PHYSIOLOGY AND ITS IMPACT ON THE PERFORMANCE OF SINGING

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Introduction

Singing, like other highly skilled performance activities, involves the acquisition of a set of complex coordinated functions, normally achieved through attempts to replicate functionally efficient behaviours, within the proper aesthetical boundaries (Doscher, 1994). This learning-practice process culminates in the realisation of solid vocal technique, which facilitates heightened artistic expression (Miller, 1996). However, unlike other musical instruments, many actions that lead to this vocal technique are internal. This hidden nature of the human voice has allowed imaginative theories to arise in the world of voice training which often lead to opposing practices concerning breath management, resonation and articulation (Miller, 1994). Although it may achieve the intended goals, learning to sing based on this imaginative terminology may not always be directly linked with the mechanisms underlying the function of the singing voice. The result may well be a vocal technique built on non-replicable strategies, leading to instabilities that compromise the singer's abilities to communicate through music. Acquiring a solid knowledge of the physiology behind the sound seems to assist singers in acquiring an efficient and effective vocal technique (Miller, 1996; Gullaer, Walker et al., 2006). This chapter explores the physiology of singing and its impacts on performance, the rationale being that, when the physiology of singing is understood, the established cyclical interplays serve the purposes of the singing gestalt (Doscher, 1994): affective and effective musical communication. Taking into account that the voice is a physiological and acoustical instrument (Miller, 2004), this chapter reviews the main physiological parameters that affect singing, organising them into three subjections: breathing, the production of a voice source, and strategies employed to modify and enhance this source for singing. The chapter ends with a summary of the key principles and approaches discussed, reaffirming their relevance more broadly within music education.

Physiological parameters affecting singing

The human voice, as a musical instrument, requires concomitantly fine mastering of all constituting elements. Through practice, singers experience the complex interrelationships between all systems (Miller, 1996): (i) the "fuel", or aerodynamic power necessary to produce a primary sound (achieved by efficient breathing control); (ii) the source, generated by converting aerodynamic into acoustic power (the vibration of the vocal folds); and (iii) the modulator (or acoustic oscillator), to modify and enhance the source energy into singing by articulation (Jian, 2006).

(i) Aerodynamic power: efficient breathing control

Breath is often regarded as the "fuel" for the voice. After all, the breath is what excites vocal fold vibration (Sundberg, 1987; Titze, 2000). This section is focused on the function of breathing as it relates to vocal performance. For the sake of simplification, breathing will be broken down into four stages (Titze, 2000). One could start at any point in the cycle, but here the beginning is considered inspiration. In inspiration, the abdominal muscles and internal intercostal muscles (responsible for pulling down the ribcage during expiration) must release. The diaphragm (main muscle of inspiration) activates and begins to flatten from its original double-dome shaped rest position. As the diaphragm moves down, the viscera displace downward to make room for its decent. The external intercostal muscles pull the ribcage up, increasing the volume of the thoracic cavity, which, in turn, keeps air moving into the lungs (Titze, 2000). During expiration (stage one), there is adequate air pressure (sometimes excess) to activate vocal fold vibration simply with the elastic recoil of the ribs and lungs, which want to return to their equilibrium from the position to which they have been moved or stretched (Ibid). With a deep breath, the pressure from the recoil will be greater than desired, and the air pressure needs to be restrained somewhat by continued contraction of the diaphragm (Leanderson and Sundberg, 1988) and/or activation of the external intercostals. During stage two of expiration, the end of elastic recoil is reached and the internal intercostal muscles begin to help shrink the ribcage (Titze, 2000). At the final stage of expiration (stage three), the abdominal muscles begin to shrink the abdominal cavity, which drives the viscera upward against the diaphragm moving it further towards its point of origin before its decent during inspiration (Hoit, Plassman et al., 1988; Watson, Hoit et al., 1989).

At stage one of expiration, the possibility for excess pressure cannot be overemphasized. In singing pedagogy, there is a method used to avoid excess subglottal pressure (Psub), i.e. an “overpressure of air in the lungs” (in Sundberg, 1987: 25) called the *appoggio.* The basic concept of this technique is to “sing on the gesture of inhalation” (in Doscher, 1994: 22), i.e. keep the external intercostal muscles engaged to keep the ribcage from recoiling too fast. In essence, the inspiratory muscles balance out the action of the expiratory muscles, so as to avoid a too rapid collapse of the thoracic cavity, as well as a rapid ascent of the diaphragm. The diaphragm stays contracted by keeping the abdominal wall out (especially the area called the epigastrium – right below the ribs in the front); expansion in this area is indicative of the diaphragm being down (Vennard, 1967). Since the beginning of singing pedagogy, terminology such as *appoggio* and *support* can be found to address the coordination between laryngeal action and breathing (Stark, 2003), a phenomenon of paramount importance to singing performance (Miller, 2004). Nevertheless, diverging explanations are found in the literature concerning the required strategies for *appoggio* or *support*. Partially, this can be related with the fact that different muscular strategies are used in accordance to the individual characteristics of each singer (Sundberg, 1987). Also, breathing patterns differ greatly among individuals, as different strategies of inhalation and exhalation exist (Leanderson and Sundberg, 1988). These facts perhaps have encouraged the many breathing methods employed by different schools of singing: abdominal or belly breathing (also know as diaphragmatic breathing); thoracic breathing; a combination of both abdominal and thoracic; and clavicular breathing (Miller, 1977). It is universally agreed upon that clavicular breathing, associated with a panic reaction or hyperventilation, is not advantageous to singing; it may lead to tensions in the neck and in the pharynx that may affect resonance (Appelman, 1967). Concerning the other breathing methods, one might argue that a combination of thoracic and abdominal breathing seems the most efficient method as it aligns nicely with the normal breathing cycle and does not restrict the movement of the ribcage wherein lie the lungs. This combination may lead to maximum expansion of the thoracic cavity as it allows the sternum to move up and forward (antero-posterior expansion), the ribs to move up and out (transverse expansion), and the diaphragm to move down (vertical expansion). With this increased expansion, a singer has more fuel at her/his disposal to maintain a healthy vibration at the vocal fold level. However, as pointed out before, there is no universal consensus on which breathing behavior is the most efficient (Miller, 1977). Consensual opinions are only reached when it comes to the fact that less efficient phonation can become more efficient by simply altering respiratory habits (Leanderson and Sundberg, 1988).

In the eighties, several investigations have been developed to understand breathing behaviours in singing (Sundberg, 1992). From these investigations, it became evident that, to phonate, a singer needs to increase the pressure inside the lungs, i.e. alveolar pressure, which is roughly equivalent to subglottal pressure (Psub). Psub is one of the main physiological parameters of voice control in singing; it controls loudness (louder singing requires higher Psub) and it affects pitch (when Psub increases, fundamental frequency (F0) is raised, although not significantly) (Sundberg, Fahlstedt et al., 2005). Each note in a musical phrase will have its own Psub, according to the loudness and the F0 required. For this reason, singers need to be constantly monitoring and adapting Psub (Sundberg, 1987). Thus, one might argue that the terms *appoggio* and *support* could be also finely described as *pre-phonatory breath management*.

Changes in Psub occur due to changes in the rib cage volume, by means of **muscular forces**, **elastic forces** and **gravitation** (Sundberg, 1987). **Muscular forces** involve the contraction and relaxation of respiratory muscles: the internal and external intercostal muscles, a paired muscle group responsible for inspiratory and expiratory forces, respectively; and the diaphragm and the abdominal wall, also a pair group of muscles that lead to inhalation and exhalation, respectively (Leanderson and Sundberg, 1988). The **elastic forces** play a major role in Psub variations, as lungs tend to possess a passive expiratory force that is higher with higher lung volumes (Sundberg, 1992). In order words, the natural movement for the lungs is to shrink after inhalation (Proctor, 1980). The same happens with the ribcage when deviated from its resting volume after an inhalation; thus, both lungs and ribcage generate a passive expiratory force (Sundberg, 1992). Unlike speech, singing often requires, at the beginning of a phrase, high lung volumes. Thus, singers need to learn how to avoid this passive exhalatory force, especially when singing pianissimo dynamics, as when the lungs are filled with air, this passive force generates a high pressure (Proctor, 1980). In such cases, singers need to contract the principal inhalatory muscles (i.e. diaphragm and external intercostals). With a decrease in lung volumes as the musical phrase progresses, this need progressively decreases until passive exhalatory forces become null. From then on, the strategy will be to activate the expiratory muscles in order to maintain sufficient thoracic pressure to move air out of the lungs and maintain vocal fold vibration (Sundberg, 1992). Summarising, to sing a pianissimo, singers need to recruit a compensatory activation of inhalatory muscles, whereas when singing a fortissimo the normal exhalatory process may suffice, especially when the lungs are not at their full volume capacity (Ibid.). **Gravitation** is another parameter affecting Psub. In an upright position, gravity facilitates inhalatory forces by pushing down the diaphragm; on the other hand, in a supine position, gravity acts as a force on the abdominal content, facilitating the recoil of the diaphragm into the thoracic cavity. A supine position of the body heightens awareness of the contraction of the diaphragm and encourages a less forceful contraction of the abdominal wall, thus being a possible strategy for singers who tend to over contract the abdominal wall during singing. One concludes that posture affects lung volume and indirectly Psub (Sundberg, Leanderson et al., 1991). This possibly explains why a good posture has been commonly referred to as an important asset in a signing performance (Schneider and Dennehy, 1997). During inspiration in an upright position, this gravitational force exerts a force upon the larynx, the **tracheal pull** (Sundberg, 1987). As the diaphragm lowers and stretches the lung tissue downwards, the trachea moves down as well. As it is attached to the lower portion of the larynx at the bottom of the cricoid cartilage, the larynx is necessarily pulled down with it. Consequently, the tracheal pull exerts its force upon the vocal folds, slightly abducting them. Due to this decrease in adduction, more air may flow through the folds during phonation (Zenker, 1964). Increased cricothyroid activity with a low diaphragm, induced by high lung volume or a co-activation of the diaphragm during singing, corroborates these effects (Sundberg, Leanderson et al., 1988). From a vocal training standpoint, tracheal pull could be very useful for a trained singer who tends to over-adduct the vocal folds. By applying exercises starting at high lung volumes, the teacher will encourage the student to use a tracheal pull effect, finding a lower larynx position and avoiding overly adducted vocal folds (Iwarsson and Sundberg, 1998). In non-trained singers, on the contrary, it is often found that larynx height increases with increasing lung volumes (Ibid.).

With the ever-increasing demands on singers, particularly with regard to physical demands while singing, one must consider the effects of being out of breath during phonation. Even short-term accelerated breathing challenges seem to affect the minimum lung pressure that is needed to sustain the oscillation of the vocal folds produced by flow, the phonation threshold pressure (PTP) (Sivasankar and Erickson, 2009; Titze and Verdolin, 2012). Accelerating breathing was found to increase PTP as well as perceived phonatory effort (Sivasankar and Erickson, 2009; Sandage, Connor et al., 2013). To counteract this effect, a teacher might introduce physical exercise into the daily normal singing practice session. If a singer is trained for a specific task where aerobic physical activity is also needed, he/she might become better at negotiating possible changes in the vibratory cycle of the vocal folds associated with this accelerated breathing. In fact, female singers were found to reduce PTP after practicing vocal warm-ups with an aerobic exercise component included (McHenry, Johnson et al., 2009).

(ii) Mechanical oscillator: production of a voice source

Thanks to technological aids developed over the past 40 years, physiological events that occur cyclically within the human body can now be monitored. In the particular case of the mechanical oscillator that produces the voice source, i.e. air pressure variations generated by the vibration of the vocal folds (Sundberg, 1987), a flow glottogram constitutes an excellent display of transglottal airflow over time. It reveals how the voice source behaves for each vibratory cycle. When the glottis starts to open (until it is completely open), the airflow gradually increases until it reaches a maximum that corresponds to a positive peak in the curve; as the glottis starts to close, the airflow decreases until it ceases at the moment that the glottis is completely closed, the zero line. Usually, the closing of the glottis is more rapid than the opening; thus, the slope of the flow glottogram is steeper on the falling part of the wave. Variations in the shape of the flow glottogram partially reflect respiratory and laryngeal muscle adjustments that singers learn in order to achieve a prephonatory control of the vocal fold mass, length and inner tension (Sundberg, 1987). These adjustments are normally achieved by regulating: (a) Psub; (b) adductory and abductory forces of the vocal folds (for breathing, the vocal folds are abducted whereas for phonation, they are adducted); and (c) tension and extension of the vocal folds (Ibid.). One way of training prephonatory control of the physiological parameters affecting the production of an efficient voice source is by practicing staccato exercises at different pitches, and using different vowels (Welch and Sundberg, 2002). Exercises that focus on voice onset and offset often facilitate the learning of efficient voice source use as they encourage the synchronisation between the activation of Psub, adductory forces and vocal fold vibration. A hard attack corresponds to overly adducting the vocal folds before establishing a Psub and vibration of the vocal folds; a breathy voice onset often is related with an existent Psub, followed by the adduction and the vibration of the vocal folds; and a synchronised onset (a staccato onset) requires concomitant engagement of Psub, adduction and vibration of the vocal folds (Sundberg, 1987; Lã, 2012).

(a) Subglottal pressure

Already described, Psub is extremely important to singers; its increase results in an increase in vocal loudness and, although to a lesser extent, pitch (Sundberg, 1987). The effects of Psub variations are far from being trivial, as variations on this physiological parameter affect a number of equally important physiological events that change voice source behaviour and, thus, regulate the properties of the final acoustic output. This complex matrix of interactions can be visualised by means of monitoring flow glottogram variations in terms of: (i) the time that the vocal folds are closed per cycle, i.e. closed quotient; (ii) peak-to-peak pulse amplitude in one vibratory cycle; (iii) glottal leakage (mean airflow during the closed phase of the cycle); (iv) maximum rate of airflow change; and the dominance of the fundamental in the voice source spectrum – in other words, the level difference between the first and second partials of the voice source, hence H1 and H2 (Sundberg, Fahlstedt et al., 2005).

The relationship between Psub and closed quotient (Q_{Closed}) can be expressed as a power function; Q_{Closed} increases rapidly at low pressures and approximates to an asymptote at higher pressures (Sundberg, Fahlstedt et al., 2005). There are differences between the sexes and trained and untrained voices with regard to this relationship (Ibid.). Q_{Closed} seems to affect voice timbre as “it determines how great a portion of the cycle will contain a formant ringing” (in Sundberg et al., 2005: 884-885). Q_{Closed} is related to another parameter that has been used as a standard measure for assessing vocal fold contact time per cycle, i.e. contact quotient ($Q_{Contact}$). $Q_{Contact}$ is measured non-invasively by means of electroglotography (Baken, 1992) or by electrolaryngography (Fourcin, 2000). Previous studies have demonstrated that the time the vocal folds stay in contact per cycle increases with vocal training (Howard, 1995). This is an important development as, by increasing $Q_{Contact}$, the singer reduces the loss of sound energy to sub-glottal dampening (Howard, 1995). A longer contact time also offers the possibility of sustaining longer phrases, as air loss is smaller for cycles with longer contacting phases (Ibid). However, if the contact phase is too long and the shape of the mucosal wave is not symmetrical, one might argue that the adductory forces of the vocal folds may be too strong, a sign of possible overpressurisation in singing (Lã, 2012). However, longer $Q_{Contact}$ might also be indicative of longer vocal folds. For example, longer $Q_{Contact}$ values are found for male singers than females; high notes such as those sung by sopranos, reveal shorter $Q_{Contact}$ as compared to low notes (Howard, 1995).

Peak-to-peak pulse amplitude in one cycle can also be affected by Psub variations. The pulse amplitude in a flow glottogram represents an important phenomenon to a singer: the amount of air passing though the glottis during the opening phase of the cycle. It reflects the amplitude of the fundamental in the voice source spectrum, i.e., the greater the airflow amplitude, the stronger the voice source fundamental (Sundberg, 1987). A combination of a high Psub and a high adduction force of the vocal folds (i.e. a great resistance of the glottis to the air flow) will lead to a smaller flow glottogram amplitude, hence a week source fundamental. In addition, one should certainly take into account vocal fold morphology. Friction has an adverse effect on the vocal fold tissue and with more Psub and increased glottal resistance, friction is increased; hence, the vocal folds are at greater risk for injury. However, one should take into account that the amplitude of the source fundamental depends not only on adductory forces but also on glottis area. Longer vocal folds tend to have a bigger F0 amplitude as the glottal area is bigger (Sundberg, 1987).

The level difference between the first and second partials of the voice source (H1-H2) is also an indicator of voice efficiency: a waste of Psub and adductory forces that do not lead to a gain in sound level exists if the level difference between the first and the second partials is negative (Sundberg, Fahlstedt et al., 2005).

Maximum rate of airflow change during a period relates to the closing rate of the vocal folds and thus how quickly the airflow is shut-off, i.e., maximum flow declination rate. This physiological event is important in singing because, for frequencies that are not high, if the closing rate is fast, the sound level will be increased. The phenomenon is that the dominance of the higher overtones in the spectrum is greater when there is a rapid closing rate. However, it is important to emphasise that sound level is also determined by the distance between the first resonance of the vocal tract (first formant) and the closest partial (Sundberg, 1987). This effect of proximity of a harmonic to a formant will be further explored in the section concerning the acoustic oscillator.

(b) Adductory and abductory forces of the vocal folds

Changes in adductory and abductory forces are crucial for achieving different phonation types, which range from breathy, to neutral, flow and pressed phonation. Acoustically speaking, changing from one extreme of adduction to the other has a major impact as the amplitude of the fundamental can be increased by 15dB when changing from pressed to **flow phonation** (Sundberg, 1987). The latter is the most efficient phonation mode for classically trained singers; a lower Psub combined with a moderate adduction and glottal resistance will promote the best setting for bigger amplitude excursions of the vocal folds, which close rapidly, resulting in a stronger fundamental with richness of high harmonic components (ibid.). Although the amplitude of the source fundamental is not the same as of the radiated F0 (the latter depends also on the modifications of the resonances of the vocal tract through articulation), **the amplitude of the voice source fundamental** plays an important role in the perceived loudness and overall quality of the voice. Many singing teachers are experts at listening to the level of the source fundamental, and are able to separate the effects of physiological adjustments to the sound (such as too much or too little adduction), from the effects of adjustments that are acoustically made (Sundberg, 1987).

The relationship between adductory forces and Psub is of paramount importance to vocal health, as excessive vocal adduction is typically detrimental for the voice (Mathieson, 2001). In addition, posterior glottal adduction has an impact on perceived vocal quality; with an insufficient posterior glottal closure (glottal chink), turbulent airflow in the glottis will lead to the perception of a breathy voice (Herbst, Howard et al., 2010). An increase in Psub will cause an increase in airflow only when glottal resistance will be kept constant. A glottal leakage occurs when one increases Psub without compensating for the increase with the degree of adduction. Singers learn to control glottal resistance to avoid changes in voice quality. For example, an increase in glottal leakage (a decrease in glottal resistance) is observed with increasing F0, an important consideration to avoid running into a pressed type of phonation in the higher range of the voice (Sundberg, 1987). Another example is the increase in glottal resistance towards the end of a phrase as a strategy to maintain the same airflow and sound level when air pressure in the lungs is being reduced (Ibid.).

Adductory forces of the vocal folds can be elevated by contraction of: (i) the lateral cricoarytenoid muscles; (ii) the interarytenoid muscles, and (iii) the lateral parts of the interarytenoid muscles. The combination of practicing specific vocal exercises, verbalisation of events and feedback using electrolaryngography/ electroglottography was shown to be useful in reducing posterior glottal chink due to incomplete closure of the glottis (Herbst, Howard et al., 2010). Singers are trained to control forces that increase or decrease adduction in the search for the appropriate balance between air volume displacement at the glottis, glottal resistance and Psub (Ibid.). During this training, it should be kept in mind that male and female singers have different relationships between the physiological parameters controlling the production of the voice source sound. Male singers have longer vocal folds than female singers (the basses displaying the longest sizes) (Roers, Mürbe et al., 2009), which will also be reflected in terms of glottal space (Sundberg, Fahlstedt et al., 2005). Also, sopranos will have smaller vocal folds than mezzo sopranos (Roers, Mürbe et al., 2009). Thus, if the voice source x will display a stronger fundamental than the voice source y, it does not necessarily mean that x is using flow phonation and y is not, as the amplitude of the source fundamental depends not only on the adducttory forces but also on the size of the glottis. Taking into account these considerations, one might agree that physiology is crucial to singing pedagogy. The way by which physiological events are expressed in singing modes, and in singer's sex and voice type, must guide the pedagogue and the practitioner in choosing the most appropriate physiological approaches for obtaining a certain sound, rather than producing that sound at any cost.

(c) Tension and extension of the vocal folds

The tension and extension of the vocal folds will determine the F0, that is to say, how many times per second that the vocal folds vibrate. F0 has significant impacts on the physiology of singing performance. For example, it is highly correlated to the perception of pitch, i.e. the “height” of the voice - a perceptual evaluation of F0 - is influenced by the timbre and loudness of the voice (Titze, 2000), and it has been pointed out to influence the performer’s expressivity (Sundberg, Lã and Himonides, 2013). Sharpening phrase-peak tones as compared with equally tempered tuning was shown to be an expressive tool used in classical singing (Ibid.).

Changes in F0 can be achieved by means of adjustments in the contraction of two important intrinsic muscles of the larynx: the thyroarytenoid (TA) and the cricothyroid (Proctor) muscles (Proctor, 1980). The TA runs longitudinally, from the thyroid to the arytenoid cartilages, whereas CT is located anteriorly, between the thyroid and the cricoid cartilages (Titze, 2000). Generally speaking, one might say that increasing F0 involves an increase in the contraction of TA for the lower/mid range and as F0 continues to rise, there will be a point when the TA can no longer be dominant, as there is a physiological limit to the active muscle stress of the TA. Thus, F0 increases at higher frequencies is fully dependent on the dominance of CT activation (Ibid.).

Pedagogically there are some important considerations that one must have in mind concerning F0 changes. The first is that raising F0 can also be achieved by increasing Psub, because less CT activity is required for singing the same F0 when Psub increases (Ibid.). One might argue that this is not an optimal strategy for singers, as the amplitude of vibration increases with increasing lung pressure, which may lead to an excessive collision force, one of the top risk factors for tissue injury (Titze, 2000). The second is that the cartilages and muscles vary in shape and size between singers. In some larynges, for example, the cricothyroid space is very narrow. In these cases, the range of rotation between the cricothyroid towards the thyroid cartilage is limited. Thus, not much can be done to stretch the vocal ligament when these two cartilages are in contact with each other. The tendency will be to increase muscular effort, which would be also a non-optimal strategy. A possible solution might be to assist the further elongation of the vocal folds by an external pull on the CT, either by applying a higher tracheal pull force or to raise the larynx with rising pitch (Titze, 2000). Although previous studies have found that the larynx raises with raising pitch for professional singers, this phenomena does not happen until a certain F0 has been reached, before which the larynx is kept in a lower position than the resting one (Sundberg, 1987). Thirdly, modifications in the relationships between CT and/ or TA activation, and or vocal loundness, may lead to perceived different vocal qualities, or registers (Titze, 2000). For those singing styles requiring evenness of timbre throughout the whole vocal range (e.g. classical singing), register events might be avoided by applying certain resonance strategies (see section on acoustical oscillator below). Other relevant pedagogical consideration is how a singer may avoid voice misuse when singing demanding repertoire in terms of F0 range and tessitura. The risk of developing vocal injury may be decreased if singers adopt flow phonation and apply sufficient ligament stretch, by creating an optimal relation between CT (and external laryngeal muscles) and TA contraction (in the case of middle register) (Ibid.). The tracheal pull strategy seems to be advantageous. Singers have a tendency to increase adduction on the higher end of their vocal range, leading to a strained vocal quality; the tracheal pull seems a key factor to avoid this, as it introduces a counter balancing abductory force, assisting the singer to maintain a flow phonation on the higher part of his/hers vocal range (Sundberg, 1992). Also, when rapid and precise movements of different parts of the human body are required, both muscles required to bring the structure into motion and those responsible for its stabilisations at a resting position are engaged (Rothenberg, 1968).

Finally, cyclical F0 modulations give rise to a vocal effect that is desirable in some singing styles, vibrato. It is commonly accepted that the amount of F0 amplitude deviation from the mean F0 should be approximately 4.5 to 6.5 Hz in frequency, and approximately 3 percent (0.5 semitones) in extent in order to produce an aesthetically agreeable vibrato (Sundberg, 1987; Tizte 2000). There are different ways of producing vibrato: by lung pressure pulsations, jaw movement or cyclical contraction of CT and TA muscles (Kempster, Larson et al., 1988). The latter as been refereed as preferable as an expressive tool for classical singing and for some non-classical styles, such as musical theatre, jazz and pop/ rock (Tizte, 2000). It is worthwhile mentioning that the vibrato extent raises with raising vocal intensity and to some extent with pitch. Signs of nervousness and/ or excessive muscle tension can be revealed by a high vibrato frequency (between 6 and 8 Hz). Poor muscle tone, on the contrary, leads to a low vibrato frequency (between 2 to 4 Hz). Acceptable vibrato quality, in frequency and extent, is therefore a sign of good vocal technique and condition (Titze, 2000).

Acoustic oscillator: modifying and amplifying the source energy into singing

Resonance is “a condition that exists between the source of energy and the configuration of the medium such that the energy of some frequencies of vibration will be kept ‘alive’ in the medium while others will quickly die off” (in Story, 1999: 1). With singing, the vocal folds are the source of energy and the medium is the air inside the vocal tract. “Resonant voice” can be defined as “any voice production that is both easy to produce and vibrant in the facial tissues” (in Verdolini-Marston, Burke et al., 1995: 2). The sympathetic vibrations towards the front of the face are indicative of an effective resonator, whereas the ease of production is indicative of an efficient use of resonance and vibrator. Resonances of the vocal tract are called formants. The lowest two formants (i.e. F1 & F2) determine the vowel sound, whereas formants three (F3), four (F4) and five (F5) have more effect on timbre (or tone colour) (Sundberg, 1987).

The source-filter theory of voice production involves the vocal folds as the source of acoustic energy and the vocal tract (the space above the vocal folds) as the selective sound filter. While the vocal tract is considered to be a highly efficient resonator, it only allows approximately one percent (or less) of the information produced at the level of the vocal folds to be emitted from the mouth (Story, 1999). The information that either receives enhancement or becomes critical dampened is determined by the shape of the vocal tract, i.e. the length of the overall tube as well as its ever-changing diameter throughout the whole length of the tube (Doscher, 1994). The shape and the length of the vocal tract are altered by means of articulation.

When a singer produces a vowel sound, the contour of the tongue creates a degree of constriction in a certain area of the vocal tract. For instance, when a person sings an /i/ vowel, the blade of the tongue moves close to the hard palate creating a constriction near the output of the resonance tube. Whereas, when an /a/ vowel is articulated, the back of the tongue creates a narrowing of the pharyngeal area. Furthermore, the /u/ vowel creates a constriction in the middle of the vocal tract tube when the mid part of the tongue approaches the soft palate. The lip rounding for an /u/ creates a secondary constriction right at the vocal tract output (Lindblom and Sundberg, 2007).

It is important for a singer to be aware of the fact that the tongue plays a major role as a modifier of the vocal tract, and thus, its resonances, along with the lips, the jaw, the soft palate and the larynx. Specific exercises to isolate the effects of these articulators in the overall sound quality during singing should be employed, especially because the singer’s awareness of the movements of these hidden elements is imperfect (Gullaer, Walker et al., 2006).

There are infinite combinations of spaces in the vocal tract, but in general, the following rules apply with regard to the adjustment of formant frequencies (Titze, 2000): (1) lengthening the vocal tract (e.g. rounding the lips or lowering the larynx) universally lowers all formant frequencies (Watson, Hoit et al., 1989); shortening the vocal tract (e.g. spreading the lips or raising the larynx) universally raises all formant frequencies (Ibid.); a mouth constriction, i.e. closing the jaw and/or moving the blade of the tongue closer to the hard palate, causes a rise in F2 and a decrease in F1 (Ibid.); and a pharyngeal constriction, i.e. opening the mouth and/or moving the back of the tongue toward the pharyngeal wall, causes a rise in F1 and a decrease in F2 (Lindblom and Sundberg, 2007).

There is no disputing that resonance plays a key role in efficient and effective voice use; however, there are differing opinions regarding how resonance is employed. Presently, many studies have been carried out involving the measurement of formant frequencies and their interactions with the partials produced at the vocal fold level (Miller and Schutte, 2005; Esternach, Sundberg et al., 2010; Henrich, Smith et al., 2011; Sundberg, Lã and Gill, 2013). In general, whenever the partials from the vocal folds are in close proximity to the formant frequencies of the vocal tract, they will be boosted, i.e., gain in intensity (Titze, Riede et al., 2008).

There is some disagreement in the voice science community regarding exactly how partials and formants interact. A theory of non-linear source-filter interaction in voice production has been developed over the last decades, tested and confirmed with experiments using, for example, physical models (Ibid.). In this case, the theory predicts that, when a low spectrum harmonic is just bellow to F1 or F2, the sound pressure level (SPL) of a vowel may increase by as much as 10 dB. On the contrary, if a harmonic is just above the formant frequency, SPL may be weakened. In other words, a non-linear interaction between the vocal folds and the vocal tract may elicit a more efficient conversion of aerodynamic to acoustic energy (Titze, 2004). Physiologically, this is related to the diameter of the epilaryngeal tube; when the impedances at the glottis and at the epilaryngeal tube are similar, a strong coupling occurs (Titze, Riede et al., 2008). Other authors, however specify that for this coupling to occur, it is necessary to tune a formant to a partial; which formant coinciding with which partial depends on the pitch area in which the singer is singing (Miller, 2008). For example, when a male voice is singing an /a/ vowel in or just above the *secondo passaggio*, it is advantageous for F2 to coincide with the third partial (H3) (Ibid.). A successfully negotiation of register transitions depends on resonant “tuning” skills rather than muscular adjustment in laryngeal muscles (Miller and Schutte, 2005). More recently, the results of a study analysing the voice of professional male singers by inverse-filtering suggested that partials will get a similar boost regardless of whether the formant is just above, right on, or just below a particular partial. It was also noted that no instabilities occurred throughout the sung scales even when formants “crossed over” partials (Sundberg, Lã and Gill, 2013). Additional findings showed that professional male singers lowered the first formant of the /a/ vowel in and above the *passaggio*, avoiding the boost of the H2 and allowing for H2 to boost H3 (Hertegård, Gauffin et al., 1990; Neumann, Schunda et al., 2005; Titze and Worley, 2009; Esternach, Sundberg et al., 2010; Sundberg, Lã and Gill, 2013). An important finding was that the second formant/third partial “tuning” seemed to occur by happenstance, whereas the lowering of the first formant seemed deliberate as when the singers were asked to sing in the same pitch range in a non-classical style the first formant was on or near the second partial (Sundberg, Lã and Gill, 2013). This non-classical tuning is similar to the tuning found in the female belt voice; the first formant giving a boost to the second harmonic is considered a “yell-belt” strategy (Miller, 2008; Titze and Worley, 2009). These authors would like to make the distinction that, while this tuning - commonly found in musical theatre, popular, folk and world music idiom

(Bozeman, 2013) - may sound “yell-like”, it should in no way be executed with the same subglottal pressure/glottal resistance combination by which most yells are produced, as this can damage the vocal fold tissue. In the case of front vowels (like /i/), there will be a considerable modification of the vowel in order to maintain this strategy; hence, the reason sometimes /ae/ is heard instead of /i/ in the higher range of the belt voice.

Although the general concept of formant tuning has been questioned (Carlsson and Sundberg, 1992), one tuning that seems to be universally agreed upon involves the upper *passaggio* for male voices and high range of the female voice; a “tuning” of F1 to F0 occurs, so as to avoid a scenario where F0 is higher than F1 (Rothenberg, Miller et al., 1987; Sundberg, 1987; Titze, 2008; Henrich, Smith et al., 2011). So, how does this tuning occur? Imagine a woman is singing an /a/ vowel on a D5 which has a frequency of roughly 587 Hz. The approximate resonance properties of F1 and F2 (the vowel formants) of an /a/ vowel are 800 Hz and 1200 Hz, respectively. The second harmonic for the fundamental D5 is twice the F0, making it approximately 1174 Hz. This frequency is in the neighbourhood of F2 and will therefore be boosted by it. While ascending into the top voice it is often instinct for a singer to continually open the mouth, the result of this will be an ever-increasing F1 frequency and if lip spreading is also occurring, it will increase all the formant frequencies universally. As the singer ascends a whole step higher to E5 (659 Hz) - if their lips spread - F2 will continue to enhance H2 and the rising F1 will remain somewhere between F0 and H2. Conversely, if the singer were to round the lips a bit, shaping the vowel more towards /Ɔ/ (as in call, saw), and universally lowering all formant frequencies, the result would be that F2 would no longer give a boost to H2 as its frequency would be in the region of 1100 Hz, and F1 would give a boost to F0/H1 as its frequency would be approximately 700 Hz (which is very near the frequency of F0/H1 on E5). This is employed in western classical singers in order to maintain an even timbre. Others suggest a passive modification of the vowel, i.e. “maintaining the tube shape while the pitch and its harmonics move” (in Bozeman, 2013: 23), and assert that this will also help avoid a loss of timbral depth or warmth (Ibid.).

Another example of a resonance strategy that finds agreement between researchers is the singer’s formant cluster. This phenomenon is a strategy used by classically trained male voices, developed to allow them to be heard over a loud accompaniment (Sundberg, 1987). Contrary to female singers that shorten their vocal tract with increasing pitch by raising their larynx and lowering their jaw (in order to avoid a situation in which F0 is higher than F1), male singers tend to do the opposite. Male classically trained singers lower the larynx, and widen the pharyngeal wall, the laryngeal ventricle and the piriform sinus to cluster F3, F4 and F5 (Ibid.). Acoustically, this strategy allows a boost in the spectrum energy around 2500-3000Hz (Ibid.), precisely in the middle of the region where the human ear is most sensible (1KHz-4KHz) (Titze, 2000).

As a general rule, a singer must learn how to adjust the resonators to create a space that is more acoustically sensitive to pitch, or part of the harmonic series of the sung pitch. “A singer who keeps a large mouth opening all the time will be wrong about 50 percent of the time. A singer who keeps a small mouth opening all the time will also be wrong about 50 percent of the time. The trick is to know when to open a little or a lot” (in Emmons and Chase, 2006: 132). Perhaps this is an oversimplification, but the spirit of the quote is clear. As different musical notes have different harmonic series, there are necessary acoustic adjustments that singers must make as they negotiate the full range of their voices. For the voice to sound full and with depth, at least one harmonic partial needs to be near F1; hence, low frequency notes do not need that much of a vowel adjustment, as harmonic partials lay within the vicinity of F1 bandwidth (i.e. the interval difference between two points identified as 3dB lower than the peak of a resonance curve) (Titze, 2000). Nevertheless, for higher frequency notes, as the harmonic partials are more widely spread, fewer will be within the range of F1 (and F2), so that more attention is needed towards strategies of modifying the vowels (Bozeman, 2013). Vowels and the inherent shape they have in the vocal tract have frequencies at which strong boosts of energy are created (the aforementioned formants). Thus, one must concede that different frequency levels require different configurations of the resonators in order to facilitate effective resonance - which means vowels, with their inherent resonance properties, must be adjusted depending on the frequencies at which they are sung (Sundberg, 1987).

Summary

The development of voice control is a rather complex ability, as the change of one parameter leads to the adjustment of many others. Understanding the physiological interactions that dictate the quality of the primary sound is a key element for ensuring proper adjustments, i.e. the ones guaranteeing the longevity of a healthy voice. In fact, audition, unlike vision or proprioception, does not allow a direct translation of the source sound (Cytowic, 2002). For singers, this is even more evident, considering the sound produced is heard differently by the singer than by others. The singer hears the voice as being high frequency. Additionally, the bone conduction of the vibrating vocal folds to both inner ears also presents the ears with a sound that is low frequency dominant (Howard and Murphy, 2008). Thus, despite the fact that listening to a sound and imitating it constitutes one of the possible ways of learning to sing, when isolated from the other forms of learning (i.e. kinaesthetic, visual, and intellectual) (McCoy, 2004), this may lead to a limited use of the vocal instrument. Today, teaching singing in an integrated manner - focusing on the student and the process, instead of the teacher and the final result - is one of the major changes with regard to approaches to instrumental/vocal teaching. The teacher's role is not solely artistic anymore, but rather also of a builder, mentor, a co-ordinator, a facilitator, an adviser, a networker, a manager and a developer (Lennon and Reed, 2012). These changing roles require new pedagogical skills for teachers, namely knowledge and understanding of all phenomena involved in successful singing performance (Ibid.), including physiological events. One might argue that the current singing teaching paradigm is shifting from "empiricists" vocal coaches, i.e. those who believe that singing should be largely taught through imagery, so that it becomes free, unconscious and reflexive, towards "mechanists", i.e. those who defend that vocal control is conscious, directly linked to the scientific based evidence (Burgin, 1973).

Scientific knowledge allows the singing teacher and the singer to uncover the meaning of vocabulary that has been around since the beginning of vocal pedagogy, as well as develop new vocabulary that is more firmly based in the reality of the physiology of voice production. In the end, finding ways to avoid an overload of the most sensitive part of the whole singing system, the vocal folds, is imperative. Understanding the basics of voice function will guide a teacher down the path of discovery. Preservation of the vocal folds will certain contribute to the longevity of a singing career. As singing is a multimodal activity, *pre-phonatory breath management* is essential to be prepared for such complex endeavour. Becoming aware of the role of muscular forces, elastic forces and gravitation in the control of Psub for a given pitch and vocal loudness is essential for achieving a final output that may serve the purpose of the desired artistic outcome. In fact, Psub influences a number of glottal parameters that are essential to a successful and long vocal career. Excessive vocal adduction is typically detrimental for the voice; and, although, for expressive purposes, the singer may want to use a wide range of different degrees of adduction momentarily, for those professionals seeking vocal efficiency, flow phonation is the best option to employ for the majority of phonation time. It is achieved by combining a low Psub with a moderate adduction and glottal resistance. The result is a strong fundamental, i.e. a big amplitude excursion of the vocal folds with rapid closure of the glottis, however without employing a high collision force. This is a highly efficient manner of exciting the resonator with acoustic energy. In addition, intonation is another key element in singing performance as sharpening phrase-peak tones as compared with equally tempered tuning is perceived as conveying more expressivity in singing. Unintentional altering of intonation, on the other hand, is often a result of poor resonance tuning (Vennard, 1967). The importance of resonance awareness in singing cannot be overstated. The ever-changing shape of the vocal tract and, hence, the resonances, are under the conscious control of the singer (Culver, 1956). A singer must be attuned to efficient resonance, which results in an easier sound production; this, in turn, can contribute to the longevity of a singing career. The monitoring of a vibrato quality can express whether a good technique has been used over the years (or is currently being used): a too rapid frequency vibrato may be related with excessive muscle tension, whereas a too slow vibrato rate may express voice fatigue and poor muscle tonus.

Finally, one might conclude that singing is a highly idiosyncratic. Despite the fact that all singers share similar anatomical structures, the way individual genotypes transduce themselves, produces different phenotypes, leading to small physiological differences in the way a singer may use the vocal instrument. This provides evidence that should encourage a singing teacher not to base pedagogical methods only on their own perceptive experiences. Moreover, the training of a singer should meet individual necessities; variables such as sex, age, personality and body type may require different approaches.

REFERENCES

Appelman, R. (1967). The Science of Vocal Pedagogy: Theory and Application. London, Indiana University Press.

Baken, R. J. (1992). "Electroglottography." Journal of Voice **6**: 98-110.

Bozeman, K. W. (2013). Pratical Vocal Acoustics: Pedagogy Applicatpms for Teachers and Singers T. New York, Pendragon Press.

Burgin, J. (1973). Teaching Singing. Metuchen, Scarecrow Press;.

Carlsson, G. and J. Sundberg (1992). "Formant Frequency Tuning in Singing." Journal of Voice **6**: 256-260.

Culver, C. A. (1956). Musical Acoustics. New York, McGraw-Hil.

Cytowic, R. E. (2002). Synesthesia: a union of the senses. London, Massachussetts Institute of Technology.

Doscher, B. M. (1994). The Functional Unity of the Singing Voice. London, The Scarecrow Press, Inc.

Emmons, S. and C. Chase (2006). Prescriptions for Choral Excellence: Tone, Text, Dynamic Leadership. Oxford, Oxford University Press.

Esternach, M., J. Sundberg, S. Arndt, M. Markl, M. Schumacher and B. Richter (2010). "Vocal Tract in Female Registers—A Dynamic Real-Time MRI Study." Journal of Voice **24**(2): 133-139.

Fourcin, A. (2000). Voice quality and electrolaryngography. Voice Quality Measurement. R. D. Kent and M. J. Ball San Diego, Singular Thompson Learning.**:** 285–306.

Gullaer, I., R. Walker, P. Badin and L. Lamalle (2006). "Image, imagination, and reality: On effectiveness of introductory work with vocalists." Logopedics Phoniatrics Vocology **31**(2): 89-96.

Henrich, N., J. Smith and J. Wolfe (2011). "Vocal tract resonances in singing: Strategies used by sopranos, altos, tenors, and baritones." Journal of the Acoustical Society of America **129**: 1024-1035.

Herbst, C. T., D. Howard and J. Schlömicher-Thier (2010). "Using Electroglottographic Real-Time Feedback to Control Posterior Glottal Adduction during Phonation." Journal of Voice **24**(1): 72-85.

Hertegård, S., J. Gauffin and J. Sundberg (1990). "Open and covered singing as studied by means of fiberoptics, inverse filtering, and spectral analysis." Journal of Voice **4**(3): 220–230.

Hoit, J. D., B. L. Plassman, R. W. Lansing and T. J. Hixon (1988). "Abdominal muscle activity during speech production." Journal of Applied Physiology **65**(6): 2656-2664.

Howard, D. M. (1995). "Variation of electrolaryngographically derived closed quotient for trained and untrained adult female singers." Journal of Voice, **9**: 163-172.

Howard, D. M. and D. T. Murphy (2008). Voice Science Acoustics and Recording. San Diego, Plural Publishing Inc.

Iwarsson, J. and J. Sundberg (1998). "Effects of lung volume on vertical larynx position during phonation." Journal of Voice **12**(2): 159-165.

Jian, J. (2006). Physiology of voice production: how does the voice work? The Performer's Voice. M. S. Benninger and T. Murry. San Diego, Plural Publishing Inc.**:** 23-32.

Kempster, G. B., C. R. Larson and M. Klistler (1988). "Effects of electrical stimulation of cricothyroid and thyroarytenoid muscles on voice fundamental frequency." Journal of Voice **2**(3): 221-229.

Lã, F. M. B. (2012). Teaching Singing and Technology. XXIV. Jahreskongress des BDG 2012 gleichzeitig EUROVOX - Kongress 2012: Aspects of Singing II: Unity in Understanding - Diversity in Aesthetics, Munique, Bunderverband Deutscher Gesangspädagogen.

Leanderson, R. and J. Sundberg (1988). "Breathing for Singing." Journal of Voice **2**(1): 2-12.

Lennon, M. and G. Reed (2012). "Instrumental and vocal teacher education: competences, roules and curricula." Music Education Research **14**(3): 285-308.

Lindblom, B. and J. Sundberg (2007). The Human Voice in Speech and Singing,. Springer Handbook of Acoustics. T. D. Rossing. Stanford, Springer**:** 669-712.

Mathieson, L. (2001). The Voice & Its Disorders, Whurr Publishers Ltd.

McCoy, S. (2004). Your Voice, an Inside View: multimedia voice science and pedagogy Princeton, Inside View Press.

McHenry, M., J. Johnson and B. Foshea (2009). "The Effect of Specific Versus Combined Warm-up Strategies on the Voice." Journal of Voice **23**(5): 572-576.

Miller, D. G. (2008). Resonance in Singing: Voice Building Through Acoustic Feedback. Princeton, Inside View.

Miller, D. G. and H. K. Schutte (2005). "Mixing the registers: Glottal source or vocal tract?" Folia Phoniatrica et Logopedia **57**: 278–291.

Miller, R. (1977). English, French, German and Italian Techniques of Singing: a study in national tonal preferences and how they relate to functional efficiency. Metuchen, The Scarecrow Press, Inc.

Miller, R. (1994). The Mechanisms of Singing: Coordinating Physiology and Acoustics of Singing. Vocal Arts Medicine: The Care and Prevention of Professional Voice Disorders. M. Benninger, Jacobson, B. and Johnson, A., Thieme Medical Publishers, Inc.**:** 61-71.

Miller, R. (1996). On the Art of Singing. New York, Oxford University Press.

Miller, R. (2004). Solutions for Singers: tools for performers and teachers. Oxford, Oxford University Press.

Neumann, K., P. Schunda, H. S. and H. A. Euler (2005). "The interplay between glottis and vocal tract during the male passaggio." Folia Phoniatrica Logopedica **57**: 308–327.

Proctor, D. (1980). Breathing Speech and Song. New York, Springer Verlag.

Roers, F., D. Mürbe and J. Sundberg (2009). "Predicted Singers'Vocal Fold Lengths and Voice Classification-A Study of X-Ray Morphological Measures." Journal of Voice **23**(4): 408-413.

Rothenberg, M. (1968). The breath-stream dynamics of simple-reased-plosive production. Basel, S. Karger.

Rothenberg, M., D. G. Miller, R. Molitor and D. Leffingwell (1987). "The control of air flow during loud soprano singing." Journal of Voice **1**(3): 262-268.

Sandage, M. J., N. P. Connor and D. D. Pascoe (2013). "Voice function differences following resting breathing versus submaximal exercise." Journal of Voice **27**(5): 572-578.

Schneider, C. M. and C. A. S. Dennehy, K. G. (1997). "Exercise Physiology Principles Applied to Vocal Performance: The Improvement of Postural Alignment." Journal of Voice **11**(3): 332-337.

Sivasankar, M. and E. Erickson (2009). "Short-duration accelerated breathing challenges affect phonation." Laryngoscope **119**(8): 1658-1663.

Stark, J. (2003). Bel Canto: a history of vocal pedagogy. Toronto, University of Toronto Press.

Story, B. (1999). A note on vibration and resonance. Denver, Wilbur James Gould Voice Research Center.

Sundberg, J. (1987). The science of the singing voice. Illinois, Northern Illinois University Press.

Sundberg, J. (1992). "Breathing behavior during singing." STL-QPSR **33**(1): 49-64.

Sundberg, J., E. Fahlstedt and A. Morell (2005). "Effects on the glottal voice source of vocal loudness variation in untrained female and male voices." Journal of the Acoustical Society of America **117**(2): 879-885.

Sundberg, J., F. Lã and B. Gill (2013). "Formant tuning strategies in professional male opera singers." Journal of Voice **27**(3): 278-288.

Sundberg, J., F. M. B. Lã and E. Himonides (2013). "Intonation and expressivity: a single case study of classical western singing." Journal of Voice **27**(3): 391.e391-398.

Sundberg, J., R. Leanderson and C. von Euler (1988). "Activity relationship between diagphragm and cricothyroid muscles." Speech Transmission Laboratory, Quarterly Progress and Status Report **2—3**: 83—91.

Sundberg, J., R. Leanderson, C. von Euler and E. Knutsson (1991). "Influence of Body Posture and Lung Volume on Subglottal Pressure Control During Singing." Journal of Voice **5**(4): 283-291.

Titze, I. (2004). "A theoretical study of F0-F1 interaction with application to resonant speaking and singing voice." J Voice **18**: 292–298.

Titze, I., T. Riede and P. Popolo (2008). "Nonlinear source–filter coupling in phonation: Vocal exercises." J Acoust Soc Am **123**: 1902–1915.

Titze, I. R. (2000). Principles of Voice Production. Iowa City, national Center for Voice and Speech.

Titze, I. R. (2008). "Nonlinear source-filter coupling in phonation: Theory." Journal of the Acoustical Society of America **123**: 2733-2749.

Titze, I. R. and A. K. Verdolin (2012). Vocology: The Science and Practice of Voice Habilitation. Salt Lake City, National Center for Voice and Speech.

Titze, I. R. and A. S. Worley (2009). "Modeling source-filter interaction in belting and high-

pitched operatic male singing." Journal of the Acoustical Society of America **126**(3): 1530–1540.

Vennard, W. (1967). Singing: the mechanism and the technique New York, Fischer.

Verdolini-Marston, K., M. K. Burke, A. Lessac, L. Glaze and E. Caldwell (1995). "Preliminary study of two methods of treatment for laryngeal nodules." Journal of Voice **9**(1): 74-85.

Watson, P., J. Hoit, R. Lansing and T. Hixon, 3, 24- (1989). "Abdominal muscle activity in classical singers." Journal of Voice **3**(1): 24-31.

Welch, G. F. and J. Sundberg (2002). Solo Voice. The Science and Psychology of Music Performance: creative strategies for teaching and learning. R. Parncutt and G. E. McPherson. New York, Oxford University Press**:** 253-268.

Zenker, W. (1964). Questions regarding the function of external laryngeal muscles. Research Potentials in Voice Physiology. D. Brewer. New York, State University of New York**:** 20-40.