ACOUSTIC EFFECT OF VOCAL WARM-UPS ON SINGERS' VOICES

by

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B.A. (Spec.), University of Alberta, 1989

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF ARTS

in the Department of Linguistics

We accept this thesis as conforming
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ABSTRACT

Singers, like athletes, use a warm-up to prepare their muscles for subsequent exertion. These warm-ups increase core and muscle temperatures causing more efficient muscular functioning. Vocal warm-ups have received relatively little attention from speech scientists. This preliminary study attempts to provide some basic information about the effect of vocal warm-ups on the acoustic output of singers.

Eight subjects (1 F, 7 M), all choral singers, were recorded performing a series of vocal tasks before and after completing their usual warm-up. The tasks involved were a repeated arpeggio, a sustained tone on a comfortable pitch, an ascending scale in their upper tessitura, a descending scale in their lower tessitura, and a sustained tone on three levels of loudness (very soft, moderately loud and very loud). The results were analysed for amplitude and bandwidth of the singer's formant, range of the fundamental frequency, amplitude of the voice source fundamental, closed quotient of the voice source fundamental and amplitude range. The significant findings were an increase in the prominence of the singer's formant, an increase in the fundamental frequency range, and an increase in the closed quotient of the vocal waveform. This means that, as a result of the vocal warm-up, the singers were more audible, they had a larger pitch range and they were using a more efficient mode of voice production.

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ACKNOWLEDGEMENTS

This thesis could not have been written without the help of many people. I would like to thank my supervisor, John Esling, who provided great encouragement and even better suggestions. Thanks also to my other committee members, Ewa Czaykowska-Higgins and Emmanuel Hérique for their contributions and encouragement.

Thanks to Jocelyn Clayards for always having the answers to my computer questions and the patience to explain them, and to Micheal Joyce; thank you so much for making the pictures work.

Thank you also to Chris and Scott, for getting me away from it all; to Anne and Susan, for the innumerable cups of tea and words of wisdom; and finally, to my family for all their love and support. Thank you all.

1
INTRODUCTION

What makes a given singing voice "good" or "efficient?" This is a question which singing teachers and speech scientists are still trying to answer. Most voice users agree that a vocal warm-up makes the voice more efficient. As a step towards answering the general question of voice efficiency, this paper explores which aspects of the voice are improved by a vocal warm-up. The effects to be looked at are not qualitative or subjective but rather those pertaining to measurable aspects of voice production – waveforms, harmonics, fundamental frequency (pitch), amplitude and the like. The question being addressed here is what acoustic effects does a vocal warm-up have on the voice? In other words, how does a vocal warm-up affect the sounds which a singer produces?

The scientific study of warm-ups is a fairly recent occurrence. Asmussen and Bøje (1945) is one of the earliest papers to deal specifically with sports warm-ups. Vocal warm-ups did not receive specific scientific attention until Elliot, Sundberg and Gramming published "What happens during vocal warm-up?" in 1995.

Most singers in the western classical tradition would never dream of singing without first warming up. As with any other challenging physical activity, it helps subsequent performance to ease the muscles slowly into the activity rather than to force unprepared muscles. Both athletes and singers have been warming up for a very long time. According to the experience of many singers and voice teachers, warm-ups do improve the efficiency of the voice. This paper will outline some of the ways in which that improvement takes place and will examine how this improvement manifests itself in the voice.

ACOUSTIC EFFECTS OF VOCAL WARM-UPS

Very little research has been done directly on the effects of vocal warm-ups on the vocal tract. Only two papers (Elliot, Sundberg & Gramming, 1995 and Elliot, Sundberg, Gramming & Iwarsson, ms) deal directly with this issue. The study presented in this paper is a pilot study which explores the effect of a vocal warm-up using a range of acoustic measures: bandwidth and amplitude of the singer's formant, fundamental frequency range, amplitude of the voice waveform fundamental, the closed quotient of the voice waveform fundamental and the amplitude range. The measures used are fairly basic but this is the first time they have been used to explore the effects of vocal warm-ups.

A group of eight subjects, all choral singers, were recorded before and after performing their usual warm-ups and the before and after results were analysed and compared. It was found that the prominence of the singer's formant increased, the fundamental frequency range increased and the closed quotient of the voice waveform increased.

WARM-UPS: SPORTS VS. SINGING

Singing is sometimes regarded as just another physical exercise like cycling or basketball. The serious singer trains in much the same way as an athlete, focusing on certain skills and honing his or her performance of those skills. Saxon and Schneider devote their entire book *Vocal Exercise Physiology* (1995) to the idea that "skeletal muscle[1] is the same throughout the body. It looks the same and functions the same, contracting and relaxing. Its responses to training and conditioning are the same"(p. 13). This physical consistency between muscles is useful when examining vocal warm-ups because the effects of warm-ups are much easier to see in large muscle groups. The effect of warm-ups (specifically, sports warm-ups) on large muscle groups has been well studied by sports physicians and trainers. Vocal warm-ups, conversely, involve much smaller muscles which are more difficult to access and, consequently, to study. Thus, much of our information about warm-ups and the vocal musculature is available only through knowledge of how other muscles work. The physiological effects of warm-ups on muscles, both in terms of sports and singing will be examined in greater detail in Chapter Two (p. 19).

Pedagogical Approaches to Vocal Warm-ups

Published materials designed for assisting singing teachers focus primarily on long term development of the voice rather than on short term preparation. Books of vocalizations such as those of Marchesi (1899), or Shakespeare (1921) are designed to work the voice on various problem areas. Such books abound and are well used (often as warm-ups) but actually say little, if anything about preparing the voice for performance or practice.

Titze (1993, p. 21) says "a primary objective [of performing a vocal warm-up] is to obtain, as quickly as possible, a uniform vocal quality over a wide pitch range." Every singing teacher consulted in this study was adamant about warming-up the voice. These singing teachers and choral directors often give warm-up procedures orally and the little that is on paper is usually written by

[1]Skeletal muscles are those under voluntary control.

hand and photocopied. The actual processes and procedures for warming up the voice seem to be passed down from teacher to student – a kind of oral (and Xerox™) history, as it were.

Most of the scant published work on warm-ups is intended for choral use (Telfer, 1995; Robinson and Althouse, 1995) – usually it takes the form of collections of vocalizations and exercises with instructions for their use. The choral approach to vocal warm-ups is somewhat broader than that for individual singers as the warm-up is also used chorally to establish and enforce the cooperative nature of the choir. Robinson and Althouse (1995, p. 5) reflect this diversity in their eight reasons why warm-ups are necessary:

1. Warm-ups establish focus.
2. Warm-ups prepare the voice for singing.
3. Warm-ups allow singers to hear themselves and others.
4. Warm-ups establish physical readiness for singing.
5. Warm-ups establish proper breathing habits.
6. Warm-ups achieve unification of vowels.
7. Warm-ups establish intonation[2] melodically and harmonically.
8. Warm-ups establish a connection with the music to be sung in the rehearsal.

Telfer (1995) provides warm-ups and hints for better singing production but does not offer much in the way of theoretical observations. Her warm-ups are also designed to provide practice in various areas of voice production such as breathing, articulation, range expansion or dynamics. It seems to be a very common practice to combine the daily warm-up with exercises for vocal development; preparing the voice for the somewhat unusual things it will have to do.

[2]*Intonation* in this context refers to tuning or the relative pitches of specific notes.

Titze (1993, p. 21) gives a hierarchy of the procedure and goals of a vocal warm-up: "first a wide pitch range of soft to medium loud voice, then a full control over voice quality, and finally a full range of loudness."

Miller (1990) published a short article entitled "Warming Up the Voice" in which he describes what he feels to be an appropriate warm-up:

> The warm-up package ought to begin with gentle, brief onsets and offsets (attack and release technique) in a comfortable range of the voice. Humming in medium range, and syllables with nasals and vowel sequences, are useful devices. Exercises that induce flexible tongue and jaw action form part of the sequence. Agility patterns, both ascending and descending, may gradually be added. After initial exercises of this sort, a few minutes of rest should be taken before turning to passages that deal with vowel definition and modification, and sostenuto[3]. Registration and *passagio* vocalises[4] follow. However, heavy vocalization must never form part of the warm-up series. The session should conclude with rapid arpeggios of extensive range, and rapidly-moving scale passages (p. 22).

Published descriptions of warm-ups for actors are somewhat easier to find. Both Lessac (1960) and Machlin (1966) give very specific warm-up procedures designed, in Lessac's words, to "help tone up, not only your voice, but your body and your concentration"(Lessac, 1960, p. 235). Machlin's exercises are intended to allow the actor to "rehearse or perform without strain" (p. 241). Machlin's warm-up procedure (pp. 241-243) is similar to Miller's description given above: a gradual progression from physical preparation (physical stretches and relaxation) on to exercises for different aspects of voice production (breath control, "resonance" articulation) to performance related tasks. Lessac's warm-up

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[3]Sustained tones.

[4]A "vocalise" /vokəˈliz/is a short piece of music designed to exercise or focus on a certain problem area. *Passagio* is the technique of minimizing perceptible transition from one register to another.

(pp. 235-236) is very closely related to his specific method of voice production. It is not dissimilar in structure from Machlin's but contains fewer exercises.

Although different in many ways, all these vocal warm-ups are similar in one respect: they are designed to modify the performer's mode of voice production, that is, to change his or her voice quality from speech mode to singing mode.

SINGING AND VOICE QUALITY

Voice quality has been described as "those characteristics which are present more or less all the time that a person is talking"(Abercrombie, 1967, p. 91). It may also be described as those peculiarities of speech which mark the voice or which make a given voice recognizable.

Some aspects of voice quality come from the individual's anatomy. Each individual has a different physical form: different lung capacity, different vocal fold size and thickness, different vocal tract length and circumference. These physical differences all influence the sound of the voice. Lung capacity can influence duration and loudness of utterances. Vocal fold and vocal tract size affect the pitch capabilities of the individual.

Other aspects of voice quality fall within the realm of voluntary control. When certain characteristics are recurrent over a longer time domain, they are usually referred to as a *setting* (Laver, 1980, p. 2). Examples of this would be quasi-permanent lip rounding or breathiness. These settings influence the sound of the voice but they are also capable of being changed.

It is possible to view the singing voice as a sociolinguistic voice quality setting, or, more specifically, as a range of settings. Some research (Sundberg, Gramming and Lovetri, 1993; Schutte and Miller, 1993, and Yanagisawa, et al., 1989 for example) has been done on the differences between the operatic voice, the pop voice, and belting (the style of singing often associated with Broadway). This research has shown clear differences, both acoustic and physiological, in the different styles of singing. It is also possible to find voice teachers who share this approach to voice training. Lisa Popeil (p.c.), for example, has devised a method (called Voiceworks™) which classifies voice technique into various styles and has accompanying mental images to get students to sing in various styles. She classifies voice types into two general categories of technique: classical and popular. Both of these techniques are subdivided into specific styles. Classical voice technique includes opera, operetta, choir and "legit". Popular voice technique covers pop, rhythm and blues (R & B), rock, "belt," jazz and country. Other styles can also be studied but those listed are the most frequently seen and used. Popeil teaches physiological settings specific to the style or styles wanted by the student.

Within the realm of the classical Western European tradition, there are different habitual settings which occur. There are singers, for example, who sing with a raised larynx and those who sing with a lowered larynx. Very few teachers advise singing with a raised larynx, but casual observation has indicated that there are certainly operatic singers who use this vocal setting.

A good example of a setting or technique which seems to contradict the traditional pedagogical view is found in Yanagisawa, et al. (1989). The impetus for their research was a singer who had been warned of potential voice deterioration due to extreme aryepiglottic constriction (traditionally considered very dangerous by singing teachers and voice specialists) but who had not suffered any of the predicted results nearly fifteen years later. This led Yanagisawa and his colleagues to do a videolaryngoscopic analysis of aryepiglottic constriction in various singing styles, the results of which challenge the traditional view of aryepiglottic constriction. In fact, they found that aryepiglottic constriction was consistently present in three of the voice styles they examined (twang, belting and opera) and that it is related to the presence of the singer's formant (see p. 13).

Voice training may thus be regarded as instilling the ability to change from one voice setting to another at will. If this is the case, then the warm-up may be viewed as the transition between the singer's speech setting and his/her desired singing setting.

INDIVIDUALITY PRINCIPLE

Saxon and Schneider (1995, p. 54) describe the individuality principle this way:

> Everybody possesses different skills, levels of fitness, body types, and so forth, which must be taken into account when designing a training and therapy program. ... The skilled voice teacher does not recommend the same training to every student in the studio, nor does a therapist prescribe a standard exercise regimen for every patient. Training is optimized when the teacher and therapist correctly address individual needs and capacities.

In terms of this study, the individuality principle means that all the subjects are warming up from a different starting point. The transition from one speech setting to another will be influenced by many different sociolinguistic factors which will not be consistent from singer to singer.

Even if we assume that the voice setting for a given singing style is fairly consistent from one singer to another; the combination of the physical characteristics of the individual singer and sociolinguistic influences such as region of residence, age, class or sex in his/her regular speech means that the transition from the speech setting to the singing setting, viz. the vocal warm-up, will not be consistent but will vary depending on the changes needed by the singer.

Acoustics

Pei and Gaynor (1954, p. 5) define *acoustic* as "relating to sound or sound perception" and *acoustic phonetics* as "the study of the sound-waves produced when sounds are uttered." The analysis undertaken in this study is acoustic and therefore relates to the sounds produced by the singers. How these sounds are produced and measured is part of acoustic phonetics.

Acoustic Phonetics – Theory & Practice

Speech sounds may be regarded as consisting of two parts: a source and a filter. The source is the interruption of airflow from the lungs by the vocal folds. This is the voice. The voice is then modified(filtered) during its passage through the throat, oral and nasal cavities (known collectively as the supralaryngeal vocal tract) and emerges as speech. What follows here is a brief description but any good phonetics text will provide a more thorough explanation. (See, to name just a few, Abercrombie, 1967; Borden and Harris, 1984; Fry, 1979; Ladefoged, 1962 or Ladefoged, 1982).

Source

Direct study of the voice source is difficult as the larynx is not readily available for independent study. Laryngoscopic analysis – a fibreoptic camera inserted either orally or nasally – does provide direct visual access, but it is intrusive and not very comfortable for the average subject. For this reason, indirect means of study are frequently used.

The simplest visual representation of sound is the waveform. The sounds which leave the mouth can be recorded and converted to waveforms quite easily but getting a waveform of just the source requires a bit more effort. One way to get a waveform of laryngeal output, and the method used in this study, is to use a laryngograph to produce a laryngogram or electroglottogram (EGG). The electroglottogram depicts the glottal waveform by means of electrical impedance. This small instrument consists of a control box attached to a neckband holding two small electrodes. The EGG is connected to a recording device; in this case a digital audio tape (DAT) recorder. The electrodes are placed on the subject's neck on either side of the thyroid cartilage and a high frequency electric signal is passed between them. Titze (1990, p. 1) explains the workings:

> Any tissue within the neck acts as a conductor, whereas any airspace between the electrodes is bypassed by the electric field lines, thereby narrowing the conducting paths. The overall conductance between the electrodes is increased, therefore, by the reduction of airgaps. Specifically, as the vocal fold tissues make contact, the conductance increases, which is interpreted as glottal closure. Conversely, decrease in the conductance is interpreted as glottal opening.

This electrical impedance is recorded as a waveform which correlates with the acoustic output of the larynx.

The EGG is not the only way to get a source waveform. The inverse filter method takes the speech waveform that leaves the mouth and passes it through a series of filters which negate the filter characteristics of the supralaryngeal vocal tract (see Sundberg, 1987, p. 66ff for a clear description). Both methods work very well; the EGG was chosen because of the accessibility of the equipment.

Figure 1-1 shows an example of an EGG waveform of the voice source. This is a representation of the voice as it enters the supralaryngeal vocal tract. This original waveform is very regular and sounds like a buzz.

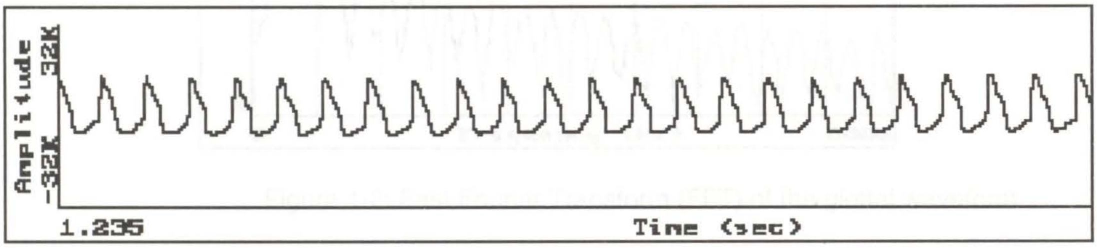

Figure 1-1: Voice source waveform

Changing the way the larynx is being used can cause changes in the glottal or voice source waveform. Singers often modify their usage of the larynx when they sing. Specific changes found in singers' voices will be discussed in detail later.

All complex waveforms are simply amalgamations of simple (sinusoidal) waveforms. The glottal waveform (Figure 1-1) is the sum of the fundamental frequency (the perceived pitch) and all of its partials or overtones. Each of these overtones can be thought of as a simple waveform at progressively higher frequencies (pitches). This is easily seen in a graph called a Fast Fourier Transform (FFT). The FFT separates the complex waveform into its component waveforms and plots the amplitude of each of the overtones that make up the complete signal. The FFT of the waveform in Figure 1-1 is shown in Figure 1-2. Again, the regularity of the voice source can be seen here. The overtones decrease at a regular rate (an average of 12 dB per octave) producing the buzz of the original voice source waveform.

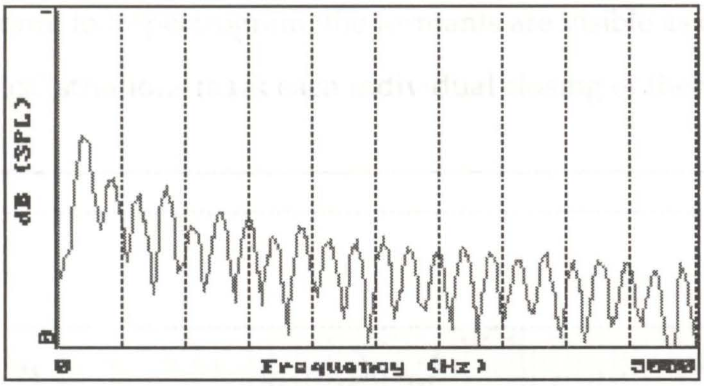

Figure 1-2: Fast Fourier Transform (FFT) of the glottal waveform

FILTER

From the moment the soundwave generated by the vocal cords enters the pharynx or throat, it starts to be manipulated. The various moveable parts of the supralaryngeal vocal tract can constrict or even stop the flow of air from the lungs. These constrictions create consonants. If the tongue does not restrict the airflow but rather divides the oral cavity into resonating cavities of different sizes, we get vowels. Different vowels are produced depending on the overall shape of the vocal tract. The resulting resonators (technically, Helmholtz resonators) affect the acoustic waveform by causing certain overtones to have more energy and, consequently, to stand out. These sections of higher energy are known as formants and it is the first two formants (and occasionally the third) which distinguish the vowels acoustically. In an FFT of the waveform which emerges from the mouth of a speaker, these formants can be seen as peaks in the upper harmonics.

A spectrogram (Figure 1-3) is a graph which provides a three dimensional representation of speech in which the formants can be clearly seen. Time is represented along the X-axis and frequency along the Y-axis. Amplitude or energy is seen as darkness: the more energy there is present, the darker the area on the spectrogram. In a spectrogram, the formants are visible as dark horizontal bands. The vertical striations mark each individual closing of the vocal folds.

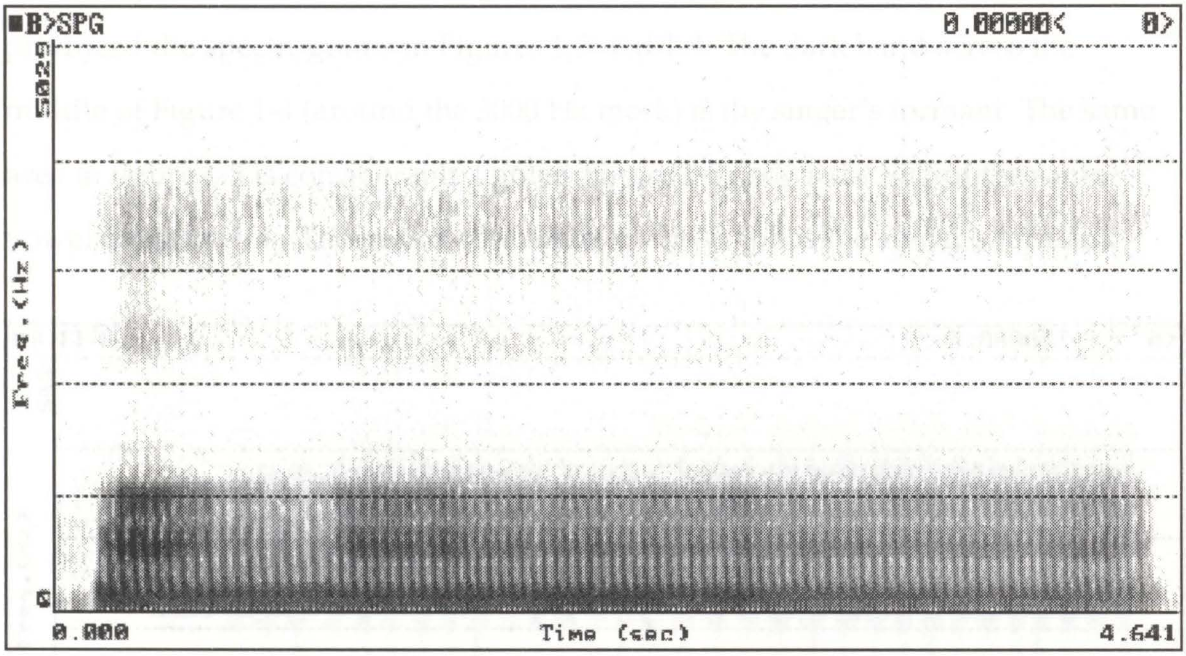

Figure 1-3: Spectrogram of the vowel [a]

THE SINGER'S FORMANT

The occurrence of the singer's formant has been observed for many years. It is a peak around three thousand Hertz due to the clustering of the third, fourth and fifth formants which gives the singing voice its particular "ringing" quality. The presence of the singer's formant assists in projecting the voice – particularly over an orchestra. The frequency of the singer's formant is higher than the frequency band of the orchestra.

Sundberg (1977, p. 842) explains the physiological model of the singer's formant: "the larynx tube act[s] as a separate resonator, the resonance of which is not affected by articulatory movements in the rest of the vocal tract. This is accomplished when the larynx tube opening is less than one sixth of the crosssectional area in the pharynx." Yanagisawa, et al. (1989) used videolaryngoscopy to show the contribution of aryepiglottic constriction to the singer's formant.

Figure 1-4 shows a spectrogram of the vowel [a]. The same subject produced the spectrograms in Figures 1-3 and 1-4. The dark band across the middle of Figure 1-4 (around the 3000 Hz mark) is the singer's formant. The same area in figure 1-3 is considerably lighter. Figure 1-5 shows the FFT of the same vowel in figure 1-4 . The peak in the centre of the graph is the singer's formant.

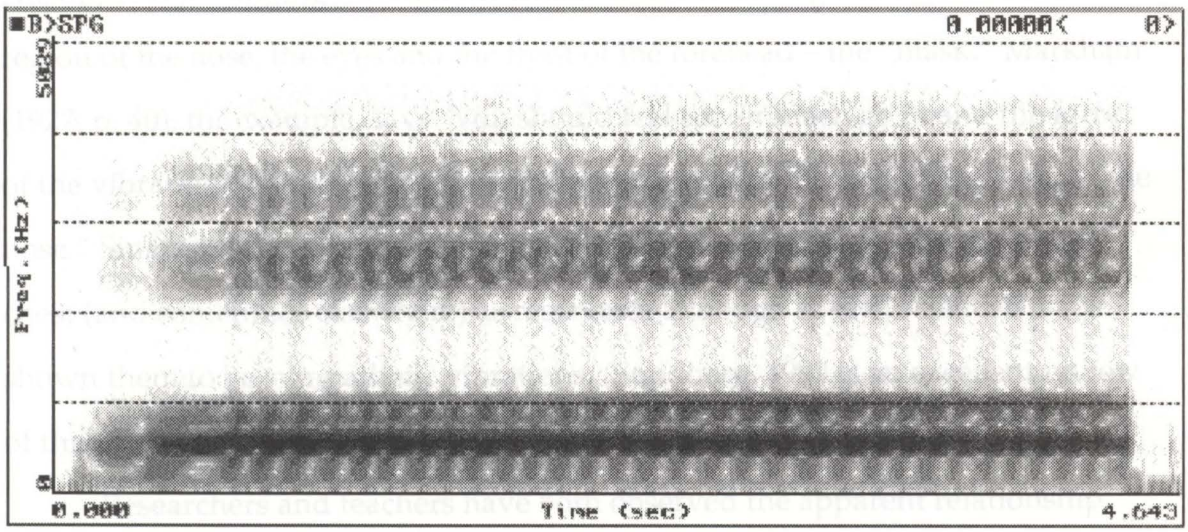

Figure 1-4: Spectrogram of the vowel [a] showing singer's formant

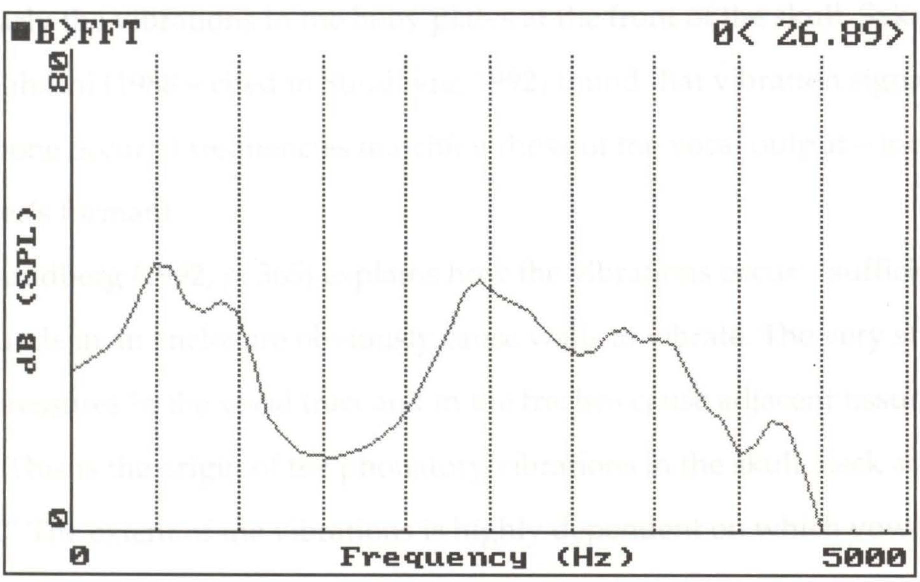

Figure 1-5: FFT of vowel [a] showing singer's formant

Production of the Singer's Formant

When singing teachers talk about the auditory qualities of the singer's formant, they use words like "ring" or "resonance." They use many different exercises and images to get their students to produce a singer's formant. The production of the singer's formant has been connected by some scholars with the concept of "singing through the mask" or "head resonance" (see Sundberg, 1987, p. 119 or Austin, 1997). "Singing through the mask" refers to feeling vibrations in the region of the nose, the eyes and the front of the forehead – the "mask." Markham (1927, p. 40), for example, says "you should feel the stomach go in and the force of the vibration behind the mask of the face–the roof of the mouth and behind the nose." Singing teachers still refer to these physical sensations in the head and chest (and sometimes elsewhere) as resonance although speech scientists have shown them to be sympathetic vibrations. (Sundberg, 1992 is an excellent review of this area of study)

Researchers and teachers have both observed the apparent relationship between "projection," or the singer's formant, and these phonatory vibrations; particularly the vibrations in the bony plates at the front of the skull. Sakakura and Takahashi (1988 – cited in Sundberg, 1992) found that vibration signals in the frontal bone occur at frequencies matching those of the vocal output – including the singer's formant.

Sundberg (1992, p. 365) explains how the vibrations occur: "sufficiently loud sounds in an enclosure obviously cause walls to vibrate. The very strong sound pressures in the vocal tract and in the trachea cause adjacent tissues to vibrate. This is the origin of the phonatory vibrations in the skull, neck and chest regions." The extent of the vibrations is highly dependent on which vowel is being produced. The vowel [i] gives much stronger levels than [a], for example (Sakakura and Takahashi, 1988).

An excellent example of a pedagogical approach to teaching projection through phonatory vibrations is found in Lessac (1960). This book is a "method" text for actors rather than singers but the vocal technique is similar. It should be noted that well-trained actors also exhibit a singer's formant; singers do not have a monopoly on this phenomenon.

Lessac uses two techniques: the "Ybuzz" (pronounced y [the name of the letter] – buzz) and the 'call' to identify and control what he calls "tonal action" (his name for the technique which produces a singer's formant). The Ybuzz takes its name from the use of a high, front vowel to build awareness of the accompanying sympathetic vibrations in the front of the skull. The call is then developed to "place" all the other vowels. He writes

> To understand either the Ybuzz or the call thoroughly, you must remember that tonal action is the control of a vibratory current of sound in a state of constant movement, radiation, and transmission, propagating in the bones of the face and the head … every vowel is a voiced tone incorporating the elements of pitch, volume, and quality, and that every tone is to be felt as a vibration in that solid bony mass consisting primarily of hard palate , nasal bone, sinuses and forehead. (p. 112)

Lessac uses both the Ybuzz and the call as integral parts of his warm-up procedure for actors. His specified warm-up (p. 235-236) starts with the Ybuzz (viz. sustaining the vowel [i] on a fairly low pitch to develop the sympathetic vibrations in the front of the skull). The call (using increased airflow to maintain the sympathetic vibrations on mid vowels) is practiced and then the performer returns to the Ybuzz to "slide into" the various vowels while maintaining the sympathetic vibrations without the high energy levels of the call.

In this study, it is expected that the singer's formant will become more distinct as a result of a vocal warm-up. The singer may not focus as exclusively on "singing through the mask" as an actor following Lessac's warm-up, but as these vibrations are considered an important part of good singing, it is expected that some attention will be paid to them by the singer during the warm-up and the results of this should be measurable. Two different measures were used in this study to examine changes in the singer's formant: its bandwidth (how wide it is) and its amplitude (how loud it is). Acoustically, the singer's formant is regarded as a compression of the fourth and fifth formants around 3000 Hz. As the singer's formant becomes more distinct with the vocal warm-up, the compression of these formants should be greater. In other words, they should move closer together. This tighter compression should be reflected in the bandwidth of the resulting singer's formant; more compression should mean a smaller bandwidth. The tighter compression of the two formants should also mean that the energy contained by the two formants is being moved closer together, resulting in a higher amplitude peak. As the two energy peaks get closer together, their energies combine and interact to a greater degree. This should be reflected in an increase of the amplitude of the singer's formant.

THE ACOUSTIC EFFECTS OF VOCAL WARM-UPS ON THE SINGING VOICE

Referring back to Robinson and Althouse's (1995) eight reasons why vocal warm-ups are necessary (on page four of this paper), this study examines two of these reasons: warm-ups prepare the voice for singing (number two) and warm-ups establish physical readiness for singing (number four). Reason number five, warm-ups establish proper breathing habits, will be explored indirectly.

To explore how vocal warm-ups influence the acoustic qualities of the voice a range of acoustic measures has been used to determine which aspects, if any, of the voice seem to be most affected by a vocal warm-up. Chapter Three lays out which measures were looked at and provides an explanation of each. Chapter Four presents the results and Chapter Five discusses the conclusions. Before the details of the study, however, Chapter Two provides background information on warm-ups and their effect on the muscles of the human body.

2
PHYSIOLOGICAL RESPONSE TO WARM-UPS

Warm-ups and their physiological effects have been well studied by exercise physiologists and sports medicine practitioners. Warm-ups can be either active – warming up the muscles with physical exercise; or passive – using hot water baths, massage or short wave diathermy. Active warm-ups can be further subdivided into general and specific warm-ups.[1] Specific warm-ups involve just the muscles and nerves required for the subsequent activity while general warm-ups affect the whole body.

One of the primary purposes of a sports warm-up is to increase body temperature: both the tissue temperature of muscles involved in the activity and the core temperature of the body. Tancred and Tancred (1995, p. 39) summarize the effects of an increase in body temperature as :

1. An increase in muscle blood flow.
2. An increase in the sensitivity of nerve receptors.
3. An increase in the dissociation of oxygen from hæmoglobin and myoglobin.
4. An increase in the speed of nerve impulse transmissions.
5. A reduction in muscle viscosity.
6. A lowering of the energy rates of metabolic chemical reactions.

What follows in this chapter is a discussion of research into sports related warm-ups as well as vocal warm-ups. The first part of the chapter examines research in

[1]This is only one of various taxonomies extant; the basic principles remain the same but the groupings vary. See Tancred and Tancred (1995, p. 38) for a fuller discussion of variations on this theme.

sports warm-ups and their effect on the muscles involved in sports. Then the same categories will be examined from the perspective of vocal warm-ups. There will be an attempt to extrapolate from the sports research onto the vocal physiology as well as an examination of the voice research literature.

Bloodflow and Biochemistry

Body temperature (including both muscle and core temperatures) is in a symbiotic relationship with both muscle tissue bloodflow and biochemical functions – they affect each other. Muscle temperature is increased as a result of three physiological processes: the friction which occurs within the sliding filaments during muscle contraction, the metabolism of fuels and the dilation of intramuscular blood vessels (Hendrick, 1992, p. 25). As temperature increases, metabolism requires less energy, oxygen is dissociated more readily and blood flow increases (Tancred and Tancred, 1995). Heart rate increases to ensure that a greater volume of blood reaches the muscles which need it. The blood carries oxygen to the muscles which extract the oxygen they need to work. This, in turn, helps to increase tissue temperature. Increases in muscle temperature affect short term performance. Longer term performance relies more on increases in core temperature (Asmussen and Bøje, 1945).

Effects on Nerve Impulses and Receptors

Tancred and Tancred (1995, p. 37) point out that

> [the] increase in nerve function … is of particular value to sports people whose events or activities demand complex movements of various body segments. The increased rapidity of nervous signals becomes important when different body parts move rapidly,

> because it is vital for the central nervous system to receive relevant feedback, in order to execute and control movements efficiently and effectively.

Research has shown that warm-ups which incorporate the muscles actually involved in the main activity are more likely to prove beneficial than those which simply elevate core temperature (see, for example, Asmussen and Bøje, 1945). Hardcastle (1976, pp. 8-9) says that "once an impulse has succeeded in passing through the synapse the threshold to future excitation at that synapse is lowered… Because of this facilitation process it is favoured over others and in time becomes stereotyped." By warming-up the muscles involved in the activity, not only do the muscles get prepared, so do the nerves. The minutiæ of control can be checked and refined – preparatory practice, in fact. By the end of the warm-up, the nerves and muscles "know" what to do.

Changes in Viscosity

Viscosity is the internal friction in a fluid. The viscosity of a muscle may, perhaps, be described as the "stickiness" of the fluid within the muscle. This affects the muscle's stiffness or ability to change shape. A muscle's viscosity greatly influences its functioning and viscosity is temperature dependent. Tancred and Tancred (1995 pp. 36-37) in their review of the literature report that "muscles whose temperatures are below that of body temperature tend to increase their viscosity, which can cause soreness, stiffness and possible weakness, whereas muscle temperatures slightly above body temperature facilitate more rapid and forceful contractions." Safran, et al. (1989 p. 244), also summarizing research findings, note studies which have "postulated that at higher temperatures the viscous properties of collagenous connective tissue prevail, whereas at lower temperatures the elastic properties prevail. Warming alters the stiffness of the connective tissue." The viscosity of muscle and connective tissue must, then, be affected by a warm-up. Decreasing the viscosity improves the ability of the muscle to contract and should provide the connective tissues with more flexibility.

STRETCHING

Kimoto (1990, p. 70) summarizes the theoretical benefits of stretching for physical and athletic skills: "a possible decrease in the incidence of musculotendinous injuries, minimization and alleviation of muscle soreness and possible enhancement of athletic performance."

It is necessary to differentiate between stretches as a warm-up and stretches for flexibility. Safran, et al. (1989, p. 245) say that "stretching to a constant tension results in lengthening of the muscle with subsequent stretches…[and]…a greater length is necessary to attain the tension for tearing muscle, indicating that the role stretching plays in muscle injury prevention may be large." It is important to note that the muscle only lengthens with subsequent stretches; this implies stretching as training, viz. repeated regularly over a period of time. This may be called stretching for flexibility.

Stretches are often incorporated into warm-ups or used alone as warm-ups. It is not clear, however, how useful stretches are as a warm-up. Kimoto (1990) found no significant differences between a bicycle ergometer (stationary bicycle) test performed cold and one performed after a stretch regimen. Safran, et al. (1989, p. 245) cite several articles that actually note an increase in musculotendinous injuries with pre-performance stretching.

Psychological Aspects of Warm-up

The psychological benefits of warming-up must not be overlooked. Tancred and Tancred (1995), in their review of physical warm-up literature, discuss the role of warm-up in focusing prior to a performance: "most sports participants who perform a warm-up prior to their main activity tend to be more mentally tuned or prepared" (p. 36). Such athletes, they say, may have a competitive advantage. Safran, et al. (1989, p. 243) say that "psychologically, it [a warm-up] relaxes the athlete by calming him/her and aiding concentration."

Rochelle, Skulic and Michael (1960) studied the effects of warm-ups on softball throwing. Forty-six male students threw a softball three times and the distances of the throws were measured. Each subject was tested twice, on different days; once without a warm-up and once following a five minute warm-up. The control for the psychological variable was to offer a financial incentive: "the subject was told that a monetary reward would be given for each throw greater than the norm established for his weight, height and body type ... In addition, to motivate the individual further, the first throw was valued at twice the monetary amounts of either the second or third attempts" (p. 501-502).

Despite this incentive, throws after a warm-up were significantly farther than those without a warm-up (an average of 10.2 feet farther). As well, in the throws without a warm-up, the third throw was significantly farther than the first throw. There was no similar significant increase over three throws following a full warm-up.

On the other hand, Massey, et al. (1961) used hypnosis to remove the psychological variable of a physical warm-up. Subjects were put in a deep hypnotic state prior to a bicycle ergometer test and were unaware if they had warmed-up. The examiners found no significant difference between performance with a warm-up and performance without a warm-up.

ATHLETIC VS. VOCAL WARM-UPS

Both singers and athletes are trained early into a regular warm-up regimen. It is possible that vocal warm-ups are not equivalent to other physical warm-ups but given current research such a hypothesis seems unlikely. As Elliot and colleagues (1995) point out, "the vocalis muscle is participating in the vocal fold vibrations and is active in control of pitch. Hence, it is vibrated and also it alternately contracts and is stretched during the singing exercises. It is hard to doubt that this muscle is subject to a warm-up effect similar to that in other muscles" (p. 42). Nonetheless, it is difficult to know to what extent the physiological changes due to sports/athletic warm-ups can be assumed to apply to vocal warm-ups. Athletic warm-ups involve quite drastic temperature changes in muscle tissue as well as changes in core temperature. We do not know to what extent the temperature of the laryngeal musculature (as well as the respiratory and articulatory muscles) changes. It is an area which has not received the study it deserves. Physiological changes due to warm-up will probably not be as readily observable as for the athletic warm-up, especially if we have to rely on indirect measures.

Determination of the physiological response to vocal warm-ups is very difficult; direct measurements of laryngeal temperature or blood flow are not easily taken so reliance on related, more measurable phenomena is what is left. The problem is that such phenomena are influenced by factors other than the warm-up which cannot always be controlled.

It seems safe to assume that most of the results found in sports research on warm-ups will be applicable to voice production. As Saxon and Schneider (1995, p. 3) observe, "skeletal muscles are the same throughout the body and the rules which apply to one group of muscles apply to all."

Neither core temperature changes nor heart rate changes are generally associated with vocal warm-ups but temperature increases due to muscular friction, in all probability, do occur. It is difficult to know how much these temperature changes will affect the biochemical functioning of the laryngeal muscles. Any increase in tissue temperature should, however, be accompanied by the related increase in blood flow and the readier dissociation of oxygen.

It is interesting to note that both Miller (1990, p. 22) and Machlin (1966, p. 241) advocate starting a vocal warm-up with mild physical exercise which would help to increase core temperature. Saxon and Schneider (1995) strongly advocate extensive physical training accompanying voice training. Large and Patton (1981) found that a long-term (twelve week) exercise program did not have an adverse effect on vocal development of ten male singers. As the subjects in Large and Patton's study continued their voice training during the time of the training, it was not possible to state for certain that the improvements in voice production shown by all singers were due to the exercise program but all the subjects did report in questionnaires that "they felt the fitness training had been responsible for vocal improvement – including support and range extension – and that the psychological benefits were considerable" (p. 31).

Effects on Nerve Impulses and Receptors

Most experts agree that, of the physiological effects of warm-ups, the ones most likely to be of benefit to singers are those effects dealing with the functioning of the nervous system (Murray Morrison, personal communication, David Docherty, personal communication). The muscles involved in voice production require very delicate control and consequently take up a relatively large part of the motor cortex area (Hardcastle, 1976, p. 10). The innervation ratio (the number of muscle fibres innervated by a single motorneuron) for muscles requiring delicate manipulation is extremely low (Hardcastle, 1976, p. 11). Thus, the neural pathways are an extremely important part of speech and singing. The singer's control over extremely fine adjustments to the laryngeal musculature is sharpened by running through the process in advance. Tancred and Tancred's (1995, p. 37) comments on sports warm-ups that "the increased rapidity of nervous signals becomes important when different body parts move rapidly, because it is vital for the central nervous system to receive relevant feedback, in order to execute and control movements efficiently and effectively" could just as easily be applied to vocal warm-ups.

Changes in Viscosity

The viscosity of the vocal fold tissue plays an important role in vocalization. According to Finklehor et al. (1988, p. 320), viscosity

> determines the amount of energy loss due to internal friction in the folds. As viscosity is increased, more energy is required to maintain the same phonatory conditions. Therefore, from the standpoint of vocal efficiency, the viscosity of fluids within the vocal folds should be low enough that most of the energy

> provided by the lungs is converted into acoustic energy in the vocal tract rather than heat within the vocal fold tissue.

Finklehor, et al. (1988) conducted experiments on viscosity changes of the larynx using excised canine larynges. Four larynges were bathed sequentially in three different solutions providing varying degrees of viscosity. The threshold oscillation pressure (the minimal air pressure required to make the vocal folds vibrate) was then measured for a range of glottal configurations. They found that a decrease in the viscosity of the larynx lowers the threshold of oscillation. This has a direct bearing on warm-ups. Lower viscosity as a result of an increase in temperature due to a vocal warm-up should mean that less energy is required to make the vocal folds vibrate.

Elliot, et al. (1995) attempted to examine changes in viscosity of the larynx due to warm-up by looking at phonation threshold pressure (another way of saying threshold oscillation pressure). They hypothesized that the decrease in viscosity due to warm-up should lower the phonation threshold pressure. The results, however, showed great interindividual variability due, in all probability, to the fact that phonation threshold pressure is dependent on factors other than viscosity. There were, however, clear effects of the warm-up on the phonation threshold pressure. The actual effects of the warm-up seem to vary between individuals.

Similar results were found in a follow-up study by the same authors (to appear). This time the approach was to look at the amplitude of the spectrum overtones. The premise of this study is that with decreased viscosity, the glottis should close more quickly which should increase the amplitudes of the overtones. Again results were inconsistent.

Viscosity changes may not be that dramatic for vocal warm-ups. Changes in viscosity are temperature dependent and the temperature changes are probably not nearly as great as for an athletic warm-up.

STRETCHING

It is difficult to know if research on stretching has any relevance for vocal warm-ups. Stretch of the vocal folds is an important aspect of phonation and an essential part of singing as it determines pitch; but does this compare with an athlete using stretches as a form of warm-up? The vocal folds, and in particular, the lamina propria, are known to contain large amounts of elastin fibres, particularly in the middle and deeper layers (Hammond, et al., 1997; Ishii, et al., 1997 – conference notes). Elastin is "a rubberlike protein ...[and]...the major component of elastic fibers, which can stretch to several times their length and then rapidly return to their original size and shape when tension is released" (Struyer, 1985, p. 274). According to Hammond et al. (1997, p. 60) "elastin plays a large role in the actual vibration of the vocal folds."

Titze (1993, p. 21) discusses stretching during the vocal warm-up. He says that

> optimal vocalization is based on flexibility and control rather than on brute force. If singers are like athletes, then they are like those athletes who rely heavily on precision and range of movement (gymnasts, figure-skaters, dancers) rather than on peak muscle strength. Warm-up time is spent in stretching joints, tendons, ligaments, and muscles. Cyclic stretching and releasing promotes cell and fiber growth and strengthens all tissue, whether muscle or connective.

Athletes stretch to increase their flexibility. This "ability to move muscles through their full range of motion" (Kimoto, 1990, p. 69) very likely applies to singers as well; particularly in their ability to hit extreme pitches. Singers do not stretch their vocal cords in the same way hurdlers stretch their hamstrings or dancers stretch, well, just about everything; however, it is not unreasonable to assume that stretching of the vocalis muscle occurs during the vocal warm-up and, indeed, during the training process. Establishing a full range of motion for this muscle seems an important part of preparation for singing.

Psychological Aspects of Warm-up

Miller (1990) states that "an established warm-up routine offers psychological as well as physical security to the singer" (p. 23).

The effects of the psyche on the voice must not be underestimated. For example, Murray Morrison (1997, p. 112) classifies emotion as one of the four "major causative factor fields in muscle misuse voice disorders." Morrison says (p. 113) "voice problems are often the result of repression of negative emotion." If psychological problems are readily observable, then psychological benefits should also be present.

Mental preparation is very important to the voice user. As Miller (1990, p. 23) points out, "the singer who has little notion of how his or her voice will feel until hearing it on stage is bound to be a nervous performer."

The warm-up books designed for choirs (Telfer, 1995, Robinson & Althouse, 1995) make full use of the psychological aspects of warming-up. Looking at Robinson and Althouse's list of eight reasons why warm-ups are necessary (see chapter one for the full list), both the first and last reasons are purely psychological: "warm-ups establish focus" and "warm-ups establish a connection with the music to be sung." Warm-ups provide a way for the singer to prepare him- or herself for what is to come – singing.

INJURY PREVENTION

Both physical and vocal warm-ups are often thought to be effective as a method of preventing injury. The evidence for this is nowhere near as strong as many would believe. This has been noted by others including Tancred and Tancred (1995, p. 38) who point out that

> conclusions about the preventative effects of warm-up are not solidly substantiated, in that little experimental evidence presently exists. The problem lies in determining whether an injury was caused solely by a lack of warm-up or by the activity itself and there is the obvious problem ... that researchers would not try to induce injury as a part of their experimental design.

Safran, at al. (1988) found that it required a statistically significant increase in force and length of stretch to tear "warmed up" rabbit muscle as opposed to muscle which had not been warmed up.

When comparing sports and vocal warm-ups, the types of injuries being prevented seem to differ. The problems which vex the athlete are strains and tears in the muscle tissue thought to be caused by "excess tension on contracted muscle...violent contraction during an excessively forceful stretch" (Safran, et al., 1989, p. 240). According to the same researchers (p. 243), "most authors attribute the injury reduction associated with warm-up to an increased range of motion."

What kinds of injury are being prevented by vocal warm-ups? Sundberg (1987, p. 184) explains that

> the vocal folds are exposed to excessive stress when the vibrations happen too forcefully or for overlong periods. Then the vocal folds react in various ways....Phonation under conditions of high adduction activity, high subglottic pressure, and high activity in the cricothyroid and vocalis muscles (high pitch) may involve unnecessarily exaggerated stress of the vocal folds.

These behaviours result in hoarseness and vocal fatigue (phonastenia) and can, if continued over long periods, develop into organic disorders such as nodules or contact ulcers. The problems which worry the professional voice user are almost all functional disorders of the vocal folds.

Do vocal warm-ups help in the prevention of injuries? We simply do not know. Studies such as Kitch and Oates' (1993) survey of voice users show that both singers and actors report experiencing vocal fatigue quite regularly. It can be assumed that of the twenty subjects questioned in the study, most of them would use a warm-up prior to performance but we do not know this for sure. Nor do we know if sensations of vocal fatigue are greater when no warm-up has been used – an interesting thought for future study.

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3
THE STUDY

Singers, like others who undergo demanding physical exertion, feel that they benefit from a warm-up prior to full use of the muscles involved in the exertion of singing. The mechanics of vocal warm-ups, as we have seen, are not thoroughly understood. People who use vocal warm-ups know that they work but the scientific study of them has been somewhat overlooked.

The physiological responses to sports warm-ups are well documented (see Chapter Two) and it may be assumed that vocal warm-ups trigger similar responses: an increase in muscle tissue temperature and bloodflow with the accompanying increase in efficiency of biochemical functioning; improved neural functioning and a decrease in muscle viscosity as well as psychological preparation for performance. The purpose of this study is to examine whether the physiological changes due to a vocal warm-up affect the acoustic output and, conversely, to see if the acoustic output can give us information about the physiological changes.

SUBJECTS

Eight choral singers (one female and seven males) of varying degrees of training and experience were recorded performing simple vocalization tasks before and after completing their regular warm-up. The voice types consisted of one soprano, four tenors and three basses. Choral singers were chosen following the example of Elliot et al. (1995) and Elliot et al. (to appear). The voices of professional singers are in such good condition that the effects of the warm-up are very hard to see. In the words of Elliot and colleagues (1995, p. 38):

> The reason we chose amateurs was that the warm-up appears to typically have a greater effect on the voice in such subjects compared with professional singers, who seem to be more or less constantly warmed-up, perhaps because of the frequent use of their professional voice.

Frequent voice use plays an important role in this difference between the professional soloist and the amateur choral singer. Titze (1993, p. 21) sums this up very elegantly: "rarely does a voice respond instantly after prolonged silence, sleep or days of rest. Not only does the instrument need to be primed but the player needs to be recalibrated to the instrument."

Regular training of the singing voice will result in increased muscular strength and flexibility (Saxon and Schneider, 1995). Titze (1993, p. 21) states that "the gifted vocalist spends the bulk of warm-up and training time in refining and grooming vocal quality, whereas the less gifted vocalist struggles to establish a useful pitch range." It is expected that singers who train extensively would have the muscles and nerves used for singing in top condition and consequently would not, in fact, need as extensive a warm-up as someone whose muscles were less well conditioned. In the case of the highly trained singer, the function of the warm-up would be predominantly to increase the muscle temperature and the metabolic functioning within the muscles. For singers with less muscular conditioning, the warm-up would function almost as a miniature training session. This can be compared with the students throwing the softball in Rochelle, Skulic and Michael's (1960) study (see Chapter Two, page 23). Simply throwing the ball twice acted as a warm-up and significantly increased performance on the third throw when the exercise was not preceded by an actual warm-up. Use of a specific warm-up improved the performance of all three throws. Similarly, choral singers should show marked improvement in all aspects of singing with their warm-up.

Choral singing is regarded by many to be a style of singing distinctive from solo operatic singing. Ternström and Sundberg (1989) and Rossing, Sundberg and Ternström (1987 & 1986) all examine differences between choral and solo singing. They found that "in the choir mode, the singer's formant was less prominent, and the amplitude of the fundamental was higher; ... the articulation was closer to that of speech" (Ternström and Sundberg, 1989, p. 517). As all the subjects in the present study are choral singers, it can be expected that during the warm-up they are moving to a setting similar to that described in these studies.

All but one of the subjects were native English speakers whose dialect was West Coast North American. The one non-native speaker was French but had lived in Canada for many years. All subjects were in good health. This means that, as a group, they were fairly homogeneous vocally. The differences in pre-performance vocal setting would be primarily based on innate physiological differences.

Based on this homogeneity, the original hypotheses were set out: as a result of a vocal warm-up, the amplitude and bandwidth of the singer's formant were expected to increase, the pitch range was expected to increase, the level of the glottal waveform fundamental was expected to increase, the closed quotient of the glottal waveform was expected to increase and the amplitude range was expected to increase.

TASKS

The subjects in this study were asked to sing:

- an arpeggio[1] (three times)
- a sustained tone at a comfortable pitch
- an ascending scale in their upper range to the highest note they could comfortably control
- a descending scale in their lower range to the lowest note they could comfortably control
- The same pitch at differing loudnesses – *pianissimo, mezzo forte, fortissimo*[2]

All recordings took place in the sound-proof room of the University of Victoria Phonetics Laboratory. The singers were recorded performing the above tasks on a Sony DTC-750 Digital Audio Tape (DAT) using an AKG C 1000 S condenser microphone. The singers were then asked to warm up and were recorded again, using the same equipment and performing the same tasks. The structure of the warm-up was left to the discretion of the individual singer as it was felt that use of a familiar warm-up would provide the greatest effects. The psychological advantage of the warm-up was desired as well as the physiological. The singers were recorded performing vocal tasks rather than singing a song as it was felt that this would eliminate any influence of the pre-warm-up recording as a possible warm-up in itself. The tasks requested of the singers were similar to many warm-up tasks and make the recordings more analogous to recording at the beginning and end of a warm-up.

The recordings were then analyzed and the before and after recordings were compared looking at the following phenomena:

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[1] An *arpeggio* refers to playing or singing the notes of a chord sequentially rather than simultaneously.

[2] *Mezzo forte* (*mf*) means medium loud; *fortissimo* (*ff*) means as loudly as possible and *pianissimo* (*pp*) means as softly as possible.

- Bandwidth of the singer's formant
- Amplitude of the singer's formant
- Fundamental frequency range
- Amplitude of glottal waveform fundamental
- Closed quotient
- Energy (amplitude) range

SINGER'S FORMANT

Two measurements were made of the singer's formant: the bandwidth and the amplitude. As the voice warms up and settles into the "ideal" mode of production, the singer's formant should become more focused: the bandwidth of the singer's formant is expected to become narrower and its amplitude higher.

To examine the singer's formant, the sustained tone was digitized at a sampling rate of 50,000 Hz and analyzed on the CSL (Computerized Speech Laboratory) program from Kay Elemetrics. The bandwidth of the spectrogram was set at either 122 or 144 Hz, depending on the pitch of the sample. The width of the singer's formant was then measured by cursor on the computer screen. For those subjects who did not exhibit a singer's formant, the span of the fourth and fifth formants was measured instead. This was done following the assumption that the singer's formant involves compression of these two formants (and possibly the third, as well). The changes in the pharyngeal structure which would cause the singer's formant to focus would also cause formants four and five to move closer together; that is, to move towards the formation of a singer's formant.

The amplitude of the singer's formant was measured from a long term average spectrum (average of all the FFTs) of the sustained vowel. The highest value of the formant was taken as its amplitude. In cases where no singer's formant was observable, the highest value of the fourth or fifth formant (whichever was higher) was taken instead; again on the assumption that these formants conflate to form the singer's formant.

F0 RANGE

Singers use a wide range of fundamental frequencies and it seems to be generally accepted by singers and pedagogues that the pitch range of the singing voice increases with voice use (viz. with a warm-up). As the range of motion of the vocalis muscles becomes greater because of the vocal warm-up, the muscles and connective tissues should become more agile and pliable and consequently a greater pitch range should result.

The fundamental frequencies of the top and bottom notes were measured using the VRP (voice range profile) program on CSL from Kay Elemetrics. The samples of the ascending and descending scales were digitized at a rate of 50, 000 cycles per second and displayed on a scattergram from which the highest and lowest pitch were easily ascertained. The frequency range was measured from the ascending and descending scales instead of from a *glissando* or slide. Although most singers can reach slightly higher and lower pitches when performing a *glissando* than when singing with full control, controlled production (the sustaining of frequencies by the singer with "good vocal technique") is the norm in singing so it was chosen for study here.

EGG

The electroglottogram (EGG) produces a waveform corresponding to the waveform produced by the glottis, uninfluenced by any filter characteristics. It was expected that changes in the vocal production technique due to the vocal warm-up would be reflected in the glottal waveform. Two measurements were taken off the EGG waveform: the amplitude of the fundamental and the closed quotient.

As the velocity of the closure increased, it was hypothesized that the ratio of time the glottis is closed in a single period should increase; that is, the glottis should remain "closed" longer. This should be reflected in an increase of the closed quotient.

Increased transglottal airflow may be interpreted as a more efficient use of the voice. In the waveform, increased transglottal airflow corresponds to an increase in the fundamental of the glottal waveform (also called the source fundamental). The amplitude of the source fundamental has been shown (Sundberg and Gauffin, 1989) to be directly related to the peak-to-peak amplitude and to the maximum value of the transglottal airflow in a period. An increased amplitude correlates to greater transglottal airflow which should mean a more "efficient" use of the voice.

The amplitude of the fundamental of the glottal waveform also has a correlation with the mode of vibration of the vocal folds (Sundberg , 1987). "Flow phonation" is a term used by Sundberg to describe a laryngeal setting with low adductive force and low subglottic pressure (Sundberg, 1987, p. 80). It is the state of the glottis where any further decrease in closure would result in breathy phonation. It is this laryngeal setting which can be viewed as the most "efficient" for singing – minimal glottal constriction with maximal airflow.

Sundberg's concept of flow phonation is very much what traditional voice paedagogy views as the ideal singing voice. Shakespeare (1921, p. 25), in his section on *The Voice on the Breath* writes "the vocal cords … are poised and balanced, as it were, on the breath. They seem almost too far apart. The fullest tone is produced with the *least breath*."[3] Johnson (1916, p. 20) holds that "economy of breath is of great importance. Too great a pressure of the breath is particularly destructive of musical quality in voices, producing hard and harsh singing."

Esling (1984) examined the glottal waveforms of various laryngeal settings and also looked at laryngoscopic pictures of these settings. He says that "a relatively long closing phase and consequently high RT/FT remains the salient feature of whispery and breathy voice"[4] (p. 61). Changes in the laryngeal waveform are gradual, not absolute. As a singer moves towards a breathy voice quality setting there should be a gradual increase in the closing phase. In dealing with the ideal singing voice, the singer will not, in fact, become breathy, but will reach flow phonation; viz. the state of the glottis just prior to breathiness. There should still, however, be an increase in the time of the closing phase.

The closed quotient is the time the vocal folds are in contact expressed as a percentage of the period. Howard and his associates (1990) found that the closed quotient was greater in trained male voices than in untrained voices. A subsequent study (Howard, 1995) found that similar results occur with female voices but that there seems to be a certain pitch or, possibly, register dependence. Howard, et al (1990, p. 211) summarize their findings as:

> by increasing [the closed quotient], the professional singer is able to make use of a natural acoustic consequence of an adjustment to the manner in which the folds vibrate to increase overall system efficiency, by means of (a) an increase in output acoustic energy associated with (b) a decrease in the expenditure of stored input energy.

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[3] *Least breath* here refers to effort, not airflow.

[4] RT/FT is the ratio of rise time to fall time. This refers to the shape of the glottal waveform

Griffin et al. (1995) looked at the open quotient (percentage of time in a cycle when the glottis is open) as part of their study on the physiological characteristics of the supported singing voice. They found that "glottal open quotient decreased for all conditions in supported voice" (p. 49). If the amount of time the glottis is open decreases, then the amount of time it is closed increases.

The vocal warm-up is intended to "prepare the voice for singing," to "establish physical readiness for singing" and to "establish proper breathing habits" (Robinson and Althouse, 1995, p. 5). If the singer's voice is undergoing these changes during the warm-up, then it should be observable in the voice waveform. As the singer moves towards a more efficient or better supported voice, both the closed quotient and the amplitude of the voice source fundamental should increase.

The EGG signal was digitized and analyzed using both the EGG program on CSL and the regular CSL program. The level of the fundamental was measured off a long term average spectrum of the EGG signal of the sustained vowel using the regular CSL program and the closed quotient was derived by using the closed quotient algorithm of the EGG program.

AMPLITUDE

In musical terms, this section looks at the singer's control over dynamics (or his/her ability to sing loudly and softly). In acoustic terms, we are looking at energy. To measure the acoustic side of this, measurements of the singer's performance at three amplitudes (relative to each other) were taken. Measurements taken after the warm-up were expected to show a greater dynamic range; *fortissimo* would be louder and *pianissimo* would be softer.

Amplitude was measured off a scattergram done on the VRP program of CSL (the details are the same as for the scattergrams on page thirty-six in the section on F_0 range). The singers were asked to sing a comfortable pitch at three different loudnesses, *mezzo-forte, fortissimo* and *pianissimo*. These were displayed on the scattergram and measurements were taken of highest and lowest energy samples.

4
RESULTS

BANDWIDTH OF THE SINGER'S FORMANT

As the voice is warmed-up, it was expected that the bandwidth of the singer's formant would decrease. The results are shown in Table 4-1. Subjects are labeled according to voice type with S indicating soprano, T indicating tenor and B indicating bass (including baritones).

	before	after
S1	1623 Hz	1829 Hz
T1	822 Hz	705 Hz
T2	238 Hz	238 Hz
T3	545 Hz	562 Hz
T4	1642 Hz	1837 Hz
B1	710 Hz	474 Hz
B2	446 Hz	610 Hz
B3	972 Hz	864 Hz

Table 4-1: Bandwidth of singer's formant

The results here did not support the hypothesis; no statistical significance was found. (The levels accorded to significance are discussed in the section on statistical analysis below.) Half of the subjects showed an expansion of the bandwidth of the singer's formant; one remained the same (T2) and only three showed the expected decrease. This, however, may be explained with reference to the amplitude of the singer's formant (*q.v.*). As the amplitude of the singer's formant increases due to the clustering of formants four and five, the slope of the formant decreases as energy from further areas is incorporated into the singer's formant. This will be interpreted as an increase in colour in the spectrogram, making the formant appear not narrower but wider. In cases where there is a marked singer's formant prior to the warm-up, however, further focusing would reduce the slope.

Amplitude of the Singer's Formant

With this measure, the warm-up was expected to increase the amplitude of the singer's formant.

	before	after
S1	25.89 dB	38.72 dB
T1	26.19 dB	32.36 dB
T2	19.67 dB	20.87 dB
T3	26.81 dB	32.28 dB
T4	28.84 dB	32.42 dB
B1	27.31 dB	30.13 dB
B2	35.68 dB	38.27 dB
B3	17.74 dB	24.00 dB

Table 4-2: Amplitude of singer's formant

This measure showed the most remarkable results. It is a very simple measurement but, apparently, a very important one. All eight singers showed a marked increase in the amplitude of either the upper formants (F_4 and F_5) or of the singer's formant if it occurred. Using a t-test for correlated samples, the change from before the warm-up to after the warm-up was shown to be highly significant ($p \leq 0.005$). The warm-up made quite a considerable difference in the singers' ability to project the voice.

F_0 RANGE

For this portion of the study, the subjects were asked to sing an ascending scale in their upper *tessitura*[1] continuing up to the highest note they could comfortably control and a similar descending scale in the lowest tessitura. The warm-up was expected to increase the pitch range. The results are shown in Table 4-3. The results under the heading "top pitch" were expected to have higher results (higher pitches) after the warm-up while the post warm-up results under the "bottom pitch" heading were expected to be numerically (and aurally) lower.

The actual results of this section show some interesting characteristics which are dependent on voice type. The t-test for correlated samples showed the expansion of the F_0 range in the upper tessitura to be significant ($p \leq 0.025$). Expansion in the lower tessitura was not found to be significant. The tenors and the soprano (both classified as "high" voice types) showed a pitch range increase at the upper end of the scale (in the upper tessitura) while the bass/baritones showed an increase at the lower end of the scale. The results for singer B1 fall in with the high voice types and it is interesting to note that he is a very high baritone who sings predominantly in the upper tessitura.

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[1] *Tessitura* is an Italian term meaning an unspecified subsection of the pitch range.

	TOP PITCH		BOTTOM PITCH	
	before	after	before	after
S1	987 Hz (B^6)	1108 Hz (C^6)	155 Hz (D^3)	185 Hz ($F\#^3$)
T1	523 Hz (B^5)	587 Hz (D^5)	98 Hz ($F\#^2$)	77 Hz (D^2)
T2	311 Hz ($D\#^4$)	330 Hz (E^4)	82 Hz (E^2)	82 Hz (E^2)
T3	370 Hz ($F\#^4$)	440 Hz (A^4)	82 Hz (E^2)	92.5 Hz ($F\#^2$)
T4	370 Hz ($F\#^4$)	415 Hz ($G\#^4$)	92.5 Hz ($F\#^2$)	98 Hz (G^2)
B1	440 Hz (A^4)	493 Hz (B^4)	73 Hz (D^2)	73 Hz (D^2)
B2	370 Hz ($F\#^4$)	370 Hz ($F\#^4$)	65 Hz (C^2)	61 Hz (B^2)
B3	349 Hz (F^4)	330 Hz (E^4)	69 Hz ($C\#^2$)	65 Hz (C^2)

Table 4-3: Highest and lowest pitches; controlled production

The results indicate that the part of the pitch range which expands is that part which is used predominantly when singing. This split may also be a result of letting the singers perform their own warm-ups. The singers are preparing for singing what they usually sing, which includes the general pitch range of performance.

LEVEL OF THE FUNDAMENTAL

This portion of the study examined the influence of a vocal warm-up on the level of the fundamental of the glottal waveform. The level of the fundamental of the glottal waveform was expected to increase after the vocal warm-up.

Singer T3 is excluded from these results as mechanical problems with the laryngograph prevented the recording of an adequate EGG signal for analysis. The results are shown in Table 4-4.

The difference between these results was not found to be significant but the results show an unexpected trend. The high voices all showed the hypothesized increase but the bass/baritones all did not. While a split along the same dimension seems intuitively acceptable for the pitch range , it is difficult to speculate on what could cause a similar split in the amplitude of the glottal fundamental. Further study with a larger subject pool is obviously necessary to determine if this split is simply an anomaly or the result of register or pitch differences.

	before	after
S1	35.11 dB	36.64 dB
T1	48.00 dB	48.41 dB
T2	42.94 dB	44.71 dB
T4	40.68 dB	46.37 dB
B1	43.49 dB	41.29 dB
B2	49.73 dB	47.77 dB
B3	47.74 dB	44.74 dB

Table 4-4: Level of the fundamental of the voice waveform

CLOSED QUOTIENT

The second measurement taken from the electroglottographic signal was the mean closed quotient. Vocal warm-up was expected to produce an increase in this measure. Again, singer T3 is omitted due to the mechanical problems with the EGG during his recording session. The results are in Table 4-5.

Six of the seven subjects showed the hypothesized increase with the results of a t-test for correlated samples showing significance ($p \leq 0.025$). The soprano's very large standard deviation in the post warm-up should be noted. This subject had a relatively unstable waveform in the post warm-up recordings. She also had the longest warm-up (about 45 minutes) and may, in fact, be showing signs of vocal fatigue. Singer B3 is the one singer whose closed quotient decreased. However, he had quite a high closed quotient to start with (45.20%) and is quite an experienced singer so perhaps this is an area where his voice needs little warming-up.

	before	after
S1	32.45%±3.14%	35.25%±10.53%
T1	44.33%±1.15%	48.31%±1.19%
T2	36.57%±1.46%	41.24%±2.00%
T4	40.67%±1.30%	47.65%±0.96%
B1	40.68%±2.22%	47.61%±2.63%
B2	40.88%±0.82%	49.25%±1.82%
B3	45.20%±0.96%	43.88%±0.84%

Table 4-5: Closed quotient; percentage of period that glottis is closed or closing

These results show that the singers are moving away from breathiness. It would seem that most singers "overshoot" in terms of voice production and gradually refine the voice to its optimal quality. They go past the point of flow phonation and work their way back to it. Intuitively this makes sense as it should be easier to gradually close the vocal folds than to gradually open them.

AMPLITUDE

Warm-ups are considered to produce a greater dynamic range. The amplitude was expected to be higher for the loudest tones and lower for the softest tone after the warm-up.

These results (Table 4-6) showed insignificant results; no significant correlation was found. The results for B2, for example, had a lower numerical amplitude for the post warm-up *fortissimo* than for the *mezzo forte*,[2] yet, having done the recording, I can state that the *fortissimo* was, indeed, perceptibly the louder of the two. It can only be assumed that he moved away from the microphone.

	LOUD		SOFT	
	before	after	before	after
S1	122 dB	122 dB	93 dB	90 dB
T1	119 dB	119 dB	101 dB	101 dB
T2	111 dB	113 dB	94 dB	93 dB
T3	108 dB	117 dB	95 dB	97 dB
T4	114 dB	117 dB	88 dB	93 dB
B1	116 dB	116 dB	89 dB	92 dB
B2	130 dB	113 dB	110 dB	103 dB
B3	117 dB	104 dB	73 dB	74 dB

Table 4-6: Dynamic range

[2]It should be noted that the *mezzo forte* was included only as a reference for the singer and was not included in the analysis.

The most interesting result was that of tenor, T1. His results before and after the warm-up were exactly the same! It is difficult to know if he has a preset level for *fortissimo* and *pianissimo* – are they, in fact, absolute values for him?[3]

This portion of the study could be organized differently in future studies. A head mounted microphone would be a great asset and, when instructing the singers, they should be asked to sing as loudly and as quietly as they can (while still singing safely) rather than being asked to sing *fortissimo* and *pianissimo* . Such modifications would provide more consistent results.

STATISTICAL ANALYSIS

A summary of the statistical results is given in Table 4-7 below along with the actual probabilities of error for the significant results.

The results of the measurements in this study were analysed using a t-test for correlated samples which showed significance in three of the measurements: the amplitude of the singer's formant; the upper expansion of the fundamental frequency range and the closed quotient of the glottal waveform. The null hypothesis was not rejected if the probability of significance was below $p \leq 0.05$. As the number of subjects in this study was small, the results of the three measurements showing significance were put through a Wilcoxon signed rank test, a non-parametric test for correlated samples (Butler, 1985), as an additional test of significance. All three of the measurements showed significance in these

[3]In Italian, *fortissimo* (*ff*) is the superlative of *forte*, 'loud' and *pianissimo* (*pp*) is the superlative of *piano*, 'soft'. They are literally translated as "as loudly/softly as possible'. However, by the late nineteenth century, composers had begun to use *fff* and *ppp* or even longer strings, which have no linguistic correlate but are terms of relative loudness. Thus, the concept of an absolute value for *ff* or *pp* is not unreasonable.

tests, as well. The measurements which showed statistical significance all did so with a high probability; the lowest level of significance was ($p \leq 0.025$).

	t-test for correlated samples	Wilcoxon signed ranks test
Singer's formant bandwidth	not significant	n/a
Singer's formant amplitude	significant ($p \leq 0.005$)	significant ($p \leq 0.005$)
F_0 Range – top	significant ($p \leq 0.025$)	significant ($p \leq 0.025$)
F_0 Range – bottom	not significant	n/a
Level of glottal fundamental	not significant	n/a
Closed quotient	significant ($p \leq 0.005$)	significant ($p \leq 0.025$)
Amplitude	not significant	n/a

Table 4-7: Statistical results of experimental measurements.

5
DISCUSSION & CONCLUSIONS

SPEECH AND SINGING

When singing teachers train their students, they are usually trying, in the beginning, to get them to produce sounds with a very definite sound quality. This sound quality has its corresponding physiological make-up which may be viewed as a voice quality setting. If singing is regarded as a voice quality setting then training the voice is, in fact, learning to switch voice quality settings voluntarily. In this context, the vocal warm-up is the transition between the two settings. Following this idea, the acoustic analysis of the singer's voice before and after the warm-up should show measurable differences.

In order to study the differences before and after a vocal warm-up, it is customary to use choral singers rather than professional singers. Professional singers (and highly trained amateurs), like their athletic counterparts, are in such good physical condition that they are capable of highly skilled performance even in a "cold" state. It must also be remembered that voice quality settings are defined as "habitual." This means that, in highly trained singers, there is the possibility that the habits of singing may be carried over into their speech. An analogy may be drawn here with highly trained dancers who automatically move with noticeable grace and precision, even when not dancing.

The study in this paper examined eight choral singers performing simple tasks before and after their usual vocal warm-ups. They were asked to sing a repeated *arpeggio*, a sustained tone on a comfortable pitch, an ascending scale in their upper *tessitura*, a descending scale in their lower *tessitura*, and a sustained tone on three levels of loudness (very soft, moderately loud and very loud). These data were then analysed for amplitude and bandwidth of the singer's formant, range of the fundamental frequency, amplitude of the voice source fundamental, closed quotient of the voice source fundamental and amplitude range.

CONCLUSIONS

What effect do vocal warm-ups have on the voice? The measures examined in this study provide some very interesting results.

The vocal warm-up was predicted to have a significant effect on the prominence of the singer's formant. This hypothesis is well supported in terms of the amplitude of the singer's formant. Even in singers who did not exhibit a clear singer's formant, there was a significant increase in the amplitude of the upper (fourth and fifth) formants. The use of bandwidth as a measure of focus in the singer's formant was not a successful measurement, probably due to the fact that the increase in amplitude caused a general increase in energy in the area surrounding the singer's formant. Likewise, similar patterns occurred in cases with no readily observable singer's formant. Amplitude is translated as darkness on the spectrogram and as the amplitude of the centre of the formant increases, the amplitude of the surrounding harmonics is also increased. This could cause the bandwidth to appear wider.

The expected expansion of the fundamental frequency range was only partially supported. Only the upper limit of the range was significantly improved. This seems to be a factor of voice type: the pitch range expands in the tessitura of general use. This study was not controlled for voice type and, as a result, contained a disproportionate number of singers with high voices. The results of the low-voice singers indicate that it is likely that the main expansion of their pitch range would be on the bottom end of the range. This, of course, needs to be examined more fully. Future analysis must include more altos and basses.

In terms of the glottal waveform, the warm-up was expected to increase both the amplitude of the source fundamental and the closed quotient. The results for the amplitude of the fundamental proved not to be significant but the closed quotient was shown to exhibit the expected increase. There was an unexpected split in the results of the amplitude of the fundamental: the increase was found only in the high voices. Again, further study with a larger, more evenly distributed data pool is required before any generalizations can be made. In future studies, it may prove useful to find another way of getting a measurement of the amplitude of the glottal waveform fundamental. Measurements taken off the FFT are limited by the resolution of the computer and are consequently a bit imprecise. It may be possible to determine the amplitude mathematically which may provide more conclusive results.

The amplitude range was expected to increase but the results were inconclusive. The experimental set-up made it very difficult to control the distance of the subject from the microphone. As some singers seem to change their posture when singing loudly (probably to increase lung capacity) this may have had a direct effect on this section of the experiment. As well, the instructions given to the singers may have been ambiguous causing some subjects to sing at pre-determined levels rather than at the extremes of production.

PHYSIOLOGICAL IMPLICATIONS FOR THE VOICE USER

It is possible to make a few inferences about physiological changes due to the vocal warm-up from the results of this study .

The increase in amplitude of the singer's formant implies that there is an improvement in the singer's physiological production of it. The singer, by warming-up, has improved his/her ability to project the voice. If we follow Sundberg's model of production of the singer's formant of two tubes with a ratio of one to six, then presumably there is a physiological change towards that ratio. That is, the singer is assumed to be narrowing the laryngeal and aryepiglottic region and opening up the pharynx so as to produce the two tubes of differing radii.

If the prominence of the singer's formant has increased, this will mean that the singer will be better able to project his or her voice. The singer's formant provides an increase in energy at a pitch level above the average level of an orchestra (or, for that matter, a single piano or any other accompanying instrument). Any increase in the singer's formant will only be an asset to the singer.

Physiological implications also arise out of the glottal waveform results. The increase in the closed quotient shows that the warm-up helps to modify the laryngeal functioning of the singer. An increase in the closed quotient means that the voice is moving towards flow phonation, an extremely efficient phonation type with minimal subglottic pressure and minimal glottal constriction. The singers appear to be improving the voice; starting with a very free, breathier flow of air and gradually refining the production of the voice.

The increase of the fundamental frequency range implies a greater range of motion of the laryngeal muscles and vocal folds. Increasing the pitch range at the top means that the vocal folds are capable of being stretched more tightly after the warm-up than before. This may be a result of either decreased viscosity or increased flexibility; probably it is a combination of both. The advantage of an increase in pitch range is fairly self-evident. Most singing repertoire requires a wide pitch range and anything which expands the pitch range will be welcomed by the singer.

WARM-UPS AND BEYOND

The results of this study lead to further areas for research. Some measures showed great promise in this study – prominence of the singer's formant, the closed quotient, the fundamental frequency range. These need to be examined on a grander scale to search for general trends in a larger population. Modifications in the experimental structure such as the use of head mounted microphones and changing the instructions would very likely provide significant results in the amplitude range, as well.

It would be interesting to examine the effects of warm-ups on subjects who are not choral singers. One suspects that singers in other styles would show similar results – in particular that voice production would become more efficient. There will probably always be an increase in pitch range; singing requires a much wider pitch range than speaking, regardless of the style. It would also be interesting to compare the results of vocal warm-ups on singers with the results of trained actors. Again, strong similarities would be expected.

Direct physiological studies on the influences of vocal warm-ups would be invaluable but the invasiveness of this kind of study makes this virtually impossible. Electromyographic analysis is a possibility. This could be used to see if the warm-up increases the efficiency of the nerve functioning.

Study of vocal warm-ups provides an alternative way for speech scientists to examine the singing voice without having to look at long-term changes. To examine characteristics of the singing voice, the changes found in moderately trained singers before and after a warm-up can give useful information about what is important in the singing voice. It should be repeated here that choral singers and moderately trained singers are the best subjects for such studies as highly trained singers are like highly trained athletes – in very good shape. They are capable of very skilled performance even in a "cold" state.

The Ideal Warm-up

Is there an ideal warm-up? Probably not. It is possible, though, to provide a few general guidelines.

The warm-up should be tailored to the needs of the performer and the performance or training regimen which is to follow. The warm-up should certainly target voice production in the desired style of singing; an opera singer and a belter should use slightly different warm-ups. An observation arising out of allowing the subjects to choose their own warm-up is that the warm-up should have relevance for the voice user. The results of the fundamental frequency range show that the subjects warmed up in the range in which they were expecting to perform. If you do not sing at the bottom of your range, why bother to focus on that area?

The psychological implications of warm-ups are also very important in regard to the appropriateness of a warm-up. The warm-up is intended to prepare not only the voice but the singer as well. The singer wants to know that he/she will sound "good," particularly in performance. A belter performing an operatic warm-up still has no idea how his/her belting voice sounds; a belting warm-up is required. Much of the bare bones structure of the two warm-ups may, in fact, be the same but the differences are very noticeable to the performer.

The warm-up should be more than simply singing a song; it should focus on voice production and the gradual building of physical and mental readiness for singing. Miller's (1990) suggestion of starting with mild physical exercise is a good idea. This would get the blood flowing and start to increase the core temperature. Increased exercise leads to greater oxygen intake which, in turn, works the breathing muscles, viz. warms up the breathing muscles. This could lead into specific exercises for breath control. A good combination might be Machlin's (1966, p. 241) warm-up exercises two and three:

2. *Relaxation*. Yawn, inhaling deeply and stretching the jaw as wide open as possible. Vocalize as you exhale, *aaaaah!*
3. *Breath Control*. Breath in deeply and fully. Exhale as slowly as possible through rounded lips.

Follow this with exercise 1a from Telfer (1995, p. 5) which consists of inhaling over a count of four followed by eight repeated, accented s's. This exercise takes the equivalent of three bars of 4/4 timing:

4/4 *Breathe* 2 3 4 | s! s! s! s! | s! s! s! s!

A good way to segue[1] from breath to voice would be a vocalise involving long, sustained tones at a comfortable pitch (Marchesi, Opus 15, no. 1 is an excellent example for classical technique warm-ups). A vocalise of this sort continues to work the breathing muscles while initiating contraction of the muscles involved in voicing and articulation. The tissue temperature of the specific muscles involved would be increased by this gentle use of the voice. Easy vocalization will also help to initiate the neural pathways necessary for efficient voice use. It is at this point that changes in the glottal waveform and the singer's formant would be expected to start appearing. Easy vocalizations where the singer can concentrate on "placing" the voice and improving the quality of the tone would help to further these changes. The singer should be comfortable with basic tone production before moving on to extending the range of either pitch or amplitude.

Working on the extremes of the voice (both pitch and amplitude) should be approached gradually so as to minimize the risk of potential damage. For pitch expansion in the top of the range, any sort of *arpeggio* type exercise would work. These are very common and often consist of an ascending *arpeggio* and descending scale joined with a small mordent or decoration – although there is nothing wrong with unadorned arpeggios. The pattern is repeated on rising semi-tones to gradually expand the upper pitch range. Similar pattern based exercises repeated on descending semi-tones would work to expand the pitch range downwards. Singers often equate dynamics (amplitude variations) with breathing so amplitude warm-ups could be placed either with range expansion or with breathing exercises, depending on the individual's approach. Exercises involving gradual crescendos and decrescendos help expand both the singer's

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[1] pronounced /'sɛgwe/

range and his/her control over amplitude changes. Again, gradual expansion is generally safest.

Warm-ups for the articulation muscles may, in fact, be combined with many of the other warm-ups by adding words or syllables particularly in combinations which require rapid lip and tongue movement. If further work is needed for the articulators (the lips, the teeth, the tongue), simple exercises with these rapid transitions can be added to the warm-up regimen.

The warm-up should not be viewed as a training exercise but as a preliminary to training or performance. Much of the warming-up of all the muscles involved can be done simultaneously, as singing does not isolate the individual components of voice production but requires the cooperative effort of all of them.

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Title of Thesis:

Acoustic Effects of Vocal Warm-ups on Singers' Voices

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January 21, 1999