A Review of Singing Voice Subsystem Interactions—Toward an Extended Physiological Model of "Support"

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Summary: During phonation, the respiratory, the phonatory, and the resonatory parts of the voice organ can interact, where physiological action in one subsystem elicits a direct effect in another. Here, three major subsystems of these synergies are reviewed, creating a model of voice subsystem interactions: (1) Vocal tract adjustments can influence the behavior of the voice source *via* nonlinear source-tract interactions; (2) The type and degree of vocal fold adduction controls the expiratory airflow rate; and (3) The tracheal pull caused by the respiratory system affects the vertical larynx position and thus the vocal tract resonances. The relevance of the presented model is discussed, suggesting, among others, that functional voice building work concerned with a particular voice subsystem may evoke side effects or benefits on other subsystems, even when having a clearly defined and isolated physiological target. Finally, four seemingly incongruous historic definitions of the concept of singing voice "support" are evaluated, showing how each of these pertain to different voice subsystems at various levels of detail. It is argued that presumed discrepancies between these definitions can be resolved by putting them into the wider context of the subsystem interaction model presented here, thus offering a framework for reviewing and potentially refining some current and historical pedagogical approaches.

Key Words: Voice subsystem interactions–Singing voice support–Voice pedagogy–Source-tract interactions–Tracheal pull.

INTRODUCTION

The (singing) voice is typically created by the vibrating vocal folds, which convert a steady airflow, as supplied by the lungs, into a sequence of airflow pulses. The acoustic pressure waveform resulting from this sequence of flow pulses excites the vocal tract, which filters them acoustically, and the result is radiated from the mouth and to a certain degree from the nose.[1] This description of the sound production mechanism suggests three basic subsystems of sound generation and modification: the respiratory system, the larynx, and the vocal tract. These subsystems are sometimes termed the *power source*, *sound source*, and *sound modifiers*[2]; see Figure 1 for a rough anatomic (*left*) and a schematic (*right*) representation of the three subsystems.

For didactic purposes, both in the classroom and in the studio, it is often useful to conceptually separate these subsystems and consider their function in isolation, particularly in the presence of clear deficits in a singer's vocal technique. Isolated consideration of voice subsystems is however in seeming contradiction with holistic approaches in vocal pedagogy where the functional unity of the singing voice is acknowledged.[4,5] Support for this notion is found by considering the effect of certain physical interactions between the subsystems of the voice.

The purpose of this manuscript is twofold: In the first part, three major subsystem interactions, all described in the previous literature, are reviewed: nonlinear source-filter interactions, airflow control *via* glottal adduction, and vocal tract elongation induced by tracheal pull. A conjunct model covering these three subsystem interactions is suggested.

The second part of this manuscript is concerned with the concept of singing voice "support," a notion for which controversial definitions exist.[6,a] Here, a number of fundamentally different definitions of support are evaluated in the context of the newly introduced subsystem interaction model, and potential implications for voice pedagogy are discussed.

SUBSYSTEM INTERACTIONS

Source-filter interactions

A linear acoustic model for explaining voice production was proposed in 1941 by Chiba and Kajiyama.[7,8] This model was later reformulated as the "source-filter theory,"[9] which proposes a simple linear superposition of source and filter. According to this theory, the acoustic output of the laryngeal voice source is linearly affected by the vocal tract transfer function. This process results in frequency-dependent amplitude scaling of the harmonics generated by the voice source, determined by the vocal tract resonances and radiation characteristics; see Ref.[10] for a tutorial-style description. The source-filter theory is a simplified model, created for the purpose of explaining voice production during speech. It predicts that the voice source itself is typically not influenced by vocal tract resonances. In other words, alterations in vocal tract configuration presumably have no influence on vocal fold vibration, the time varying glottal airflow waveform, or the source acoustic excitation of the vocal tract.

In contrast, early works done by Flanagan[11] and later by Rothenberg[12] predict the presence of nonlinear source-filter

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[a] "Few terms concerning the singing voice have evoked equally imaginative descriptions as the term 'support.' The greatest misapprehensions result from lack of knowledge of anatomical and physiological principles." *["Zu kaum einem Fachausdruck in der sängerischen Praxis läßt sich aus der Literatur derart Phantasievolles zusammentragen wie zu dem der 'Stütze'. Die größten Irrtümer resultieren aus Unkenntnis der anatomischen und physiologischen Grundlagen,"[6(p62)]]*. Translated from German by C.T.H.

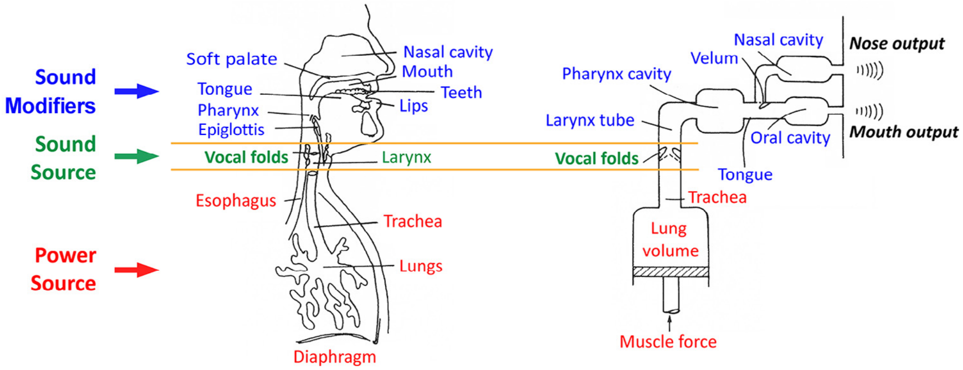

FIGURE 1. Human vocal organ and a representation of its main subsystems[3] (modified by C.T.H.).

interactions, particularly if one of the lower voice source harmonics is in close vicinity to a supraglottal (or subglottal) vocal tract resonance, as is the case in formant tuning.[13–15,b] The possible influences of the supra- and subglottal vocal tract have been classified as[16]:

- Level 1 interactions, where the positive reactance of the vocal tract, caused by the inertance of the air column, influences the wave shape of the glottal air pulse. This skewing of the flow due to an inertive vocal tract effectively strengthens existing and possibly introduces additional harmonics into the glottal wave shape (and as a consequence also into the acoustic output), which would not be present without an attached vocal tract.[16]
- Level 2 interactions, where a change of the vocal tract reactance, induced by changes of the vocal tract geometry, directly influences the mechanics of vocal fold vibration and glottal flow. This can have a possible effect on fundamental frequency (decreasing with more inertive loads), glottal flow amplitude, and mode of vocal fold vibration,[16] potentially even destabilizing vocal fold vibration and resulting in bifurcations, that is, abrupt "breaks" and chaotic patterns.
- Story et al[17] suggested a third level of interaction (partly biomechanical and partly neurologic), which might be useful to explain intrinsic vowel pitch.

In contrast to these predictions, recently produced empirical evidence[18] would suggest that professional classical singers do not necessarily rely on level 1 nonlinear source-tract interactions (ie, by placing a vocal tract resonance just above the frequency of a harmonic; see footnote a). It might be speculated that a performance-based selection process could cause successful professional classical singers to have predominantly more robust sound sources with pronounced mucosal waves and large vertical phase differences during vocal fold vibration, resulting in a weaker coupling of source and tract, thus not relying so much on vocal tract resonance tuning (see Ref.[19] for a review of the underlying principles according to the myoelastic-aerodynamic theory of voice production). More empirical data, stemming from different singer populations involving different anatomy, singing styles, and levels of proficiency, are needed to conclusively determine under which circumstances and to what degree nonlinear source-tract interactions are relevant in singing.

Airflow control *via* glottal resistance (glottal adduction)

The mean airflow rate in voice production can be approximated in analogy to Ohm's law as the ratio of the mean subglottal pressure divided by the glottal flow resistance.[20] Subglottal pressure is largely influenced by both contraction of expiratory musculature and passive recoil forces of the pulmonary system,[21] and in part by glottal flow resistance. The main determinant for glottal flow resistance is the degree of glottal adduction.[22,23,c] The surprising consequence of applying Ohm's law is that there is no single physiological parameter that controls the mean airflow rate. Rather, it is determined by a combination of expiratory forces and glottal adduction.[d]

Recent work by Herbst et al[24] distinguished two types of glottal adduction: cartilaginous adduction *via* choice of phonation type along the dimension "breathy" to "pressed,"[25] and membranous medialization *via* choice of the singing voice register.[26] Both trained and untrained singers can (learn to) vary these physiological parameters independently, giving the singer the freedom to generate a variety of vocal timbres at the laryngeal level.

Both adduction types (cartilaginous adduction and membranous medialization) have an effect on the glottal airflow,[27] as does variation of subglottal pressure. The type and degree of vocal fold adduction thus serves a dual purpose: (1) to control the phonation type and register, determining the voice source spectrum (ie, strength of upper harmonics, amplitude of the voice source fundamental, and noise components)[28–31] at the laryngeal level,

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[b] In the opinion of this author, the term "formant tuning" is ambiguously defined. First, it would be more appropriate to speak of "resonance" tuning (see Ref.[76] for a distinction between formants and resonances). Second, one might conceptually distinguish between (1) an effect according to linear source-filter theory, where tuning the vocal tract resonance to a harmonic would result in increased output energy at the harmonic's frequency as governed by the vocal tract transfer function, regardless of whether the harmonic is at, slightly below, or slightly above the resonance center frequency; and (2) a nonlinear effect, for which theory predicts that the harmonic's frequency has to be slightly below the resonance center frequency for a positive effect to occur.

[c] In this text, the terms "glottal adduction" and "vocal fold adduction" are used interchangeably. Strictly speaking, the glottis (ie, the air space between the separated vocal folds) cannot be adducted but only reduced *via* adduction of the vocal folds.

[d] In some singing styles, the ventricular folds are also adducted to a varying degree, thus potentially also affecting the glottal flow resistance.

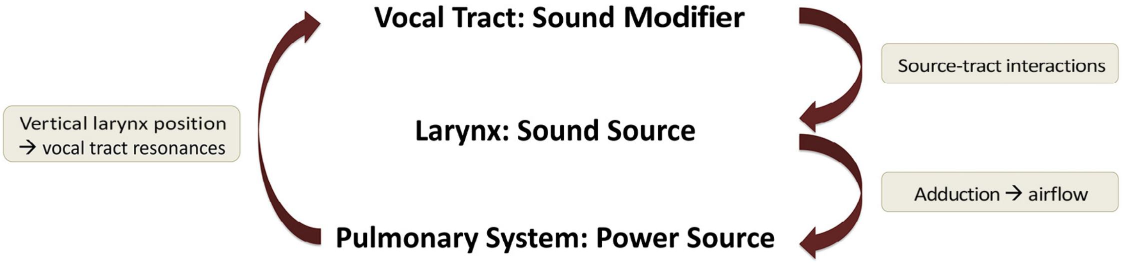

FIGURE 2. Schematic model of three major subsystem interactions of the (singing) voice.

and (2) to influence the mean glottal airflow rate in combination with subglottal pressure, thus constituting an interaction of the laryngeal system with the respiratory system.

Interestingly, this dual purpose of adduction has already been observed in the mid-19th century by Manuel Garcia,[32] who suggested

> When one very vigorously pinches the arytenoids together, the glottis is represented only by a narrow or elliptical slit, through which the air driven out by the lungs must escape. Here each molecule of air is subjected to the laws of vibration, and the voice takes on a very pronounced brilliance. If, on the contrary, the arytenoids are separated, the glottis assumes the shape of an isosceles triangle, the little side of which is formed between the arytenoids. One can then produce only extremely dull notes, and, in spite of the weakness of the resulting sounds, the air escapes in such abundance that the lungs are exhausted in a few moments.

Tube lengthening *via* tracheal pull

As a simple approximation, the supraglottal tract can be modeled as a duct with an unchanging cross-sectional area (a uniform tube) and thus as a quarter-wave resonator with the resonance frequencies at $R_n = (2n - 1)(c/4L)$ Hz,[33] where n is the resonance number, c is the speed of sound, and L is the vocal tract length from the glottis to the lips (with the velopharyngeal port closed). Shipp and Izdebski reported variations of vertical larynx position of up to 2 cm in untrained singers,[34] and data by Švec et al revealed that a trained baritone could vary the vertical larynx position by about 3.7 cm while phonating at the same musical pitch.[35] Assuming a resting vocal tract length of 17 cm, such an extreme articulatory gesture would affect all resonance frequencies of a neutral vocal tract (pronouncing the "schwa" vowel) by about ±10%. An increase of supraglottal vocal tract length by lowering the larynx will lower the frequencies of all vocal tract resonances, creating a "darker" timbre. A variation of the vertical larynx position is also likely to affect the length of the subglottal vocal tract, introducing changes into the subglottal resonance frequencies.[36]

On a functional level, the vertical larynx position can be influenced by two mechanisms: (1) directly, *via* contraction of the infrahyoid or "strap" muscles, that is, the sternohyoid, omohyoid, and sternothyroid muscles[37]; and (2) indirectly, *via* the pulmonary system as suggested by Iwarsson et al,[38] who report an inverse correlation between lung volume and vertical larynx position. In the latter case, the larynx tends to be lower because of lowering of the diaphragm as singers increase their lung volumes. The relevance of this phenomenon, called "tracheal tension"[39,40] or "tracheal pull,"[38,41–43] is supported by empirical data from Pettersen and Eggebø,[44] showing a lowered diaphragm at the initial phase of a sung phrase, potentially leading to a lowered larynx.[45]

The relative contribution of these two mechanisms to lowering the larynx in various singing styles has as yet not been evaluated empirically. However, at least the temporal aspect of this can be discussed on theoretical grounds: Although the strap muscles could theoretically be activated equally throughout a phrase, the effect of vertical tracheal pull *via* the diaphragm position naturally decreases as the lungs are depleted during a sung phrase. This would be a supplementary explanation as to (1) why classical singers, requiring a somewhat lower vertical larynx position and thus lower formants, typically sing in their inspiratory reserve at 40%–90% vital capacity[46,47]; and consequently (2) why phrases are initiated at high lung volumes despite their being short in duration, potentially even involving a quick decrement of lung volume following the termination of singing.[46]

From a subsystems point of view, tracheal pull originates in the pulmonary system and exerts a direct mechanical effect on the supraglottal vocal tract. It is thus considered as the third subsystem interaction in this manuscript.

INTERACTIVE MODEL

The three major subsystem interactions described in the previous section are schematically illustrated in Figure 2. These interactions can be summarized as follows:

1. Vocal tract adjustments can influence the behavior of the voice source *via* two levels of nonlinear source-tract interactions.
2. The type and degree of vocal fold adduction controls the average glottal airflow rate.
3. The tracheal pull caused by the respiratory system affects the vertical larynx position and exerts thus an influence on the supraglottal (and potentially also the subglottal) vocal tract resonances.

The three singing voice subsystem interactions described here are all directly causal on a physical level, and no further muscular action by the singer is needed to arrive at the described effects.[e] Under certain conditions, even complex combinations

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[e] Even though it is quite plausible that the singer might (sub)consciously introduce an additional functional component by adapting to changing conditions in the various subsystems.

of the three interactions may be possible, such as changes of the voice source behavior through nonlinear interaction with vocal tract resonances that are shifted by vertical tracheal pull caused by activity in the respiratory system.

A number of further interactions have been reported in the literature, such as voice source effects[f] of lung volume,[48] particularly in untrained singers[38]; increase of sound intensity, fundamental frequency, and closed quotient as a function of subglottal pressure[49]; or the potential for fundamental frequency to covary with the spoken vowel, that is, "intrinsic vowel pitch,"[50] which potentially must be overcome in most singing where vowel-dependent fundamental frequency variations are generally to be avoided. All these additional effects are, to various degrees, relevant for the singing voice. However, they were not included in the model shown in Figure 2 to keep that model conceptually simple and allow discussion of "support" concepts (see below).

PEDAGOGICAL RELEVANCE

On a pedagogical level, several insights into the functionality of the singing voice can be derived from the interactive subsystems model outlined in this text:

1. The voice source cannot be fully optimized by considering only laryngeal adjustments, even though working on laryngeal adjustments is a crucial component of that process. Rather, fine-tuning the vocal tract shape and particularly the epilaryngeal region, to facilitate a skewed airflow waveform (thus producing stronger upper voice source harmonics), appears to be a principal ingredient for optimizing sound generation and output.
2. Rather than concentrating on the respiratory system only, airflow rates (and thus maximum phrase durations) are probably best adjusted by optimizing vocal fold adduction.[g] Average airflow rates in "breathy" phonation are considerably greater than in "normal" and "flow" phonations.[51–53] Therefore, there is ample potential for improving maximum phrase durations during singing *via* adjustments of glottal flow resistance through vocal fold adduction. For instance, the method of choice for helping singers who "run out of breath" is probably a gently applied increase of the degree of vocal fold adduction (with the typical side effect of a "strengthened" voice timbre with stronger voice source intensity and a flatter spectral slope), rather than haphazardly applied breathing exercises. On the other hand, too low a degree of airflow in "tense" voices is best adjusted by decreasing the degree of vocal fold adduction, instead of solely increasing subglottal pressure (which would most likely still result in "pressed" phonation, having a smaller glottal flow pulse amplitude and thus a weaker voice source, if adduction were not changed).
3. In classical singing, a comfortably low larynx position is required as an ingredient for a somewhat darker sound quality induced by lower vocal tract resonances. Even in some nonclassical singing styles, which generally advocate a larynx position that is not as low as that in classical singing, the increase of vertical larynx position might be avoided as fundamental frequency is raised. In such cases, the vertical alignment of the larynx *via* tracheal pull can be a viable strategy, at least when phonating in the inspiratory reserve, that is, above the functional residual capacity at *ca.* 40% vital capacity. This strategy might be preferred to the extreme "yawning" approach, which can cause a state of tension of the muscles of the mandibular-lingual (jaw/tongue) complex,[54] potentially limiting the upper fundamental frequency range, and tends to result in an excessively dark voice timbre without supporting the "*chiaro*" aspect of "chiaroscuro."

These considerations suggest that pedagogical work on a particular voice subsystem may evoke side effects or benefits on other subsystems, even when having a clearly defined and isolated physiological target. On a larger scale, these notions might explain why more holistic approaches in vocal pedagogy,[4,55] such as the concept of "primal sound,"[5] have merit. However, the indiscriminate application of holistic didactic methods without prior physiologically based diagnosis should be avoided.[56]

It should be noted that the model presented here does not claim to cover all relevant aspects of singing technique. It is limited to empirically researched physical phenomena. For a more complete picture, other potential key issues like the activity of the extralaryngeal framework[57–59] in relation to posture,[60] or the pelvic floor activity,[61] amongst others, need to be considered, and ongoing empirical research is required to increase the available knowledge base.

ADVANCING THE NOTION OF "SUPPORT"

"Support" has received much attention in the literature over the past centuries, and many seemingly contradicting definitions exist. Four exemplary definitions, addressing different voice subsystems at various levels of detail, are discussed here, without claiming that any of these is more correct than another; see Figure 3 for an overview:

1. Lamperti defined *appoggio* as "the support afforded to the voice by the muscles of the chest, especially the diaphragm, acting upon the air contained in the lungs."[62] This simple definition is purely centered on the action of the pulmonary system but does not consider the passive recoil forces as a function of lung volume.
2. Luchsinger and Arnold cite Winckel who maintained that "breath support is the resistance that the inspiratory musculature offers to oppose the expiratory collapse of the organ,"[63] and they add that "[b]reath support serves to reduce the subglottic air pressure, necessary for phonation, to a critical value of tension."[64] This physiological definition is centered on the subglottal pressure aspect,

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[f] That is, higher subglottal pressure, greater flow amplitude, a lower closed quotient, greater glottal leakage, and greater relative estimated glottal area at high as compared with low lung volume, and an almost significantly greater difference between the two lowest voice source spectrum partials, H1 and H2.

[g] Adduction can be either controlled directly or influenced indirectly through semi-occluded vocal tract exercises like lip trills and other exercises providing direct feedback on airflow. The aim would be to maintain high flow by avoiding too strong glottal adduction.

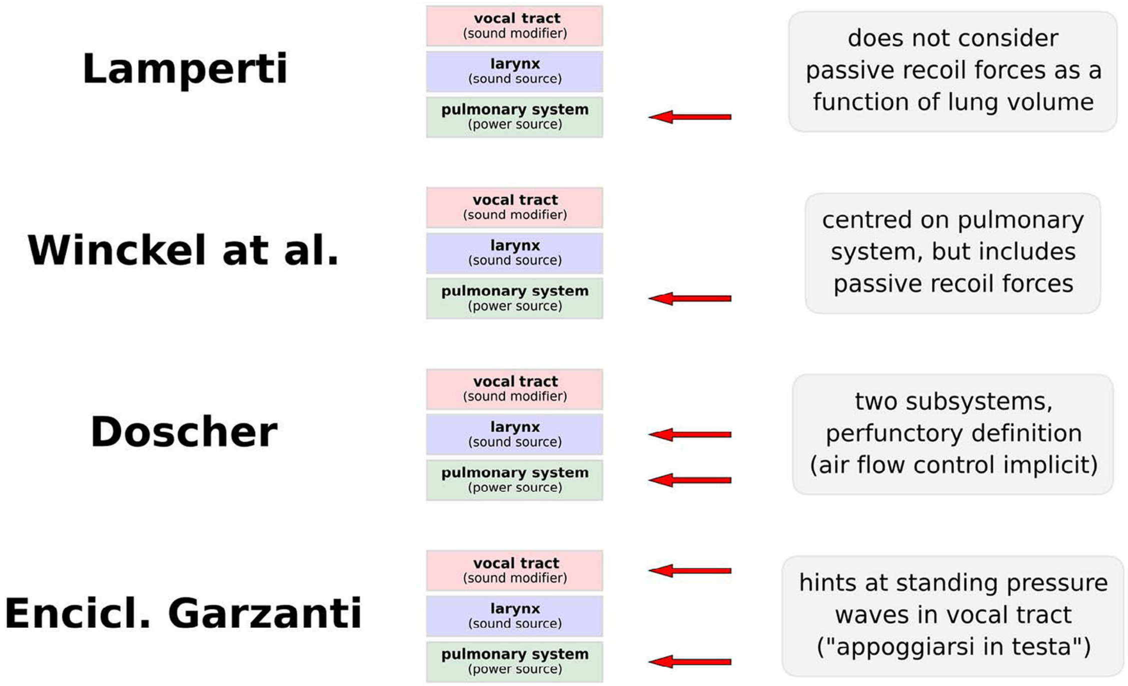

FIGURE 3. Four definitions of "support" and their relation to the subsystem interaction model introduced here.

including passive recoil forces of the pulmonary system; see Ref.[48] or Ref.[65] for an excellent overview of the topic.

(3) Doscher suggested that the objective of support is "the proper coordination of expiration and phonation to provide an unwavering sound, an ample supply of breath, and relief from any unnecessary and obstructive tensions in the throat."[4] This synoptic definition encompasses two voice subsystems, that is, the respiratory system and the larynx.

(4) Finally, the *Enciclopedia Garzanti della musica* proposed "[a]ppoggio, in the terminology of vocal technique, refers to the point of appoggio, whether it be on the abdominal or the thoracic region where the maximum muscular tension is experienced in singing . . . , or the part of the facial cavity where the cervical resonances of the sound are perceived."[66] This is a predominantly sensory definition that includes the notions of "*appoggiarsi in testa*" and "*appoggiarsi in petto*," possibly hinting implicitly at kinesthetic sensations caused by standing wave patterns in either the supraglottal or the subglottal vocal tract. Hence, two voice subsystems are involved: the respiratory system and the vocal tract.

In this context, the key question is whether a definition of support should pertain only to the pulmonary system, or whether other voice subsystems should be included, as they might be contributing to the phenomenon. Two empirical studies addressing this matter have shown that supported singing not only affects the breathing apparatus.[67] Rather, singers make adjustments in glottal and/or laryngeal configuration when producing supported voice.[68] Along those lines, various authors have considered including voice generation (at the laryngeal level) and vowel modification (in the vocal tract) in the "support" definition,[6] resulting in a "unified act of expiration and phonation."[55] This may be best summarized by a quote from Luchsinger and Arnold who state that "the technique of breath support demonstrates the close interrelationship among the functions of respiration, phonation, and resonance."[64]

The apparent discrepancies between the four exemplary definitions of support discussed here (Figure 3) can thus be dissolved when considering the voice subsystem interactions discussed in this text: The laryngeal configuration (through adduction) is a core regulator of mean glottal airflow and glottal acoustics. Inhalation gestures are a substantial determinant of the geometry and hence the resonance characteristics of the supraglottal vocal tract, which in turn may under certain circumstances influence the sound source. Hence, a more advanced concept of singing voice support is advocated here, incorporating (1) active muscular patterns and passive recoil forces of the pulmonary system; (2) glottal resistance resulting from the laryngeal configuration, that is, adduction; and (3) acoustically linear and nonlinear vocal tract resonance phenomena induced by tracheal pull affecting the vertical larynx position.

Such a concept might also be relevant vis-à-vis the notion of *chiaroscuro*, that is, the "bright/dark tone . . . which designates that basic timbre of the singing voice in which the laryngeal source and the resonating system appear to interact in such a way as to present a spectrum of harmonics perceived by the conditioned listener as that balanced vocal quality to be desired—the quality the singer calls 'resonant'"[69] cited by Stark.[70] Whereas the quality of vocal fold adduction, termed "firm glottal closure" in Ref.[70], and potentially the configuration of the (epilaryngeal) vocal tract, would be main actors for determining the strength of high-frequency partials, thus constituting the "*chiaro*" (bright) aspect, a lengthened vocal tract, possibly helped by tracheal pull, would help establish the "*scuro*" (dark) quality.[70] Alternatively, the "*scuro*" aspect might also be induced by a strong voice source fundamental as obtained in "flow" phonation,[71,72] particularly when the vocal folds are slightly abducted by tracheal pull.[40]

Finally, it might be worthwhile to conjecture inasmuch subsystem interactions are in agreement with the idea of *inhalare la voce*[73] ("*inhaling the voice*," but also translated as "*drink in the tone*"[74]). A well-executed inspiratory gesture will lead to a pre-phonatory configuration of the voice production system where the tracheal pull, through lowering the larynx, can aid in lowering the vocal tract resonances, typically creating a desired sound quality in classical singing.

Inhalare la voce might thus in part be interpreted as the suggestion to carry this pre-phonatory configuration over into the phonatory phase, thus preventing involuntary timbre alterations by aiding the vocalist to maintain a relatively stable vertical larynx position, at least in the initial portion of the phrase. An adequate degree of vocal fold adduction may safeguard against excessive air loss during the phrase. An alternative, but not mutually exclusive interpretation of *inhalare la voce*, might be derived from the insight that at high lung volumes the expiratory recoil forces can produce subglottal pressures higher than the target pressure,[75] therefore requiring the recruitment of inhalatory muscles at the initial phase of expiration.[48,65]

SUMMARY

In this article, three major voice subsystem interactions, all described in previous literature, were identified and described: source-filter interactions, airflow control *via* glottal adduction, and lengthening of the supraglottal vocal tract, thus lowering vocal tract resonances *via* tracheal pull. These three interactions are all constituted by physiological input into one subsystem, which in turn has a causal physical effect on another subsystem. Given this physical causality, the interaction effects cannot be avoided or "trained away." Rather, they may aid in enhancing voice quality in singing, if used in a knowledgeable way.

The original contribution of this manuscript is to present these three subsystem interactions in a synoptic context, giving rise to a model that may be useful in voice pedagogy. It is argued that individual systems of the singing voice cannot be addressed in an isolated fashion in voice building, but that input into a single subsystem is likely to have an effect on other aspects of the voice and thus the whole system. This is in agreement with holistic concepts of voice pedagogy, but with the provision that these be only applied with clear understanding of the physiological and physical interrelationships of individual voice subsystems. Based on this model, a number of exemplary definitions of singing voice support are discussed, leading to the insight that a physiologically adequate definition of support ought to encompass all three voice subsystems, including interdependences between them.

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