INTRODUCTION

The teaching of singing has developed over many centuries, but there is still much controversy about what techniques will optimize singing performance. Experienced singers and teachers refer to the importance of abdominal or diaphragmatic muscle “support” for achieving optimal control of the breath, influencing tone quality, range, dynamics, and especially projection of the sound over an orchestra. However, the nature of the contribution of abdominal/diaphragmatic muscle support to vocal control and efficiency (if any) is not clear, and the methods used to teach breath control for singing vary widely. Recently there have been attempts to quantify the physiological characteristics of support and its effect on the singing voice. The results of these investigations have however shown a wide variability in the respiratory strategies employed by different singers. In Leanderson et al., the use of the diaphragm in generating support was shown to vary between singers. Griffin et al. showed that although there was a difference in voice quality between supported and unsupported singing, the breathing patterns were highly variable, and furthermore the singers’ perceptions of their own breathing differed from the empirical measurements. Recently Thomason and Sundberg have shown that professional singers show consistent breathing patterns when repeating the same music a number of times, implying that the singers are following some optimized breathing pattern.

In this study we attempt to reduce the intersubject variability by recruiting singers who have been trained by a single teacher and so presumably follow a more consistent method of support than a more...
general sample of singers (acknowledging thereby that our results may be strictly applicable only to this method). We take the term “support” to encompass adjustments in respiratory patterning throughout the breath cycle, and specifically those made by singers to facilitate the requisite control of subglottal pressure without compromising the vibratory operation of the vocal folds. The implication is that the method used to achieve support is not independent of the functioning of the vocal folds, so that achieving a goal such as “enhanced” projection requires concomitant adjustments to the support mechanism. We therefore measured the acoustic output and respiratory patterns of singers as they sang with and without “enhanced” levels of voice projection. Our hypothesis is that increasing the level of projection should be accompanied by changes to the respiratory patterns reflecting the changed use of support.

METHODS

The subjects comprised 5 professional singers, 4 of whom are or have played leading roles in international-class opera companies (refer to Table 1 for subject details). One subject was at an early stage in her professional career (2 years as soloist). Coauthor JC was herself one subject, and chose the other four based on her knowledge of their proficiency in her breath support technique. One subject was therefore aware of the aims of the experiment, whereas the other four were given a general explanation that we were investigating breathing in opera singing. All procedures were approved by the University and Hospital Human Ethics Committees.

All subjects had been taught and were proficient in a specific method of support taught by author JC as part of a strategy to increase the intensity of “projection” in the voice quality. This method emphasizes the use of abdominal support synchronized with the onset of phonation. The principal abdominal muscles actively involved are thought to be transverse abdominis, rectus abdominis, and internal and external obliques. The support activity can be palpated by the teacher or student, particularly at three “centers of activity”: at the level of the xiphoid anchor just below the sternum; around the lateral abdominal girdle; and at the pubic junction 1–3 in. above the pubic bone. In each of these three areas it is possible to feel the muscles contract by firm palpation at the onset of phonation or fractionally ahead in response to prephonatory tuning. As part of the process of learning this method, JC invokes “primal sounds” (e.g., cry, laugh, yell) that when produced seem to naturally generate muscle contractions in the same centers of activity. JC teaches that all singing should be supported, but it is noticeable that during “projected” singing, there is a particular increase in muscle contraction in the lateral abdominal region. This lateral abdominal support appears to provide stability to the actions of the rib cage and diaphragm during phonation. JC emphasizes that this support should never be used during inspiration, but that the abdominal muscle tension should be released at the onset of inspiration to allow a rapid descent of the diaphragm. From the pedagogical experience, it appears that the total release of the abdominal support during inspiration facilitates the smooth reactivation of support for the subsequent phrase.

Because of the requirement to schedule experiments when subjects were available, it became necessary to make use of two separate recording environments. The first was a respiratory laboratory in a hospital, where three subjects were recorded, and the second a television studio where a further three subjects (including a repeat of one subject) were recorded. The reverberation time constant (RT60) was measured as 0.3 s for the laboratory and 0.2 s for the

<table>
<thead>
<tr>
<th>Subject</th>
<th>Voice Type</th>
<th>Age/Years Performing</th>
<th>Aria</th>
<th>Opera</th>
<th>Composer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tenor</td>
<td>43/20</td>
<td>“Salut! Demeure chaste et Pure”</td>
<td>Faust</td>
<td>Gounod</td>
</tr>
<tr>
<td>2</td>
<td>Soprano</td>
<td>59/35</td>
<td>“Vissi d’arte”</td>
<td>Tosca</td>
<td>Puccini</td>
</tr>
<tr>
<td>3</td>
<td>Soprano</td>
<td>26/2</td>
<td>“Quando me’n vo”</td>
<td>La Bohème</td>
<td>Puccini</td>
</tr>
<tr>
<td>4</td>
<td>Baritone</td>
<td>35/14</td>
<td>“Io morro, ma lieto in core”</td>
<td>Don Carlos</td>
<td>Verdi</td>
</tr>
<tr>
<td>5</td>
<td>Tenor</td>
<td>38/9</td>
<td>“Nessun dorma”</td>
<td>Turandot</td>
<td>Puccini</td>
</tr>
</tbody>
</table>

TABLE 1. Subject Characteristics and Aria Details

television studio. Because of these factors, absolute sound pressure levels could not be reliably determined across the entire spectrum or compared between subjects. We therefore normalized the sound levels for each subject to the maximum sound pressure achieved by that singer. Intersubject comparisons can therefore be made based on the limited assumption of relative equivalence between each subject’s maximum sound pressure level. Recording levels and the microphone to subject distance were, however, kept constant so that sound levels could be compared between conditions for each subject. Sound was recorded on a digital audio tape (DAT) recorder (DA-P1, Tascam, Montebello, CA) at a sampling rate of 44.1 kHz, and subsequently transferred to computer via a digital sound interface (Audiomedia II, Digidesign, Palo Alto, CA) and resampled at 22.05 kHz to reduce memory requirements.

Linear magnetometers (GMG Scientific, Burlington, MA) were employed to measure the anterior-posterior (AP) and lateral dimensions of the rib cage and abdomen. Sensors were attached to the skin with double-sided tape at the umbilical level for abdominal dimensions and the nipple level (axilla for female subjects) for the rib cage dimensions. An adjustable frame was provided for the subjects to rest their arms on to reduce movement artifacts. The magnetometer signals were sampled at 100 samples per second (Maclab, AD Instruments, Castle Hill, NSW Australia) together with a representation of the acoustic signal for synchronization purposes. The magnetometer signals were calibrated in centimeters so that the relative movements of the lateral and AP dimensions of the rib cage and abdomen could be compared. For the purposes of lung volume estimation, calibrations were also performed against spirometric measurements obtained with a drum spirometer (Morgan Spiroflow, PK Morgan, Andover, MA) while performing vital capacity (VC), isovolume, and relaxation maneuvers. The volume estimate signal was formed from a weighted sum of the two AP magnetometer signals, with the weighting factor calculated by a least squared error fit to the isovolume data. The measurements of residual volume (RV) and total lung capacity (TLC) obtained during the VC maneuvers were then used to derive a volume scale of percent VC, with the zero level at RV and 100% VC representing TLC. This scale was used instead of absolute volume units to allow for comparisons between subjects. Relaxations were obtained through a high-resistance orifice switched into the expiratory circuit after the subject had relaxed against a closed valve at TLC. Three or four coached relaxations were attempted, and the most consistent two used here.

Subjects sang a part of an aria from their repertoire, selected in consultation with coauthor JC. The arias are listed in Table 1. The aria was sung twice, and the singers were instructed first to “perform as if projecting their voices over a large orchestra,” and for the second take, to “perform as if with a smaller accompanying orchestra, without such a need to project their voices.” Coauthor JC understood these instructions to mean singing with and without the use of “enhanced projection.” For the second group of three subjects, each condition was repeated so that four takes in total were performed by these singers. The order was randomized as shown in Table 2. The singers were accompanied by a pianist playing an electronic piano whose output was fed into open-field headphones which allowed the performers to hear the accompaniment with little disruption to hearing their own voices.

Individual breaths in the recorded data were numbered for identification and the times of initiation and termination of vocalization within each breath were manually located and marked. Figure 1 illustrates the placement of these markers. It was necessary to refer to both the respiratory and acoustic data to accurately position these markers—as indicated in Figure 1A, the instants at which vocalization is initiated or terminated within a phrase may not correspond to maxima or minima of the magnetometer signals. On occasion breaths were taken at different locations in the two takes (i.e., a single breath in one take was replaced by two shorter breaths in the other take), so these breaths were identified and excluded from the paired comparisons between the conditions. Table 2 details the total number of breaths in each take and how many breaths were taken at different locations between takes. For the subjects from which two takes of each condition were recorded, the per-phrase parameters were averaged across the two takes before performing subsequent statistical analyses.

We define here the initiating lung volume (ILV) and terminating lung volume (TLV) for each individual phrase as the values of the estimated volume signal at the instants where vocalization begins and ends within that phrase, respectively (refer to Figure 1).
Total volume used during vocalization $V_{\text{exp}}$ is defined by the difference $\text{ILV} - \text{TLV}$, and mean vocalization flow (MVF) is defined as $V_{\text{exp}}/T_{\text{exp}}$, where $T_{\text{exp}}$ is the duration of the phrase vocalization and $V_{\text{exp}}$ is volume expired. We also measured the inspired volume $V_{\text{insp}}$, and duration of inspiration $T_{\text{insp}}$, for each individual phrase. From the magnetometer signals we obtained the AP and lateral dimensions at the initiation and termination of vocalization and the maximum movement extent during each phrase (note that the maximum extent is not necessarily equal to the initiation minus termination values since, as indicated in Figure 1, the extremes of movement may occur sometime between the phrase endpoints).

The relative contributions of rib cage and abdomen to the respiratory cycle are indicated by the Konno-Mead diagram, which plots the relative movement of one against the other. Referring to Figure 1B, abdominal movement is indicated on the horizontal axis and rib cage movement on the vertical axis. Outward motion (implying inspiration) is upward and toward the right. Any breathing pattern can be displayed on the plot by simultaneously tracing the dimensions of the rib cage and abdomen. Reference points are provided by the relaxation curve, RV, TLC, and functional residual capacity (FRC) points on that curve, and the slope of the isovolume line. By scaling the axes such that an isovolume maneuver displays at a slope of $-45$ degrees, the axes indicate abdominal and rib cage movements in equal volume units. A straight line was fitted through the raw relaxation rib cage and abdomen displacement data for presentation on the Konno-Mead diagrams here. Because our subjects were not experienced in the performance of relaxation maneuvers (and the upright posture imposes some muscle tone anyway), we only made use of the data from the upper part of the volume range. We present Konno-Mead plots for representative breaths from the data. The path followed during a breath, in particular its relative position with respect to the relaxation curve, can implicate different muscle activation patterns.

For each phrase, the mean acoustic power in dB (unweighted) was computed. We then computed the average power spectral density by means of the fast Fourier transform (FFT) calculated on a series of overlapping segments throughout the duration of the phrase. The segment size was set to 20 ms (440 samples), with segments spaced at 5 ms. A Blackman window was applied to each segment which was then extended to 2048 samples before computing its FFT. The mean of the squared absolute FFTs was calculated and normalized to take account of the effects of the window. The power in the average spectrum is thus comparable to the power obtained from the time domain acoustic signal. From the average power

<table>
<thead>
<tr>
<th>Subject</th>
<th>Order of Takes</th>
<th>Number of Breaths</th>
<th>Anomalous Breaths</th>
<th>Duration of Extracts (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P-P-NP-NP</td>
<td>30, 29</td>
<td>30, 30</td>
<td>206, 207</td>
</tr>
<tr>
<td>2</td>
<td>NP-P-P-NP</td>
<td>23, 24</td>
<td>24, 24</td>
<td>166, 167, 163, 166</td>
</tr>
<tr>
<td>2A</td>
<td>P-NP</td>
<td>10, 10</td>
<td>0</td>
<td>69, 63</td>
</tr>
<tr>
<td>3</td>
<td>P-NP-P-NP</td>
<td>23, 23</td>
<td>23, 23</td>
<td>132, 134, 130, 134</td>
</tr>
<tr>
<td>4</td>
<td>P-NP</td>
<td>24, 24</td>
<td>0</td>
<td>133, 136</td>
</tr>
<tr>
<td>5</td>
<td>P-NP</td>
<td>22, 22</td>
<td>2 (phr 15 in take 1, phr 11 in take 2)</td>
<td>154, 177</td>
</tr>
</tbody>
</table>

Abbreviations: NP, nonprojected; P, projected.

*The anomalous breaths are indicated by the phrases in which two breaths were taken in the other takes in place of one breath in the indicated take.
spectral density for each phrase, the power in the frequency bands 0–2 kHz and 2–4 kHz was obtained and denoted by $P_{lo}$ and $P_{hi}$, respectively. The choice of these frequency bands was based on previous studies that have shown that the acoustic energy or peak amplitude within the band 2–4 kHz gives a good representation of the “ringing” quality in a singer’s voice.\textsuperscript{11-13} The ratio $P_{hi}/P_{lo}$ was also calculated.

**RESULTS**

Figures 2 and 3 illustrate the respiratory patterns of the subjects during singing their aria both with and without projection of their voices. The rib cage and abdominal AP motion during the loudest phrase is shown in Figure 2 on Konno-Mead plots, sized so that the length of each axis equals an equivalent volume contribution of 100% of the subject’s VC. Isovolume lines are shown at both RV and TLC lung volume levels (note that the actual isovolume maneuvers were performed at around FRC, but these lines indicate the volume extremes of movement defined by the model of breathing based on rib cage and abdominal movement only. A straight line fit through the relaxation curve, and the FRC configuration during relaxed quiet breathing, are also indicated for reference purposes. We should point out that time is not represented on these plots, so that slow and fast movements that follow the same path are not distinguished. Figure 3 shows the time-course of the magnetometer and lung volume signals for the same phrases represented in Figure 2, with the lengths of the vertical axes again set equal to 100% of each subject’s VC.

The “smoothness” or otherwise of the vocalization paths shown in Figures 2 and 3 is of course affected by the phrase structure, which differs between subjects because of the differences in their singing repertoire. Despite this, notable similarities between the patterns shown by different subjects include the inspiration path, which in nearly all cases begins with a rapid “isovolume” movement in which a rapid expansion of the abdomen occurs concurrently with a decrease in rib cage dimension such that there is negligible net change in volume. It should be noted that the duration of this initial part of the inspiration path is of the order of 100 ms, as indicated by the tracings shown in Figure 3. The inspiration then continues, with both rib cage and abdominal movement following the path of the relaxation line, after which a further realignment occurs involving a simultaneous elevation of the rib cage and drawing in of the
abdomen. Vocalization is often initiated part-way through this change, after which it continues with a simultaneous decrease in both rib cage and abdomen dimensions, so that the respiratory path followed is roughly parallel to the relaxation line. There do not appear to be consistent changes in the paths followed.
between the projected and nonprojected conditions, although this could simply be because of the musical differences between phrases shown for each subject. It is worth noting that the two plots for Subject 2 (2 and 2A) in Figure 2, representing the same phrase sung by the same singer, were obtained a year apart.

FIGURE 3. Time waveforms of the rib cage and abdomen AP movements, and resulting lung volume estimate, for the phrases shown in the Konno-Mead plots of Figure 2 for each subject. The dark line represents the projected condition and the gray line the nonprojected condition. The horizontal line on each graph indicates the FRC configuration, while the instants at which vocalization begins are indicated by a vertical line. Note that for Subject 1 there is an additional short inspiration for the projected condition only. As in Figure 2, only the lower left chart is annotated.
Although the overall shape is similar, there is quite a difference in the detailed shape at the pitch transition in the phrase, with a sharp movement upward and to the left on one occasion (2A) but a smoother (although convoluted) movement to the left on the other occasion (2). When the temporal tracings of the signals (Figure 3) are examined, this difference is seen to occur because the rib cage movement is later, and slightly larger, on the earlier occasion (2A).

Figure 4 shows average power spectra obtained from each singer for the two conditions. Male singers are on the left and female on the right, highlighting the prominent singer’s formant in the male voice. However, it is evident that the energy in the higher frequency regions is greater for the projected condition in both male and female singers (although it is clear that there is not just a single “formant” that is enhanced). The differences between Subject 2 and 2A (the same singer) are partly because only a portion of the aria was recorded on occasion 2A (including the most dramatic phrases, which possibly accounts for the greater observed difference). Only two singers (Subjects 4 and 5) show some increased energy within the 0-2 kHz band for the projected case. The difference between the projected and non-projected conditions, averaged across all subjects, is shown in Figure 5, indicating that there is increased acoustic energy throughout the frequency range 1.6–6 kHz (although the average energy in the singing voice falls off rapidly above 3–4 kHz as shown by the curves in Figure 4).

**FIGURE 4.** Average power spectral density over all breaths for each condition shown for each of the subjects. The *solid line* represents the projected condition and the *dotted line* the nonprojected condition. Each graph has the same axis dimensions and labels as identified on the lower left chart.
Descriptive parameters extracted from the respiratory and acoustic data are presented in Figures 6 and 7, respectively, with a summary of the overall statistics appearing in Table 3. Because much of the wide spread in parameters indicated in the overall statistics is a consequence of differences in the musical demands of individual phrases, it is appropriate to perform a phrase-by-phrase comparison between the projected and nonprojected conditions. The scatter-charts shown in Figures 6 and 7 represent the parameter for each phrase as a point having a position specified by the parameter’s value in both the projected (horizontal axis) and nonprojected (vertical axis) conditions. The line of identity, corresponding to the null hypothesis when both conditions yield identical parameter values, is also drawn. A preponderance of points on one side of the identity line reveals a shift in that parameter between the two conditions, even when the range of values overlaps considerably as shown.

Statistical analyses of the phrase-by-phrase comparisons (Table 3) reveal that ILV is not significantly different between the two conditions, but TLV is significantly higher for the projected condition, and hence $V_{exp}$ and MVF are significantly lower. The phrase durations $T_{exp}$ do not differ significantly, but $T_{insp}$ is significantly faster in the projected condition. In the acoustic parameters, there is a significant increase in the acoustic power when the singers employ greater projection, but this increase is almost entirely in the high-frequency band, with the average ratio $P_{hf}/P_{lf}$ increasing by 2.4 dB.

As illustrated in Figure 8, there are some differences between subjects, both in their average parameter values, and in the amount of change consequent on the change in condition. However, the overall trends across conditions in the respiratory parameters were opposed by only one or two subjects, in particular Subject 5 who had shorter phrases and hence higher MVF with little change in $V_{exp}$, and Subject 3 who slightly decreased TLV and increased $V_{exp}$, $V_{insp}$, and MVF. Subject 2 showed consistency between the two experiment occasions except for ILV and TLV, both of which decreased with projection on the first occasion (2A) only. Subject 4 increased $P_{lf}$ and $P_{hf}$ almost equally with projection, resulting in a minimal change to $P_{hf}/P_{lf}$. Notably, all subjects decreased $T_{insp}$ and increased both $P_{hf}$ and $P_{hf}/P_{lf}$ with projection.

Although there is a change in both the acoustic output and some of the respiratory parameters between the two conditions, there is little correlation between
relevant acoustic and respiratory parameters, as shown by the scatter plots in Figure 9. There is some suggestion of a negative correlation between MVF and \( \text{Phf/Plf} \) (\( r^2 = 0.2 \)) for both conditions, implying that the higher values of this acoustic ratio are associated with more efficient glottal vibration patterns (e.g., shorter open quotient and closing transient).

To quantitate the contributions of the rib cage and abdominal compartments, we gave parameters to each breathing cycle by measuring, with reference to the relaxed FRC state, the positions on the Konno–Mead diagram of the start and end of vocalization, and the minimum and maximum extents of the curve in each dimension. Equivalent measurements were also performed on the lateral dimensions. These parameters were then subjected to paired \( t \)-tests between the projected and nonprojected conditions. Results of these comparisons appear in Table 4. Consistent with the lung volume results shown in Table 3, there is little change in the AP dimensions. Notably, there is a significant increase in the RC-AP dimension, particularly at phrase termination, indicating that the previously observed increase in TLV is obtained largely by an increase in rib cage dimension.

However, the lateral dimension of the rib cage is significantly wider for the projected condition at both initiation and termination of the voice, and the lateral abdominal dimension is significantly narrower at initiation. Note that although the lateral dimension of the rib cage was only measured for three subjects, the significance levels of the other measurements are only slightly changed if they are also computed for these three subjects only.

**DISCUSSION**

Although the use of “correct” breath support is generally regarded as necessary in order to effectively produce the singing voice, the relationship between breath support and voice projection is still little understood. Our findings in the experiments described here provide some insight into this relationship.

**Measurement accuracy**

It is relevant to first comment on the measurement accuracies of volume estimates based on rib cage and abdominal dimensions. These are predicated on a linear relationship between the measured dimension

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**TABLE 3. Statistics of Measured Parameters Over All Breaths for All Subjects (Excluding Repeat of Subject 2)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Overall Value</th>
<th></th>
<th>Projected – Nonprojected Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>ILV (%VC)</td>
<td>80.4</td>
<td>12.1</td>
<td>1.9</td>
</tr>
<tr>
<td>TLV (%VC)</td>
<td>36.0</td>
<td>22.3</td>
<td>5.6</td>
</tr>
<tr>
<td>V(_{\text{exp}}) (%VC)</td>
<td>44.4</td>
<td>20.1</td>
<td>-3.8</td>
</tr>
<tr>
<td>V(_{\text{insp}}) (%VC)</td>
<td>43.2</td>
<td>20.5</td>
<td>-4.3</td>
</tr>
<tr>
<td>MVF (%VC/s)</td>
<td>8.7</td>
<td>3.4</td>
<td>-0.71</td>
</tr>
<tr>
<td>T(_{\text{exp}}) (s)</td>
<td>5.4</td>
<td>2.6</td>
<td>-0.07</td>
</tr>
<tr>
<td>T(_{\text{insp}}) (s)</td>
<td>0.90</td>
<td>0.77</td>
<td>-0.08</td>
</tr>
<tr>
<td>P(_{\text{TOT}}) (dB)</td>
<td>-26.3</td>
<td>6.0</td>
<td>1.1</td>
</tr>
<tr>
<td>P(_{\text{H}}) (dB)</td>
<td>-28.2</td>
<td>5.6</td>
<td>0.57</td>
</tr>
<tr>
<td>P(<em>{\text{H}})/P(</em>{\text{L}}) (dB)</td>
<td>-32.9</td>
<td>8.3</td>
<td>3.0</td>
</tr>
<tr>
<td>P(<em>{\text{H}})/P(</em>{\text{L}}) (dB)</td>
<td>-4.69</td>
<td>4.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>

*Abbreviations: NS, not significant; SD, standard deviation.

*The significance of differences between the conditions is computed with the paired \( t \)-test. Note that because multiple comparisons are performed, only differences with an individual significance \( P < 0.002 \) are significant at an experimentwide level of \( P = 0.05 \). These differences are indicated by **."
FIGURE 6. Scatter charts illustrating the breath-by-breath comparison of the respiratory parameters between the projected and nonprojected conditions. The parameters are: ILV = Initiation Lung Volume; MVF = Mean Vocalization Flow; $T_{\text{exp}}$ = expiratory duration; $T_{\text{insp}}$ = inspiratory duration; TLV = Termination Lung Volume; $V_{\text{exp}}$ = Volume expired. Each point on the charts represents the parameter value obtained from a particular phrase in the aria, its $(x, y)$ coordinates on the chart specified by the pair of values obtained in the projected and nonprojected conditions respectively. Individual singers are represented by the following symbols: ○, Subject 1; △, Subject 2; ▲, Subject 2A; ×, Subject 3; +, Subject 4; □, Subject 5. The line of identity, where both the projected and nonprojected values are equal, is also shown on each chart.
and the internal volume, with an assumption that two compartments are sufficient.\textsuperscript{9} It is known however that this model loses accuracy at high thoracic pressures or with movement of the torso.\textsuperscript{14,15} Although we attempted to reduce extraneous movements by supporting the singers’ arms, the high pressure swings inherent in singing activities mean that the volume estimates are limited in accuracy. Furthermore, our measurements of the lateral dimensions showed that significant movements are not always correlated with the AP dimensions, indicating that the AP measurements alone may not be sufficient to represent all changes in torso volume. Particularly at points in the breath cycle when there are large changes in thoracic pressure, it seems likely that the chest wall shape is distorted to an extent that the simple relationship between AP dimension and volume is lost. Such events can be observed in several of the results shown in Figures 2 and 3 where there are momentary increases or decreases in estimated lung volume associated with sudden motions of the rib cage and abdomen (in most cases occurring at points where there are large changes in musical dynamics).

Possible inaccuracies in the lung volume estimation are also implied by the results that apparently show certain singing breaths extending beyond the TLC and RV limits (e.g., refer to Figures 2 and 6). This may be due to the effect that breathing on a mouthpiece (as during the calibration) has on breathing behavior,\textsuperscript{16} but also because the TLC and RV
limits were obtained during somewhat artificial respiratory maneuvers that may not reflect the true capabilities of the singers when naturally engaging their trained respiratory responses during singing. However, because our experiment is designed so that we perform paired comparisons between the two conditions, the absolute accuracy limitations of the volume measurements do not overly detract from the results. Rather, it is the differences between the conditions that are important in our interpretations. We assume that any measurement distortions are similar between the two conditions.

**Lung volumes**

It is perhaps surprising that breathing patterns changed so little when the singers increased the intensity of their voice projection. Previous studies,\textsuperscript{13,17-19} have indicated a relationship between the sound intensity of speech and singing and the lung volumes used, in particular that at higher intensities both speakers and singers tend to breathe at higher lung volumes. In contrast, our results show that breaths are not initiated at higher lung volumes when the voice intensity is increased in the projected condition. The ILV values during singing an aria are of course much higher than in speech and quieter singing,\textsuperscript{20} so one would not expect that much of an increase was possible. There is, however, a significant decrease in the average flow rate, and hence breaths terminate at higher lung volumes.

Our finding that the initiation volumes of the phrases did not change even when the acoustic output increased perhaps indicates the extent to which the breathing of these singers is optimized for the requirements of the particular music. The sizes of the breaths for each phrase are set by the requirements of the music, and must be learned sufficiently well so that the singer can automatically take in a breath of the required size for each phrase during a performance. Watson and Hixon (1996)\textsuperscript{20} showed that there was a strong training effect when one singer became more familiar with a particular aria. Because our subjects all sang arias that were part of their performance repertoire, we can assume that they always took the size of breath required for each phrase, as determined by their previous practice and performance. This consistency between different takes was also observed in the study of Thomasson and Sundberg,\textsuperscript{7} and its appearance in our data, even though we instructed our subjects to sing with different levels of projection, confirms that the memory of the inspiration required, which evolves during the training period, is strongly fixed in well-learned arias. Indeed,

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Individual subject averages for each parameter, shown in both nonprojected (NP) and projected (P) conditions. The parameters are as in Figures 6 and 7. Individual singers are represented by the following symbols: ○, Subject 1; △, Subject 2; ●, Subject 2A; ×, Subject 3; +, Subject 4; ⊙, Subject 5.}
\end{figure}
singers often say that they only sing a piece in one dynamical manner according to its musical and emotional requirements. The consistency of breathing patterns affirms the singers’ perception, but the observed increase in acoustic output in the singers’ formant suggests that subtle alterations in the singing output are indeed possible in response to appropriate stimuli.

**Acoustic output**

It is pertinent to note that the increase in acoustic output we observed is predominantly comprised of an enhancement in the frequency band 2–4 kHz, with only a marginal increase in sound energy in the frequency band 0–2 kHz. Indeed, some negative correlation occurs between the average flow rate for each phrase and the high-frequency/low-frequency acoustic power ratio. This implies that there is a move toward more efficient vocalization in the projected condition. Griffin et al. also found that the glottal open quotient was lower when their singers were using a supported voice. As described by Sundberg, there is a tendency for higher frequencies to be enhanced as sound intensity increases, simply because of the nonlinearity of the glottal flow waveform. However, the actual decrease in MVF suggests an alteration in the laryngeal configuration when the singers are asked for “greater projection,” with the shift in acoustic energy to the high-frequency band caused by a steepening of the glottal closure transient as the glottal open quotient reduces.

Several other studies have utilized the long-term average spectrum (LTAS) to quantify the level of the singer’s formant. Rossing et al. compared the acoustic characteristics of experienced soprano soloists who sang similar passages “as if in a choir”
and “as a soloist.” They found that with “solo singing” there was a significant increase in the energy of spectral peaks around 3 kHz in the LTAS suggestive of an increased singer’s formant. They also measured increased energy in the frequency band 2–4 kHz. Omori et al.12 characterized the “ringing” quality of a singer’s voice by the ratio between the greatest harmonic peak in the 2–4 kHz band to that in the 0–2 kHz band. They found a significantly greater ratio for professional singers than for nonprofessionals or nonsingers. Ekholm et al.13 examined the relative energy in the region of the “singer’s formant” peak identified in the LTAS (choosing a bandwidth defined by the trough between this peak and lower harmonics, which for our male singers at least is approximately at 2 kHz). They compared this measure to perceptual ratings of the voice, finding a high correlation with ratings of “color/warmth” and “resonance/ring.” In combination with these studies, our results also suggest that the relative energy in the band 2–4 kHz in the LTAS provides a good measure of what singers achieve by increasing the projection characteristics of their voices, which may be related to qualitative terms such as “ring” or “twang.”

It seems likely that the relationship between vocal loudness and lung volume may be related to the way in which the increased loudness is elicited. In a study by Stathopoulos and Sapienza (1993)17 in which a positive relationship between speech intensity and lung volume was observed, speech intensity was controlled by means of visual feedback of sound pressure level (SPL). By contrast, Winkworth and Davis (1997)24 employed the Lombard effect (i.e., an increase in ambient sound level) to increase speech intensity without explicitly mentioning SPL to the subjects. They found no relationship between speech intensity and lung volume. In our study likewise, the instructions to the subjects were to imagine that they were projecting their voices over a “large” or “small” orchestra. It is possible that this indirect elicitation of

<table>
<thead>
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<th>Variable</th>
<th>Overall Value</th>
<th>Projected – Non-projected Difference</th>
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<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
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<td>RCAP-I (cm)</td>
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<td>RCAP-T (cm)</td>
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<td>RCLAT-EXT (cm)</td>
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<td>0.22</td>
</tr>
<tr>
<td>ABLAT-EXT (cm)</td>
<td>0.38</td>
<td>0.28</td>
</tr>
</tbody>
</table>

*Note that RCLAT was not obtained for two subjects. Dimensions of the rib cage (RC) and abdomen (AB) in the anterior-posterior (AP) and lateral (LAT) axes are shown relative to the FRC configuration at initiation (-I) and termination (-T) of vocalization, together with the maximum movement extent (-EXT) along each axis.
increased vocal output is associated with a different physiological process than is invoked by a direct conscious demand for “more sound.”

**Chest wall configuration during the singing breath cycle**

The Konno-Mead plots of the rib cage versus abdominal motions are interesting with respect to their correspondence to the pedagogical instructions. Indeed, it is remarkable that all five singers showed a similar overall pattern. When we examine the inspiratory part of the breath, there is an initial rapid outward movement of the abdomen, often associated with a momentary inward motion of the rib cage. This paradoxical pattern was also noticed by Watson and Hixon in their study of classical singers. The short duration of the paradoxical motion, on the order of 100 ms as indicated in Figures 1A and 3, implies that it is simply a mechanical effect of the decompression of the thoracic cavity as the expiratory muscles are released and the diaphragm activated for inspiration. This action appears to correspond to the “splat” maneuver taught by Chapman, where she encourages a rapid deactivation of abdominal “support” musculature together with the diaphragmatic contraction (resulting in a rapid outward movement of the abdomen). The word “splat” is sometimes used to remind the singer to rapidly release the abdominal tension. The release of the support muscle activity, in combination with the negative thoracic pressure generated by the rapid diaphragm contraction, results in the rib cage quickly returning to its relaxation position. This is what produces the rapid “paradoxical” isovolume motion observed at the beginning of most of the fast inspirations in the data.

It seems reasonable to suggest that the “splat” maneuver, which combines a cessation of all support muscle activity (presumably including both inspiratory and expiratory muscle groups) with a rapid and strong activation of the diaphragm, is necessary to achieve the rapidity and depth of inspiration that is necessary for this type of singing. Even in the data of Watson and Hixon, where a variety of patterns are exhibited, comparable patterns to what we observed are seen in some of their more experienced singers, notably in the aria and “fast singing.” The opposite pattern, of inspiration via an increase in rib cage dimension with the abdomen held in, was most often observed by them in slow singing in one subject who apparently came from a different pedagogical tradition than the other subjects. In our data, the smallest extent of the “splat” pattern was seen in the singer (Subject 3) with the least experience.

After the “splat” event, the inspiration continues with both the rib cage and abdominal compartments expanding, roughly along the relaxation line. This implies that the rib cage and abdomen compartments fill in proportion to their relative relaxed compliances, which implies an efficient allocation of inspiratory muscle action to the two compartments. With respect to the pedagogy, this part of the inspiration corresponds to the “all round expansion of the rib cage and belly” described by Chapman and other practitioners. As shown in the detailed results, there is a wide spread in the inspiratory durations, ranging from 0.2 to 4.4 s (note that musical pauses were not counted as part of an inspiration). There was a significant decrease in the inspiratory duration in the projected condition with all subjects, which could be a side effect of the slightly smaller volume requirements, or perhaps because this condition was closer to the performance situation that the singers were used to, thus facilitating a more natural, faster, inspiration.

At the end of inspiration, the chest wall again moves away from the relaxation line, with an inward movement of the abdomen coupled with a continued outward motion of the rib cage. However, the increase in lung volume at this point is negligible, and again the movement can be seen as a paradoxical isovolume maneuver to prepare for the subsequent vocalization. Other studies have examined this “prephonatory posturing” in vocalization, with the consensus being that this movement away from the relaxation configuration optimizes the chest wall mechanics for phonation. This phase corresponds to the activation of support, obtained by a drawing in of the abdomen to create the pressure required for vocalization. Indeed, the results shown in Table 4 indicate that the rib cage is raised from its relaxed position throughout the vocalization, and to a greater extent in the projected condition. The abdominal AP dimension is somewhat greater than the relaxed position at the beginning of vocalization, but moves to a smaller size at the end. There is no difference with the two projection conditions.
Significantly, the lateral dimension of the rib cage increased, and that of the abdomen decreased, in the condition of increased projection. Both changes were greater than any shift in AP dimension, implicating a distortion of the chest wall shape brought about by a change in the activation pattern of support. The dimension changes are suggestive of an increased abdominal pressure with the greater "support" invoked for the projected condition. Because the lower part of the rib cage apposes the abdominal compartment, an increased abdominal pressure exerts an increased outward force on this part of the rib cage,\(^{27}\) which could account for the increase in the lateral dimension of the rib cage during the projected condition. Likewise, strong activation of the transverse and oblique abdominal muscles would tend to compress the circumference of the abdomen and therefore narrow its lateral dimension, as occurs in our results. This finding concurs with the practice of teachers such as author JC who train singers in the actions required for support by asking them to feel with their hands the increased tension in the lateral regions of their abdomen when they successfully "engage the support."

The "phonatory posturing" maneuver can also occur during vocalization when there is a need for a sudden increase in vocal output (either SPL or fundamental frequency) during a phrase, as indicated in Figure 2 by the patterns for several of the subjects. For instance, Subjects 1 and 2 both require a significant increase in subglottal pressure part way through the phrases illustrated in order to attain large pitch leaps. The opposite pattern, when sudden brief cessation of vocalization requires a rapid release and re-activation of support, is shown by the phrase of Subject 3 in Figure 2. In general it appeared that the inward movement was accompanied by an elevation of the rib cage as the pleural and abdominal pressures increase. However, if expiratory muscles in the rib cage are activated simultaneously or earlier than the abdominal contraction, the resulting movement can in fact be reduced as indicated in the two recordings obtained (1 year apart) for Subject 2, shown in Figures 2 and 3. It appears that on the later occasion that muscles driving the rib cage movement may have been activated somewhat earlier (and hence more in synchrony with the abdominal muscle activation) so that the outward movement in response to the contraction of the abdomen was significantly reduced. If pressures had been measured, one would have expected that the increase in subglottal pressure would have been delayed on the earlier recording because of the transient movement of volume between the abdomen and rib cage, but more rapid on the second occasion due to the simultaneous activation of rib cage and abdominal muscles. The implication of this observation for singers is that simultaneous activation of rib cage and abdominal muscles may result in more rapid and possibly better controlled changes in subglottal pressure. Note that for Subject 1 the rib cage movement occurs even earlier (with respect to the abdominal motion) than in Subject 2, although this difference may be partly due to the /s/ between the two notes. Wilder\(^{26}\) suggests that different patterns of prephonatory motion may occur because of differences in posture or in the biomechanical properties of the chest wall between subjects. Both effects could also have contributed to the observed change for Subject 2 between the two recordings, in addition to possible changes in technique over the intervening year, as there are differences in the relaxation curve and FRC configuration which imply some biomechanical change. Overall, however, the resulting parameter values for this subject are very similar for the two occasions (Figure 6).

Vocalization often begins during the movement away from the relaxation line, particularly when the vocal output required is relatively low for the start of the phrase. However, subsequent to the activation of support, sustained vocalization occurs with both the rib cage and abdomen moving inward at a remarkably similar rate (relative to the isovolume and relaxation references). The consistency between subjects seems to be greater than in some previous studies where a range of breathing patterns was found,\(^{7,20}\) probably due to our selection of subjects who follow the technique of a single teacher. Only one singer (Subject 3) shows much greater rib cage than abdominal contribution to the volume expired, but in all subjects the motion is roughly parallel to the relaxation line, suggesting that (during a sustained vocalization) the rib cage and abdominal muscles are activated jointly so that the respiratory system acts as a single compartment. This could provide a gain in efficiency or perhaps improved control of the sustained high pressure required for such vocalizations. This
pattern is in contrast to some of those observed in other studies\textsuperscript{20,28} where patterns of either predominantly rib cage or abdominal motion were also observed. Indeed, some pedagogical traditions teach different patterns such as holding the rib cage out throughout a vocalization, with abdominal movement providing the volume change.\textsuperscript{1}

**CONCLUSIONS**

In conclusion, our findings tend to reinforce the observation of many teachers and singers that “good support” provides needed assistance in projecting the voice. The use of support exhibits itself here as a movement away from the relaxation state, with abdominal muscle activation and a raising of the rib cage, coupled with a rapid release of expiratory muscle activity at the start of inspiration. With the request for an increased level of projection, the rib cage was raised slightly further, and there was a significant shift in the lateral dimensions of the abdomen and rib cage that was suggestive of an increased activation of the abdominal muscles in the lateral area. However, the lung volume at phrase initiation was remarkably consistent, suggesting a well-developed muscle memory of the inspiration required for each phrase. With respect to the increased acoustic output when the subjects were asked to “project as if over a large orchestra,” it is interesting that the additional energy is indeed concentrated in the region of the singer’s formant. This, together with the associated reduction in flow, suggests that the increased projection is accomplished by an alteration in the glottal vibratory pattern. Based on other experimental\textsuperscript{5,22,29} and analytical\textsuperscript{30} studies, it seems likely that the condition of greater support leads to an increase in subglottal pressure, which, together with simultaneous adjustments to the laryngeal musculature, gives rise to the changed glottal flow waveform. The mechanisms by which the integration between the respiratory and laryngeal control is effected still needs some elucidation, however.

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**REFERENCES**


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