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Neuroscience for Singers, Part 1: Neuroanatomy

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Cognitively speaking, singing is a complex motor task, stringing together numerous individual motor skills ranging from very fine (e.g., variations in adductory forces) to relatively gross (e.g., jaw opening and closing). In fact, the complexity of this task is nearly unrivaled in other fields of performance, be they artistic or athletic. But, because our art is rooted in a task as routine as speech, the complexity is often underrated.

Lest there be any doubt regarding the difficulty of singing, consider comparing a collegiate gymnast performing a floor routine (certainly a difficult task) to an operatic baritone performing "Largo al factotum." Both require precise coordination while performing specific motor tasks in a prescribed sequence; both require memorization of athletically difficult sequences; both require agility and flexibility; both require stamina. No one would question the athleticism of either performer. Yet, the floor routine is comprised primarily of large limb positioning tasks. The aria, in contrast, requires all of the same coordination and precision, but from groups of very small muscles that respond dramatically to quite small changes in activity level. For example, a 5% change in the activation level of the cricothryoid muscle can result in a change in fundamental frequency (i.e., pitch) of as much as a semitone.[1]

With a better appreciation of the complexity of the act of singing, it is easy to recognize the difficulty of training this behavior, and perhaps become overwhelmed by the prospect. What skills to do we prioritize in our teaching? To what sensations do we draw the attention of our students? What can we ask our students to "do" to achieve a desired outcome? To aid the teacher in answering these questions and countless variations of the same, what follows is the first installment in a series that aims to provide a basic overview of what is known of the neurology of breathing, phonation, articulation, and audition (hearing). This article will focus on the structure and general function of the nervous system. The overview will provide a basis of understanding to support the subsequent installments, which will turn attention to the cognitive neural function governing the singing voice and the perception thereof.

THE NERVOUS SYSTEM

"The human nervous system, which consists of the brain, spinal cord, nerves, and ganglia, controls the body's response to internal and external stimuli."[2] In other words, the nervous system is what allows us to perceive the world around us and to act and react in response to, and with consideration of, that perception. It is comprised primarily of two basic types of cells, *neurons* and *glia*. Neurons transmit information between the brain and the body, using electrical and chemical transmissions. The function of glial cells is less well understood, but they are generally considered to provide support for the function of the neurons. Neurons can be described as having three basic parts: the cell body, containing the nucleus of the cell; the *axon* carries information from the cell body to other neurons; and the *dendritic tree* is the portion of the cell that receives information from the axons of nearby cells.

The nervous system is subdivided into the central nervous system, consisting of the brain and the spinal cord, and the peripheral nervous system, consisting of all neural tissue that is not in the central nervous system. *Sensory neurons* carry information into the central nervous system, while *motor neurons* carry information from the central nervous system to the muscles.

Working from the bottom up, the spinal cord is a collection of nerves through which nearly all sensory and motor information is relayed between the brain and the rest of the body. The spinal cord is divided into groups of nerves that share names with the regions of the vertebrae through which they enter and exit. Five sacral nerves enter and exit through the sacrum, innervating portions of the legs. The five lumbar nerves innervate the pelvic region and the remainder of the legs. Twelve thoracic nerves service the trunk of the body and portions of the arms. Finally, eight cervical nerves provide sensory and motor information to/from the jaw, neck, arms, and hands. Above the spinal cord sits the medulla. While not structurally part of the central nervous system, the most notable element of the medulla is that it contains the cell bodies of many of the twelve *cranial nerves*, which innervate the head and the larynx and are of utmost importance to human communication, including speech and (by extension) singing.[3]

THE CRANIAL NERVES

The cranial nerves weave a complex web of functions that encompass all sensation and motor control of the eyes, ears, face, mouth, neck, and throat. They also innervate several internal organs including the lungs, heart, and digestive tract. Of the twelve total, seven cranial nerves play particularly important roles in singing.[4]

The *trigeminal* nerve (cranial nerve V) carries sensory information from three branches (hence *tri* of trigeminal) from the forehead, eyes, nose, lips teeth, cheeks, palate, tongue, jaw, and outer ear. In addition to this sensory role, the motor control of the masseter, temporalis, lateral and medial pterygoids, tensor tynmpana, tensor veli palatine, mylohyoid, and the anterior belly of the digastric muscles are all innervated by the trigeminal nerve.[5]

The *facial* nerve (cranial nerve VII), controls the muscles responsible for facial expression such as the orbicularis oculi, zygomatic, buccinators, and orbicularis oris. Additionally, the facial nerve innervates the stylohyoid (possibly impacting vertical laryngeal position), the posterior belly of the digastric, and the stapedius (possibly impacting function of the middle ear).[6]

The *vestibulocochlear* nerve (cranial nerve VIII) carries afferent (sensory, toward the brain) information from two systems within the ear. The vestibular portion carries information from the utricle, saccule, and semicircular canal regarding position of the head, neck, and body (i.e., balance and relative spatial positioning). The cochlear portion carries auditory information from the cochlea (described in more detail below) to the auditory cortex.[7]

The *glossopharyngeal* nerve (cranial nerve IX) supplies motor control of the stylopharyngeus muscle, which impacts vertical position of the larynx as well as dilation of the pharynx. It also provides sensory information regarding the sensation of the pharynx, soft palate, and portions of the tongue.[8]

Two branches of the *vagus* nerve (cranial nerve X) innervate the intrinsic laryngeal musculature. The *recurrent laryngeal branch* innervates all but one of the intrinsic laryngeal muscles, including the thyroarytenoid, lateral and posterior cricoarytenoids, and interarytenoids. Only the cricothyroid is innervated via the *superior laryngeal branch* of the vagus nerve. Efferent (motor, toward the muscles) fibers of the vagus also innervate the involuntary muscles of the upper airway, heart, and gastrointestinal tract. Perhaps this shared pathway helps explain the difficulty in phonation when one experiences a visceral emotional response. [9]

The *spinal accessory* nerve (cranial nerve XI) innervates the muscles responsible for positioning the head in relation to the shoulders and trunk, such as the trapezius and sternocleidomastoid muscles. Additionally, the uvula and levator paletine are partially innervated by the spinal accessory nerve.

Finally, the *hypoglossal* nerve (cranial nerve XII) controls movement of the tongue by innervating all of the intrinsic tongue muscles as well as four of the extrinsic tongue muscles: the genioglossus, hyoglossus, chondroglossus, and styloglosssus.[10]

THE CEREBRAL CORTEX

The cerebrum comprises the bulk of the human brain. It is divided into two hemispheres, right and left, and each hemisphere is further divided into four lobes: the frontal lobe, parietal lobe, occipital lobe, and temporal lobe. The outermost layers of the cerebrum are known as the *cerebral cortex*, which is comprised of the cell bodies (gray matter) of the neurons of the cerebrum. For the study of singing, three regions of the cerebral cortex are of particular importance: the primary motor cortex, the primary somatosensory cortex, and the primary auditory cortex.

The *primary motor cortex* is home to the cell bodies of neurons responsible for fine motor control of the muscles in the body.[11] This area is organized such that cells that control certain areas of the body are grouped together. Note, however, that the motor cortex of one hemisphere contains the neurons that control movement on the opposite side of the body. This is because the nerve fibers descending from both hemispheres converge at the medulla and cross to the opposite side of the body before continuing to their destination. This crossing is a process called decussation, and it means that an injury or lesion on the primary motor cortex on one side of the brain will result in a motor deficiency on the opposite side of the body.[12]

The *primary somatosensory cortex* receives information from specialized nerve endings (called receptors) that are found in tissues throughout the body. Receptors send information to the cortex regarding pressure, position, pain, temperature, and vibration at the receptor site. It is important to note that while receptors of different types are found in all areas of the body, the density at which they occur varies significantly from location to location. The fingertips, for example, are much more densely packed with receptors than are the vocal folds. This has a significant impact on our ability to accurately process sensation in various areas of the body and, by extension, accurately respond to changes in stimuli with updated motor signals.

Similar to the motor cortex, the primary somatosensory cortex is arranged according to areas of the body from which sensory information is received. The relative area of the cortex devoted to sensory information from any given area is strongly correlated to the density of receptors in that region.

The *primary auditory cortex* processes information from the ear regarding all of the sounds around us. This area of the cerebral cortex is organized according to sensitivity to sound wave frequency. In other words, different frequencies of sounds are each processed in different areas of the auditory cortex. This organization (called a *tonotpoic* organization) may suggest some evolutionary advantage for our species to possess the ability to finely discern differences in sound wave frequencies. Indeed, the processing of speech sounds necessitates rapid and accurate processing of individual frequencies of the complex sound wave. However, while the auditory cortex is organized tonotopically, note that information concerning frequency, intensity (and various combinations of these two that define sound quality), and location of the sound source are all processed in the auditory cortex.

In addition to the primary auditory cortex, a discussion of the neuroanatomy for hearing must also include a description of the *cochlea*. Found in the inner ear, the cochlea is responsible for translating mechanical energy (which was converted from acoustic energy by the tympanic membrane) into neural impulses. The cochlea has a pair of membranes, wound into a snail-like formation, which move in relation to one another in response to changes in sound energy. Mirroring the tonotopic organization of the auditory cortex, different areas of the cochlear membrane respond to sound waves at different frequencies. When a region of the membrane is displaced in response to a frequency, tiny hairs called *cilia* are moved back and forth, sending a signal via the auditory nerve (cranial nerve VIII) to the auditory cortex. The ability of the cochlear membrane to respond to multiple frequencies and intensities at once allows, on a very basic level, for our ability to perceive the quality as well as the pitch of a sound source.

As I write this article, I have just taken a cohort of Summer Vocology Institute students through the University of Utah's human cadaver lab. During this experience, we were privileged to view and handle the elements of the human nervous system described here. This activity always fills me with an intense sense of wonder at the seeming disconnect between the physical realness of the structures of the nervous system and the almost mystical function of mind to govern the physical system. This mind-body connection is at the root of the field of cognitive neuroscience, and at the core of the mission of the "Mindful Voice" column.

NOTES

1. Ingo R. Titze, *Principles of Voice*, 2nd ed. (Iowa City: National Center for Voice and Speech, 2000), 226.
2. Marie T. Banich and Rebeca J. Compton, *Cognitive Neuroscience*, 4th ed. (New York: Cambridge University Press, 2018), 4.
3. Other cranial nerve cell bodies are found in the midbrain.
4. Wanda Webb, *Neurology for the Speech-Language Pathologist*, 6th ed. (St. Louis: Elsevier, 2017), 150–164.
5. Ibid., 150
6. Ibid., 154.
7. Ibid., 156.
8. Ibid., 158.
9. Ibid., 159.
10. Ibid., 162.
11. Banich and Compton, 27.
12. Webb, 116.