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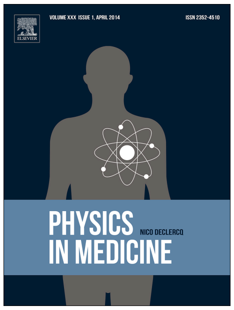

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Acoustical properties in Inhaling Singing: a case-study

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Abstract

A highly experienced versatile female professional singer displaying no apparent vocal complaint, developed inhaling singing, an innovative approach to reverse phonation. Although there are some reports in literature that describe the characteristics of ingressive phonation and sounds, to the best of our knowledge, no reports on actual inhaling singing are available in literature. This paper reports a case study on the acoustical analysis of inhaling singing, comparing this innovative technique with traditional exhaling singing. As this is rather undiscovered territory, we have decided to address several questions: is it possible to match the same pitches using inhaling singing compared to exhaling singing? Is the harmonic structure and energy distribution similar? Is it possible to maintain the same phonation duration in both techniques? Are there differences in volume and tessitura (vocal range)? This paper, reporting on the experience of one individual, demonstrates that a tessitura can be mastered in inhaling singing. Spectral analysis reveals a similar frequency distribution in both conditions. However, in inhaling singing the energy of the harmonics is significantly lower for the first 3 overtones, while the maximum phonation time is larger, than in exhaling singing. The singer reports that less effort is required for inhaling singing in the high register. As such, inhaling singing offers new possibilities for vocal performance.

Keywords: Inhaling singing – Spectrography – Videostroboscopy - Voice Range Profile – Maximum Phonation Time – ISFV

Introduction

A case study comprises two experiments focussed on the acoustic properties of Inhaling Singing technique registered as ISFV is based on simultaneous control of aspiration and phonation. This study is in addition of the article by (Moerman et al., 2015), which focuses on the morphology of the vocal tract in Inhaling Singing, based on MRI established on the correlation in terms of physiological processes between inhaling and exhaling vocalisation/singing, by the same singer and the differences between inspiratory and expiratory phonation revealing the inversion of the mucosal wave (Vanhecke et al., 2015). This prospective study contains the same notes of the MRI study from F5 to Bb5 and on the same /a/vowel. The MRI study showed statistically significant differences of the vocal tract describing the anatomical structure between inhaling and exhaling singing lying in the supraglottal morphology. The singer controls the inspiratory airflow using the breathing muscles, such as the costo-diaphragmatic breathing for stabilizing the transglottal pressure and hens vocal fold oscillation regulating the resonator capacities (Moerman et al., 2015). In this present paper, we focus on ‘pure sounds’, one of the three aspects of inhaling singing, comprising and defined as ‘multiphonics’ and ‘vocal electronics’.

Breathing sounds, including sounds of aspiration often occur in daily human and animal life (Darwin, 1872): related to expression and emotion, for example, astonishment or laughter is sometimes produced with reverse phonation (Trouvain, 2003); children make inhaling sounds as they imitate animals, and when crying (Grau, 1995); comedians sometimes produce inhalatory voice effects (Boon, 2008; Foresti, 2011). People from Germany and Scandinavia, are known to use ingressive airstreams from time to time; and native French and Swedish speakers, for example, often phonate their respective words for ‘yes’ while inhaling [Fr. ‘Oui’; Swe. ‘Ja’] (Clarke & Melchers, 2005). The pronunciation of both these words requires speakers to change the shape of the inside of the mouth, that is, to model the buccal cavity and the larynx (Gagnard, 1987). Different types of inhaling sounds are also found in ethnic music, such as the Tibetan monks’ chanting and that of the Lamas (Ellingson, 1970; Smith & Stevens, 1967); the Inuit use the voice and the breath simultaneously (Feld & Fox, 1994).

Inhaling singing (ISFV) is a specific form of inspiratory phonation, which, in turn, is a particular extended vocal technique. In the case of inspiratory phonation, vocal production is realised using an inspiratory airflow, that is, a voiced sound is made while the performer inhales (DeBoer, 2012; Edgerton, 2004).

This vocalized breathing techniques, which originates in speech and Inuit music making, has been explored in various musical contexts since the 1960s and is taken here as the starting point for ISFV, which we see as a contribution to the historical trend of extending and expanding expressive means in music making. Inverse phonation in speech for therapeutic and clinical applications, and acoustic comparisons have also been reported (Orlikoff, Baken, & Kraus, 1997; Robb, Chen, Gilbert, & Lerman, 2001). This technique is now considered as a new vocal extended technique in today’s contemporary music platform as an extension of timbral palette for new ways of interpretation, intention and expression. The singer is capable to control intended affect and emotion, meaning and expression with this inhaling singing technique and in combination with all kinds of other singing styles. New compositions were made that demonstrate this clearly (Vanhecke, 2013).

The goal of this study was to derive an understanding of the acoustic aspects of inhaling singing, by comparing recordings of ISFV with those of conventional exhaling singing. The subject for all measurements and observations in these experiments was the first author. Videostroboscopic examinations carried out before and after experimenting with this technique, showed no laryngeal pathologies.

The study sought to address several questions:

- Is it possible to sing the same pitches using Inhaling Singing as in exhaling singing, using Inhaling Singing-pure sounds?
- Is the harmonic structure and energy distribution of the resultant vocal sound similar in these two conditions?
- Is it possible to maintain the same phonation duration in both conditions?
- Are there differences in volume and tessitura between the two conditions?

Materials & Methods

Two experiments were carried out, in which recordings of ISFV and conventional singing were made for acoustic analysis. In the first experiment, pure, sustained sounds with a controlled breath and without vibrato were recorded in the inhaling condition, with equivalent sounds for the exhaling condition. Subsequently, the spectral characteristics and energy distribution of the recordings were analysed, for comparison. The second experiment sought to examine the implications of ISFV for vocal pitch range, again, by comparison with conventional singing. A voice range profile (VRP), i.e. a schematic reproduction of the frequency range and dynamic range of the voice, is used as a measure for comparing ISFV and exhaling singing. Again, recordings made in each condition were compared and analysed.

Protocol and measurements

In the first experiment, the subject sang six separate notes with chromatically ascending pitches from F5 to Bb5, on the /a/ vowel. This particular sonant eliminates formant influences on high-pitch singing (Garnier, Henrich, Smith, & Wolfe, 2010). This is in contrast to the case where an ascending scale on /u/, or /o/ (Van Deinse, 1994). Each note was sung for as long as possible and without vibrato, first in the exhaling condition, and immediately afterwards by the inhaling condition. The protocol is summarized in Table 1.

Sounds were recorded using two calibrated Brüel & Kjaer (type 4955) microphones positioned at a distance of 30cm from the sound source, in a soundproofed room at the Acoustic Lab of the School of Arts, in Ghent, Belgium. Recordings were made with 24-bit digital sampling and a sampling rate of 96 kS/s. A grand piano set outside the soundproofed room was used to play the target note before the experiment, providing a reference for the subject. The two sets of six audio recordings were obtained and digitally stored as wav files. Spectral analysis was performed using the Matlab MIR-Toolbox (Lartillot & Toiviainen, 2007).

N	Condition
Vibrato	no vibrato
Duration	As long as possible
Vowel	/a/
Lowest note	F5
Highest note	Bb5
Order	Chromatic ascent
Conditions	Exhaling followed by Inhaling
Loudness	Constant
Environment	Sound proof room
Microphones	Calibrated Brüel & Kjaer
Distance to microphones	30 cm
Warming up	None
Reference pitch	Piano

Table 1. Experimental setup

In the second experiment the subject sang single-pitched notes on the /a/ vowel across her entire pitch range, each one by exhaling-singing first followed immediately by the same pitch using ISFV during three seconds as soft and as loud as possible intensities. The voice range profile (VRP) was found using a Kay Speech Lab CSL model 4510b with a Shure SM48-LC microphone at 30 cm distance, in a quiet room. in the Maria Middelares Hospital voice laboratory, Ghent, Belgium, according to the clinical standards currently in use. It was placed at 30cm distance from the sound source, in a silent room. The protocol is summarized in Table 2.

N	Condition
Vibrato	no vibrato
Duration	Minimum 2s
Vowel	/a/
Lowest note	As low as possible
Highest note	As high as possible
Order	Chromatically up from A4 followed by chromatically down
Conditions	Exhaling and Inhaling
Loudness	As loud and as soft as possible
Environment	Silent room
Equipment	Kay Speech Lab CSL model 4510b
Distance from microphones	30cm
Vocal warm up	None
Reference pitch	Electronic keyboard

Table 2. Experimental setup

Experimental results

In what follows are the reported results. Pitch, duration and tone quality (amplitude, spectral content and energy distribution) were taken into consideration in analysing the recordings made in the first experiment. In the second experiment, VRPs were obtained in each condition.

Statistical analysis

For Experiment 1, pitches were extracted from the recordings using a Sonic Visualizer based on the Yin pitch tracker, using standard values (Yin threshold 0.15, 2048 samples/block with an increment of 256 samples) (Cannam, Landone, & Sandler, 2010). Using the pitch-time series (spectrogram) to establish the measurable portion of each recording, mean pitches were calculated, as well as the extent to which the pitch varied within each sung note (Table 3). The spectrogram uses a window length of 50ms, with a 50% overlap and a Hamming window. A paired Wilcoxon and ANOVA statistical analysis was used to quantify the differences between the harmonic structures of the corresponding exhaling and ISFV pitches. For the second experiment, Voice Range Profiles were assessed by a professional speech therapist.

Results

Pitch

Histogram analysis enables comparison of the extent to which the recorded pitch deviates from the reference pitch across the two conditions (see Figure 1).
The results for F5 show that the deviation from the reference pitch is higher for the inhaling condition than for the exhaling condition. F#5 and G5 deviate further still from the reference pitch in both conditions. For A5 the deviation is higher in the inhaling condition. For G#5 and Bb5, the deviation is lower in the inhaling condition than in the exhaling condition. As the target pitch gets higher, the frequency variance increases in the exhaling condition and decreases in the inhaling condition. Notably, the highest pitch (Bb5) is very stable in the inhaling condition.

Note	Reference Pitch (Hz)	Exhaling Mean (Hz)	Exhaling Stdev (Hz)	Exhaling Diff. (Hz)	Exhaling Diff. (cents)	Inhaling Mean (Hz)	Inhaling Stdev (Hz)	Inhaling Diff. (Hz)	Inhaling Diff. (cents)
F5	698.46	694.43	5.56	-4.03	-10	674.94	23.99	-23.52	-59
F#5	739.99	696.73	9.00	-43.26	-104	698.51	9.39	-41.48	-100
G5	783.99	731.18	11.15	-52.81	-121	715.15	9.79	-68.84	-159
G#5	830.61	814.90	12.27	-15.71	-33	826.41	6.34	-4.20	-9
A5	880.00	866.20	12.45	-13.80	-27	861.61	7.03	-18.39	-37
Bb5	932.33	914.38	22.21	-17.95	-34	930.41	4.51	-1.92	-4

Table 3. Mean, Standard Deviation and Deviation from reference pitch (Mean, Standard Deviation).

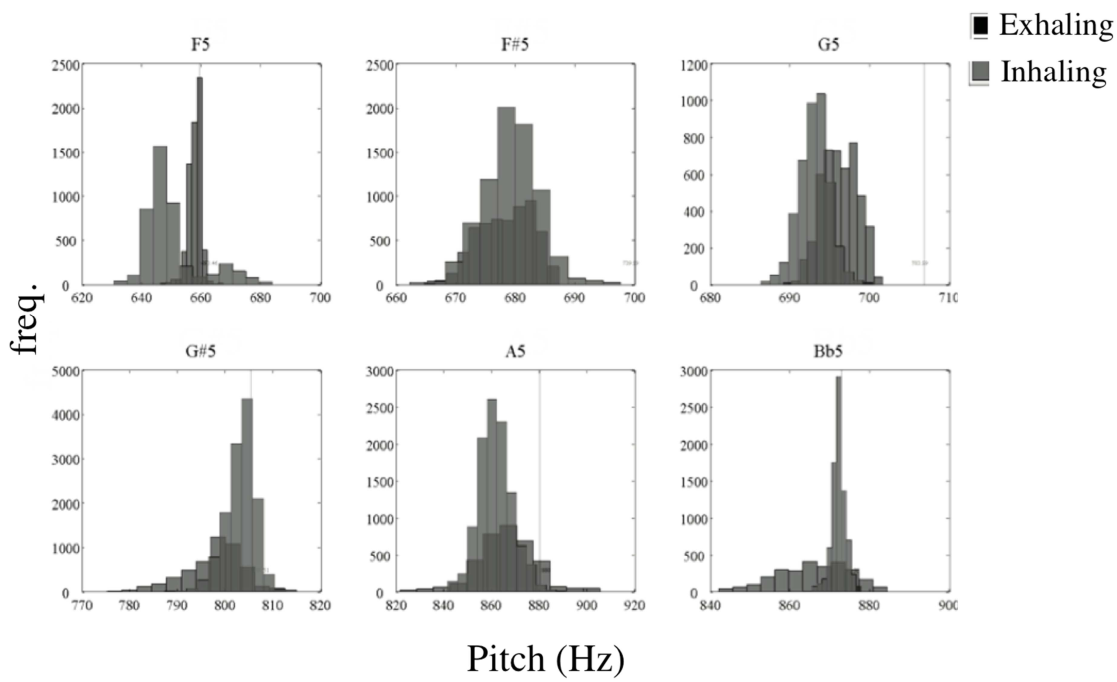

Figure 1. Histogram analysis of exhaling and inhaling pitch time series.

ANOVA analysis of a random sample (n=1000) ms (milliseconds) from the measured time series indicates that there is a significant difference for all notes for the factor (condition) (Table 4). In general, higher pitches are more stable in the inhaling condition; in the exhaling condition, a greater degree of pitch stability is obtained in the lower notes.

Note	F	Prob. > F
F5	707.02	< .000
F5#	12.72	< .000
G5	1278.62	< .000
G5#	718.54	< .000
A5	109.76	< .000
B5b	448.99	< .000

Table 4. ANOVA analysis of pitch between condition.

Maximum Phonation Time

The singer was asked to hold her notes for as long as was possible in the first experiment, and Maximum Phonation Times (MPT) were calculated from the pitch-time series for each note in both conditions (Ptacek & Sander, 1963). A MPT plot for the two conditions reveals that for F5, F#5 and G5 the values are similar in the two conditions. However, for the higher pitches G#5, A5 and Bb5, the maximum phonation time is substantially higher for ISFV (Figure 2.).

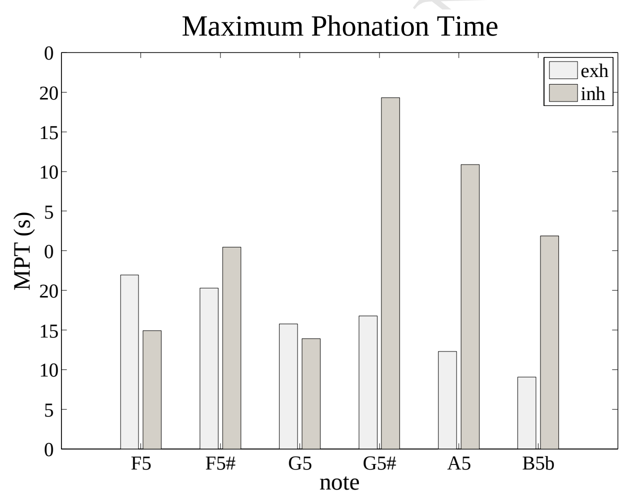

Figure 2. Maximum phonation time in both conditions.

Tone quality

a) Comparison between signal amplitude and modulation

Visual representations of tone quality in the sound signals reveal several differences between exhaling singing and ISFV. In the ISFV condition, amplitude is generally lower than in exhaling-singing, and it is characterized by a less-pronounced amplitude modulation (vibrato) (Figure 3).

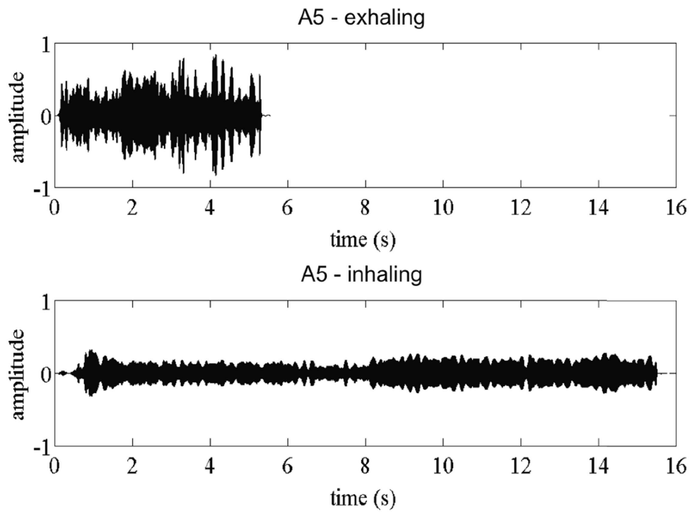

Figure 3. Differences in amplitude modulation for exhaling and inhaling conditions (pitch: A5).

b) Spectral analysis

Fourier analysis provides insights into the harmonic structure of the sounds. Figure 5 shows that the spectra reveal the same fundamental pitch ('F0'), which is denoted as the first harmonic ('H1' = F0) in both conditions (see **Error! Reference source not found.** However, there are fewer harmonics in the inhaling-singing condition.

The difference in dB between the fundamental and first overtone (H2) amplitude is in the order of 24-50dB for inhaling singing; whereas for exhaling-singing, other than for the two highest tones (A5 and Bb5), this registers as 2-30 dB on average (Figure 4). For Bb5, the spectral difference between the two conditions is small. Figure 6 illustrates the spectral difference for A5.

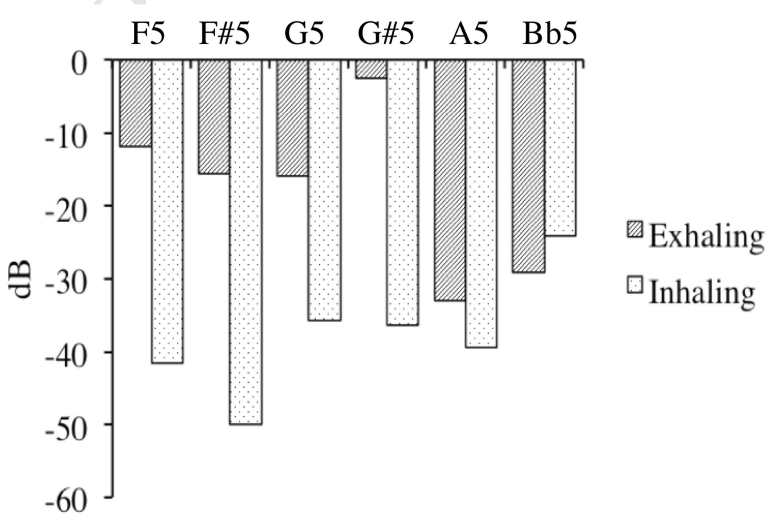

Figure 4. Decay in magnitude between H1 and H2 for both conditions.

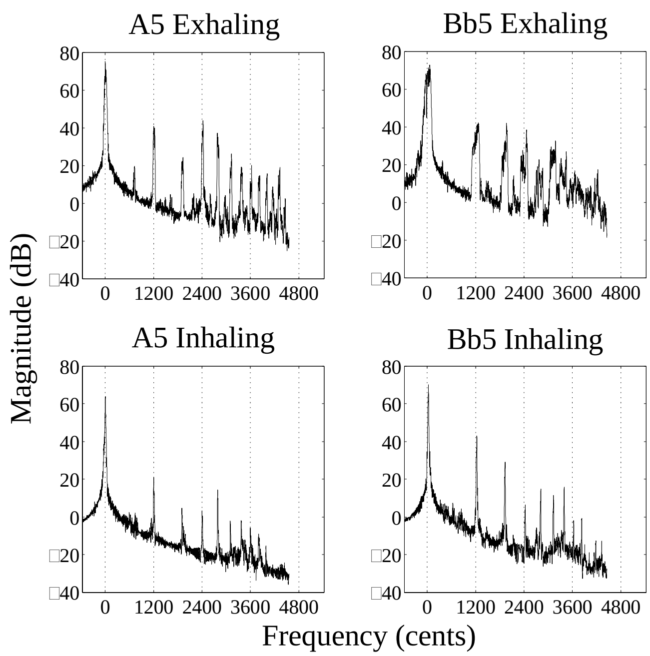

Figure 5. Spectral differences for A5 and Bb5 in the two conditions: for A5 the harmonic content is richer in the exhaling condition than in the inhaling condition; for Bb5, the harmonic content is similar.

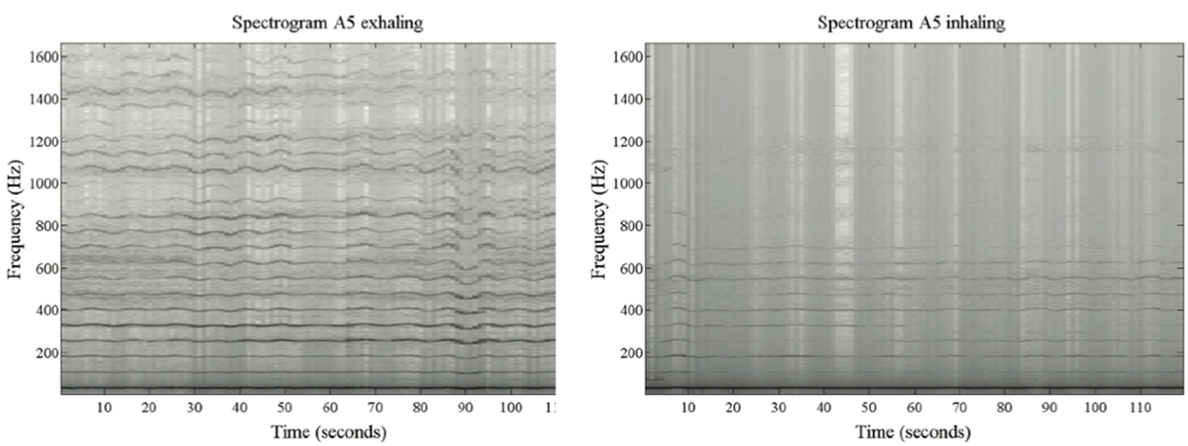

Figure 6. The spectrograms of A5 (exhaling and inhaling).

c) Energy

The decay of the harmonics provides an index of the energy-distribution of a single note (measured in dB), and as shown in Table 5 and Figure 7, the two conditions differ significantly in this aspect (Paired Wilcoxon, $p = 0.043$ at $\alpha = 0.05$).

	Exhaling (dB)			Inhaling (dB)		
Note	$H1_{ex}$	$H2_{ex}$	$H3_{ex}$	$H1_{in}$	$H2_{in}$	$H3_{in}$
F5	63.60	51.67	46.37	63.87	22.26	11.99
F5#	72.41	56.86	46.13	60.63	10.68	16.97
G5	68.15	52.19	43.27	61.73	26.01	22.79
G5#	53.26	50.84	37.70	51.48	15.17	13.18
A5	72.23	39.26	24.49	59.40	20.11	4.70
Bb5	70.63	41.45	40.74	65.44	41.39	29.73

Table 5. Decay of the first three harmonics for each pitch (dB).

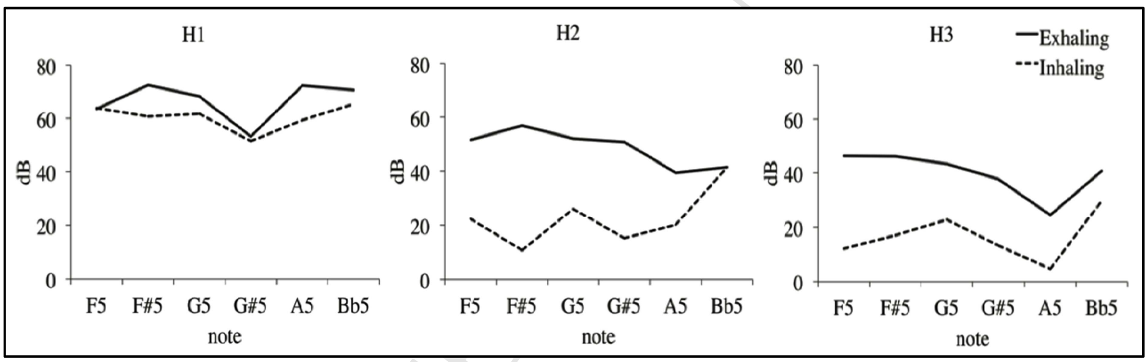

Figure 7. Energy (in dB) of the first 3 harmonics for each pitch.

A two-way ANOVA test was used to quantify the effect of each condition on the energy levels of the harmonics, and on their decay over time. The change of condition is a significant factor for all three harmonics ($F_{(5.30)} = 8.96$, $p = .005$), and the energy levels are lower for inhaling-singing than for exhaling singing (Table 6).

Dependent Variable: Energy (dB)					
Source	**Type III SS**	**Df**	**Mean Square**	**F**	**Sig.**
Corrected Model	3684.28	5	736.86	2.13	.089
Intercept	64921.34	1	64921.34	187.94	.000
Harmonic	363.77	2	181.88	.53	.596
Condition	3093.58	1	3093.58	8.96	.005
Harmonic * Condition	226.93	2	113.47	.33	.723
Error	10362.88	30	345.43		
Total	78968.51	36			
Corrected Total	14047.17	35			

Table 6. ANOVA analysis of Energy levels across by condition and harmonics

The variance of the harmonics is not significant ($F_{(5.30)} = 0.53$, $p = .596$). There is no indication that the harmonics are more unstable in the inhaling condition than in the exhaling condition.

Voice Range Profile

Figure 8 shows the difference in tessitura between exhaling and inhaling singing.

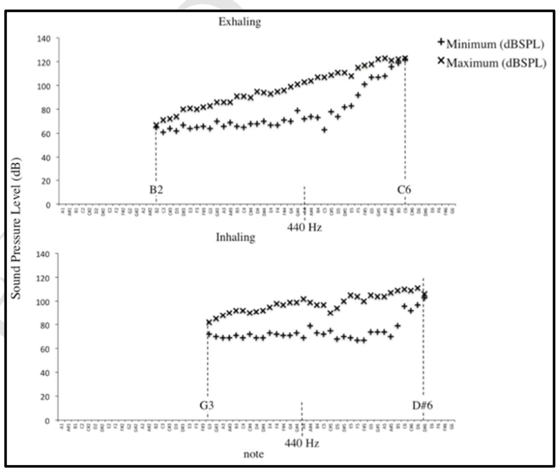

Figure 8. Voice Range Profiles in the two experimental conditions. The X-axis shows the frequency range (Hz are converted to International Pitch Notation), the Y-axis the loudness (dB SPL). The lowest detected intensity is called I_{min}; the highest I_{max} (values in dB SPL).

In the exhaling-singing condition the tessitura is B2 to C6, in terms of musical pitches. Across that range, the I_{max} increases from around 65 dB at the bottom of the pitch-range to around 120 dB at the top. By contrast, I_{min} stays at a stable level (approximately 70 dB) for the bottom three octaves and one semitone (B2 to C5). Beyond this, there is a clear pattern: in the top octave, as frequencies get higher, so loudness increases, up to 120 dB. In the inhaling condition, the tessitura narrower, although it reaches slightly higher, extending from G3 to D#6. Across that range, the I_{max} increases from approximately 80 dB to about 110 dB, although a dip occurs at around C#5. I_{min} stays at a stable level (approximately 70 dB) over almost the entire range, although at the higher extreme (from C6 up to D#6) it increases, as the pitches get higher, to a maximum 110 dB. Thus, within that extremely high register, ISFV offers a larger dynamic range than conventional singing, although the highest intensities are around 10 dB lower. Therefore, exhaling-singing and inhaling-singing have different implications for voice range profile.

Discussion

Acoustical analysis

The results show that it is possible to sing reference pitches using ISFV, just as in conventional singing. Further, whereas pitch stability decreases moving from the bottom to the top of the vocal range in conventional singing, in inhaling-singing, it increases. This contradicts with what others have found (Edgerton, 2004; Wishart, 1996). A possible explanation for this, can be found in variations in breath control and the structural configuration of the resonator cavities (Miller, 2008).
Edgerton found that the potential duration of vocal sounds is typically shorter when using ingressive airflow (Edgerton, 2004). The present study, however, observes an equal MPT for inhaling singing and conventional singing in the lower register (lowest 3 notes), and a longer MPT in the higher register under the inhaling condition. This indicates that inhaling singing may facilitate high-register singing better than exhaling singing, and suggests it may give added value in performance.
Inhaling-singing has a poorer (more sinusoidal) harmonic content than conventional singing. We are well aware that this depends also on the listeners' taste and appreciation' The energy distribution of the harmonics reveals that, in inhaling singing, the energy decrease over the first three overtones is larger than that of exhaling singing. Notably, the highest tones in exhaling-singing contain fewer harmonics, and are in fact equal in content to the corresponding inhaling tones. The peaks in exhaling singing are wider. These differences in peaks may be due to the efforts in reaching the highest notes of exhaling singing. This is mainly due to the vibrato, which is applied in the exhaling condition and not in the inhaling condition. It can be seen as a frequency modulation. Blind listening differentiates these high voicing modes, which is contrary with the low notes in inspiratory phonation (Vanhecke et al., 2015).
Furthermore, the VRP is different for inhaling-singing than for exhaling-singing. Around the time of the experiment, in performances and improvisations the same singer reached a pitch of F#6.
An important drawback of this case study is its sample size: the only subject is the also the researcher is a limitation and subsequent studies would hopefully involve far more subjects. However, to some extent, this limitation is inevitable, given the embryonic, developmental state of ISFV in performance culture: simply, very few singers use this technique, and there are no others who have mastered it. As such, impossibility of comparing results between one subject and the next does not lie solely in experimental design.

Subjective perception by the singer

Numerous environmental factors brought to bear on the singer's experience during these experiments. In the first experiment the singer was instructed not to use vibrato. Nevertheless, vibrato installed itself automatically in the inhaling condition. This was probably an unconscious compensation for the dry, dead acoustics of the soundproofed room. It is assumed that vibrato is related to pressure, due to laryngeal musculature and the breathing system (Sundberg, 1987). The singer confirms the findings of Sundberg, who stated that singers tend to exert more pressure when singing at higher pitches (in exhaling singing), than for low notes (Sundberg, 1987). This was not the case using ISFV, which made it easier to sing higher. It was difficult for the singer to match the exact pitch due to the location of the piano (outside the recording room), and the lack of any opportunity to warm up. Inevitably, performing an act as culturally embedded as singing in experimental conditions brings ecological validity into question, and indeed the singer felt it was difficult to maintain long notes while exhaling in a non-musical (laboratory) context.

Neither vocal fatigue nor pressed phonation, nor any recovery was required after performing ISFV. Accordingly, there was no sensation of pain or strain while inhaling-singing. This was also the case during the period in which ISFV was developed, quite probably due to the singer's good muscle coordination, see Titze (Titze, 2010). The singer is convinced that it is possible to maintain and even to improve vocal quality using inhaling singing. In inhaling singing there is no filtering of air by the nose because the air is directly aspired while inhaling. Therefore, when applying the technique, the space should be room temperature to avoid catching a cold, or other infection. During the experiment, the singer was able to switch between the two conditions at any point, and to pick up the sounds by hearing the note played on the piano. It should be valuable to explore the use of costo-diaphragmatic breathing, as well as to measure the singers' resting expiratory level (REL) and the embodied implications.

Conclusion

This experiment, reporting on the experience of one individual, shows that a tessitura can be mastered in inhaling-singing. Spectral analysis reveals a similar frequency distribution in both conditions. However, in inhaling-singing the energy of the harmonics is significantly lower for the first 3 overtones, while the maximum phonation time is larger than in exhaling singing. The author reports that less effort is required for inhaling-singing in the high female register. Thus, there is potential for singers to learn to expand their tessitura using ISFV.

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