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Belly-in or belly-out?
Effects of Inhalatory Behaviour and Lung Volume on Voice Function in Male Opera Singers

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Abstract
Both effects of inhalatory abdominal wall (AW) behaviour and lung volume (LV) on voice function during singing were investigated. Nine professional opera singers phonated throughout their vital capacity range at different pitches and loudness levels using two polar inhalatory AW conditions, belly-in and belly-out. Subglottal pressure, vertical laryngeal position and voice source parameters were analysed. No significant effect of AW behaviour was found. However, in this non-habitual inhalatory behaviour significant effects of LV were found. High LV was associated with higher subglottal pressures and higher peak-to-peak flows than low LV. Also trends towards significant differences were found, such that high LV was associated with a lower vertical laryngeal position and a smaller closed quotient than low LV. These LV effects of singers’ non-habitual inhalatory behaviour are compared both with those previously found for the same singers’ habitual inhalatory behaviour, as well as with those found for vocally untrained subjects.

Introduction
Respiratory events during singing can be produced with a variety of chest wall configurations, i.e., with several relative displacements of the rib cage (RC) and abdominal wall (AW) compartments (Bouhuys & al. 1966; Proctor 1980; Watson & Hixon 1985; Watson & al. 1990). While singers and singing teachers generally agree that respiratory behaviour is important to voice function, there is a lack of consensus of what constitutes an “appropriate” behaviour (Blades-Zeller 2002; Hines 1983; Miller 1977). One possible explanation for the lack of consensus is suggested by the reported discrepancy between how vocal performers perceive their respiratory behaviour and what actually happens as revealed by e.g., magnetometers (Watson & Hixon 1985; Hixon & al. 1987). Inhalatory behaviour is often mentioned as being of special interest for the subsequent phonation.

The demands on the respiratory apparatus in singing are different in the inhalatory and exhalatory/phonatory part of the breathing cycle. The ability to perform rapid and forceful inhalations is of great importance, as opera singers often use a large portion of their vital capacity in sung phrases and have a limited time frame to replenish this volume (Thomasson & Sundberg 1997; Watson & Hixon 1985; Watson & al. 1990). On the other hand, during the phonatory phase the primary function of the respiratory apparatus is to provide the laryngeal system with an appropriate subglottal pressure ($P_s$) for the different musical events. $P_s$ is affected by both active and passive forces, respiratory muscles being active and lung volume (LV) dependent recoil forces in the respiratory apparatus and gravity being passive. It is particularly important during singing to have accurate and consistent control of the constantly changing target $P_s$, as $P_s$ not only is the prime control factor for loudness, but it also affects pitch (Cleveland & Sundberg 1985). In other words, the primary demands on the respiratory apparatus during inhalations are for speed and force, and during phonation for control and precision.

Apart from the above mentioned demands, there is an implicit assumption that respiratory behaviour also can be used as a tool for optimising the function of the voice source during singing, inhalatory AW behaviour being a relevant factor (Blades-Zeller 2002; Griffin & al. 1995; Hines 1983; Miller 1977). If this assumption is true, there is a possibility that some inhalatory strategies might be more
advantageous for voice production than others. However, if different inhalatory AW behaviours affect the subsequent phonation in different ways is still unclear, and objective data clarifying this relationship are needed.

Even if professional opera singers have demonstrated an inter-subject variability, depending on factors such as body type, gender, age and training (Hixon & al. 1973, 1976; Hoit & Hixon 1986, 1987, 1987; Proctor 1980; Thomasson & Sundberg 1997; Watson & Hixon 1985; Watson & al. 1990; Winkworth & al. 1994, 1995), they have shown to be highly consistent in their individual breathing activities during singing (Thomasson & Sundberg 1999, 2001). As classical operatic singers can be assumed to have good control of their voice function, breathing behaviour should be important to voice function; the opposite, a chaotic respiratory behaviour in operatic singing would imply that it is insignificant to voice function. The singers also demonstrated an inhalatory behaviour slightly more consistent than the exhalatory behaviour, thus providing another reason to assume that inhalatory behaviour is particularly relevant to voice function.

The phonatory breathing activities are superimposed on the life sustaining function of the respiratory system. The intricate interdependence between the laryngeal and respiratory systems can for example be demonstrated by neurological factors linked to LV. For instance, slowly adapting pulmonary stretch receptors are responsible for the Hering-Breuer reflex. This is a reflex inhibition or delay of both inspiratory pump muscle activity and inspiratory laryngeal activity in response to lung inflation. Further, rapidly adapting pulmonary stretch receptors initiate protective reflexes in the larynx in response to rapid lung inflation and deflation (Feldman & McCrimmon 1999). The effect of such neurological factors during phonation is not yet known.

The so-called tracheal pull appears to represent another force of possible relevance to the relationship between inhalatory behaviour and phonation, since it is a bio-mechanical link between the respiratory and the laryngeal systems. During deep inhalation, the tracheobronchial tree is lowered in the torso (Fink & Demarest 1978; Maklin 1925). Because of the elastic interconnections between the tracheal cartilages, the lowering of the trachea induces a caudally directed force on the larynx. (Shipp & al. 1985; Vilkman & al. 1996; Zenker & Glaninger 1959; Zenker & Zenker 1960). Hence, this force, i.e., the tracheal pull, is greater at high LV than low LV (Zenker & Glaninger 1959). If muscles elevating the larynx exert no compensatory action, this will result in a lower laryngeal position on high than on low LV, i.e., the vocal tract would be longer on high than on low LV. A reduction of vocal tract length causes formant frequencies to rise. If this change is large enough this could alter the perceived tone quality during a phrase, a result clearly unfavourable in professional singing (Sundberg & Askenfelt 1981).

According to Zenker (1964) the tracheal pull is associated with a passive glottal abductive force. This force is relevant to the mode of phonation. A low abductive force associated with a hypofunctional/voiced-whisper type of phonation and a gradual increase of adduction will change the phonation mode on a continuous scale toward flow, normal, to hyperfunctional/pressed phonation (Gauffin & Sundberg 1980, 1989). This association between the breathing apparatus and phonation has been corroborated by a number of investigations (Hoit & al. 1993; Iwarsson & al. 1996; Shipp & al. 1985; Sundberg & al. 1989).

As the tracheal pull varies with LV and is significant to phonation, LV should affect phonation. This has been confirmed in a series of investigations. Thus, Milstein (1999) and Iwarsson and collaborators (1998b) found significant effects of LV on voice function in vocally untrained subjects, such that high LV was associated with a more abducted glottal configuration than low LV. In addition they found that vertical laryngeal position (VLP) tended to rise as LV decreased (Iwarsson & Sundberg 1998a). These LV effects were explained in terms bio-mechanical factors such as the tracheal pull even though neurological factors related to LV could not be ruled out as contributing to the results. Also behavioural factors were discussed, mainly described in terms of non-compensation of LV dependent change of the elasticity forces in the breathing apparatus. When the effect of LV on phonation in professional singers was investigated only a few of the effects reported regarding untrained voices were found (Thomasson 2002).

The physiology of the breathing apparatus suggests that the positioning of the AW is relevant to the tracheal pull. An expansion of the AW must be caused by an anterior-caudal movement of the abdominal content, associated
with a lowering of the diaphragm. In other words, an expanded AW during inhalation should be a sign of a lowered diaphragm and should hence increase the tracheal pull. Iwarsson and collaborators thus instructed their subjects to expand the AW during the inhalation preceding the analysed vocalisations. On the other hand, the tracheobronchial tree fans out in all directions in the lungs and it is possible that also an inhalatory expansion of the rib cage affects the tracheal pull in a similar way. If the tracheal pull also differs with inhalatory behaviour is still unclear.

Iwarsson and Sundberg (2001) studied the effects of inhalatory AW position on VLP in vocally untrained subjects, instructed to either expand or contract their AW during inhalation. They unexpectedly found that the belly-out condition was associated with a higher larynx than the belly-in condition, which, however, seemed related to a postural effect rather than to the inhalatory AW behaviour.

Professional singers have to meet particularly high demands on voice control. This concerns not only fundamental frequency, determining intonation, but also $P_v$, determining vocal loudness, and VLP and voice source parameters, being relevant to voice timbre. Another basic requirement is equalisation of voice timbre implying that voice timbre should not change abruptly with other voice parameters, e.g. pitch and loudness. This suggests that singers have to learn how to compensate for audible phonatory effects of musically irrelevant factors such as LV.

The purpose of this exploratory investigation was twofold. One purpose was to study effects of the belly-in and the belly-out inhalatory strategies on voice function and VLP in professional singers. The results should elucidate whether inhalatory AW behaviour can be used as a tool to optimise the voice source in singing.

A second purpose was to study possible LV effects on voice function when singers are asked to abandon their habitual inhalatory behaviour. As the investigation largely replicated the conditions used in both the studies of untrained subjects and of professional singers’ habitual inhalatory behaviour (Iwarsson 1998a, 1998b; Milstein 1999; Thomasson 2002), a comparison of results of LV effects on voice function should provide information relevant to voice education. If LV induces audible effects both under habitual and manipulated breathing conditions it can be hypothesised that these effects are difficult or even impossible to avoid completely, most likely being caused by biomechanical and/or neurological factors related to LV.

**Experiment**

**Subjects**

Nine male professional opera singers - age range 29 to 45 years - highly trained in the Western classical tradition (3 tenors, 3 baritones, and 3 basses) participated in the study. They were all professional in the sense that at the time of the experiment they all earned their livelihood from singing either on national or on international opera stages. Their professional careers extended between 2 and 20 years. The subjects were not informed of the purpose of the study.

**Experimental set-up**

The experimental set-up is shown in Figure 1. Breathing data was recorded by means of respiratory inductive plethysmography (Respiritrace, Ambulatory Monitoring, Inc., Ardsley, NY). To reduce effects of warming, the Respiritrace system was turned on at least 1.5 hours before the experiment. The elastic transducers of the Respitrace system, (respibands), reflecting changes in cross-sectional area were placed around the RC and the AW, with the upper edge at the level of the axilla and the level of the umbilicus, respectively. To avoid slippage during the experiment, an elastic retainer was worn over the respibands. In order to calibrate the RC and AW signals such that their sum reflects relative LV, the subjects performed a series of iso-volume manoeuvres, i.e., shifting the AW inwards and outwards with occluded airways. This was carried out at high, middle, and low LV. For determination of VC the subjects performed 3 maximum inhalations and exhalations. Resting expiratory level (REL) was captured after a series of relaxed sighs. All these calibration manoeuvres were recorded both before and after the singing tasks.

The audio signal was picked up by a head-mounted microphone, keeping the distance between mouth and microphone constant at 30 cm. The audio signal was not used in the analysis except for orientation. VLP was recorded by means of a Glottal Enterprises electroglottograph (EG2) provided with a double pair of electrodes. Glottal airflow was captured by means of a Rothenberg flow mask (Glottal Enterprises). Flow was calibrated by means of
airflow obtained from a pressure tank and measured by means of a Rotameter (VEB Prüfgeräte-Werk, Medingen, type TG06). Sub-glottal pressure, low pass filtered at 100 Hz, was measured as the oral pressure during the occlusion for the consonant [p] and captured by means of a plastic tube placed in the flow mask; vertical laryngeal position (VLP), as recorded by an electroglottograph; rib cage (RC) and abdominal wall (AW) signals from a Respitrace. All signals were recorded on a multi-channel digital instrumentation data recorder. The AW signal was simultaneously displayed on an oscilloscope as a feed-back to the subjects for the inhalatory manoeuvres.

The subjects were standing in an unrestrained upright position, however asked to avoid body movements. Whenever they failed to meet this condition they were asked to repeat the sequence. Their task was to sing the syllable /pae:/ repeatedly, starting at a maximum LV and continuing throughout their entire vital capacity (VC) range. This syllable sequence was performed at three different pitches, a middle comfortable pitch and the pitches seven semitones below and above this pitch. At each of these pitches, the sequence was sung in three different loudness levels, mezzo-forte (mf), forte (f), and piano (p). For each of these nine conditions the sequence was sung twice.

First, the subjects performed the whole procedure without any specific instructions regarding breathing. These data were analysed in a previous investigation on LV effect on voice function (Thomasson 2003). Second, the subjects performed the whole procedure two more times applying two different inhalatory strategies, expansion and contraction of the abdominal wall during inhalation. For these conditions the Respitrace signal from the AW respiband was displayed on a separate oscilloscope channel as a feedback. A beam of the second channel was fixed to the subject’s AW value captured at REL. For one set of /pae:/-syllable sequences, the subjects were asked to inhale maximally while expanding their AW such that the AW respiband signal raised above the fixed REL beam. During another set, they were asked to contract their AW during inhalation checking that the AW respiband signal reached a value below the fixed REL. Thus, expansion and contraction of the AW
during inhalations was determined with reference to the individual relaxed state of the AW.

**Analysis**

All signals recorded from the two repetitions of each experimental condition were digitised on separate channels in data files using the Soundswell Signal Workstation program (Hitech Development AB), see Figure 2. As a rule the second of these repetitions was selected for analysis. The first repetition was primarily considered a rehearsal of the new condition, and was used as a back-up.

**Respiratory data**

LV, AW and RC data are shown as the three lowest curves in Figure 2. In order for the sum of the RC and AW signals to represent relative LV, an amplification factor must be applied to one of these signals. This factor was determined by plotting the amplitudes of the AW and RC signals recorded during the iso-volume manoeuvres against each other. The correlation and the best linear fit of these data were then determined. For each subject the iso-volume manoeuvre that yielded the highest correlation was selected for computing the amplification factor; this correlation was found at middle LV for all subjects except one where it was found for a higher LV. The factor thus obtained was then applied to the AW signal and thereafter the corrected summed signal was calculated. Custom-made software executed this entire procedure automatically on pre-selected iso-volume recordings.

As the experimental conditions involved the extreme LVs, there is a possibility that the respibands were not tracking LV in a linear way. Using the iso-volume at middle LV tends to yield a calibration error at LV extremes. However, as LV estimates were used only for identifying a /pæ:/-syllable produced at a low LV, these calibration errors seemed of little concern. To check the maximum timing error caused by such non-linearity, the calibration factors derived from iso-volumes performed at high and low LV for all subjects were compared with the calibration factor at the iso-volume performed at REL. The largest timing error was found to be one /pæ:/, meaning that the voice data would still be measured at a low LV.

Measuring LVs with plethysmography, such as the Respirtrace, presents a difficulty when comparing non-phonatory and phonatory segments due to differences in gas compression in the breathing apparatus. A plethysmograph would record such compressions as a change of LV when in fact no gas has been exhaled. Hence, the greater $P_s$ needed in forte as compared to piano singing is a source of error in

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*Figure 2. Example of the first and second versions of the signals recorded from a /pæ:/ syllable sequence, performed at middle pitch in mezzo-forte, and using an inhalatory belly-out strategy. The curves show, from top: audio, airflow, subglottal pressure ($P_s$), vertical laryngeal position (VLP), rib cage (RC), abdominal wall (AW), and lung volume (LV).*
LV estimation. LV range was therefore determined within each syllable sequence thus avoiding VC measures. This range, henceforth referred to as LVr, was defined as the LV interval measured at phonation start and after phonation end. The second /pæ:/-syllable in the sequence was chosen to represent high LV. On average this LV corresponded to 88% of LVr in the AW out condition (inter-subject variation range 77-96%) and 85% LVr in the AW in condition (inter-subject variation range 79-92%). The /pæ:/-syllable located at 20% LVr was chosen to represent low LV, thus avoiding extremely low LVs that may be associated with non-typical vocal behaviour (Shipp & al. 1985; Watson & Hixon 1996).

**Voice data**

Subglottal pressure was captured from the oral pressure during the [p]-occlusion preceding the vowel sound chosen for analysis. The glottal airflow signal, low pass filtered at 2000 Hz, was inverse filtered using the DeCap, a custom made software. A ripple-free closed phase was used as a criterion to for tuning the first two formant filters. The flow glottogram measurements were taken from the middle part of the vowel section, where traces of articulatory movements were absent. The flow glottogram characteristics measured in this study are seen in Figure 3: (1) period time (T0), (2) quasi-closed phase time (Tcl), (3) flow peak amplitude (Û), (4) mean flow during the open phase, (5) and the mean DC flow during the closed phase reflecting glottal leakage. Further, mean AC flow during the flow pulse was calculated by subtracting DC leakage from the mean flow during the open phase. The closed quotient (Qclosed) was calculated as the quasi-closed phase duration divided by the period time, T0.

As glottal adduction was a phonatory factor of prime interest, a flow glottogram measure capturing this factor was needed. Unfortunately, however, the optimum flow glottogram measure of glottal adduction is not yet known. For this reason five flow glottogram measures were calculated: (i) H1-H2, the level difference between the first two partials of the voice source measured by means of spectrographic analysis of the flow glottogram. (ii) Peak-to-Peak (PtP) flow computed as the difference between flow peak amplitude and glottal leakage. (iii) Glottal permittance computed as the ratio PtP flow over Ps. (iv) Estimated glottal area, the ratio PtP-flow over the square root of subglottal pressure. (v) Glottal compliance, computed as the ratio between mean AC flow during the flow pulse to Ps. The voice data were gathered for all pitch, loudness, LV and AW conditions.

**Vertical laryngeal position data**

Vertical laryngeal position was analysed in an arbitrary unit. As movement of the larynx during the selected syllable was not uncommon, the average of the middle 0.5s of the vowel section was chosen to represent the VLP for that syllable. These data were normalised with respect to the individual subject’s total variability range observed during all phonations produced in the entire experiment. Henceforth, this normalised VLP measure will be referred to as VLPN. Thus, 0% and 100% VLPN correspond to the lowest and the highest VLP values observed in that subject. VLPN data were gathered for all pitch, loudness, LV and AW conditions.

**Statistical analysis**

Data were subjected to a 2 x 2 x 3 x 3 within-subjects repeated ANOVA, with AW behaviour (belly-in, belly-out), lung volume (high, low), pitch (low, middle, high) and (p, mf, f) as within-subject variables and VLPN, Ps, Qclosed, glottal leakage, PtP flow, H1-H2 level difference, glottal compliance, glottal permittance, and estimated glottal area as dependent measures. To correct for the relatively large number of dependent variables, a Bonferroni correction of the standard alpha level of 0.05, gave the level of significance to p<0.0055. This introduces a greater possibility of a statistical Type II error, rejecting a true significant result.
Caution when analysing the statistical data was therefore needed. As this is an exploratory study also statistical results within the standard alpha level of 0.05 will be discussed and referred to as trends towards significance.

Results

Hixon and Hoffman (1978) have pointed out that the two polar modes of inhalation studied here are associated with certain respiratory advantages and disadvantages that should be relevant to the control of Ps. Our material allows us to examine to what extent these modes are associated with different effects on voice source parameters and the VLP. This can be seen from the data listed in Table 1.

The p-values in the table demonstrate that there were no significant effects of the two inhalatory AW behaviours on any of the parameters analysed. In other words, the two different inhalatory strategies failed to significantly affect these singers’ voice behaviour with respect to Ps, voice source parameters and VLP. As the VLP data are not necessarily comparable across subjects, a within-subject comparison of matched conditions is relevant. This was been realised in terms of the scatter plot shown in Figure 4. The graph shows no clear trend, although in many cases a high LV seemed associated with a lower VLP when inhalation was combined with a belly-in displacement than when it was performed with a belly-out displacement.

The effects of LV on voice function were found to be very small when singers used their normal inhalatory behaviour. It is therefore interesting to analyse the effect of LV on the voice parameters for non-habitual inhalatory behaviour. If inhalatory behaviour is relevant to voice function in professional singers there should be a different result as compared to the singers normal inhalatory behaviour. However, this would likely reflect a breath control aspect rather than the strategy per se.

Figure 4 compares, in terms of scatter plots, values for various parameters observed for high

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Table 1. Result of analysis of variance (2 x 2 x 3 x 3 within-subjects ANOVA) of the effect of inhalatory abdominal wall position (belly-out and belly-in) on the various parameters listed, averaged across all subjects, lung volumes, pitches and loudness levels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Belly-out</th>
<th>Belly-in</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLPN (% ind. range)</td>
<td>47.6</td>
<td>43.3</td>
<td>1.8</td>
<td>1.532</td>
<td>0.251</td>
</tr>
<tr>
<td>Ps (cm H2O)</td>
<td>16.09</td>
<td>16.11</td>
<td>1.7</td>
<td>0.000</td>
<td>0.983</td>
</tr>
<tr>
<td>Qclosed</td>
<td>0.44</td>
<td>0.45</td>
<td>1.8</td>
<td>0.874</td>
<td>0.377</td>
</tr>
<tr>
<td>Gl. leakage (l/s)</td>
<td>0.12</td>
<td>0.11</td>
<td>1.8</td>
<td>0.296</td>
<td>0.601</td>
</tr>
<tr>
<td>PtP flow (l/s)</td>
<td>0.55</td>
<td>0.55</td>
<td>1.8</td>
<td>0.362</td>
<td>0.564</td>
</tr>
<tr>
<td>H1-H2 (dB)</td>
<td>8.22</td>
<td>7.92</td>
<td>1.8</td>
<td>1.238</td>
<td>0.298</td>
</tr>
<tr>
<td>Gl. compliance</td>
<td>0.070</td>
<td>0.066</td>
<td>1.7</td>
<td>0.046</td>
<td>0.836</td>
</tr>
<tr>
<td>Gl. permittance</td>
<td>0.038</td>
<td>0.038</td>
<td>1.7</td>
<td>0.000</td>
<td>0.997</td>
</tr>
<tr>
<td>Est. Gl. area</td>
<td>0.139</td>
<td>0.137</td>
<td>1.7</td>
<td>0.003</td>
<td>0.959</td>
</tr>
</tbody>
</table>
and low lung volume. The results of the statistical analysis are listed in Table 2. Two parameters revealed a significant difference between high and low LV; $P_s$ and PtP flow both showed greater values at high than at low LV. Further, trends towards LV effects can be seen for VLP, $Q_{\text{closed}}$ and estimated glottal area. Most of these LV effects are, at least qualitatively, similar to those previously reported for untrained subjects. The results support the hypothesis that high LV is associated with an abductive glottal force component. On the other hand the $P_s$ effect deviates from the results observed for singers’ habitual inhalatory behaviour and even though the VLP trend is similar, some of the trends were also different.

For VLP there was a significant interaction effect between AW behaviour and loudness ($F_{1.48, 11.87}=13.44$, $p=0.002$), such that the larynx at both loudness $p$ and $mf$ showed a higher position in belly-out than belly-in. But, for loudness $f$ the larynx had a lower position in belly-out than belly-in. Further, a trend towards a significant interaction effect between LV and loudness was seen ($F_{1.73, 13.84}=6.16$, $p=0.015$), such that at all loudness levels the singers’ larynx was in a lower position at high LV than

![Figure 5. Scatterplots comparing parameters in high versus low lung volume: normalised vertical laryngeal position (VLP), subglottal pressure ($P_s$), peak-to-peak flow (PtP) and closed quotient ($Q_{\text{closed}}$). Each data point refers to a given pitch, loudness and abdominal wall condition in a given subject. For VLP, each subject is represented by a specific symbol. Filled and open symbols represent high and low lung volume condition, respectively, for the subject.](image-url)
at low LV, but the difference decreased as loudness was increased.

For $P_s$, a trend towards a significant interaction effect between AW behaviour and LV was found ($F_{1, 7}=11.98$, $p=0.011$), such that both inhalatory strategies showed a higher $P_s$ at high LV than at low LV, the effect being larger in the belly-out condition.

**Discussion**

In the present investigation we studied effects of the two polar inhalatory behaviours, the belly-in and the belly-out strategies on phonatory parameters. Hixon and Hoffman (1978) discussed possible advantages and disadvantages of these same strategies with regard to mechanical properties of the respiratory mechanism. Any effect of inhalatory behaviour on voice function should be evident when these two polar modes are compared. A major difference reported between these polar shapes is the degree of curvature that the diaphragm assumes. In the belly-in case the diaphragm has a highly domed shape in which its radius of curvature is increased from its relaxed state. In the belly-out case, on the other hand, the diaphragm is at a decreased radius of curvature relative to that it assumes at the end of a tidal breath. Thus, the tracheal pull and the associated abductive force component should be greater in the belly-out than in the belly-in inhalations.

By using a within-subjects comparison and matching LV, pitch, and loudness levels we controlled for a variety of factors known to affect respiratory behaviour and voice function, such as individual morphology, age, training, LV etc. It is therefore interesting that, contrary to the above expectations, none of the parameters analysed showed statistically significant differences between the belly-out and the belly-in conditions. This suggests that the aspects of voice function analysed in this study were not affected by AW position during inhalations. There may be two reasons for this. One is that the singers compensated phonatory effects of different tracheal pull forces by muscular means. The other is that the belly-in/belly-out poles indeed fail to affect the tracheal pull, such that it was essentially identical in both inhalatory conditions. This suggests that the aspects of voice function analysed in this study were not affected by AW position during inhalations. MR imaging data might be revealing for further elucidating the effects of different inhalatory behaviours on the tracheal pull.

It should be observed that these results do not imply that inhalatory AW behaviour is irrelevant to phonation. As pointed out by Hixon and Hoffman, one behaviour may be more advantageous for quick and precise control of the constantly changing target $P_s$ during singing. Interestingly, $P_s$ was the only parameter that showed a trend towards an interaction effect between AW behaviour and LV. Thus, inhalatory abdominal wall behaviour may be more

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**Table 2.** Result of analysis of variance (2 x 2 x 3 x 3 within-subjects ANOVA) of the effect of lung volume (LV) on analyzed voice parameters, averaged across all subjects, abdominal wall conditions, pitches and loudness levels. Statistical significance is marked with *, $p<0.0055$, and trends with (*), $p<0.05$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HLV</th>
<th>LLV</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$VLP_N$ (% ind. range)</td>
<td>$38.4$</td>
<td>$52.5$</td>
<td>$1.8$</td>
<td>$11.511$</td>
<td>$0.009$ (*)&amp;</td>
</tr>
<tr>
<td>$P_s$ (cm H$_2$O)</td>
<td>$16.8$</td>
<td>$15.41$</td>
<td>$1.7$</td>
<td>$19.882$</td>
<td>$0.003$ *</td>
</tr>
<tr>
<td>$Q_{closed}$</td>
<td>$0.44$</td>
<td>$0.45$</td>
<td>$1.8$</td>
<td>$6.348$</td>
<td>$0.036$ (*)&amp;</td>
</tr>
<tr>
<td>Gl. leakage (l/s)</td>
<td>$0.12$</td>
<td>$0.11$</td>
<td>$1.8$</td>
<td>$4.028$</td>
<td>$0.080$</td>
</tr>
<tr>
<td>PtP flow (l/s)</td>
<td>$0.58$</td>
<td>$0.51$</td>
<td>$1.8$</td>
<td>$25.767$</td>
<td>$0.001$ *</td>
</tr>
<tr>
<td>H1-H2 (dB)</td>
<td>$8.19$</td>
<td>$7.95$</td>
<td>$1.8$</td>
<td>$1.404$</td>
<td>$0.270$</td>
</tr>
<tr>
<td>Gl. compliance</td>
<td>$0.070$</td>
<td>$0.066$</td>
<td>$1.7$</td>
<td>$1.445$</td>
<td>$0.268$</td>
</tr>
<tr>
<td>Gl. permittance</td>
<td>$0.039$</td>
<td>$0.038$</td>
<td>$1.7$</td>
<td>$1.005$</td>
<td>$0.349$</td>
</tr>
<tr>
<td>Est. Gl. area</td>
<td>$0.144$</td>
<td>$0.132$</td>
<td>$1.7$</td>
<td>$10.834$</td>
<td>$0.013$ (*)&amp;</td>
</tr>
</tbody>
</table>
important to $P_s$ control than to other voice parameters.

In vocally untrained subjects Iwarsson and Sundberg (2001) found a significantly higher VLP for a belly-out than for a belly-in behaviour, a finding incompatible with the idea that the tracheal pull is greater for the belly-out condition. A post hoc experiment revealed body posture effects likely to affect the biomechanical forces acting on the suspensory mechanism of the larynx. We found a similar, although far from significant tendency in our singers. It is unlikely that singers would allow for an inhalatory postural change, such as that found for untrained singers, to occur. On the other hand, both active strap-muscle action and passive bio-mechanical forces such as the tracheal pull affect the VLP. Singers have been reported to normally sing with a lowered or well-controlled (Shipp & Izdebski 1975; Pabst & Sundberg 1993). To achieve well-controlled VLP while using widely differing LV, singers need to develop an accurate strap muscular compensation of tracheal pull variations. It is however, not possible to decide if the minor effect on the singers’ mean VLP was due to random factors, to a residual non-compensated difference in tracheal pull between AW conditions, or to strap muscle action. It should be noted, though, that our study included no more than 9 subjects, all professional singers.

More information seems needed for a deeper understanding of the relationship between inhalatory strategy and VLP.

The LV factor turned out to be more relevant than the inhalatory behaviour to the phonatory parameters examined. We have studied this factor in two previous investigations. The results can be compared in Table 3. The most striking effect of LV on voice function in non-habitual inhalatory behaviour concerned $P_s$, high LV being associated with a higher $P_s$ than low LV. A similar result was found for untrained subjects. The author agrees with both Milstein and Iwarsson and co-workers that an important cause of this effect is non-compensation of the LV dependent elasticity forces in the breathing apparatus. Interestingly this effect was not present when the singers used their habitual behaviour. Apparently, a strategy for compensating for the ever-changing contribution from elasticity forces is included in their habitual inhalatory behaviour.

Another effect of LV on voice function concerned the VLP. A trend towards lower VLP on high LV than on low LV was found. As mentioned, the lack of statistical significance for this effect may be a statistical Type II Error. Although further studies are needed to reach conclusive results, this result is interesting, as it is similar to what was found when the singers used their habitual inhalatory behaviour. Thus,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Untrained subjects</th>
<th>Professional singers</th>
<th>Professional singers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>belly-out</td>
<td>non-habitual</td>
<td>habitual</td>
</tr>
<tr>
<td></td>
<td>high LV-low LV</td>
<td>high LV-low LV</td>
<td>high LV-low LV</td>
</tr>
<tr>
<td>$P_s$</td>
<td>s</td>
<td>s</td>
<td>ns</td>
</tr>
<tr>
<td>VLP</td>
<td>s</td>
<td>t</td>
<td>t</td>
</tr>
<tr>
<td>$Q_{closed}$</td>
<td>s</td>
<td>t</td>
<td>ns</td>
</tr>
<tr>
<td>$P_tP$ flow</td>
<td>s</td>
<td>s</td>
<td>s</td>
</tr>
<tr>
<td>Gl. leakage</td>
<td>s</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>$H_1-H_2$</td>
<td>t</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Gl. comp</td>
<td>ns</td>
<td>ns</td>
<td>t</td>
</tr>
<tr>
<td>Gl. perm</td>
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<tr>
<td>Est gl area</td>
<td>s</td>
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</tbody>
</table>
also when the singers used their habitual inhalatory strategy, VLP was lower at high LV than at low. This implies that neither inhalatory strategy, nor acquaintance with the inhalatory behaviour used had any appreciable effect on VLP, LV being the dominant factor. The same seems to be true also for untrained subjects (Iwarsson & Sundberg 1998a; Iwarsson 2001). This suggests that the influence of LV on VLP is great and difficult to avoid completely. It may, however, be important for singers to avoid substantial VLP changes with changing LV, such that salient formant frequency and voice timbre changes are avoided.

As can be seen in Table 3, LV had a significant effect on Qclosed in untrained voices, no significant effect when the singers used their habitual inhalatory behaviour and a trend to an effect when they used a non-habitual inhalatory behaviour. Avoiding salient voice timbre changes with decreasing LV would be an important goal of a voice education. As Qclosed is relevant to voice timbre, its independence of LV in professional singers singing under normal conditions is not surprising.

Previous studies have revealed that an increase in P_s is associated with an increase of Qclosed (Sundberg & al. 1999). In the present study we found a trend for the opposite relationship. Although P_s was somewhat higher at high than at low LV, Qclosed was slightly lower at high LV. This is in accordance with the hypothesis that high LV is associated with an abductive force component, possibly originating from the stronger tracheal pull.

PtP flow is the only parameter that showed a significant difference between high and low LV in all three studies, Table 3. This implies that regardless of inhalatory behaviour or degree of training, the effect of LV on PtP flow remained. The relative change of PtP, however, was clearly smaller in the singers, again suggesting that singers strive to reduce salient changes of voice timbre with decreasing LV.

Glottal leakage did not seem sensitive to the inhalatory strategies or to the singers’ acquaintance with the inhalatory strategy they used, Table 3. It can be argued that training has an effect, as the untrained subjects showed a LV effect. From visual inspection Milstein found that high LV was associated with a posterior glottal gap in untrained female singers, a glottal configuration not likely to be present in these professional singers.

It is interesting that PtP flow and VLP are the only parameters that changed with a decrease in LV in all three studies. This suggests that LV is a dominant factor for these parameters.

We analysed a number of flow glottogram parameters likely to be related to glottal adduction: Qclosed, PtP flow, glottal leakage, H1-H2 level difference, glottal compliance, glottal permittance and estimated glottal area. All effects as listed in Table 3 suggest that glottal adduction was firmer at low than at high LV. On the other hand, the statistical significance of the effects varied between the parameters. Our material cannot demonstrate if one of these parameters reflects adduction more faithfully than the others.

Even if the LV effects seen in this study are in accordance with what could be expected from the chain of hypotheses of a changing tracheal pull presented in the introduction, we have no possibility to determine whether a changing tracheal pull is the cause of these effects. When comparing results of LV effects between studies our FB factors such acquaintance with the task could affect the results. Further, neurological factors related to LV could also be important, but the effect of such neurological factors on phonation is still poorly understood.

In any event, from a pedagogical point of view the reported effect of LV in singing is equally important as the possible cause of this effect. Training would imply accessing full control of perceptually salient and/or expressively relevant voice parameters, such that any influence of musically irrelevant factors such as LV, whatever the cause of this influence, is compensated for by muscular activation or inhibition.

We found no significant differences between the belly-out and belly-in conditions, and at the same time LV was found to have effects in non-habitual behaviour that were not found for habitual behaviour. This suggests that none of the non-habitual inhalatory behaviours was similar to the singers’ normal inhalatory behaviour. Singers’ inhalatory behaviour cannot be exhaustively described simply as belly-out or belly-in, even though some of our singers showed a behaviour more or less similar to one or the other. In fact, some singers found the belly-in condition highly uncomfortable, while others complained about the belly-out condition.

No difference was found between the belly-out and belly-in conditions, thus implying that inhalatory AW behaviour has no compulsory effect on voice function. On the other hand, the
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non-habitual inhalatory behaviour induced a disturbance of the voice function as compared with habitual inhalatory behaviour. This strongly suggests that certain aspects of inhalatory AW behaviour are important to voice function. The most striking difference between habitual and non-habitual behaviour was associated with $P_v$. These results suggest that inhalatory AW behaviour could be important to voice function in an indirect way, being more important to control and precision of $P_v$, rather than directly affecting voice source and VLP. In other words, inhalatory behaviour may be more relevant to breath control than to laryngeal factors.

Conclusions

No voice parameter differences were found when comparing the belly-out and belly-in conditions. This observation can be interpreted in two ways. One is that neither biomechanical nor behavioural influences differ between the belly-out and belly-in conditions. The other is that the possibly different biomechanical effects of these polar conditions were counteracted by a behavioural factor.

On the other hand, when the singers were forced to abandon their habitual inhalatory AW behaviour their voice function was indeed influenced by LV, the effects being qualitatively similar to those found for vocally untrained subjects. This supports the hypothesis that high LV is associated with a passive glottal abductive component. The same effect was not found when singers inhaled with their habitual behaviour, suggesting that singers can learn how to compensate for effects induced by a change in LV.

$P_v$ control was less precise when the singers applied a non-habitual rather than a habitual inhalation pattern, suggesting that the different LV effects found for habitual and non-habitual AW behaviour may be due to acquaintance rather than to the AW position per se.

As with untrained subjects the singers’ VLP tended to rise with decreasing LV regardless of whether or not they applied their habitual inhalatory behaviour. This suggests that VLP is more closely linked to LV than to inhalatory strategy or amount of voice training.

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