1958
vol6#4
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THE EMPORIA STATE
Research Studies

THE GRADUATE PUBLICATION OF THE KANSAS STATE TEACHERS COLLEGE, EMPORIA

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By Robert M. Taylor

Np:2g.2
v.6 no.4

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EMPORIA, KANSAS

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VOLUME 6 June 1958 NUMBER 4

THE EMPORIA STATE RESEARCH STUDIES are published in September, December, March and June of each year by the Graduate Division of the Kansas State Teachers College, Emporia, Kansas. Entered as second-class matter September 16, 1952, at the post office at Emporia, Kansas, under the act of August 24, 1912.

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This publication is a continuation of *Studies in Education*
published by the Graduate Division from 1930 to 1945.

Papers published in this periodical are written by faculty members of the Kansas State Teachers College of Emporia and by either undergraduate or graduate students whose studies are conducted in residence under the supervision of a faculty member of the college.

ACKNOWLEDGMENTS

To the late Dr. George Walter Stewart, Professor of Physics at The University of Iowa, who furnished the original inspiration for this study and who gave freely of his counsel;

To Dr. Jack Juergens, Dean of Fine Arts, Southwestern College, Winfield, Kansas, who was forbearing enough to discuss such matters with the author;

To Mr. William Vennard of the School of Music, University of Southern California, Los Angeles, who by word and deed has given much encouragement;

To Dr. S. Winston Cram, Head of the Physical Science Department, Kansas State Teachers College, Emporia, who willingly gave the manuscript a critical appraisal;

To Mrs. Grace Chance, Secretary of the Beach Music Hall office, Kansas State Teachers College, Emporia, who graciously typed the several revisions;

To the many others who have offered approbation, the author expresses his sincerest thanks.

Acoustics for the Singer

By Robert M. Taylor*

The average singer is not scientifically trained nor is he familiar with scientific terms and concepts, usually because he has had no opportunity to have any appreciable training in this line. Therefore, there is no reason why he should be conversant with the terminology. Many singers have found scientific concepts very difficult to assimilate and understand, and a slight aversion to, or in some cases a downright fear of, this incomprehensible jargon has been the reason for avoidance of a wider understanding of the role played by acoustics in the mechanics of singing. As a national officer of the National Association of Teachers of Singing recently confided, it was largely for this reason that no consideration of acoustics was given in arranging the program at their national convention.

It is therefore unfortunate, but understandable, that this aversion should be so widely extant among singers and voice teachers. One reason is presumably the lack of leaders in the field who speak both languages—singing and scientific. It is the earnest hope of the author that both languages can find an easily comprehendible common meeting ground in this present work.

Many singers and singing teachers look with extreme scorn on acoustical considerations, and not without reason. There has been so much quasi-scientific information used in teaching by both the innocently misinformed and the crackpot that many singers have eschewed everything that smacked of the scientific approach. Reference will be made to some of these concepts later. On the other hand, the author, while lecturing on the acoustics of singing, has encountered rather wide-spread and forward-looking attitude among voice teachers who seem truly eager to supplement their knowledge of the art of singing with whatever offerings science may have to contribute. Much of this is due to the progressive attitude of the National Association of Teachers of Singing. This attitude has been demonstrated by the caliber and type of articles appearing in the official journal of the organization and also by the type of speaker and topics presented at the various voice workshops held in summer sessions at selected colleges across the country.

It is certainly true that one cannot learn to sing by merely reading a book. Certainly this study is not, nor does it intend to be, a cure-all for miscellaneous vocal ills. It is hoped, however, that the material contained

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in this study will help the analytical singer to avoid mistaken ideas and some common difficulties caused in part by misinformation. Since there are many fine books available at present which discuss acoustics of music, the need for another treatment of the subject might be questioned. Nevertheless, a careful glance through these books will reveal that the application of acoustical principles to the human voice is considered very briefly in them and not in a manner that could be of aid to voice students seeking practical help in their art. This study is by no means complete. Material has been arbitrarily included or omitted, according to the extent to which the facts presented throw light on the problem of understanding singing or the teaching of singing. It is written with the beginning college or conservatory student in mind, who needs his concepts adjusted before he can progress into the background or understanding prerequisite to advanced voice work.

THE NEED FOR ACOUSTICS

It is human to disdain that which we do not understand; and, since many voice teachers are aware of their lack of acquaintance with the field of science, they are afraid the knowledge will jeopardize their "system." If their system proves to be wrong, they are, ideologically, without a refuge. For this reason many teachers scorn and ridicule acoustical considerations because, usually, the subject has not been presented properly and understandably. Perhaps, if they have relied largely on acoustical principles, they have found that such practice will not do the job *per se.* Too often there seems to be no relation between their manner of singing and the acoustical principles supposedly involved. The seeming discrepancy between scientific fact and the empirical method with which problems must be approached can and does cause severe skepticism. All singers realize the tremendous part played by psychology in the art of singing, but unfortunately psychologists have not been physicists, physicists have not been familiar with psychological phenomena, and neither have been singers nor musicians.

First, it might be helpful to mention some of the things which the study and utilization of acoustical principles will *not* do:

1. The understanding of acoustical principles cannot supply information or method which can be used as a direct approach to the teaching of singing. A good piano tuner is not necessarily a good pianist and neither is causative to the other.
2. The understanding of acoustical principles cannot correct fundamentally wrong vocal tone goals on the part of the singing student or singer. This is the result of the misunderstanding of the end to be achieved and not a misunderstanding of a process by which it is achieved. Incorrect tone concepts can cause the misuse of acoustics or the unwitting transgression of

acoustical laws. Often this is the basis of vocal difficulties which so often react stubbornly to treatment.

3. The understanding of acoustical principles cannot teach musicality. Science is not an art, but, of course, can be an aid to art. Singing is basically an art, not a scientific concept.

4. The understanding of acoustical principles cannot eliminate or ameliorate the human fact wherein the laws of psychology alter or evade the mechanical scientific principles. Reference here is made to the fact that frequency and pitch are not always identical, nor is loudness and intensity. Frequency and intensity are physical states; pitch and loudness are the human psychological reception of those conditions. In this connection matters of taste, discrimination, and judgment must be considered. It is not practical to attempt to avoid the human element.

One might ask, "If all these things the study of acoustics will *not* do, what is then to be gained by studying it?" The following is a discussion of some of the possible benefits to be derived from familiarity with acoustical principles. Perhaps the most important of all is the correcting of erroneous impressions in reference to singing, and the prevention of striving for impossible or misleading goals and vocal procedures.

This study has no particular quarrel with vocal fairy tales in approching the teaching of voice when these imagery approaches prove to be harmless; but often the singer finds himself in a blind alley, as far as progress is concerned, when endeavoring to follow some supposedly valid principle, which is in opposition to all physical law. Conversely, the singer who does not find himself at odds with basic physical principles will gain considerably from the understanding and utilization of correct acoustical factors. This will help to teach respect for and use of the marvels of the human capabilities; to simplify the problems of singing; to bring a sense of comfort and understanding that certain coordinations of the body are aids rather than elements which must be conquered and tamed. Moreover, the study of tone color is a very complex one and the application of acoustical principles to this study as well as to such problems of vowel color and projection is quite pertinent and revealing.

Perhaps the most difficult factor in all voice teaching is the ability to ascertain the actual voice of the student (by discounting the wrong tone goals which are the result of fear, ignorance, inhibitions, and misconceptions) and to assist the singer to achieve an imaginary picture of a voice which he has never heard from himself before and to help him produce that voice. (At its most extreme, this problem is that of teaching a congenitally deaf child to learn to speak.)

Since it is so difficult for the student (or anyone else) to imagine precisely a tone he has never heard, it is no wonder that in the past the teacher has too often relied on tangible and mechanical reactions, as raising the palate, lowering the tongue, and other devices in an effort to guide the student to produce a better tone goal for his future imitations. Because of this difficulty, and the lack of acoustical knowledge at the rise of the art of singing, some misconceptions have arisen which amount almost to superstition insofar as their connection with the truth is concerned, but which nevertheless have been found to be somewhat effective by generations of voice teachers. This problem has been the basis for much discussion and argument among voice teachers for many decades. However, Bartholomew has done a superb bit of reasoning in the reconciliation of these apparently opposite points of view and shows how and why certain problems cannot, because of human psychology, be attacked directly from the scientific facts.[1]

It is only natural that "superstitions" arose concerning certain procedures that couldn't be explained. Witch doctors get results through either psychology or the fact that the body does wonders in healing itself. In myriad cases the good student learns by induction, not necessarily because the teaching devices have any direct connection with the problems to be solved or the basic truth. Today the modern doctor does not do his healing by virtue of detailed anatomical description or elaborate explanations of materia medica involved. These treatments will be just as effective whether the patient understands everything or not, as long as he has confidence in the doctor. Certainly the doctor does not resort to anything but the most proved scientific facts in his diagnosis and consequent treatment of the case.

The competent voice teacher should know the basic laws of acoustics and the principles on which the voice operates. Whether he teaches the student directly by the fact or inveigles the student to follow correct acoustical principles by parable, inference, or outright fiction, is a personal matter of teaching technique.

BACKGROUND OF ACOUSTICAL THOUGHT

The reason that there have been so many misunderstandings between science and singing is that human beings are human beings and not machines. One source of the problem is the fact that there was a real lack of scientific understanding of acoustics at the rise of the "golden age" of singing. It is interesting to note that it was through music that the early great philosophers became concerned with sound, and it is generally conceded that the science of sound began with Pythagoras in 550 B.C. There is much fiction as well as fact in the records, but at least it is interesting to note the comparison of philosophical and scientific concepts of these early Greeks in regard to beauty. Pythagoras judged musical beauty by numeri-

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[1] Wilmer T. Bartholomew, *Acoustics Of Music* (New York, 1942), pp. 152-153.

cal criteria, not by the ear. He held that the simpler the mathematical ratio, the more consonant the sound. Thus music was a mathematical beauty, not aural. It makes one wonder if Pythagoras ever heard a complex tone rich in partials. Most of the Greek philosophers understood the nature of sound as vibrations in air. As scientists of their time, they wrote as authoritatively as they could about music.[2]

Acoustics was probably neglected as a science because (a) it was not concerned with visible principles and (b) problems of work, energy, and mechanics were more practical in providing an impetus to the improvements in the machines which did the world's work.

Little is known of the science of acoustics until about 1600, when Galileo proved to have amazing insight into the elements of acoustics. He quotes a good example of the power of resonance:

> Even as a boy, I observed that one man alone, by giving impulses at the right instant, was able to ring a bell so large that when four or even six men seized the rope and tried to stop it, they were lifted from the ground, all of them together being unable to counterbalance the momentum which a single man by properly timed pulls had given it.[3]

The first systematic investigation of the nature of vowel sounds—verified by their synthetic production by models—was published in 1829, by Robert Willis, Fellow of Caius College, Cambridge, in a very remarkable paper read in 1828.[4]

Sir Charles Wheatstone introduced the fixed pitch theory of vowels in 1837, which was proved and developed by Helmholtz. Helmholtz established that tone color depended on order, number, and relative intensity of the partial tones constituting the whole. In 1860 he also pioneered in the construction of the resonator which serves as the basis for analyzing and calculating the operation and characteristics of the human voice. Not until 1860, therefore, could a scientific understanding be achieved concering those factors which had been used with unsurpassed artistry for at least two hundred years. It is unfortunate that almost one hundred years later so little of the acoustical background of singing is understood by singers.

The science of acoustics, while tracing back to Pythagoras in a general way, was still in a very elementary stage in 1800, but not so the art of singing. The research of the time was mostly in the realm of speed of sound in air and frequency determination. In the next one hundred years great advances were made, mostly in mechanical and abstract observations. These were not applied to music very greatly, except perhaps in the case of organ pipes. Since 1900, and especially since World War I, with the rise of the telephone, radio, phonograph, movies, and with the electrical

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[2] D. C. Miller, *Anecdotal History of the Science of Sound* (New York, 1935), pp. 3-5.
[3] *Ibid.*, p. 10.
[4] Arthur Taber Jones, *Sound* (New York, 1937), p. 363.

computation of resonance and further use of electric devices, a real impetus has been given to the science of acoustics. In spite of all this there has been no thorough analysis of the acoustics of the voice until quite recently. Outstanding has been the work of Bartholomew, especially in the matter of reconciling science and the art of singing, to which reference was made earlier. Another real difficulty has been that of separating the physical from the psychological in, for example, the matter of auditorium acoustics and tone quality preferences. The basis for preference has been almost as much psychological as physical.

REVIEW OF THE PERTINENT FACTORS OF SOUND

First let us consider what sound is, and what it is not.

Sound is not a mass of air speeding across space at the rate of eleven hundred feet a second, but, rather, a series of concentric bubbles (usually very complex) in which the concentric spheres consist of alternate layers of condensation and rarification of air. These successive pulses cause the particles of air to move very slightly; roughly speaking, four thousandths of an inch displacement in normally loud sounds. Just as it is the wave motion and not the actual water that travels in ever-widening circles when a pebble is dropped into a pond, so alternate layers of compression and rarefaction travel eleven hundred feet per second in air, not the actual air itself. Through these pulses, the vibrating body induces the ear drum to vibrate in sympathy, thus giving rise to the inner ear pulsations which the brain finally interprets as sound.

Since the velocity of sound in a certain medium is the product of frequency times the wave length, it is a simple matter to ascertain these wave lengths of sound in air when frequency is known. Taking for example, the violin A at 440 and the velocity of sound in air at approximately 1100 feet per second, it will be seen that the wave length emitted by this string (or any other tone source at this frequency) will be exactly two and one half feet long. Consider for a moment a child in his swing making one complete round trip. If this should take one second, he would have created, since sound travels 1100 feet per second, one complete "sound" wave 1100 feet long, or a frequency of vibration of one, even though this wave could not be heard by the ear. Such waves, whether in air or in water, cannot be reflected except from surfaces which are large compared with the wave length itself. On the sea shore, for example, single posts or piles which support docks are unable to make any significant reflection in the waves rolling in from the ocean, whereas a long breakwater might make a significant reflection in these waves.

Amplitude, or size of wave, is analogous to volume of sound as received by the human ear. Many times, however, amplitude and frequency (or the time of the period) will be confused. Using the example of a child's swing when hung from a high branch of a tree, it will be noticed that whether the child is swinging through a wide arc or "letting the cat die," the time or frequency of each round trip is identical, regardless of the space through which the swing moves. A common misconception is that in the round trip, the swing moves faster as the breadth or amplitude of the arc is reduced. As the violinist draws the bow faster, the string emits a louder tone (vibrates with greater amplitude) but does not vibrate faster. So for practical purposes, it may be assumed that a vibrating body oscillates at a certain number of round trips or cycles per second, regardless of the variation of energy supplied which causes it to vibrate.

Vibrating media have the fortunate property of vibrating not only as a whole but also in fractional parts. As a violinist plucks a string, the resulting blur as the string swings to and fro usually conceals the fact that the string is not only vibrating as a unit throughout its whole length, but also that each of two segments is adding to the composite tone a weak sound of the octave higher. At the same time, each third of the string is vibrating to a certain extent as a unit and is adding a small fragment of the twelfth above the original tone. Likewise, each fourth of the string is adding a touch of the pitch two octaves higher than the original tone, and so on for the fifths, sixths, sevenths, eighths, ninths, tenths part of the string, and theoretically to infinity. Even though the terms "overtone" and "partials" are sometimes used interchangeably, it should be understood that since the fundamental is a "part" of the complex tone, the term "partials" includes the fundamental and any or all partials. Overtones, however, are actually "overtones" above the fundamental tone. Each fractional part present contributes its particular pitch to the composite tone and the particular combination of these tones in varying amplitudes constitutes what we call the distinctive tone color of an instrument. By sighting down the string of the violin as the performer plays a variety of natural harmonics, the vibration of the various fractional parts can easily be seen. There is an interesting example of this in the movie of the harp made by Mildred Dilling. It was by accident that the stroboscopic effect of the frames of the film reveals the first overtone or octave harmonic of a low bass string as it is plucked. The two vibrating segments can be observed quite plainly. It is the relative strengths or weaknesses of these various partials that give the instruments their characteristic sounds. For example, in instrument "A" the partials 2, 7, 9, and 14 may be quite strong, whereas instrument "B" partials 3, 10, 13, and 20 might be relatively prominent. Moreover, it is this difference in the number and relative intensities of the various partials that make it possible to distinguish between speaking voices and/or singing voices, even though any two given voices might be quite similar. This general principle can be readily illustrated on certain electronic organs wherein tone colors can be created synthetically by adding a choice of overtones in varying amplitudes to a basic fundamental pitch. It is interesting and worth while to note at this point that vowels and consonants are merely tone colors of the human voice, which have become identified and relatively standardized through frequent usage. As a matter of fact, vowels have been created synthetically through the procedure of analyzing the vowel sound for the number and strengths of the various component overtones, then supplying those pitches at the indicated volumes.

There could be much discussion as to whether the vocal cords were strings or reeds, since in many ways they seem similar to both. However, because of certain muscular controls, it is quite justifiable to think of the vocal cord as operating on the same laws as vibrating strings. In the case of vibrating strings three elements determine the frequency of vibration: tension, thickness, and length. Actually the vocal cords can and do adjust themselves in these three ways, and, of course, in myriads of combinations of these three factors.

For those who are interested, it might be mentioned here that the following formula illustrates the relationship of tension, thickness (or mass), and length in the action of vibrating strings:

f=frequency
L=length of string (cm.)
k=tension in dynes (980 dynes=1 gram)
m=mass (grams per unit length)

$$f = \frac{1}{2L}\sqrt{\frac{k}{m}}$$

Once again, by using the violin as an illustration, several facets of the human voice can be more readily understood. In line with the above formula, it will be seen that should the violinist put equal tension on the A and D strings (since both have the same vibrating length), the D string will still be the lower pitch because of its added thickness. Let us also imagine that the violinist exchanged the positions of the E string and G string. Conceivably the E string could be loosened enough to make the low G string pitch and the G string could be tightened enough to make the E string pitch, but in either case it would cause a very unequal tension on the instrument and in neither case would the tone color be satisfactory. When played in the higher positions, the tension and excessive thickness of the G string would make it almost unmanageable and, as any violinist knows, it is difficult enough to make good tone color in high positions on the G string when it is in its rightful place, simply because in the upper positions the vibrating length of the string becomes too short for its relative thickness. Some of the same problems are avoided in the construction of the piano. It will be noticed that the triple treble strings, as the chromatic scale ascends, will not get much tighter as they will get noticeably shorter. Conversely, the bass strings, with relatively equal tension, will not get any longer but will increase noticeably in diameter.

Since the resonant cavities of the voice act as a combination of Helmholtz resonators, it is through the understanding of the action of these resonators (Fig. 1.) that many of the complexities of the voice can be explained:

HELMHOLTZ RESONATOR

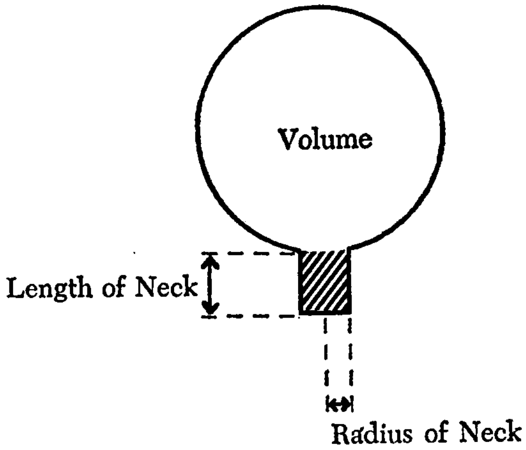

Figure 1.

Helmholtz discovered that such a hollow sphere would react strongly to a given pitch when constructed according to specific conditions. As a matter of fact, through a variety of such resonators, because of this special property of reacting strongly to appropriate pitches, he was able to detect, isolate, and identify specific overtones in a complex sound. It will be noted that the presence of a constricted neck on a resonating volume (as opposed to a straight resonance tube) creates certain special properties which again refer pertinently to the structure of the human vocal mechanism.

Sir Richard Paget in his book *Human Speech*, gives us an excellent description of the nature of the action of air in such a Helmholtz resonator.

> When a mass of air finds itself enclosed in a cavity, such as that of the human mouth and throat, the air as a whole behaves as an elastic mass or spring. If it is jogged in any way, it starts palpitating, invisibly, in and out of the mouth of the cavity—very much in the same way as the spring of a jack-in-the-box would jump up and down if suddenly depressed and then released.
>
> What actually happens is that, at the first moment of disturbance, a little of the air is jerked out at the mouth of the cavity, or a little extra air from outside is sucked in. In either case the air inside the cavity will then have a very slightly lower or higher pressure than the air outside. There will therefore be a return movement set up—from the high pressure side to the low pressure side—to readjust the difference. But as the air, besides being elastic, also has mass of its own, it does not at once cease to flow as soon as the pressure is equalized inside and outside the cavity; it always overshoots the mark by a little—just as the beam of a balance, or the bob of a pendulum, overshoots its position of rest on returning from its swing. In this way the original disturbance of the air inside a cavity results in rhythmical surging of

> the air in and out of the mouth of the cavity, each surging movement being a little less than the one before, till the air finally comes to rest. The rate at which this surging movement takes place—in other words, the number of surgings per second—depends mainly on three things. First, on the volume of the cavity. The larger the cavity, the longer it takes for the difference of pressure between the air inside and outside the cavity to adjust itself. We may imagine the cavity as being like a concert hall, with the air for audience—the bigger the hall the slower will be the process of filling and emptying. A big cavity, therefore, makes for slow surgings or pulsations of the air at its mouth. Secondly, the rate of surging depends on the size of the opening through which the surging takes place. The bigger the opening the more quickly the pressure differences can readjust themselves—just as, in a concert hall, the audience could get in and out more quickly if the doors were made bigger. And, just as in a concert hall, we might add more doors instead of enlarging the existing ones, so in an air cavity we may add orifices, instead of enlarging the existing orifice, and produce the same effect. Lastly, the rate of surging depends on the length of the neck of the orifice through which the surging takes place. We must remember that the movement—like that of any pendulum—is one of successive starting, accelerating, retarding, stopping, and of repeating these actions in the reverse direction. The time required to do this in the case of our air-cavity depends on how much air is set in motion. If, in our concert hall, we prolong the sides of the doorway outwards, so that the doorway becomes a passage, and we imagine that passage crowded with people, all of whom have to "get a move on" before the filling or emptying process can start, it will be clear that the longer the passage, the slower the rate of filling and emptying will be. Now, every time the air inside a cavity, such as we have been considering, comes surging out, it gives rise to an invisible ripple which travels out in all directions from the mouth of the cavity in the form of a sound wave. If, therefore, the air inside a cavity is disturbed, it naturally tends to produce a series of sound waves which succeed one another at a uniform rate, depending on the volume of the cavity, the size of its orifice (or orifices) and the length of the neck or necks of these orifices.[5]

Dimensions being small in respect to wave length and the aperture not large, the shape of the Helmholtz resonator cavity is of no consequence in determining frequency response. This will be seen to have a very marked bearing on the question of "shape" of the mouth as discussed in the last section of this study. Since it is possible to "tune" these resonators, by constructing them in such a way that each will react strongly to a given frequency, the inter-relationship of the volume of the sphere, the length of the neck, and the radius of the neck is the critical factor in determining the frequency to which any given resonator will react strongly. The following formula will show this relationship:

f=frequency (cycles per sec)
a=speed of sound in air (cm. per sec)
v=volume (cm^3) of the resonating cavity
c=conductivity factor

$$f = \frac{a}{2\pi}\sqrt{\frac{c}{v}}$$

As will be shown later, the "conductivity factor" provided by the neck of the resonator, or in the description of Paget above, the "prolonged sides

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[5] Sir Richard Paget, *Human Speech* (New York, 1930), pp. 4-6.

of the doorway outwards," plays a most vital part in explaining some of the more astounding capacities of the human voice. It may be calculated by the following formula:

r=radius of neck (cm)
L=length of neck (cm)

$$c = \frac{2\pi r^2}{2L+\pi r}$$

The conductivity factor in the Helmholtz resonator is determined by the length and radius of the neck leading into the resonating volume. Likewise, in the case of the vocal cavities the complex relationship of the radius and length of the various apertures between cavities play a tremendously important part in the capabilities of the human voice. Since relatively small volumes of air are usually used to resonate high pitches (and since the actual volume of the cavities of the head is rather small), it is the conductivity factor which makes low frequencies possible with relatively small changes in volume. This is the reason why a bass can sing and resonate a low C with a neck and mouth cavity of a few inches in length, while an organ pipe needs an eight-foot resonating cavity to produce the same pitch. Generally speaking, as Paget has explained, in the Helmholtz resonator, the longer and narrower the neck the lower the pitch to which the resonator will respond and the more sharp will be the tuning. That is, the resonator will respond at its maximum effect to a very small deviation in frequency. Conversely, the shorter and wider the neck, the greater the frequency and also the wider the range of frequencies to which the resonator will respond significantly.

For illustration, let it be assumed that a hollow sphere about the size of a golf ball has a hole or aperture only a half inch in diameter. The volume will approximate 40 cc and will, according to the above formula, respond strongly to a frequency of 940 vibrations per second. Upon the addition of a collar to this aperture which will, in effect, create a neck one-half inch in length the resonant frequency will be found lowered to about two-thirds of the former–615 vibrations per second. To produce the same lower frequency by the increase of volume rather than the addition of the neck, the needed amount would be 91 cc. or more than double the original volume. This will illustrate somewhat the vital significance of the conductivity factor in such resonators and will throw light on the reason why the cavities used in singing resonate such a wide range of frequencies with relatively small changes in volume of the singing cavities. Therefore, in singing, the desired results are obtained by a more appropriate cavity interrelationship through the conductivity factor, not the continuous expansion of those cavities.

Resonance takes many forms and performs useful functions in our daily lives, sometimes where least suspected. The incident of the bell, told by Galileo, which was quoted earlier, is an interesting example of the use of resonance in a physical sense. To refer again to the illustration of the child's swing, it is interesting to note that the person doing the pushing is always very careful not to oppose the momentum of the swing. Peak efficiency is reached by the person pushing, just as the swing has come to a fleeting stop, and is changing direction. At that instant a push in sympathy with the downward arc of the swing is very effective. This is a very simple and effective example of resonance. In this case, even slight miscalculations in timing can be rather disastrous.

Thus we find that resonance in sound is a condition, not a tone color. A champion strong man would be rather ineffective in swinging the child if he ignored resonance or the synchronous pushing in sympathy with the swing. On the contrary, a very small weak child can, by taking advantage of resonance, swing a quite large person very satisfactorily. Thus it is seen that resonance does not create energy, but it rather acts as a catalytic agent or makes the transference of energy possible. In the often quoted story of the singer breaking the wine glass with his voice, it is not necessarily the power or force of the voice that does the trick, but rather the fact that the frequency of vibration of the glass is that of the frequency of the voice and the mounting synchronous vibrations between the sound and solid material finally pulls the glass to pieces. The same situation would exist if a column of marching soldiers did not break step in crossing a small bridge. Resonance could also be illustrated by picturing a vibrating tuning fork being held over a long, narrow tube closed at the far end. It will be assumed that the tube in which the sound will be reflected is just long enough so that as one of the prongs of the fork bends towards the tube and sends a wave of compression (and/or rarefaction) down to the bottom, the wave will bounce and return just in time to catch the prong on the upward swing. In which case, the returning wave of compression actually assists the prong to bend upward. Let us suppose also that the tube be lengthened enough that a reflected wave of compression be delayed so that by the time it returns, the prong is on a downward path and collides with the returning wave of compression. It can be readily understood that such a collision would definitely inhibit the movement of the fork, obviously resulting in a feebler tone being given off. Thus it can be seen that lack of resonance can actually prove to be deleterious.

In a much more complex fashion, this synchronous vibration or relative lack of it can be applied very closely to the singing voice. This application will be discussed more fully in a later section. The relationship between the source of tone and the resonant area or volume is a state, or condition, spoken of as coupling. If the influence of each on the other is great, it is spoken of as a tight coupling; otherwise, as a loose coupling. In such vibrating systems it might be said that resonance is the qualitative term and coupling is the quantitative.

Another familiar example of resonance is that of the difference in volume of sound emitted by a tuning fork when held in the hand or pressed against a large sounding board such as a table or piano case. It is true that the fork seems to have more volume (sound energy) when held against a sounding board but such a fork can give off no more energy in sound than it receives. For example, if a certain quantity of energy is imparted to a tuning fork, it will sound a long time, though softly, because the energy can escape only through contact of the tuning fork with the surrounding air. On the contrary, as the fork is given the same quantity of energy and touched against the sounding board, its vibrations are imparted to the sounding board, which presents a much larger surface to the surrounding air; therefore, the energy is given off from the tuning fork in a much shorter time with, of course, more loudness. Here again resonance has not created energy; it merely has made the energy more readily available. Striking examples of resonance frequencies will frequently be displayed by bottles, jugs, vases, and relatively small volumes in buildings such as passageways, open air wells, and small rooms, when such openings are lined with tile or other material which will cause them to be highly reverberant. For example, in Western Kansas there is a colosseum in which a long enclosed ramp leads to an upper floor. At the midpoint of this ramp a sharp stamp of the foot on the floor will cause the ramp to resound a low G (bottom line of bass staff.) In most shower rooms a little experimentation with a slight chromatic glissando hum will reveal a pitch at which the room seems to surge with sound. At the exact frequency an extremely soft note will summon forth a surprising volume of tone.

The Bernoulli principle deals with change of speed and accompanying change of pressure in a fluid. The diagram (Fig. 2) pictures a set of conditions under which a flow of water, for example, could be given a greater or less velocity as it flows through the tube.

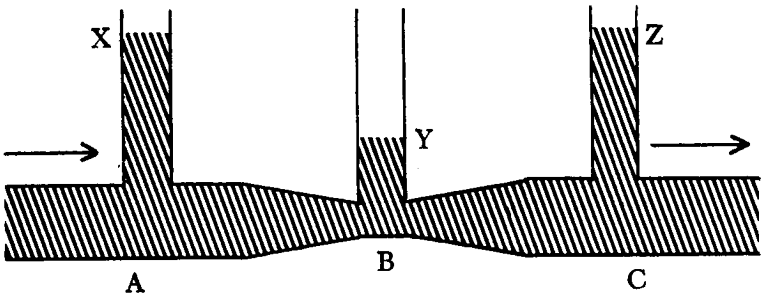

Figure 2.

It will be seen that with a constant speed and quantity of flow of a liquid at A the pressure would maintain a column at the height indicated X. It is obvious that if the same quantity of fluid must pass B that is flowing at A, the speed of the fluid at B must be distinctly greater. It will be found that the lateral pressure at B, because of the increased speed, has been reduced as indicated at Y. At C, where the speed is reduced to that of A, the pressure as indicated by Z has equalled that of X. This principle is utilized in aspirators, sprayers, atomizers, and is the chief source of lift on the wings of an airplane. Later, reference will be made to this principle wherein the point B with the consequent lowered pressure at Y will be compared to the passage of air at the glottis in singing.

PHYSIOLOGICAL AND PSYCHOLOGICAL CONSIDERATIONS AND IMPLICATIONS

The basic anatomical factors of the human singing mechanism are left to other authors. There are many good books on the anatomy of the vocal cords, breathing, etc., and it is unnecessary that these descriptions be repeated here.[6]

Slow motion movies of the human vocal cords in action demonstrate that the cords act as vibrating strings even though on superficial inspection they seem to be more similar to double reeds. In direct similarity to the laws of vibrating strings noted earlier, three factors affect the frequency emitted by the vocal cords, namely vibration length, tension, and thickness. It can be shown mathematically that changes in frequency can be made by very small co-adjustments of the three factors taken together. Obviously, a greater tension and less vibration length and thickness would be required for higher frequencies. Conversely, less tension and greater vibration length and thickness would be required for lower frequencies. For example, if length only were the variable factor, to take half the length would create the octave higher or twice the frequency, but by taking half the length and thickness together would make four times the original frequency. In raising the frequency with a proper change in all three factors, a one per cent change in each results in a two per cent raise in freqency.

It is interesting to notice on every hand the unconscious realization that the ear is more sensitive to higher tones than to lower. For example, a young child in unsuccessful attempts to call attention to his desires will instinctively pitch his shrieks into successively higher tones. At this point the child knows nothing of higher frequencies or the use of the human vocal cavities to give greater resonance to higher overtones. (The automatic coordination patterns of the human being in this regard are truly marvelous.)

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[6] G. Oscar Russell, *Speech and Voice* (New York, 1931); Robert Curry, *The Mechanism of the Human Voice* (New York, 1940); William Vennard, *Singing—the Mechanism and Technique* (Ann Arbor, Michigan, 1950); W. E. Negus, *Mechanism of the Larynx* (London, 1929).

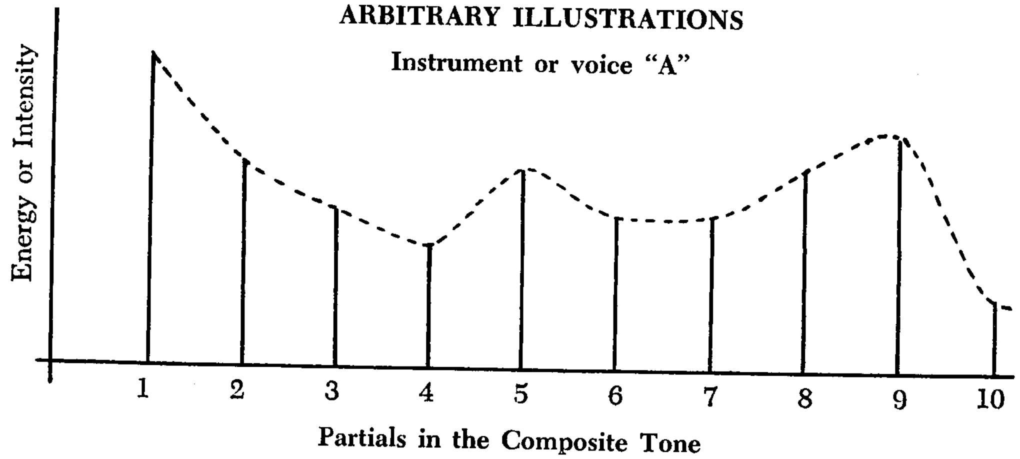
Beginning at the lower limit of pitch identification, it should be noted that the human ear is increasingly sensitive to each successively higher pitch until the top "f" on the piano is reached. (Frequency approximately 2800.) As the pitches go higher, the sensitivity of the ear drops somewhat.

The singer and particularly the choral director will do well to remember that if the energy of singing is distributed more in the upper partials, the effect will be greater on the listening ear. As a matter of fact, the shifting of energy from the fundamental to the partials will require no more total energy; but the choral group will give the impression of a more powerful tone and clearer vowels and greater audibility. This could be used to a distinct advantage in choral groups. In similar manner, the low tones of the basses should be brighter for better carrying quality, since the upper partials through tone color and what will be discussed later as *difference tones* will give to the listening ear a more solid low tone. This device is frequently used in orchestration where the doubling of an instrument in an upper octave gives more power and penetration to the lower octave.

In any given tone, the total energy will obviously be distributed between the fundamental and the overtones present. However, in spite of the fact that it is not at all unusual to have an instrumental tone wherein one or more of the upper overtones are stronger than the fundamental, it is still the fundamental that establishes the pitch to the listener. For example, as a flute plays middle C an analysis of the distribution of energy may show that the first overtone (an octave above) is much stronger, but the ear still identifies middle C as the pitch.

Most tones are a combination of more than one frequency. Tones which consist of only one frequency, such as a tuning fork tone, are very colorless and lacking in texture or vitality. We find that stage sets of a solid color in the theater are quite often spattered or stippled—sometimes with widely contrasting colors—in order to give "life" to the set. A piece of gray tweed cloth may have tiny nubs of bright blue, red or green; a penny in bright sunlight, if inspected closely, will be seen to have a myriad of tiny rainbows of reds, greens, and blues. In the same way that these elements prevent a dullness and drabness of color, so do the overtones in a complex tone give life and brilliance and interest to the musical sonuds. As a single low tone on the piano is played, the trained ear will be able to detect sometimes as many as a half dozen notes of the overtone series which are more prominent than others. Often specific overtones can be detected and identified in well-trained voices. The accompanying illustrations (Fig. 3) will show how the variety and strength of the various overtones combine to give the unmistakable colors of sound.

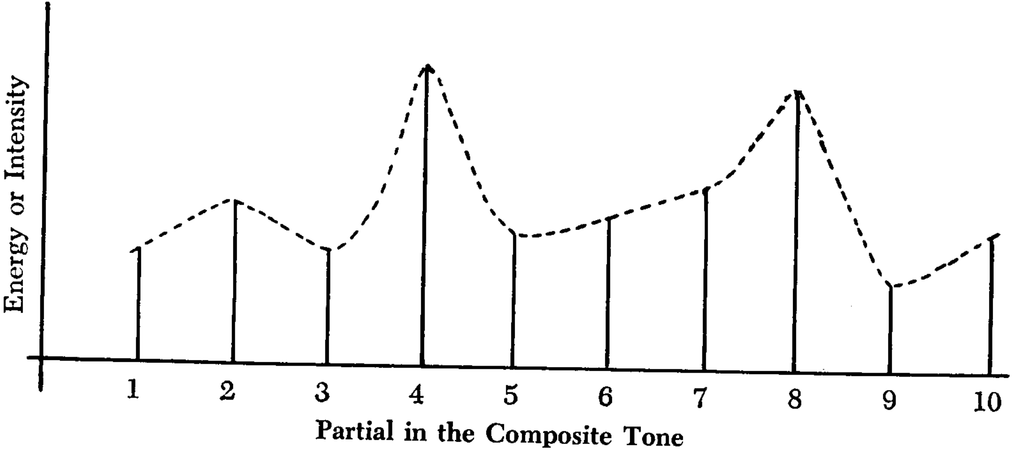
The "profile" of each tone which is a result of the varying amounts of the partials in the composite sound, represents the difference in the tone colors of the instrument or voice as the case may be. This distribution will



ARBITRARY ILLUSTRATIONS

Instrument or voice "A"

Instrument or voice "B"



(The dotted lines are added only for the purpose of emphasizing the different characteristics of the composite tones.)

Figure 3

also explain the difference between the child female voice and adult female voice. Even though in this case the voice does not change as does the male voice, it is the difference in overtone spectrum which gives the characteristic sound of each. In the adult female these different overtones are provided by longer and thicker vocal chords and larger vocal cavities.

In every day situations where exact distinctions are not of prime importance, the words "intensity" and "loudness" can be used interchangably. Factually speaking, it should be understood that intensity is a physical attribute as measured by machines, whereas loudness is that quality assigned by the brain to the stimulus of sound as received by the ear. Obviously, as there are differences in human beings, there will be differences in judgements as to the degree of loudness, particularly for those people who might have slight hearing losses in certain frequency ranges. Occasionally, also, background noises will enter into such judgements; and, due to human psychology, there is a difference between frequency and pitch.

Frequency is the number of measurable vibrations of a medium per second, while pitch is the interpretation of that frequency by the human ear. Again, physiological and psychological differences will create a difference between pitch and frequency. Intensity will occasionally distort pitch. Further vagaries of the human ear are emphasized by the fact that the piano tuner can and does make wide variations in the frequencies of the top and bottom octaves of the piano in order that the pitch may sound "right" to the ear. In some cases the tuner will tune each note in the top octave of the piano as much as a half step sharp, so that the playing of a major 7th will sound a perfect octave. Usually the notes are not tuned more than a quarter tone sharp.

There is another factor in the human psycho-physiology, which has little direct bearing on the actual problem of singing but which, nevertheless, because of its importance in understanding the mass of tone which comes from a choir or orchestra, might be worth while to consider at this point. Because of a certain peculiar construction, the human ear drum will vibrate in a non-linear, or asymmetrical manner. This factor gives rise to a sensation which we interpret as beats, and to what is known as summation and difference tones. In other words, this particular quality of the human ear drum gives rise to tones received by the brain, which do not actually exist in the vibrations of air impinging on the ear drums. These difference tones have long been known as Tartini tones. If, for example, a violinist will play carefully the open G string and E (first finger on the D string) together, the trained ear will perceive a third tone C, a fifth below the open G string. Since the E vibrates at approximately 330 cycles per second, and the G at 198 per second, this particularly peculiar quality of the ear will create a tone from the difference of the two frequencies: namely C at 132 vibrations per second. In like manner, summation tones are created but are much more difficult to identify. For example, if tones of 500 cycles and 700 cycles were sounded together, the summation tone would be 1200 cycles. This procedure, at least theoretically, will continue with the 500 and the 1200, combining to make one of 1700, and the 1200 and the 700 combining to make one of 1900. In bringing into this also the difference tones, the 500 and 700 combination would produce a tone of 200, which conceivably could combine with the 1200 to produce one of 1400 vibrations. This process proceeds theoretically to an indefinite degree.

The above is a very arbitrary illustration, but it does point to the explanation of the tone color produced by a chorus or orchestra with uncounted myriads of combinations of tones all having their effect on the human ear, even though these effects may be quite small. It is a reason why a single soprano, alto, tenor, and bass cannot by electrical amplification be made to sound like a large chorus and, likewise, a single group of five strings cannot produce the noble timbre of a symphony orchestra.

Many students, on having their voice recorded for the first time, have found themselves in quite an apprehensive state of mind and with their faith in the accuracy of such recordings distinctly shaken, simply because, upon playing back the recording, the voice sounds so utterly different from what they had expected. There are several reasons why the recorded voice, regardless of how accurate the machine may be, will never sound "normal" to the singer. In the first place, the individual hears himself in two different ways: As he sings, the sound is carried through the air by reflection and refraction to the external ear; also the sound, to a certain extent, will travel through the bones of the head into the inner ear. This fact finds common use in those individuals whose air conduction hearing is absent and the hearing aid is placed on the bone directly behind the outer ear. The person who plugs the ear with the fingers and then sings or speaks is hearing himself largely through bone conduction. It will be noted that this is a completely different color of sound from that coming through the air. In other words, as he sings, an individual may shut out air conduction of sound but he cannot eliminate bone conduction, and of course as the sound traverses a different medium, the quality will be changed accordingly. Thus, the individual hears himself as a mixture of the two colors of tone, but the microphone of the recorder, it must be remembered, can receive only air conduction of sound and, since the recording machine can hear the individual in only one way instead of two, it is obvious that the individual hears himself in a way that no other person or machine can possibly hear him.

Another consideration in this reference is the fact that the singer is always "behind his voice" whereas the microphone is usually directly in front. A simple experiment will show readily the difference in tone color. Let the student sit and listen with closed eyes while the teacher with continuous singing or speaking rotates slowly, making one complete revolution of the compass. The difference in tone color is quite obvious as the singer faces directly toward or away from the listener. It should be pointed out that while the singer is always "behind" his voice, the microphone is always in front. Thus the singer hears himself (by air conduction) largely through reflection and diffraction with a resulting deviation in tone color.

The student of course is constantly and inevitably faced with the problem of either singing the way it sounds best to him or the way it sounds best to his teacher, because the two tones are by no means the same color. Many singers attempt to circumvent this problem by the practice of cupping the hand behind one ear when attempting to determine the true sound of the voice. This device can really do nothing but mislead the singer, since the hand can reflect frequencies no lower than approximately 2000. Actually, then, the hand aids the singer in hearing only the higher frequencies and does not assist the lower ones at all, which again gives a slightly distorted concept of the true nature of his own voice.

It is thoroughly understandable that the sensations in the head consequent to good singing should give rise to the idea that the bones of the head act as "reflectors." Actually, these feelings are the result of resonance and not a contributing or causative factor. Usually in this concept of "reflection" of tone, the various sinuses in the skull are given credit even when there was a chance that they did not exist, for some people do not have the usual number of sinuses.

In comparing the resonating values of sinuses by applying the formula of the Helmholtz resonator, we find that the contribution could be very small even under the most optimum conditions and only at very high frequencies. Actually, in many cases the openings into the sinuses are so filled with mucous or the sinus itself is filled with fluid, so that in actual practice their contribution amounts to practically nothing. Those who believe otherwise will often quote the fact that sinus infection or irritation will severely affect or handicap singing. The actual explanation is probably the fact that with colds and similar difficulties, the general feeling of malaise is such that the individual could not sing well regardless of the actual cause. In addition, Curry[7] mentions that the irritation of the nerves in the sinuses will affect the nerves of the throat.

Tonsillectomies have been subject to much criticism and likewise the physicians concerned because "they ruin the voice." Some individuals have expressed the belief that the surgeon by some inadvertency nicked the vocal cords in the process. This of course is absurd, because the tonsils are, surgically speaking, quite a distance away from the vocal cords. The probable explanation lies in the fact that the person who needs a tonsillectomy has probably had enlarged tonsils for some time and has gradually become adjusted to the diminished volume in the throat through the enlargement of the tonsils. When the operation is performed, the singer finds that he must overnight adjust to the problem of singing with perhaps a fifty per cent increase in volume in the throat cavity. This will naturally leave him at somewhat of a loss until he can readjust his singing concepts and find new resonance cavity relationships with which to produce the voice, and perhaps even then the voice will have a somewhat new color. It will be some time before it will sound "normal."

The human voice, even when only moderately trained, is such a powerful instrument that it is easy to forget that vocal cords in men are only just under an inch long and in women about three-fifths of an inch long. If it were possible to remove the human head just above the larynx and still let the vocal cords act, it would be the equivalent in sound and

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[7] Curry, *op. cit.*, p. 117.

volume of buzzing the lips through a wedding ring. The illustration might be more appropriate if only the rim of the mouthpiece of a trombone were used for men and that of the trumpet for the women. In any case, it would be quite difficult to imagine these two small slabs of flesh slapping together being capable of filling a whole auditorium with sound unassisted. This will illustrate the immensely important role played by resonance.

VOCAL IMPLICATIONS AND APPLICATIONS OF ACOUSTICAL PRINCIPLES

Of all the words used by singers to describe the process of voice teaching, "focus" and "placement" are perhaps the more common. The teaching of voice placement (or focus) consists of inducing the student to adjust unconsciously the cavities of the head and throat in such a way that their interaction creates, through increased resonance, a richer spectrum of overtones. Note that this has nothing to do with "placing" the voice in a certain region or area of the mouth or head. It is true that properly adjused tones do give rise to certain localized sensations, but these are a result of resonance, not an inherent cause. It has been the custom of voice teachers for years to speak of a resonant tone when the intended meaning was that of a satisfying musical vocal sound. This terminology has become rather standard. It should be noted however, that all musical tones are resonant, but not all resonant tones are musical. Resonance is actually a condition, not a tone color. A high degree of resonance allows the energy with which the vocal cords are motivated to be used in the actual singing tone and not wasted in tenseness, straining, and muffled voice production.

"Coupling" between the source of sound and the resonator can be graphically demonstrated by the following illustration: Let the mouthpiece of a trumpet or trombone be inserted loosely so that it will slide out easily. Sustain a tone and without changing anything, slowly pull the horn away from the mouthpiece. Long before the end of the mouthpiece is seen, the tone will falter and break, showing that there is a very close acoustical coupling wherein the vibrations from the mouthpiece must be transferred accurately and without disturbance into the resonance chamber, or horn.

The lack of acoustical coupling in the human voice cannot be described or illustrated so dramatically, but in effect all tones which have not achieved a normal maximum of power and resonance are subject to somewhat the same acoustical "leak" that was observed when the mouthpiece was not set firmly in the horn. The vocal mechanism, being more perfect than man-made instruments, will serve under adverse circumstance that would completely handicap a non-human instrument.

As long as the student desires to improve his voice, the search for more efficient combination of the factors of resonance never ceases. It should be noted in passing that the sensations which in many instances are quite valuable in guiding the student along this path and which become apparent in the chest, face, head, etc., are results of increased resonance.

The achieving of this resonance is, to be sure, an extremely complex matter. It consists of searching, largely through trial and error, always holding in mind a tone goal to be achieved, and producing the proper tone color through myriad interactions of the various resonators of the throat, mouth, and head by adjusting the volumes and the all-important conductivity factors between the various separate resonators. In spite of its complexity, this focus or placement is not difficult to achieve if the resulting increase in the overtones of the voice are acceptable to the singer. The human voice is capable of producing almost any type of tone the individual wants to produce. In beginning stages of the voice training, the ear will not accept these overtones because they are so high in pitch and small that sometimes the voice seems to acquire a "scratchy" or harsh ring. The usual student has conceived progress to the contrary in terms of a very warm rich, round, velvety sound, all of which is quite lacking in overtones and practically the opposite of true progress in the art of singing. For example, fear of this unwanted and unaccustomed brilliance supplied by additional overtones causes some students to push the jaw forward, since they have learned that this device makes a darker tone. The resulting tightness of jaw, therefore, is a result of wrong singing, not a cause, and will not disappear until the student can be assured that the brighter tones are preferable.

Many students confuse volume or carrying power with a heavy, hollow cavernous approach to tone color. This actually reduces the effectiveness of the voice because it cuts out the higher overtones to which the ear is more sensitive, and in addition it causes a more difficult tone production, since, in terms of vibrating strings, they are making the string much too thick for the pitch to be produced, thereby increasing tension and adding difficulty as they endeavor to produce more volume.

In the matter of gaining the desired "projection" of tones, much distress will be spared the student and teacher if it can be kept in mind that in singing the sound cannot be focused like a beam of light or a stream of water from a garden hose. In discussing the widely held fallacy that the hard palate and teeth and skull act as reflectors and sound boards and that sound in the mouth can be thrown or directed in various directions, Sir Richard Paget in his book *Human Speech* presents the following discussion:

> In voice production, the wave-lengths employed vary in length from between fourteen feet and three feet, in the case of a bass voice, and to between four feet and just under one foot for a soprano. If by a "sound-board" in voice production is meant a reflector, such as is suspended over pulpits to throw the speaker's voice down amongst his audience, then the palate of the basso profundo would need to measure twenty feet either way (if not more) to be effective on his lower notes. A so-

prano might be able to manage with a palate of, say, six feet square, and teeth (if these are to be included) of the same length. [8]

Again, much distress and futile effort can be avoided if it can be kept in mind that since the ear is more sensitive to higher pitches, more adequate projection consists in a more pertinent focus so that the tone may have a richer spectrum of overtones.

In a sense it might be said that the efficiency of projection of the voice depends upon tone color, which again is the result of focus or placement. Tone color is of course a result of the number and relative strengths of the overtones comprising the composite and complex tone of the singer. The control of tone color is the result of the unconscious interaction and co-adjustment of the various resonant cavities of the voice and their connecting apertures.

Many singers are under the fallacious impression that in order to have a balanced tone line from top to the bottom of the voice all tones should have the same timbre or color. This leads to difficulty and conflict in the vocal production because higher tones simply cannot be deprived of brilliance and the bright characteristics of high tones if proper production is to be maintained. As an illustration of the change in color (normal), play the chromatic scale of the piano from bottom to top and notice how each successive tone is just a shade brighter and more penetrating than the preceding one. Brass and woodwind players are very sensitive to the fact that high tones on their instruments cannot be played with the relaxed loose embouchure that produces low tones. The higher the pitch, the greater the relative intensity of the embouchure to produce it. The problem of producing high tones, however, is not dependent on only "tightening" the vocal cords. This is explained in the section on vibrating strings.

All trained singers have a wide variety of overtones which have been cultivated in order to give the voice a richer tone color. It could almost be said that the concert-goer pays an admission charge in direct ratio to the amplitude and number of overtones in the singer's voice. This same principle is applicable in buying a fine violin. The frequency response is the desired characteristic. In this regard it is of incidental interest that Stradivarius used Norway spruce for the top of his famous violins. It was not until many years later that scientists discovered that this wood transmitted sound at a faster rate (that is, offered less resistance) than similar woods.

There is nothing mysterious about vowels. They are simply concrete and identifiable tone colors which have been repeated for endless ages and have finally become established as a coherent means of expression or language. The mysteriousness and difficulty of vowels is usually caused by the fact the singer holds fallacious concepts concerning the "shape" or "formation" of the vowels in a physiological sense.

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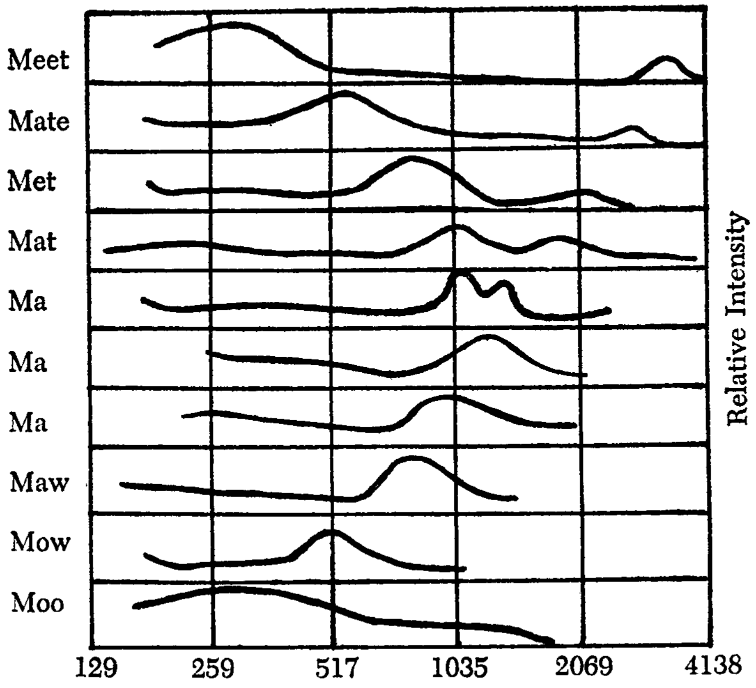
[8] Paget, *op. cit.*, p. 212.

Robert Willis, English scientist of the nineteenth century, observed that when the human mouth was set to pronounce a particular vowel, the mouth cavity gave rise to a resonant note of a particular pitch—due to the natural rate of vibration of the air in the mouth cavity. He believed that it was the pitch of the resonant note of the mouth cavity which determined the vowel sound produced, and that the differences between the vowel sounds were essentially due to differences of resonance in the cavity which produced them.[9] It will be seen by the accompanying illustration (Fig. 4) that when the resonators of the voice are so used that certain overtone regions are emphasized, the result is a recognizable vowel in that language.

RESONANCE REGIONS*



* Stewart, G. W., "Introductory Acoustics."

Figure 4.

These prominent resonant regions are called formants. Investigators have ascertained that some vowels have as high as four of these formants or resonant regions. It is probable, however, that the one or two formants shown for each vowel in the accompanying illustration are the ones necessary to the basic recognition of the vowel. Students of French and

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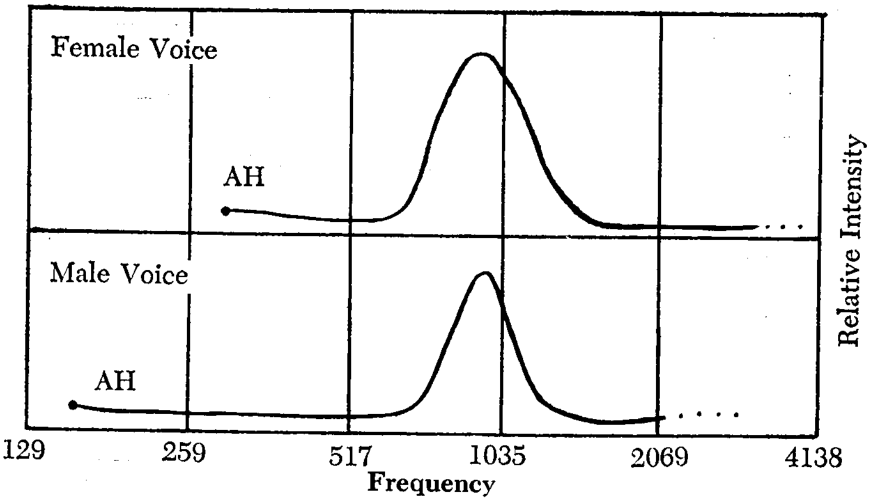
[9] Jones, *op. cit.*, pp. 363-364.

German will be interested to note that the umlaut U constitutes the connecting link between the two extremes of vowel sounds of e and oo. The similarity between the formant of the oo and the lower formant of the e is quite marked.

Further observation of the figure will show why a soprano can sing little else but the vowel ah on the higher notes of her scale. It will be noticed that at this frequency (1035) she is well beyond and above formant regions necessary for e and a and o and oo, and even the words "met" and "maw" are somewhat in doubt.

RESONANCE REGIONS—VOWEL "AH"*



* Stewart, "Introductory Acoustics."

Figure 5.

In the accompanying illustration (Fig. 5) it will be apparent that even though a male and a female voice may be an octave apart in singing ah, the vowel formant for ah (about 900) is the same. This is the reason why different voices with different resonance cavity conditions can sing the same vowel with somewhat different arrangements of these cavities. The point is to create a cavity adjustment which will create a formant of approximately 900 cycles regardless of the particular arrangement of cavities necessary to produce this in each case.

Singers who are interested in delving further into the acoustics of the voice will be interested to know of the excellent work done in analyzing the action of the human voice by Dr. Vernon Albert.[10] The accompanying diagram (Fig. 6) of the network of resonators and its analogy to the

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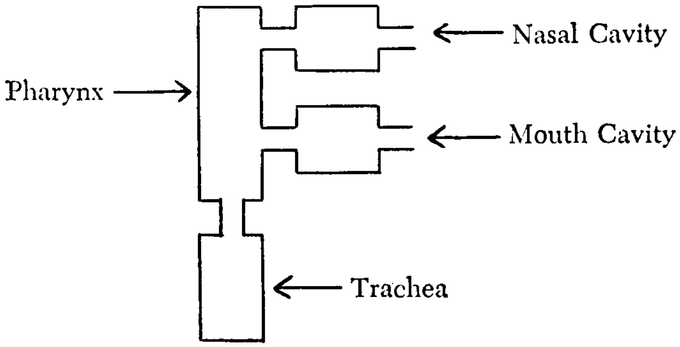
[10] Vernon Albert, *Experimental and Theoretical Analysis of Network of Resonators,* Ph.D. Thesis (Temple University, 1951).

human voice shows close correlation and, generally speaking, his findings corroborate certain tenets which voice teachers have held for many years, but which were discovered purely by empirical approaches and were therefore not easily proved.

CYLINDRICAL RESONATORS USED
IN ANALYZING THE HUMAN VOICE



Vernon Albert Ph.D. Thesis
Temple University, Philadelphia, Pa.

Figure 6.

Dr. Albert used a large number of interchangeable parts in the apparatus, by which,he could create, as desired, any given combination of cavity volumes and conductivity factors in the various apertures. An earlier description of the conductivity factor describes it as a function of the radius and length of the neck of the aperture. The apertures used in the apparatus illustrated above were variable in both length and radius.

It will be noted that Dr. Albert includes a resonance cavity analagous to the trachea,in his researches. Many prominent authorities have felt (because of its juxtaposition to the larynx) that the pharynx, or back throat, was the most important resonator. Researches of Dr. Albert demonstrate very convincingly the fact that the effective combination of cavities in voice production includes the trachea at all times. It is not surprising to find that the cavity below the vocal cords enters into the combination when it is remembered that in whistling the pitch is controlled by the cavity behind the aperture. Also, it is common knowledge among wind players that the use of the mouth cavity behind the embouchure can be utilized to advantage.

One of the most misleading and prevalent of all fallacies in the world of singing is the concept that the vowel is "formed" by a certain shape of the mouth and the striving to attain a certain excellence in diction by using certain preconceived "molds" has caused untold frustration. True, there will be certain superficial similarities in certain vowel shapes in all singers, but it should be emphasized again that in actuality the inter-play of volumes and the conductivity factor of the connecting apertures determine, by appropriate resonance, the prominence given to certain overtones of the voice and these overtones determine the vowel. Because of the anatomical differences in various students, the given vowel or tone color should be sought through mental imagery of the tone desired, not by placing the various vocal factors in certain preconceived shapes or inter-relationships. Dr. Albert mentions that because of the great number of combinations possible by the human vocal mechanism a given set of overtones may be resonated in more than one manner. Furthermore, if a perfect vowel came from a certain arbitrary shape of mouth and throat, some enterprising voice teacher long ago would have managed to secure a model or mold around which young singers could learn to shape the voice cavities and thus also achieve a good tone. It is interesting to note that ventriloquists achieve surprisingly good diction without using the *sine qua non* of many voice production methods.

Further corroboration of the fact that the vowel is a tone color can be obtained by experimenting with a grand piano. In a quiet room and with the lid up, press down the sostenuto pedal so that the strings are freed from all dampers and then sing clearly a variety of vowels one by one. The piano will re-echo, weakly though unmistakably, the vowels sung. This is explained by the fact that the strings are excited to sympathetic vibration in whole or fractional vibration by the number and strength of the overtones in the voice. In this way a recognizable vowel is returned.

Negus, in his masterful book *The Mechanism of the Larynx*[11] tells of an instance where the tongue of a patient was removed surgically because of disease. The patient was nevertheless able to reproduce the various vowels quite plainly. The explanation of this, of course, is the fact that the individual was able to create the proper combination of cavity volumes and conductivity factors of the apertures in the mouth and head so that the required vowel formants were created.

The combining of the various cavities to create the proper resonances is not a matter of absolute dimension but a matter of *relative* dimensions and inter-relationships. It is because of this fact that such teaching practices as consciously and purposefully flattening the tongue, raising the uvula, widening the pillars of the fauces, and other similar devices, can achieve only a minimum of beneficial results and a maximum of delay in the acquiring of trouble-free tone production.

Dr. Albert has also shown through his network of resonators that in

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[11] Negus, *op. cit.*, p. 148.

making changes in frequency by use of cavity volume only, a one hundred per cent increase in volume created only ten per cent change (decrease) in frequency. This shows that the variation of cavity volume alone cannot create the resonance of the various tones in the range of the singer's scale. The evidence points again to the fact that it is the conductivity factor between the cavities that creates the wide range of possibilities in the human voice, and that, to a certain degree, cavities of the mouth and throat opened or closed beyond a certain optimum or normal usage is useless effort.

Investigating frequency changes with respect to diameter of the apertures between the various resonance cavities, Dr. Albert found that smaller than optimum diameters show a marked drop in frequency of vibration, showing that narrow apertures favor low pitches. On the contrary, however, larger than optimum diameters show almost no increase in frequency. Therefore, beyond comfortably open constrictions or conductivity passages between the resonating cavities, there is no point in making the connecting channels larger.

This suggests another fallacy which has been widely followed: Many voice teachers encourage the student to open the mouth and throat as large as possible, apparently in the belief that if one tablespoonful of medicine is good for a sick person, then eight or ten ought to be that many times better. To a limited degree, the wider the mouth opening, the more satisfactory response there will be to a wider range of frequencies as well as higher frequencies, but, according to the above paragraph, any effort beyond a certain optimum is futile. Many teachers encourage this situation by the device of the smiling upper lip, which in effect assures that the conductivity factor of the mouth (the oral opening) will have an ample radius but no neck, and it will be remembered that, generally speaking, the longer the neck into a resonator the smaller (as well as lower) the number of frequencies it will emphasize. This is why it is natural for basses to protrude the lips when attempting the lower ranges of the voice. Here again it should be emphasized that a big hole does not necessarily mean a big or low tone.

In following the description of resonance and coupling as described in an earlier section it will be apparent that tight coupling and a high degree of resonance between the vocal cords and the vocal cavities can play a tremendous part in the establishment of ease of singing. Just as the sound wave assists the prong of the tuning fork to vibrate when the wave travels reflected through the proper distance in the resonating tube, just so is the vibrating of the vocal cords assisted by the proper combination of resonance cavities. Actually this coupling in a resonance tube can be so tight that by creating a slightly longer or shorter round trip for the reflected wave, the tuning fork can actually be made to emit a frequency slightly higher or lower through forced resonance, depending upon the exact timing of the reflected wave.

It will be readily seen that tight coupling and sharp resonance would add a very material and tangible aid to the vibration of the vocal cords, which will result in much easier singing. In applying the above example of forced vibration to the vocal cords, it will be seen that this could easily be the explanation of the difficulty in the case of the young music student who has a good ear and is musical but, much to the annoyance of everyone concerned, has persistent intonation troubles. Since voice training consists of focusing or placing the voice, which means discovering the proper arrangement of cavities to supply the correct resonance for any given pitch, it can be said that such a student has unintentionally created the wrong resonance cavity inter-relationship and the reflected sound waves are causing the vocal cords to alter slightly their intended frequency because of the strong influence of the tight coupling. The student who has such pitch difficulty usually has other difficulties with voice technique also. Usually it consists of a fallacious concept or approach to vowels or tone color, which in turn is causing wrong cavity relationships.

The following illustration will show the futility of dealing with such intonation problems by the device of attempting to alter muscle action directly. When the cavity resonance affects the pitch issuing from the vocal cords (assuming that the coupling will affect only the vibrating length of the cord with the thickness and tension remaining constant) at a pitch of 440, for example, as the singer pulls a quarter tone sharp (452 vibrations) the twelve additional vibrations will be equivalent to a three per cent change in length of the vocal cords. Assuming (in the case of women's voices) that the vocal cords are about three-fifths of an inch long, this sharping will shorten the vibrating length of the cord about one one-hundredths of an inch (a hair is about three one-hundredths of an inch in diameter). It is no wonder that singers stray from the pitch occasionally.

Another elemental factor should be mentioned in connection with Bernoulli's theorem which was discussed briefly at the end of an earlier section. By referring to the illustration (Fig. 2) it will be seen that if point B could be imagined as the site of the vocal cords and that the point A would be the trachea just underneath the vocal cords, providing the same flow and pressure of air were present in constant quanity, the closure of the vocal cords at B would create a narrowing of the channel at that particular spot. Thus, according to the Bernoulli theorem, there would be less lateral pressure as shown at Y. Actually, therefore, the vibrations of vocal cords provide repeatedly a situation which induces the cords to close, rather than vice versa. Too many singers have the mental concept wherein, particularly as the voice goes higher, with the vocal cords stretching tighter, similar to the action of a rubber band, the air pressure in the trachea must rise higher and higher to oppose this increased tension. Actually, this rubber band tension does not exist for still another reason. For successively higher pitches it is true that the tension is increased somewhat, but just as meaningful and significant is the fact that the vocal cords also become more slender and, in addition, decrease their vibrating length. Roughly speaking, the same thing happens to the embouchure of the lips as the brass player would go from tuba to trombone to trumpet.

In discussing the effect of Bernoulli's theorem, a very significant corollary is worth consideration at this point. The student hears the constant admonition to "support the voice with the breath." Obviously, increased support results in increased pressure, which in turn results in increased speed of air passing through the glottis. This would accordingly result in a further decreased lateral pressure and more assistance in the closing of the glottis. It seems reasonable that this would be the ultimate reason for breath support and would bring the maximum amplitude and freedom of action of the vocal cords with the minimum of effort, efficiently utilized.

The registers of the voice have been a subject for much discussion over a period of many years and have been subjected to all extremes of consideration from that of the most vital and careful solicitousness to the complete ignoring of such considerations. Apparently, register shifts are those places at which each of the three controlling factors of the voice (thickness, length, and tension) make significant shifts or combinations of inter-activity. Register breaks, however, are largely where we look for them or where they appear as dictated by tradition and custom. There seems to be no physiological or acoustical reason why co-adjustment of the cords and cavities should be more difficult one place than another, except, perhaps, in terms of the adjustment mechanism, but not in terms of pitches in given voices.

Familiarity with the concepts discussed in this study may provide the clue to the solution of many perplexing difficulties for the singer and add materially to the ease of singing through the intelligent avoidance of wrong or impossible procedures. At least, the student will see that there are some elements that are distinctly in his favor if he will but consider and use them. To the singer who has had little or no direct contact with science in a formal way, this material may seem to be rather complex, even though the presentation is somewhat simplified here, so that those unfamiliar with such concepts can understand more readily. It is hoped that enough of the fundamental principles can be absorbed to help the singer realize the wonders implied in the human mechanism. In singing, as in every other endeavor, nothing is accomplished except through cooperation with the established laws of nature.

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