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Physiological Foundations

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1.1 Introduction

An understanding of biological structures and functions is important for anyone wishing to explore inter-speaker variation in phonetic output, to understand coarticulation, to interpret ultrasound/magnetic resonance imaging (MRI)/X-ray images or to understand speech production associated with atypical anatomy or physiology (e.g. in cleft lip and palate). Descriptions of speech anatomy and physiology often give the impression that there is a 'standard' structure, shared by all. In fact, the extent of between-speaker variation in size and shape of soft and hard tissues is considerable, and it is testament to the flexibility of the articulatory structures that, despite these differences, similar phonetic targets can be reached by morphologically dissimilar speakers. There is evidence, however, that morphological bias within a population may correlate with phonetic inventory. Recent research shows that communities that include clicks in their language have a high proportion of the population with palate shapes that seem to facilitate their production (Dediu et al., 2017).

1.2 Historical Overview

The neuroanatomical and neurophysiological underpinnings of speech are still only partially understood. Historically, the neurophysiological control of speech has been treated somewhat as a black box, and theoreticians have proposed various models to explain the serial and parallel processes that are required to translate a communicative concept into physical realisation as speech (e.g. Levelt, 1989). With the advent of optical, magnetic and electrical instrumentation to measure correlates of cellular activity and with chemical tracing of neurotransmitters, efforts are being made to map elements of these models to different regions of the brain or to develop new models based on physiology (e.g. Guenther, 2016). Similarly, despite many descriptions of anatomical detail of the vocal tract that date back to Galen in the second century and beyond, the anatomy of the vocal tract, particularly from a functional perspective, remains an active area of research (as indicated in Section 1.4).

1.3 Critical Issues

This section reflects the task of speech production, starting with an overview of the neurophysiology that coordinates movement of the speech apparatus, followed by an overview of each component of that apparatus starting with the respiratory system, then the larynx, the pharynx, the velopharyngeal and oral articulatory systems, the jaw and the lips. Each part of the system is described in turn, but it should be noted that anatomical and neural interconnectivity is such that muscular adjustments in any part of the vocal apparatus are likely to affect other parts of the speech production system.

1.3.1 Central Nervous System (CNS): Cortical

The primary motor cortex forms part of a distributed network of cortical motor areas, each with its own role in speech motor control (Figure 1.1). The primary motor cortex can perhaps be thought of as a neuroplastic map whose internal organisation converts central signals about motor intentions into motor output commands, mediated by auditory and somatosensory feedback. The upper motor neurons of the primary motor cortex are modified by the premotor and somatosensory areas as new skills are practised (Dayan & Cohen, 2011). The pre-supplementary motor area (pre-SMA) is thought to be involved in the learning and adaption of motor sequences. The neighbouring supplementary motor area (SMA) takes input from the basal ganglia and the cerebellum to adjust the timing and rate of articulation. Although areas shown in Figure 1.1 are bilaterally active during simple speech tasks, the two hemispheres may play different roles during higher-level language tasks. Active language-related regions (not shown) of the cerebral cortex are generally left lateralised (Guenther, 2016).

1.3.2 Central Nervous System: Brainstem

The brainstem contains lower motor neurons and interneurons which are organised in clusters (nuclei), linked to muscles via the cranial nerves, numbered I to XII (Figure 1.2). These motor nuclei form a system of low-level muscle control stimulated by electrical synaptic discharges from the primary motor cortex which can be enhanced or suppressed by neuromodulation of levels of neurotransmitting chemicals. Motor nuclei share the brainstem with sensory nuclei and can utilise the inflow of afferent (auditory, somatosensory,

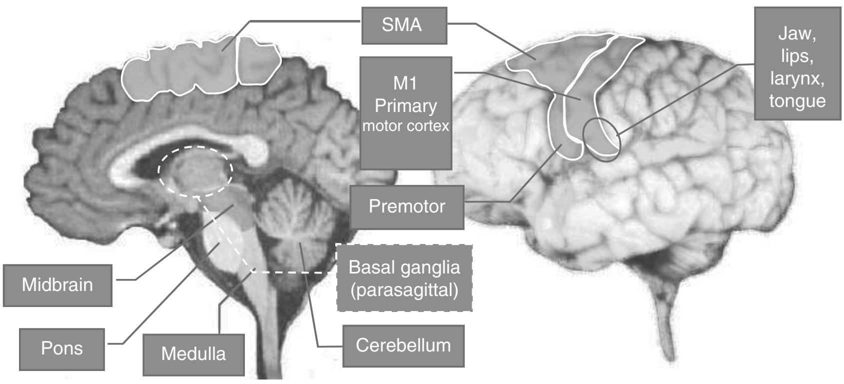

Figure 1.1 Organisation of motor system for simple speech tasks
Left: midsagittal view; right: exterior.

proprioceptive) signals directly to manage reflexive responses to external events. The groupings and proximity of these *nuclei* allow low-level interaction between muscles as well as high-level coordination via the motor cortex.

Most physiology courses and textbooks teach the association between cranial nerves and the articulators. Although grouping muscles according to the primary cranial nerves is helpful for surgeons who need to know the consequences of nerve damage, nerves are simply the pathways by which messages are sent from the lower motor nuclei to the muscles. Here we will focus instead on the link between the *nuclei* and the articulators, as this provides a better viewpoint from which to understand functional organisation. Some nerves are connected to more than one nucleus and some nuclei are connected to more than one nerve. Within nuclei, synaptic contact allows the associated muscles to work closely together. Each nucleus is subdivided into musculotopic regions and the size of these subnuclei may provide a guide to the importance of the corresponding muscles in terms of function. The clustering of cranial motor neurons in the brainstem into nuclei is therefore an important clue in the organisation of vocal tract function.

The trigeminal nucleus (of which the motor nucleus is just a small part) ranges from the midbrain through the pons to the medulla (see Figure 1.2) and receives sensory messages from the tongue, velum, pharynx and parts of the face including the lips. It is proximal to the reticular formation, which also extends along the length of the brainstem and consists of interneurons that link to the separate motor nuclei, allowing communication between them.

The four cranial motor nuclei involved in speech articulation can readily be associated with stages in preparation and swallowing of food (Komisaruk et al., 2002): facial – oral sphincter; trigeminal – chewing; hypoglossal – mastication and bolus preparation; ambiguous – swallowing by peristaltic contraction of sphincters from anterior velum (palatoglossal arch) to inferior pharyngeal constrictor and including coordination of

Table 1.1 *Organisation of motor nuclei involved in speech production*

Motor nucleus	Location	Innervated muscles (*subnuclear regions in italics*)	Pathway
Trigeminal	Mid pons	*Jaw closing* – temporalis, masseter & medial pterygoid; *jaw opening* – lateral pterygoid, anterior belly of digastric & mylohyoid; *Other* – tensor tympani, tensor veli palatini	trigeminal cranial nerve V
Facial	Border of pons & medulla	*Lateral* – lip muscles (largest region) *Intermediate* – periocular face muscles *Medial* – periauricular face muscles *Dorsal* – forehead muscles	facial cranial nerve VII
Accessory facial	Pontine reticular formation	Suprahyoid strap muscles: stylohyoid and the posterior belly of the digastric (Cattaneo & Pavesi, 2014)	facial cranial nerve VII
Ambiguous	Lateral upper medulla	Striated muscle of oesophagus, all muscles of pharynx, larynx and velum (excluding tensor veli palatini but including palatoglossus)	glossopharyngeal cranial nerve IX, vagus cranial nerve X & accessory cranial nerve XI
Hypoglossal	Medulla	All tongue muscles (not palatoglossus) plus geniohyoid and thyrohyoid	hypoglossal cranial nerve XII
Cervical	Cervical spinal cord C1,C2,C3	Infrahyoid strap muscles: sternohyoid, omohyoid and sternothyroid	Ansa Cervicalis nerve loop
Phrenic	Cervical spinal cord C3,C4,C5	Diaphragm	phrenic nerve

larynx closure. Peristalsis in the striated muscle part of the oesophagus is also controlled by this nucleus. Shared innervation of the striated muscle of the upper oesophagus and larynx is thought to facilitate learning of oesophageal voice (Mathieson, 2001).

1.3.3 The Respiratory System

Speech exploits the respiratory system, whose primary role is to support oxygenation of the body, in order to drive vibrations in the vocal tract and to create the pressure needed for noise generation in frication, aspiration, etc. Speech is normally supported by a pulmonic egressive airflow (i.e. air flowing out of the lungs) and the control of inspiration and expiration has to be carefully coordinated with phonation and articulation. An utterance is preceded by a rapid and controlled intake of air, sufficient for its planned

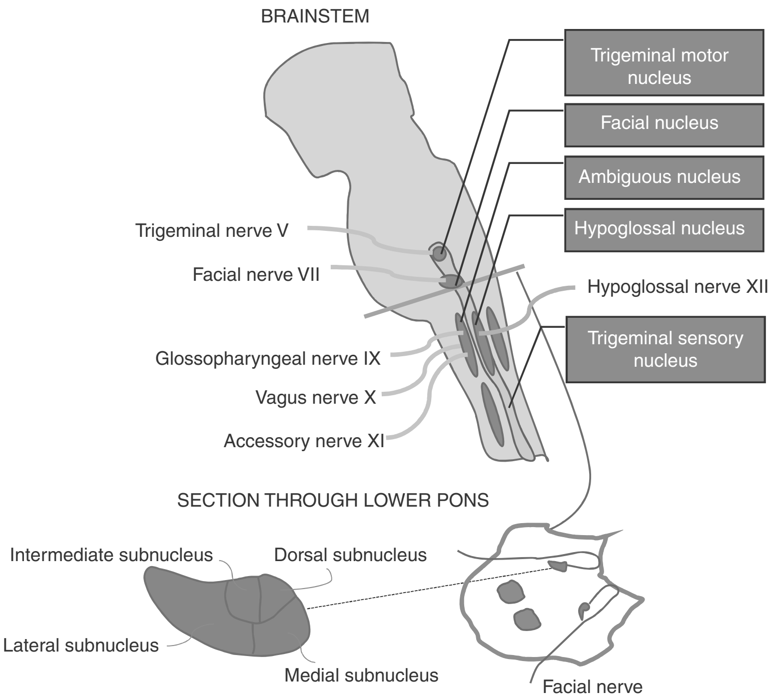

Figure 1.2 Brainstem nuclei and section through lower pons showing facial nucleus with subnuclear regions (Cattaneo & Pavesi, 2014)

duration and loudness. During the utterance, subglottal pressure is regulated to control loudness and sustain vocal fold vibration, independently of the lung reservoir. A fuller discussion of the complex physiological control of respiration for speech can be found in Laver (1994, pp. 162–7). Vocal fold vibration and noise generation may also be driven by alternative airstream mechanisms (e.g. voiced implosives, ejectives).

Although a pulmonic egressive airstream is the default expectation for speech, pulmonic ingressive airstreams may be used occasionally. This airstream is a stylistic feature of affirmative utterances in parts of Scandinavia and France (Eklund, 2008) and may also occur in circumstances where coordination of breathing and speech breaks down, as it may under conditions of extreme emotion or physical exertion, or in certain types of speech disorder. Given the cross-sectional morphology of the vocal folds, it is not surprising that phonatory quality and efficiency are different during ingressive vocalisation.

Inspiration involves expansion of the thoracic (chest) cavity, reducing the internal air pressure so that air flows into the lungs. During expiration the thoracic volume is decreased, so that air is pushed out of the lungs.

Muscles that are most directly involved in the control of respiration are the diaphragm, the abdominals and the intercostals (Figure 1.3), although there are a range of other accessory muscles that can support and influence breathing. The subtle and distributed neural control and mechanical function of different regions of the intercostals is described in detail by De Troyer et al. (2005).

In passive shallow breathing, subglottal pressure may be controlled by the diaphragm. The diaphragm is a domed sheet of muscle separating the thoracic and abdominal cavities. Contraction of the muscle flattens the dome, expanding the lungs and drawing in breath. Controlling the level of reduced contraction of the diaphragm is one means of regulating the rate of expiration that results from the elastic recoil of the lungs.

During speech, the abdominal muscles are typically in a state of constant low-level contraction maintaining upward pressure on the diaphragm. When there is a low volume of air left in the lungs, the abdominal muscles are more active in controlling expiration (Hoit et al., 1988), but usually a new phrasal breath is drawn before abdominal control is required for speech.

Inspiration can also be achieved by contracting the external intercostal muscles and the parasternal region of the internal intercostals that connect the cartilaginous part of the ribs to raise the ribs and expand the thoracic cavity. Again, controlled reduction in contraction can regulate the expiration due to elastic recoil.

Loudness and/or pitch modulation within a syllable requires increased airflow. Electromyography (EMG) studies show phased pulsatile control of internal and external intercostal muscles and increased activity related to syllable stress (Ladefoged & Loeb, 2002). It is not clear whether this action is independent of laryngeal articulation or a reaction to it. Studies indicate that glottal-flow resistance changes with loudness, and the size of the

Table 1.2 *Respiratory muscle function*

Muscle	Action
Diaphragm	Inspiration and control of elastic recoil of the lungs
External intercostals	Inspiration; elevate ribs and inflate the lung
Internal intercostals (intercartilaginous part)	Inspiration; elevate ribs and inflate the lung
Internal intercostals (interosseous part)	Expiration; increases flow beyond rate determined by elastic recoil
Triangularis sterni	Expiration; increases flow beyond rate determined by elastic recoil
Transversus abdominis	Expiration; interdigitates with diaphragm
Internal oblique	Expiration; compresses abdomen; resists downward pressure on diaphragm when internal intercostals contract thoracic cavity
External oblique	Expiration; as internal oblique
Rectus abdominis	Expiration; pulls down ribs

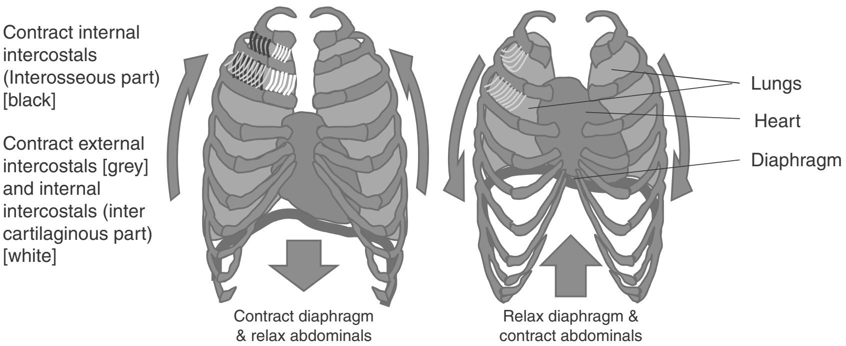

Figure 1.3 Musculature of respiration

posterior glottal opening also varies. This allows the possibility that the short-term respiratory movement is *responding* to maintain pressure/flow rather than articulating loudness.

1.3.4 Larynx Anatomy

The larynx and the hyoid bone are unusual in the context of the human skeleton in that they do not articulate directly with other bones or cartilages to form an anatomical joint. The larynx is located at the top of the trachea and is suspended from the hyoid, with additional muscular and ligamental connections to the epiglottis and the pharynx. This means that its position and orientation is susceptible to the effects of adjustments of a wide range of muscles, including some of the main postural muscles of the head and neck (e.g. the sternocleidomastoid), together with the muscles which control the position of the hyoid bone (Section 1.3.5) and the muscles of the pharynx.

The key components of the skeletal framework of the larynx itself comprise the thyroid and cricoid cartilages and the paired arytenoid cartilages. The hyoid bone is not considered part of the larynx, but is connected to it by ligaments and muscles, thus linking larynx and tongue activity. The cartilages of the larynx and the suspensory framework are shown in Figure 1.4. Vertical adjustments of the larynx, which are necessary for the production of ejectives and implosives, and which also occur in the context of pharyngeals, in tonal register or as extralinguistic or paralinguistic features of speech, can be achieved in various ways. Larynx raising is accomplished most directly by contraction of the thyrohyoid muscle, but may involve complex interactions between pharyngeal, lingual and suspensory muscles. Larynx lowering can be achieved by contraction of the sternohyoid, omohyoid or sternothyroid muscles, or by relaxation of the various muscles from which the hyoid and larynx are suspended. The configuration of the suspensory system of the hyoid and larynx means that

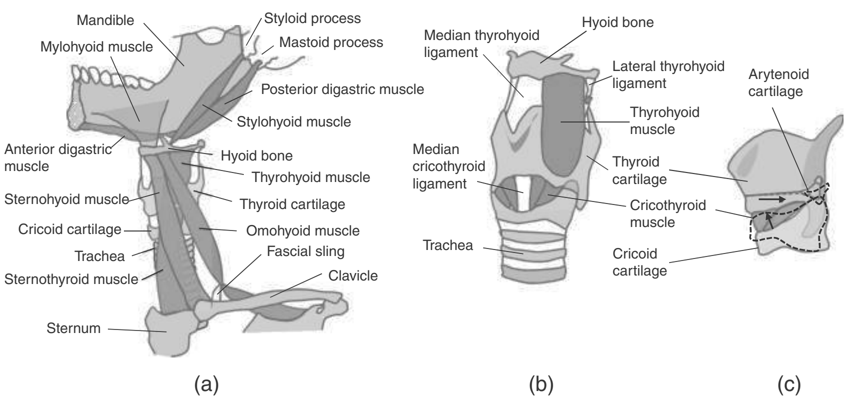

Figure 1.4 Extrinsic muscle of larynx/hyoid
(a) suspensory framework, (b) external view of larynx, (c) visor action of cricothyroid

adjustment of laryngeal height can be facilitated or inhibited by jaw and postural adjustments.

Within the larynx, the arytenoids are mounted on small prominences on either side of the posterior upper surface of the cricoid cartilage. The cricoarytenoid ligaments tether the arytenoids, but allow a rocking movement around this joint.

Similar joints exist between concave depressions on either side of the cricoid cartilage and the inferior cornu of the thyroid cartilage, tethered by the ceratocricoid ligaments. These joints allow a pivoting, hinge-like movement between the two cartilages.

The larynx is loosely connected to the hyoid by a thyrohyoid ligament extending medially and a pair of thyrohyoid ligaments linking the superior cornua of the thyroid to the greater cornua of the hyoid (Figure 1.4). The thyrohyoid muscle also links the thyroid cartilage to the hyoid bone and supports airway closure by shortening the distance between the thyroid and the hyoid bone.

This cartilaginous framework of the larynx protects and supports the vocal folds and the muscles that determine their configuration. The vocal folds protrude from either side of the airway, running backwards from an attachment point at the midpoint of the inner surface of the thyroid cartilage to the anterior point of each arytenoid cartilage (Figure 1.5). When breathing, the arytenoids swing apart so that the vocal folds are held open (abducted) such that there is V-shaped opening between the vocal folds and airflow is not impeded. The space between the vocal folds (the glottis) can be adjusted so that during phonation, and in more complex laryngeal constriction (see Chapter 9), the vocal folds are brought together (adducted) to narrow the airway. Given appropriate conditions of subglottic pressure and airflow from the lungs, paired with the right balance of muscle tension within the larynx, the vocal folds will vibrate. The detailed structure of the vocal folds is an exquisite example of biomechanics. The body of the vocal fold consists of muscle (thyroarytenoid), over which lie layers of connective tissue which form the vocal ligament, running along the edge of the vocal folds from the thyroid cartilage to the tip of the arytenoid. The gradient mechanical properties of these tissue layers are crucial for phonation (Hirano, 1981), and any change to this tissue structure, as a result of infection, inflammation, disease or ageing, is likely to have some effect on phonation. The potential range of phonation and pitch that can be produced by any individual is determined by the size and mechanical characteristics of the vocal folds, but the actual output is conditioned by muscle activity. Key actions of the individual muscles are summarised in Table 1.3.

Muscular control of phonation is highly complex, and discussion of the muscular adjustments associated with different phonation types is beyond the scope of this chapter. Speed of vocal fold vibration, and hence fundamental frequency (f_0), depends on the mechanical status of the vocal folds (mass and tension) and on respiratory control of subglottal pressure. An important mechanism for changing f_0 involves the cricothyroid joint, described earlier, in what is characterised as cricothyroid visor action. The thyroid and cricoid cartilages act rather like the visor of a helmet,

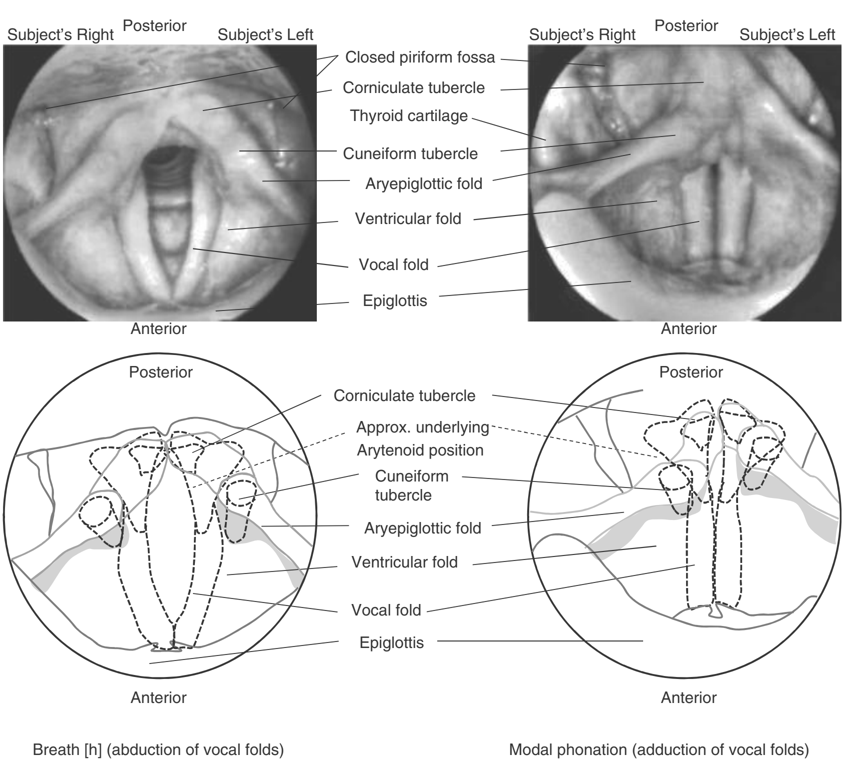

Figure 1.5 Abduction and adduction of the vocal folds
Laryngoscopic images courtesy of John Esling, University of Victoria, Canada. Thanks to John Esling and Scott Moisik for guidance.

Table 1.3 *Key muscles of the larynx*

Muscles	Action
Adductor muscles	
Lateral cricoarytenoid muscles	Narrow the anterior part of the glottis and lengthen the vocal folds by pulling the back of the arytenoids apart, thus rotating the front of the arytenoids downwards and together
Thyroarytenoid muscle – externus	Shortens and adducts the vocal folds
Thyroarytenoid muscle – internus (= vocalis)	Shortens and thickens the vocal folds
Interarytenoid muscles	Closes the posterior glottis by bringing the posterior heels of the arytenoids together
Abductor muscles	
Posterior cricoarytenoid	Separates and lengthens the vocal folds by pulling the back of the arytenoids together, thus rotating the front of the arytenoids apart
Tensor muscles	
Cricothyroid	Stretches and tenses the vocal cords (see later comments on the cricothyroid visor). It may also contribute to adduction
Extrinsic muscles of the larynx	
Thyrohyoid	Raises the larynx towards the hyoid
Sternothyroid	Lowers the larynx towards the sternum

hinging at the side, at the inferior cornu. Contraction of the cricothyroid muscle pulls the visor closed, tilting the back of the cricoid cartilage downwards. The arytenoids will tend to move with the cricoid. Since they form the posterior attachment point for the vocal folds, if the arytenoids are pulled backwards, the vocal folds will be stretched, causing them to vibrate more rapidly. Cricothyroid visor action is shown schematically in Figure 1.4c.

1.3.5 Musculature of the Hyoid and Floor of the Mouth

The hyoid bone sits at the base of the tongue. It has numerous muscle attachments (see Figure 1.4a) and is tethered to the larynx via thyrohyoid ligaments both at the front and back so extreme position change in one will move the other. It has an important role in swallowing action, but its role in the production of speech is often overlooked. For example, in Daniel Jones's account (Jones, 2018) of English phonetics, the hyoid is not mentioned, and the illustrations of all vowels and consonants maintain exactly the same shape and area from the epiglottis to the larynx. In reality there is significant positional variation evidenced by X-ray studies such as that of Wood (1979). By itself, the hyoid is not an articulator but is a fixing point for many muscles that control its position and facilitate speech production. As speech is initiated, muscles contract to move it to