Augmented Visual-Feedback of Airflow: Immediate Effects on Voice-Source Characteristics of Students of Singing

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ABSTRACT

Glottal adduction is a crucial aspect in voice education and vocal performance: it has major effects on phonatory airflow and, consequently, on voice timbre. As the voice is a nonvisible musical instrument, controlling it could be facilitated by providing real-time visual feedback of phonatory airflow. Here, we test the usefulness of a flow ball (FB) training device, reflecting phonatory airflow in terms of visualisation of height of a polystyrene ball placed in a plastic basket during phonation. Audio and electrolaryngographic recordings of five postgraduate classically trained singer students were made under three subsequent conditions: before, during and after phonating into the FB. The calibrated audio-signal was inverse-filtered using the electrolaryngograph signal to guide the manual tunning of the filters. Mean phonatory airflow, peak-to-peak pulse amplitude and normalized amplitude quotient were extracted from the resulting flow glottograms. After the FB condition, increases of mean flow and peak-to-peak pulse amplitude were observed in four singers. Also, after the FB condition, the singers' mean normalized amplitude quotient increased significantly. The findings, although exploratory, suggest that the FB phonation had an immediate effect of reducing glottal adduction.

Keywords: Real-time visual feedback; Education; Phonatory airflow; Glottal adduction; Flow phonation; Classical singing.

I. INTRODUCTION

A. Physiology of voice production

Singing results from neuronally controlled adjustments of the breathing system and of the laryngeal and vocal tract muscles (Christian T. Herbst et al., 2015). A phonatory function of the breathing system is to control vocal loudness: increasing the pressures in the respiratory system, henceforth, subglottal pressure (p_{sub}), produces louder sounds (Johan Sundberg, 1990). A singer's voice quality is highly influenced by the voice source, i.e., the pulsating airflow passing through the slit between vibrating vocal folds, the glottis. The flow-induced self-sustained vibrations, driven by a steady (DC) tracheal airflow, is thus converted into a time-varying glottal (AC) airflow, a process called *myoelastic-aerodynamic theory of voice production* (Van den Berg, 1958). The glottal vibration cycle is therefore composed by a closed and an open phase. The ratio between the durations of the closed phase and the period (i.e., total duration of a glottal cycle) is referred as the closed quotient (CQ). The maximum rate of airflow decrease during the closing phase, referred to as the maximum flow declination rate (MFDR), represents the strength of the acoustic excitation of the vocal tract (Holmberg et al., 1989); a more abrupt change of airflow leads to stronger excitation and higher relative level of the spectrum partials at high frequencies. Thus, the shape of the glottal air pulse directly influences the amplitude and the quality of the vocal sound, and hence voice timbre (C.T. Herbst et al., n.d.). The glottal airflow signal is a complex tone with harmonic partials covering a wide range of frequencies (Fant et al., 1985). Its spectrum envelope has a negative slope, the amplitudes of the partials decreasing equivalently with increasing frequency. This slope becomes less steep with decreasing MFDR (C.T. Herbst et al., n.d.). The voice source spectrum envelope is subsequently modified by the vocal tract resonances (i.e., formants). The frequencies of these formants are determined by the shape of the vocal tract, which is controlled by the articulators: lips, tongue body, tongue tip, velopharyngeal port, jaw and larynx (J. Sundberg, 1987). Figure 1 represents a summary of the classical theory of voice production (Fant, 1960), displaying a flow glottogram, i.e., glottal airflow variation over time, and the respective harmonic series of partials, i.e., voice source spectrum. The bottom graphs display the vocal tract profile, its sound transfer curve, with peaks at the formant frequencies. The right-most graph represents the radiated sound spectrum with envelope peaks and valleys.

< Please insert Figure 1 about here >

Figure 1. Representation of the classical theory of voice production.

B. Glottal adduction, a crucial component

Because of the physiological nature of the vocal instrument, the teaching of singing benefits from a deep understanding of voice production and how it relates to the student's individual needs (Gill & Herbst, 2016). Thereby, the voice sources is a physiological component of crucial significance to voice pedagogy. As first realised by Manuel Garcia (Garcia, 1847), glottal adduction is an important property determining much of the voice timbre. According to Herbst (2019), there are two types of glottal adduction, *cartilaginous adduction*, and *membranous medialization*. The former is achieved by contracting the lateral cricoarytenoid and the interarytenoid muscles, whereas the latter results from a medial compression of the vocal folds resulting from thyroarytenoid and vocalis contraction (C.T. Herbst et al., n.d.). Increase of glottal adduction changes the voice along the *Breathy-Flow-Neutral-Pressed* continuum (J. Sundberg, 1987). Breathy/hypofunctional phonation is produced with little adduction causing an incomplete glottal closure, and generating airflow also during the quasi-closed phase (Patel et al., 2020). Pressed/ hyperfunctional phonation is produced with lower glottal pulse amplitude than neutral and flow phonation, and when habitually used, may lead to voice pathologies (Baken & Orlikoff, 2000; Johan Sundberg, 2020). Flow phonation, located between neutral and breathy but – importantly - still producing a complete vocal fold closure, is characterized by an optimization of the relationship between p_{sub} and glottal adduction (J. Sundberg et al., 1993). Flow phonation seems positively related to a resonant voice quality (Verdolini et al., 1998) and also to vocal economy (Johan Sundberg et al., 2004).

Figure 2 represents airflow glottograms for these phonation types. This type of visual representation of the glottal airflow can be obtained by inverse-filtering either the audio or the flow signal (Patel et al., 2020). As shown by the arrows, the amplitude of the flow pulse varies considerably with phonation type. In addition, also the MFDR, visualised by the dashed lines, shows great difference, depending on type of phonation.

< Please insert Figure 2 about here >

Figure 2. Airflow glottograms showing glottal airflow versus time for the indicated phonation types. Dashed lines represent maximum flow declination rate (MFDR) (adapted from (J. Sundberg, 1981).

Visual feedback of glottal adduction In the teaching of singing according to the classical tradition, the development of a habitual use of flow phonation has been regarded as a corner stone in the “building of the vocal instrument” (C.T. Herbst et al., n.d.). According to Dosher (1994), teachers of singing should implement vocal exercises that promote flow phonation (Doscher, 1994). The rationale for encouraging this type of phonation is two-fold: (i) to achieve a brighter timbre; and (2) to avoid non-harmonic components (i.e., noise) in the voice source spectrum (C.T. Herbst et al., n.d.).

Real-time visual feedback combined with verbal instruction has been shown to circumvent “critical points” in the traditional voice teaching, as it provides the singer with a direct quantitative feedback of his/her response to a given instruction (Welch et al., 2005). Recently, co-author FL introduced the use of the flow ball (FB, see Figure 3) as a new real-time visual feedback of phonatory airflow for training singers (Lã et al., 2017); the user phonates into a narrow tube ending in a basket with a polystyrene ball in it. The phonatory airflow lifts the all to a height that varies proportional to the airflow. For example, an airflow of 0.3 L/s is reflected as a ball height of 5 cm (Lã et al., 2017). Phonation with different adjustments of glottal adduction, at different fundamental frequencies (f_o) and degrees of vocal loudness, p_{sub}, is visualised in terms of ball heights. Thus, the FB should help the student to direct attention to phonatory airflow, and ultimately to recognise the personal optimal relationship between p_{sub} and glottal adduction. In this sense, the FB promotes knowledge of results with regard to glottal adduction, a crucial physiological aspect of voice source control.

< Please insert Figure 3 about here >

Figure 3. Phonating into a flow ball offering real-time visual feedback of phonatory airflow in terms of ball height. In the image the ball reaches approximately 7 cm height, which corresponds approximately to an airflow of approximately 0.4 L/s (Lã et al., 2017).

It is likely that the use of FB influences also the shape of the flow glottograms. The tube elongates and narrows the air passage, producing an effect comparable to that of a semi-occluded vocal tract (SOVT) There are three types of SOVT exercises (SOVTEs): (i) frontal constriction of the vocal tract, such as hand-over-mouth technique; (ii) constriction combined with lengthening of the vocal tract, e.g. phonating through narrow straws with open end in free air; and (iii) dual source of vibration, e.g. when phonating through a tube with open end submerged in water (Amarante Andrade et al., 2016; Andrade et al., 2014). FB exercises belong to the second type. They produce an oral over pressure comparable to the one produced when phonating through a narrow straw of 3.7 mm diameter (Lã et al., 2017). This oral over pressure has been shown to have a favourable effect on MFDR and also reduces the vocal fold collision force (Titze, 2004, 2006). The latter seems critical to voice pedagogy: to learn how to singing *forte* without compromising neither vocal health nor timbre (Johan Sundberg et al., 2011).

The immediate effects of FB *messa di voice* exercise have been previously documented in terms of electroglottographic (EGG) signal characteristics (Lã & Ternström, 2020). Taking into account the above theoretical frame, the authors hypothesised that the increased supra-glottal pressure produced during FB exercise could reduce the relative duration of vocal fold contact time during the vibratory cycle, or the contact quotient. The results confirmed this hypothesis for five out of ten singers. Although contact quotient is related to the closed quotient, it is not directly related to glottal airflow (Christian T. Herbst et al., 2009; Lã & Sundberg, 2015), which, in turn, is directly related to voice quality and phonation type (Baken & Orlikoff, 2000). Thus, the most direct way of studying phonatory physiology is to analyse the voice source in terms of flow glottograms.

Here, immediate effects of FB exercise on voice source parameters will be analysed with regard to the following flow glottograms parameters: mean airflow (U_{mean}) and peak-to-peak pulse amplitude (U_{pp}). As previous results suggest an abductory effect of FB exercises (Lã & Ternström, 2020), also the abduction-related normalized amplitude quotient (NAQ) will be also included.

II. METHOD

A. Participants and recording procedures

Data were drawn from a previous investigation of the effects of FB on vocal folds vibrations, analysed by EGG (Lã & Ternström, 2020). Five males, three tenors and two baritones (mean age 28.4 years, range 23 – 37), all postgraduate students of classical singing of co-author FL, volunteered to participate. They were all recorded in a sound treated room at Aveiro University in Portugal. They were asked to perform *a messa di voce* exercise in three consecutive conditions: (1) sustaining the vowel /a/, *Pre* condition; (2) phonating into the FB, *During* condition; and (3) sustaining the vowel /a/, *Post* condition. The *messa di voce* exercise was chosen as it requires continuous control of airflow combined with changing loudness.

Effects of FB phonation on voice source parameters were analysed by means of inverse filtering. As it was new to the singers, the following instructions were given with regard to how to use it: (1) maintain a neutral non-retracted tongue position; (2) pay attention to the increase/ decrease of airflow as visualized in terms of ball height (higher position with increased loudness); (3) avoid a forward head position. For the *Post* condition, singers were instructed to attempt to retain a similar "open throat" sensation as in the preceding condition. All three conditions were repeated for different tones: for the baritones, starting at A_2 and then progressing in semitones up to $D\#_4$; for the tenors, starting at F_3 and progressing in semitones up to F_4. In this way, the pitch range was at least one octave wide. Figure 4 shows an example of the audio signal for the *Pre*, During and *Post* conditions.

< *Please insert Figure 4 about here* >

Figure 4. Example of the audio signal of one *messa di voce* exercise sung in the indicated conditions.

The audio signal was captured with a head-mounted omnidirectional electret condenser microphone (Knowles model EK3132) and recorded by a Laryngograph microprocessor (www.laryngograph.com, UK) using the *Speech Studio* software, applying a sampling rate of 16 kHz and a resolution of 16 bits. Audio files were transferred to a computer via an USB connection and saved in the wav format. The sound pressure level (SPL) of all recordings was calibrated using a steady 1 kHz sinusoid from a tone generator program (*Tone* from www.tolvan.com), the SLP of which was determined at the recording microphone by means of a sound level meter (AZ instrument, model 8928) and announced in the recording. To avoid clipping, the mouth-to-microphone distance was adjusted prior to the recording and noted for each singer, and then kept the same during the recordings. This allowed recalibration to a 30 cm mouth-to-microphone distance using the equation:

$$SPL@30cm \ = 20 \times log10\,(\frac{d1}{30}) \qquad \text{[Eq. 1]}$$

where d_1 is the mouth-to-microphone distance (Švec & Granqvist, 2018). An EGG signal was simultaneously recorded on a second channel using the same Laryngograph microprocessor. The EGG signal was used to facilitate the inverse filter analysis.

B. Voice source analysis

A section of the loudest portion of the audio signal of all *Pre* and *Post* tones was analysed by inverse-filtering using the inverse-filter module of the custom-made *Sopran* software (by co-author SG, www.tolvan.com). This program calculates the transfer function of a given combination of formant frequencies and bandwidths and then applies it inverted to the input signal. It displays the result as the flow glottogram and its spectrum, i.e., a version of the input signal, in which the effects of the vocal tract transfer function have been eliminated. For the manual tuning of the inverse filters two criteria were applied: (1) a waveform with a ripple-free closed phase; and (2) a spectrum with an envelope as free as possible from peaks and valleys near the formants. The negative peak of the derivative of the EGG signal was used to assist in the determination of the onset of the open phase. Conversion of calibrated pressure to flow was based on the mouth-to-microphone distance.

Mean phonatory airflow (U_{mean}) was estimated from an triangular approximation of the flow pulse, multiplied by the f_o (see Figure 5). The peak-to-peak amplitude of the flow pulse (U_{pp}) was extracted as the maximum flow amplitude in the vibratory cycle. As mentioned, MFDR is the negative maximum amplitude of the derivative of the flow glottogram and the NAQ ratio is defined as:

$$NAQ = \frac{fo \times Upp}{MFDR} \qquad \text{[Eq. 2]}$$

< Please insert Figure 5 about here >

Figure 5. Flow glottogram and its derivative with definition of parameters; U_{pp} = peak-to-peak pulse amplitude; MFDR = maximum flow declination rate; NAQ = normalized amplitude quotient.

C. Statistical analysis

The dimensions of the vocal folds and of the vocal tract tend to differ between singers, depending on e.g., voice classification (Roers et al., 2009). As a consequence, voice source characteristics cannot be directly compared between different singers. To circumvent such limitations and allow direct comparison between *Pre* and *Post* conditions, voice data were converted into standardized scores (z-scores), calculated separately for each singer as the difference between the voice source data and its average across conditions and pitches, and then normalised with respect to their standard deviations. Taking into account the small sample size and the non-normal distribution of the data, *Pre* and *Post* comparisons were analysed by means of a Wilcoxon Signed Ranks test.

III. RESULTS

Table 1 summarises voice source data for each individual singer. Except for tenor T3, U_{mean} and U_{pp} were higher in the *Post* than in the *Pre* conditions; NAQ was higher for the *Post* condition, except for tenors one (T1) and two (T2) (see Figure 6).

Table 1. Mean (*M*), standard deviation (*SD*) and *Post* to *Pre* ratio *(% Change*) per singer. U_{mean} = mean airflow; U_{pp} = peak-to-peak pulse amplitude; NAQ = normalized amplitude quotient.

Singer	*Post*/*Pre* averaged across pitches								
	U_{mean}			U_{pp}			NAQ		
	M	*SD*	*% Change*	*M*	*SD*	*% Change*	*M*	*SD*	*% Change*
B1	1.04	0.16	4.1%	1.04	0.18	3.7%	1.20	0.14	19.5%
B2	1.01	0.16	1.4%	1.03	0.21	2.8%	1.15	0.31	15.0%
T1	1.14	0.25	14.1%	1.01	0.16	0.7%	0.95	0.16	-5.1%
T2	1.12	0.10	11.8%	1.10	0.13	9.8%	0.96	0.13	-3.5%
T3	0.87	0.22	-13.3%	0.89	0.18	-11.1%	1.05	0.14	4.7%

< Please insert Figure 6 about here >

Figure 6. Singers' *Post* to *Pre* ratio of the indicated voice source parameters, averaged across pitches, in percent change: U_{mean} = mean airflow; U_{pp} = peak-to-peak pulse amplitude; NAQ = Normalised amplitude quotient.

Figure 7 shows boxplots of *Pre* and *Post* z-scores, averaged across singers, for U_{mean}, U_{pp} amplitude and NAQ. The Wilcoxon Signed Ranks test showed that only NAQ was significantly different, being higher in the *Post* than in the *Pre* condition [z = - 2.128; p = 0.033].

< Please insert Figure 7 about here >

Figure 7. *Pre* and *Post* comparison between mean z-scores, averaged across the 5 singers and pitches, for the indicated parameters: mean airflow (U_{mean}), peak-to-peak pulse amplitude (U_{pp}) and normalised amplitude quotient (NAQ). The boxplot represents the part of the distribution that falls within the 25th and 75th percentiles, the horizontal line crossing the interior of the box represents the median and the vertical lines outside the box connect the smallest and largest values, disregarding extremes and outliers.

IV. DISCUSSION

As mentioned in the introduction, flow phonation is a key component for determining voice timbre (Doscher, 1994). Physiologically speaking, it plays an import role in producing a healthy and sustainable vocal instrument (Sataloff, 1998). Thus, exercises promoting habitual flow phonation have been implemented by teachers of singing, especially in the teaching the classical style (Doscher, 1994).

The present pilot study analysed effects of using a FB as a real-time visual feedback of phonatory airflow for promoting flow phonation. Previous investigations have shown a linear relationship between ball height and airflow (Lã et al., 2017). Thus, the height of the ball is the essence of the visual feedback, which could be assumed to direct the student singer's attention to, and awareness of the airflow, and hopefully also transfer the underlying phonation into singing.

The study was carried out to test this assumption. The results showed that the effects of FB feedback on the five singers' voice sources were quite varied. The great individual variation observed is comparable to what has previously been found for aerodynamic and EGG effects of SOVTEs (Dargin & Searl, 2015; Lã & Ternström, 2020). Although in the present study, vibratory metrics were not investigated, a similar individual variability was found for airflow-related voice source parameters. For four out of five singers, both U_{mean} and U_{pp} increased after applying the FB feedback. Mean airflow was the parameter that showed the greatest increase, ranging from 1.5% to 14%, whereas U_{pp}, varied from an increase of about 1% to 10%. The increase of U_{mean} is in qualitative agreement with previous reports (Dargin & Searl, 2015).

The increase in both U_{mean} and U_{pp} suggests reduced glottal adduction. A similar effect was previously found for *messa di voce* exercises, performed after using FB feedback (Lã & Ternström, 2020). In addition substantial increases of NAQ were observed for the two baritones after FB, suggesting that they reduced their glottal adduction. NAQ is defined as the ratio between U_{pp} and MDFR; the NAQ increases were combined with increases of $\hat{U}$. *Similarly*, tenor 2 showed an increase of U_{pp} that however was combined with a decrease of NAQ after FB.

Tenor 3, by contrast, combined an increase in NAQ with a decrease of U_{pp}. This combination could seem unexpected. However, the FB creates a flow resistance that produces a flow resistance similar to that of phonating into a 3.7 mm straw (Lã et al., 2017). This could be the reason for the combination of NAQ increase with the decrease of U_{mean} and U_{pp} (Titze, 2006).

A FB height of 10 cm corresponds to an airflow of 0.4 L/s in rhw FB model used. Such airflow can be observed in breathy phonation, while 0.1 to 0.2 L/s are more typical for neutral phonation (Bouhuys et al., 1966). For an air flow of 0.2 L/s the ball height is close to 1 cm. Experiencing the extremes of glottal adduction and abduction may be a help to find the personal optimum degree of glottal adduction. Obviously, it is important to tailor voice teaching to the individual student. Phonation type is a continuum extending between the breathy/hypofuntional and pressed/hyperfunctional extremes. Firm glottal adduction and low glottal airflow are characteristic of the latter. For singers habitually using hyperfunctional phonation, using the FB may be an efficient help; it is likely to attract the singer’s attention to the crucial airflow/glottal adduction parameter.

According to the Wilcoxon rank test, the NAQ parameter increased significantly in the *Post* condition. Although our results were based on few subjects and the results were varied, they seem promising for future investigations with randomized, controlled experimental designs. It will be also worthwhile to investigate how much of this effect could be retained and transferred into singing.

Beneficial effects of using real-time feedback in the treatment of disorders in hearing, resonance, speech fluency, articulation, swallowing and respiration have been documented (Maryn et al., 2006). Likewise, real-time visual feedback of pitch contour as well as contact quotient by EGG has been found to improve learning of singing (Howard & Welch, 1989; Rossiter et al., 1996). The FB provides real-time visual feedback of phonatory airflow, a crucial aspect of phonation. It seems that this feedback also encourages student singers towards the acquisition of a kinaesthetic awareness of glottal adduction and of a crucial component of voice production, i.e., phonatory airflow. Both are not displyed in other forms of real-time visual feedback already in use in the voice studio, such as spectrographic displays (Nair, 1999). In this sense, the use of a FB seems to be a valid and necessary complementary type of real-time visual feedback. Moreover, it does not suffer from the disadvantage of being expensive. Singers can afford their own FB. In addition its maintenance is cheap. It would be worthwhile to apply it also to dysphonic singers and to a greater number of students of different music genres.

V. CONCLUSION

Applying FB in voice training resulted in a significant change of phonation type in terms of a NAQ increase, a sign of reduced glottal adduction. It also affected mean phonatory airflow and pulse amplitude in some of the participating students. Thus, although exploratory, these results seem to encourage further FB investigations on student's development of phonatory habits towards flow phonation, applying well controlled studies and assessing a larger number of student singers.

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TABLE CAPTIONS

Table 1. Mean (*M*), standard deviation (*SD*) and *Post* to *Pre* ratio *(% Change*) per singer. U_{mean} = mean airflow; U_{pp} = peak-to-peak pulse amplitude; NAQ = normalized amplitude quotient.

FIGURE CAPTIONS

Figure 1. Representation of the classical theory of voice production.

Figure 2. Airflow glottograms showing glottal airflow versus time for the indicated phonation types. Dashed lines represent maximum flow declination rate (MFDR) (adapted from (J. Sundberg, 1981).

Figure 3. Phonating into a flow ball offering real-time visual feedback of phonatory airflow in terms of ball height. In the image the ball reaches approximately 7 cm height, which corresponds approximately to an airflow of approximately 0.4 L/s (Lã et al., 2017).

Figure 4. Example of the audio signal of one *messa di voce* exercise sung in the indicated conditions.

Figure 5. Flow glottogram and its derivative with definition of parameters; U_{pp} = peak-to-peak pulse amplitude; MFDR = maximum flow declination rate; NAQ = normalized amplitude quotient.

Figure 6. Singers’ *Post* to *Pre* ratio of the indicated voice source parameters, averaged across pitches, in percent change: U_{mean} = mean airflow; U_{pp} = peak-to-peak pulse amplitude; NAQ = Normalised amplitude quotient.

Figure 7. *Pre* and *Post* comparison between mean z-scores, averaged across the 5 singers and pitches, for the indicated parameters: mean airflow (U_{mean}), peak-to-peak pulse amplitude (U_{pp}) and normalised amplitude quotient (NAQ). The boxplot represents the part of the

distribution that falls within the 25th and 75th percentiles, the horizontal line crossing the interior of the box represents the median and the vertical lines outside the box connect the smallest and largest values, disregarding extremes and outliers.