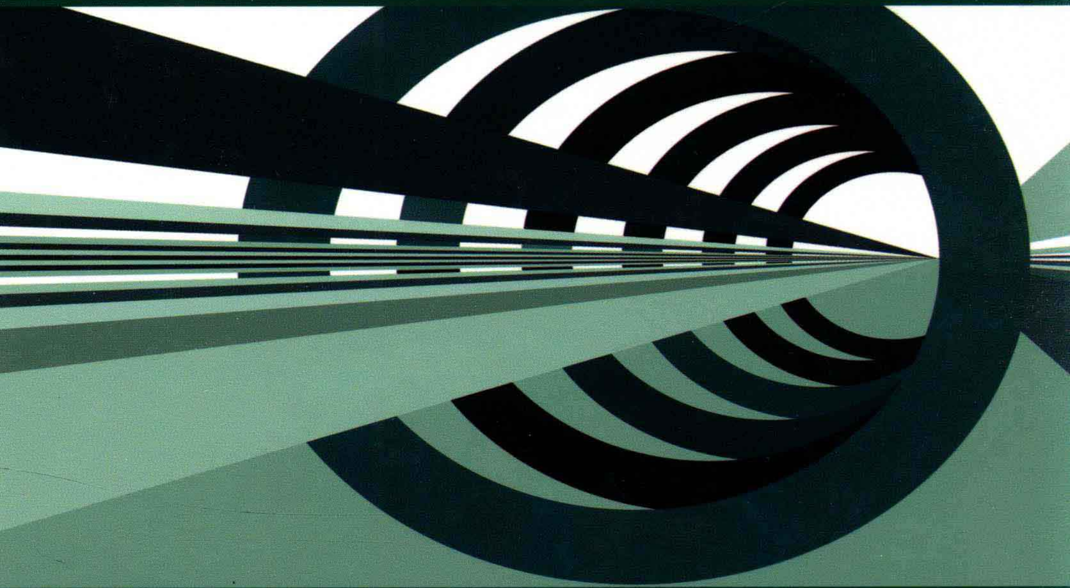

From Speech Physiology to Linguistic Phonetics

Alain Marchal

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Preface

Scientific disciplines are generally defined by reference to the methods that they use. Phonetics, by contrast, is rather defined by its object: the scientific study of speech. It calls on the methods of physiology, for speech is the product of mechanisms which are basically there to ensure survival of the human being; on the methods of physics, since the means by which speech is transmitted is acoustic in nature; on methods of psychology, as the acoustic speech-stream is received and processed by the auditory and neural systems; and on methods of linguistics, because the vocal message is made up of signs which belong to the codes of language.

Given this, phonetics finds itself at the intersection between human and social sciences, health sciences and the sciences of information technology and communication. Spoken communication has its roots in what we are accustomed to call the audio-phonatory loop. This arises in the speaker who intends to impart a message; it is followed by the selection and organization of linguistic signs, the construction of a motor plan, and the execution of motor commands resulting in a series of transformations of the geometry of the vocal tract and the transmission of an intelligible acoustic signal, from which the listener retrieves the meaning of the message by means of hearing, stimulation of the auditory and peripheral nerves, perception and linguistic analysis.

Speech constitutes a favored means of human communication by virtue of its "apparent" ease and because of the speed of information transmission that it enables. Thus, an average output of 20 phonemes per second allows not less than 150 words per minute that humans can produce for communication purposes. In addition to its semantic function, speech also conveys information about the speaker himself: his geographic origin, his social orientation, his emotions and his attitudes.

Speech is unique to humans. Nevertheless, from an anatomical point of view, there are no organs dedicated solely to this function. The organs employed in the act of speech are borrowed from the respiratory, laryngeal and digestive systems. They primarily serve other functions such as the exchange of gases for respiration, the protection of airways and lungs, mastication and swallowing. The articulatory processes consist of the manipulation of respiratory and laryngeal structures and of the vocal tract in order to create speech sounds, modulate, amplify and filter them.

Speech production involves the coordinated contraction of more than 200 muscles, including those of the lips, the jaw, the tongue, the velum, the pharynx and the larynx, as well as those concerned with respiration. The activity of the muscles involved in speech is initiated and controlled by more than 1,400 nervous impulses per second, originating in the motor areas of the cerebral cortex. These travel along the motor pathways, including those descending (upper motor neurons) from the central nervous system to the lower tract served by the peripheral nerves (including certain cranial and spinal nerves). The number of degrees of freedom to be controlled is very large.

Phonetic sciences are concerned with discovering what types of control are in place to ensure the production of intelligible meaningful speech. Particular attention is thus paid to the study of the biological bases of language. This preoccupation is not new and can be clearly discerned in the works of grammarians from the 5th century onwards. For example, in the 8 books of the *Astadhyahyi,* the Hindu grammarian Pānini proposed a phonetic and phonological classification of Sanskrit based on articulation. This treatise must encourage respect for the pronunciation of the language of the gods. In the *Edda*, Snorri Stuluson placed the principles of opposition and commutation on an articulatory basis that phonology would rediscover more than a millennium later. In the *Grammatica lingua anglicanae* (1652), J. Wallis described the production of isolated sounds for deaf-mutes.

Today, technological developments in medical imaging, progress in the observation of organs and muscles facilitated by new tools, and an interest in articulation stimulated by vocal technologies such as speech synthesis and automatic speech recognition have all provided a new impetus to phonetic research and produced significant advances in the understanding of the mechanisms involved in speech production.

The main question to be answered concerns the relationship between the physiological aspects of the vocal apparatus and their role in achieving phonetic goals. Humans make use of only some of the phonatory potential of the larynx and the configuration possibilities of the supraglottal cavities. Which principles inform the selection of a finite ensemble of phonetic segments out of the whole extent of anthropophonic capabilities? How did phonological systems evolve over time? What were the influences that shaped the modifications?

In introducing this topic, we recall that the phonetic domain is vast and interdisciplinary in nature. In this work we deal principally with the aspects that connect physiology and speech production. We indicate the methods and techniques used to observe the activity of organs in speech production. We also present the current state of knowledge in linguistic usage based on the possibilities offered by articulation and the phonatory apparatus.

Speech is the result of a neuromotor activity. It is initiated by a current of air generated by the lungs and transformed at the level of the larynx by the action of the vocal folds, and directed towards the nasal or oral cavities by the velum or soft palate. Finally, the air current is very precisely shaped at different places in the mouth by the tongue until it emerges from the vocal tract through the double shutter known as the lips (see Figure 1).

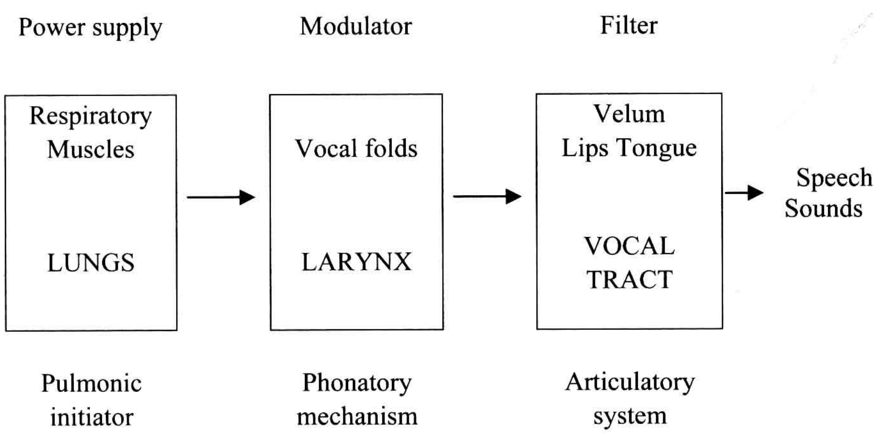

Figure 1. *Basic diagram of the speech production process*

A natural plan thus suggests itself for this book. We will follow the phonatory air-current from the lungs to the lips and address in turn the issues regarding respiration, phonation and articulation. We will indicate how the muscles and organs thus mobilized contribute to the distinction between phonemes and ensure the stability of phonological contrasts.

The temporal dimension of speech production is of vital importance. Given that the articulators move relatively slowly and that the speed of their movement varies greatly from one articulator to another, it follows that a rapid succession of segments can only occur if articulatory movements are synchronized.

It is therefore necessary to describe the role of motor coordination in realizing phonetic targets. Following the principles set by action theory, there are several theories, such as articulatory phonology and the optimality theory, which have tried to give a more adequate account of the dynamic aspects of linguistic systems by taking into account the articulatory and perceptual constraints that govern speech production. This volume adopts the same epistemological tradition and aims to provide a foundation for uniting phonetic and phonological descriptions on biological and articulatory bases.

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Chapter 1

Respiration and Pulmonary Initiation

To understand the process of speech production, it is necessary to have a good knowledge of the mechanisms that come into play during normal breathing and to know how it is affected by phonation.

Until the 17th century, man's knowledge of respiration was limited to his belief that the prime purpose of breathing was to cool the blood. Not until the 20th century did any work on ventilatory mechanics develop. In 1925, F. Rohrer published his treatise on respiratory movements, which forms the basis of respiratory physiology. W. Fenn extended this work in the 1940s. Finally, we are indebted to Ladefoged *et al.* (1957) for the first phonetic studies examining the relationship between respiration and phonation. This was the first clear evocation of the way in which respiration is modified to accommodate speech production.

The vital function of respiration is to ensure the exchange of gases between air and blood. The respiratory cycle comprises two phases: inhalation and exhalation. Inhalation allows a certain quantity of air to be stored in the lungs, bringing oxygen to the organism. The function of exhalation is to empty the lungs and expel gaseous waste from the body, in particular the carbon dioxide accumulated by the blood. The majority of speech sounds are produced during exhalation. Sounds may occasionally be partly realized on an ingressive air-stream; in very rare cases, they are made solely in this way.

The respiratory system comprises the lungs, the tracheo-bronchial tract, the larynx, the upper airways (pharynx, nose, mouth) and the rib cage (see Figure 1.1).

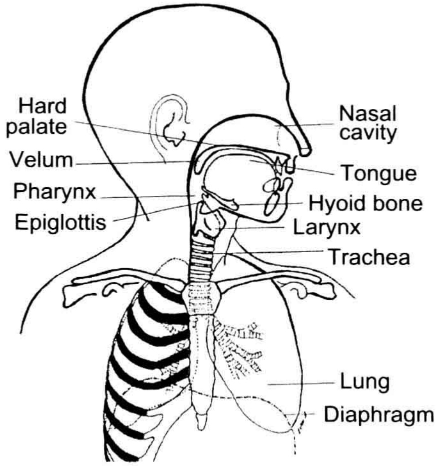

Figure 1.1. *The respiratory system*

1.1. The rib cage

The structural supports for respiration comprise:

1) the bony thorax;

2) the visceral thorax;

3) the respiration muscles.

The rib cage and its muscles behave like a pump which breathes air in and out of the respiratory system via the upper and lower airways.

The rib cage is made up of 12 spinal vertebrae, 12 pairs of ribs, and the sternum or breastbone. It is bounded at the top by the neck and at the bottom by the diaphragm (see Figure 1.2).

The ribs constitute a barrel-shaped protective shield around the thorax, the rib cage. At the back, the head of each rib is joined to the spinal column by sliding joints. At the front, the first seven ribs are attached directly to the sternum by means of costal cartilage. The next three are attached to the lower extremity of the sternum by the cartilage of the seventh rib. The last two ribs (the "floating" ribs) have no anterior attachment; their costal cartilage is embedded in muscle fibers.

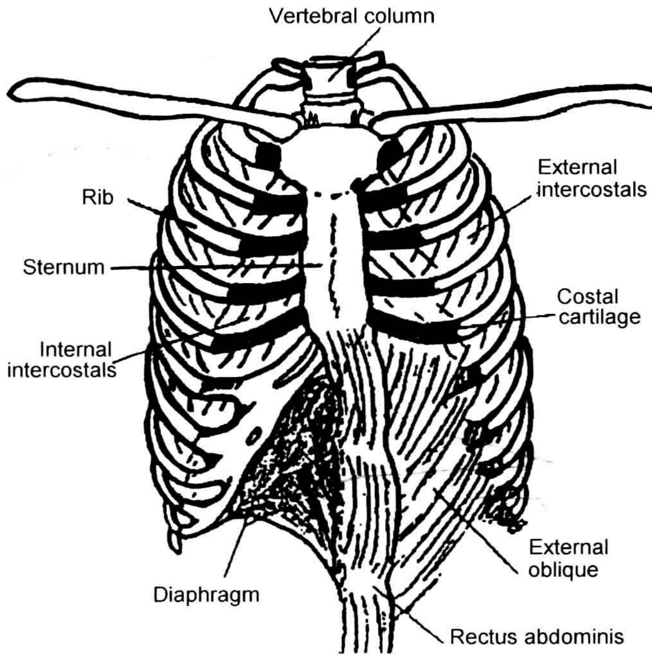

Figure 1.2. *The thoracic cavity*

Because of their shape and mode of attachment, front and back, raising of the ribs will cause an increase in thoracic volume in two directions: transverse and lateral. The simultaneous forward and upward movement of the sternum results in an increase of the anteroposterior diameter. The vertical dimension can be altered by movements of the diaphragm which lower the abdominal internal organs.

1.2. Lungs

The lungs, situated in the rib cage, have the shape of air-filled pyramids. There are two of them, one on the left, the other on the right, separated by the mediastinum. To look at, they resemble two wet sponges, with tree-like branches and twigs. They are divided into two bronchial tubes which then subdivide into bronchioles and alveoli.

The two lungs are enveloped in a serous membrane: the pleura. This has two layers: the internal layer or visceral pleura which covers and clings to the lungs, and the external layer or parietal pleura which is fixed to the internal wall of the rib cage and the upper edge of the diaphragm. The serous liquid which is excreted by the pleura allows the layers to slide over one another. The pleura ensures the functional coupling between the chest wall and the lungs.

Pulmonary tissue is extremely elastic and can therefore follow the movements of the rib cage. Elasticity is generally defined as the property which certain materials have of resuming their shape when the force which has deformed them has ceased to act. The point at which the material fails to resume its natural shape is called its limit of elasticity. If the intensity and the duration of the deforming force remains below this limit, the amount of deformation follows Hooke's law: it is proportional to the force and stays the same, except for the sign, when the sign of the force changes.

The lungs and thorax have elastic properties. These organs undergo elongation due to an external force (muscular activity) in the inhalation phase. When this force stops, they resume their natural position and shape; the effect of this is to compress the lungs, thus reducing the pulmonary volume and forcing out the air previously inhaled.

This property of elasticity plays a big role in normal respiration. Under normal circumstances, the lungs exert a continuous effect of aspiration inside the thorax. In living subjects, lung elasticity forces can be estimated by measuring the pleural pressure. It appears that the pressure is negative during inhalation, i.e. lower than atmospheric pressure. This is because of the elastic traction of the lung on the visceral sheet of the pleura; the amount of pressure varies according to the stages of the respiratory cycle. This *intra-pleural pressure* is exerted over the organs contained in the thorax, in particular the heart, the thoracic channel and the esophagus, where it can be measured more easily.

The pressure of air in the lungs depends on the force exerted on the thoracic walls by the molecules of air inside them. When the dimensions of a container are enlarged, its volume increases, the molecules of air become more spaced out, and air pressure falls. Conversely, when the dimensions are reduced, the volume decreases, the air molecules become compressed and the pressure increases (Boyle's law).

In order for air to emerge from the lungs, a difference in air pressure must be created between the air contained in them and the atmosphere outside. An increase in pulmonary volume provides a lowering of pressure which results in the drawing in of air from outside. Conversely, a decrease in pulmonary volume induces in return an increase in pressure which pushes the air out.

1.3. Normal respiration

1.3.1. *Inhalation*

Inhalation is the result of raising and widening the rib cage, effected by the contraction of the external intercostal muscles and the flattening of the diaphragm, which presses down on the abdominal viscera. This action, because of the functional coupling between the lungs and the thorax, lowers the intra-pleural pressure. When the force is great enough to overcome the elastic resistance of the pulmonary tissue, the lungs fill by aspiration (siphoning in air) and the pulmonary volume increases. The amount of air inhaled is in the region of half a liter.

1.3.2. *Exhalation*

When the inhalation impulse ceases, the lungs deflate and return to the rest position. This constitutes a return to equilibrium. Normal exhalation is an entirely passive process caused by the elastic recoil of the pulmonary tissue and the ribs, from their weight and the pressure exerted by the abdominal organs. The combination of these forces constitutes what is called *the pressure of relaxation*. The pressure of relaxation is the pressure of the air that could be measured in the inflated lungs if the intercostal muscles were relaxed and if the air were prevented from escaping from the lungs.

Exhalation in resting respiration is an involuntary activity. The ratio between inhalation and exhalation is 1:1. The typical rate of normal respiration is 12 to 18 cycles per minute.

In the adult, mean values are 0.3-0.5 liters per second (l/s) for rate of flow, 500 cm^3 for volume, and 1-3 cm H_2O for pressure. These values change and increase with work. Thus, with forced inhalation and severe muscular effort during exhalation, the rate of flow can increase to more than 50 l/s and *intra-pulmonary pressure* can go up to 100 cm H_2O.

1.4. Respiration muscles

The three dimensions of the rib cage (vertical, transversal and anteroposterior; see Figure 1.3) increase during inhalation and decrease during exhalation. Two groups of muscles are involved in the different stages of respiration: the muscles of inhalation and the muscles of exhalation (see Tables 1.1 and 1.2).

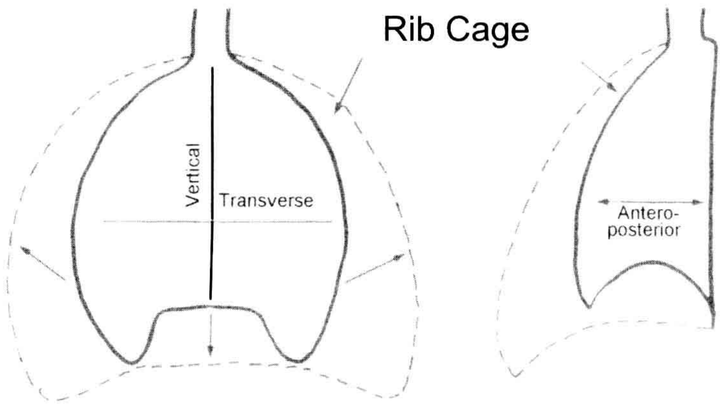

Figure 1.3. *The vertical, transverse and antero-posterior dimensions of the thoracic cavity increase during inhalation and decrease during exhalation*

1.4.1. *Inhalation muscles*

1.4.1.1. *The diaphragm*

The diaphragm is the chief inhalation muscle. This muscle is domed at the top and its fibers are attached to the base of the sternum, the lumbar vertebrae and to the inner surfaces of the cartilages of the lower ribs. It separates the thoracic cavity from the abdominal cavity. When the diaphragm contracts, the effect is to flatten the dome and push the abdominal organs down; this enlarges the thoracic cavity in the vertical dimension. The diaphragm can also help to raise the lower ribs to some extent.

1.4.1.2. *The external intercostals*

The external intercostals run between the ribs and connect the lower edge of each rib vertically and horizontally with the upper edge of the rib immediately below. Their function is to strengthen the thoracic walls so that they do not bulge through the ribs. Their action aims at overcoming the forces of relaxation. Because of their origin and insertion, their contraction makes the ribs rotate outwards and upwards, increasing the anteroposterior dimension (Dickson and Dickson, 1995).

In normal respiration, the expansion of the lungs is caused by the contraction of the diaphragm and the external intercostals. In forced respiration, a certain number of supplementary muscles come into play and increase the movement to raise the