brain.

By conceiving the mechanism as a valve, attentional directives can first be given to voicing: for example, staying on the folds in an equilibrated way. This can be imaged a "ziplock seal" or "bowing a cello" to the last note (and beyond) to intend a true legato. This also helps the system to counter the natural declination rate as the lungs deflate through the exhale, which is particularly impactful in a descending line. Voice science has explored these ideas regarding efficiency such as the "maximum flow declination rate" or MFDR. The insights into the neural signaling will certainly add to that understanding. Attending to the valve seal mitigates the loss of air and keeps the folds equilibrated.

The declination rate is a feature of the phrase component of laryngeal cortical signaling since it involves balancing equilibrium over the course of air pressure changes. This can also be a result of valve dynamics (e.g., low notes generally confer a wider opening, slowing the air flow rate; higher pitches generally indicate a narrower opening, resulting in increased air speed). One way to address this relationship of breath-to-folds pedagogically is through a simple intentional exercise. Once velocity and pressure of air is established from the mental and physical coordination at the start of a phrase (audiation, affect, motor practice, etc.), a singer can simply intend a steady flow of air while they sing. This allows signals from the laryngeal motor cortex to take over the job of micro regulation rather than other less efficient elements like large muscle groups or misplaced tension. Imagery works well for this directive: "Picture a blue stream of air emanating like a laser from your mouth constantly moving forward," or "Imagine you are singing through a straw and the air doesn't stop," or "Picture the air flowing ahead of your sound."

W. Stephen Smith in his book *The Naked Voice* explores some of these reductionist ideas through his inventions: number one deals with the ideas of voicing (vLMC), whereas number two addresses the idea of steady airflow through the context of dynamically changing fold configurations (dLMC plus airflow = valve).[23] Even in these exercises, audiation, intention, and affect are necessary prequels to setting up the system for equilibrated sound.

Neuroscience has shown that our brains treat pitch, voicing, and phrase as unique motor signaling events. Our auditory processing is also different when we vocalize (a later review will address the many unique auditory phenomena regarding the voice). To that end, we can design strategies that attend to each of these components to optimize efficiency. Some examples can be found in Tables 1 and 2. Mentally intending a pitch, vowel, timbre, energy (e.g., audiating sound, intention of affect) gives the folds a much more specific signal for pitch from the dLMC, but also attends to the stability of the voicing for the vLMC. Additionally, given the differences in speech and singing, intoning with contours is a better strategy than simply speaking text for linking up the motor systems. Given the proximity to our hands, gestures can also be a fun and freeing way to coordinate elements of the

TABLE 1. Suggested strategies based on cortical signaling of the glottis.

For a given segment (in an exercise or song):

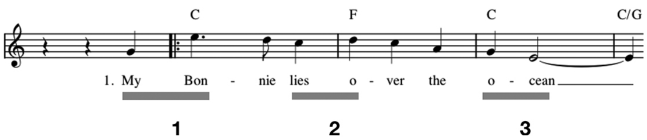
Pitch (dLMC):

- **Do NOT sing** *until you can hear* the entire excerpt you wish to practice in your head.
- Sing each note separately for each interval cluster (3-4 notes at a time is useful) on [bɔ] until the brain starts to sense that they are in the same plane. Air flow should feel energetic and easy, giving "love" to each note. Imagery can help (e.g., "sing like vibrant bouncy bunny hopping").
  - The [b] should be more like a quick kiss than a big plosive. Start slowly then add speed gradually.
- Repeat the same exercise in reverse (i.e. as an inversion) and then moving the bar line to bridge note clusters.
  - These two exercises are helpful in "fretting" the system (see also: the next figure, "interval toggle" example).
- Repeat audiation of the whole while interpolating the bouncy energy into your intention.
- Next sing the phrase on a vowel with legato, tracing the pitches with the continued energy underneath. Circling the hands round and around like the "Wheels on the bus" song can help. (Remember the proximity of the dLMC to the hands and fingers! Use them as tools for energy, vibrancy, direction, sensing the singularity of gesture, etc.)
- Incorporate the ideas from *voicing and phrasing* before moving on to text.
  - Text can be practiced using intoned speech, keeping the contours of the music in mind instead of the vernacular. The allows the brain to subconsciously imprint the native setting while imprinting the motor calculations necessary for the music.

Voicing and Phrasing (vLMC):

- Audiate the first note of the phrase on [a] (or any vowel of choice) and *mentally close the glottis*.
  - Unvoiced exercises like saying "uh oh" in a whisper can jump start the process.
- Sing the note on a vowel from that place without physical preparation, like speech. Onsets in this exercise should be *gentle* and *spontaneous* (like "petting a bunny"). This can take some practice, so be patient!
  - The first note is essential in any phrase because it jumpstarts the whole system mentally and physically, like a lawnmower pull cord.
- Once the first note feels equilibrated, sing only the first note while *audiating* the rest of the phrase.
  - Pay attention to different shapes and practice mentally directionalizing the intention to the *last two notes*. The image should also take the brain *past the phrase*, as if there were notes beyond. This helps to counter the natural declination rate.
- Sing the whole phrase on a vowel: it can be straight tone or vibrant, as long as it remains *unchanged* throughout. Alternating at this stage between straight tone and vibrancy are *not* stable voicing settings for the brain. The key is voicing in one plane and playing with palette dimensions later.
  - Imagery such as "bowing on a cello: or "sensing a ziplock seal" are useful directives for continuing the voicing gesture through a phrase.
- Gesturing is useful for more challenging intervals: swing the arms in circles or pretend you are stirring a witches brew to create the illusion of one plane. There is no up and down! That is a construct of written music and not how the brain perceives frequency to signal the voice.
- When adding text, be sure to keep the idea of a single voicing and air plane in mind before adding accentuated details of diction that shift equilibrium. The idea should be that the voicing and airflow are continuously moving forward as a unified gesture. Even staccato notes!

TABLE 2. **"Toggling" practice example: imprinting glottal equilibrium to fret pitches.**



For each interval: 1, 2, and 3

- Audiation should precede every vocal step.
- Sing each note separately for each interval on [bɔ] until the brain starts to sense that they are in the same plane. Air flow should feel energetic and easy, giving "love" to each note. Imagery can help (i.e."sing like vibrant bouncy bunny hopping"). The [b] should be more like a quick kiss than a big plosive. Start slowly giving separation and time between each note. This allows the brain to process.
- Repeat the same exercise in reverse (i.e. as an inversion)
- Audiate each note on [a] (or any vowel of choice) and mentally close the glottis. Unvoiced exercises like saying "uh oh" in a whisper can jump start the process. Sing the note from that place without physical preparation, like speech. Onsets should be gentle and spontaneous. This can take some practice so be patient!
- Audiate the whole interval and rapidly go back and forth on a single vowel (or SOVT) at least 5 times between the two notes with abandon, like Tarzan! The faster the better! It is target practice for the brain.
  - No judging of sound is allowed! The voice is just finding where things are.
  - Gesturing is useful for more challenging intervals: swing the arms in circles or pretend you are stirring a witches brew to create the illusion of one plane.
- Repeat the exercise inverting the interval.
- Take 10 second mental breaks in between tasks to consolidate the motor skill.
- Once the notes feel equilibrated, audiate the notes and then sing with the vowels alone and then add text.
  - Play with other details like acoustics, dynamics, affect. If the folds are fretted in voicing and pitch, the next stages should feel easier. Like baking a cake, the voicing dimension is the foundation which can stabilize the system.
- Yoda says "There is no try, just do!"

system, such as wiggling the fingers for vibrato, swooping the arms for energy and phrase direction, or conducting with abandon. Movement is a friend to the voice and can be used in practice in a multitude of ways.

It is always exciting when historical pedagogy aligns with the newest in scientific research. Garcia's *coupe de glotte*, although sometimes controversial, was prescient in his idea of placing fold closure first and layering on the dimension of pitch. We can modify Garcia's ideas to strategize pedagogic exercises that fit the brain's order and categorization of these systems, making singers better faster.

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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