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Glottal behavior in the high soprano range and the transition to the whistle register

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The high soprano range was investigated by acoustic and electroglottographic measurements of 12 sopranos and high-speed endoscopy of one of these. A single laryngeal transition was observed on *glissandi* above the *primo passaggio*. It supports the existence of two distinct laryngeal mechanisms in the high soprano range: M2 and M3, underlying *head* and *whistle* registers. The laryngeal transition occurred gradually over several tones within the interval D#5-D6. It occurred over a wider range and was completed at a higher pitch for trained than untrained sopranos. The upper limit of the laryngeal transition during *glissandi* was accompanied by pitch jumps or instabilities, but, for most singers, it did not coincide with the upper limit of $R1$:f_0 tuning (i.e., tuning the first resonance to the fundamental frequency). However, pitch jumps could also be associated with changes in resonance tuning. Four singers demonstrated an overlap range over which they could sing with a *full head* or *fluty resonant* quality. Glottal behaviors underlying these two qualities were similar to the M2 and M3 mechanisms respectively. Pitch jumps and discontinuous glottal and spectral changes characteristic of a M2-M3 laryngeal transition were observed on *decrescendi* produced within this overlap range.
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I. INTRODUCTION

Sopranos demonstrate several changes in voice quality during *glissandi*, often accompanied by pitch jumps or instabilities (Miller, R., 2000). Although the main lower transition (below A4, 440 Hz) has been much described by scientific studies, relatively little is known about transitions and registers in the higher range. There is still no consensus on the number of transitions, on the pitch at which they occur, nor on their physical nature.

The first transition in the soprano voice typically occurs around E4–F4 (∼340 Hz) (Miller, D.G., 2000; Miller, R., 2000; Roubeau *et al*., 2004, 2009; Henrich, 2006). Commonly known as the *primo passaggio* or the *chest-head* register transition, this transition corresponds to the M1–M2 change in laryngeal mechanism (Roubeau *et al*., 2009). Classical sopranos are trained to lower this transition to avoid a voice "break" and changes in quality toward the bottom of their tessitura. Consequently, they often extend the range of the M2 laryngeal mechanism to pitches as low as C4 (∼260 Hz).

A second transition somewhere in the range C5–G5 (∼500–700 Hz) is mentioned by some authors. Known as the *secondo passaggio*, this transition divides the C4–C6 range into a *middle* and an *upper* register (Sonninen *et al*., 1999; Miller, D.G., 2000; Miller, R., 2000; Echternach *et al*., 2010). Some authors suggested that this transition could be related to vocal-tract tuning (Miller, D.G., 2000). Indeed, B4–D5 corresponds approximately to the pitch range where the fundamental frequency (f_0) reaches the frequency range of the first vocal tract resonance for closed and mid vowels and above which sopranos tune the frequency of their first vocal tract resonance ($R1$) to the fundamental frequency (f_0) (Sundberg, 1975; Joliveau *et al*., 2004a; Garnier *et al*., 2010). In some sopranos, B4–D5 also corresponds to the pitch range from which they start increasing mouth aperture (Sundberg and Skoog, 1997; Echternach *et al*., 2010; Garnier *et al*., 2010). Another study showed significant changes in distance and position of laryngeal structures, supporting the idea that the *secondo passaggio* corresponds to a significant change in laryngeal behavior and pitch control mechanism (Sonninen *et al*., 1999).

A third transition is commonly reported in the top range of the soprano voice, occurring somewhere in the broad range E5 (660 Hz) to G6 (1570 Hz) (Behnke, 1880; Van den

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Berg, 1963; Van Deinse, 1981; Shipp *et al.*, 1988; Walker, 1988; Keilmann and Michek, 1993; Miller and Schutte, 1993; Herzel and Reuter, 1997; Chuberre, 2000; Thurman *et al.*, 2004;Svec *et al.*, 2008; Roubeau *et al.*, 2009). The physical nature of this transition is poorly understood. Several authors associate it with a switch to the highest vocal register (*whistle, flageolet, flute, bell, small, pipe*).

This *whistle* register is characterized by consistent acoustic features, such as a concentration of the acoustic power in the two first harmonics (Walker, 1988), reduced power around 3 kHz and enhanced jitter (Keilmann and Michek, 1993). Perceptually, its voice quality is well recognized (Walker, 1988) and consistently described as *fluty*, although some other perceptual attributes can vary considerably with the singer's expertise. Untrained singers often sound *squeaky* or *breathy* with reduced intensity and reduced range of intensity (Thurman *et al.*, 2004), whereas trained coloratura sopranos can produce very intense and "resonant" sounds (Thurman *et al.*, 2004; Garnier *et al.*, 2010). The biomechanical properties of the larynx in this high range are unknown. Some previous studies reported several significant differences in laryngeal behavior compared to laryngeal mechanism M2; this suggests that the whistle register may result from a third, distinct laryngeal mechanism M3 (Chuberre, 2000; Henrich, 2006; Roubeau *et al.*, 2009): these studies measured significantly weaker levels of subglottal pressure (Miller and Schutte, 1993) and air flow (Walker, 1988) as well as high values of open quotient (*OQ*) (Henrich, 2001; Svec *et al.*, 2008; Roubeau *et al.*, 2009). Glottal vibratory amplitude was reported as smaller than in laryngeal mechanism M2, sometimes without contact between the vocal folds (Rothenberg, 1988; Miller and Schutte, 1993; Svec *et al.*, 2008; Tsai *et al.*, 2008). As a consequence, glottal contact may be difficult to detect, and electroglottographic (EGG) signals are of very small amplitude (Miller and Schutte, 1993; Chuberre, 2000; Henrich, 2001; Roubeau *et al.*, 2009). A constriction of the supraglottal and pharyngeal cavities has been reported (Shipp *et al.*, 1988; Svec *et al.*, 2008). This can make endoscopic exploration difficult or impossible.

Three theories have been proposed to explain the physical nature of the *whistle* register. A first acoustic theory proposes that the weakening of the vocal fold vibration at very high pitch does not correspond to a fundamentally different laryngeal mechanism from M2 but simply arises from a change in source-filter interaction (Miller and Schutte, 1993). Indeed, sopranos are known to adjust the frequency of their first vocal tract resonance ($R1$) close to the fundamental frequency (f_0) from ~500 to 1000 Hz (C5–C6) (Joliveau *et al.*, 2004b; Garnier *et al.*, 2010; Henrich *et al.*, 2011). Miller and Schutte (1993) showed that the weakening of vocal fold vibration at very high pitch coincides, for some singers, with the end of the $R1{:}f_0$ resonance tuning. Rothenberg (1988) showed that the artificial lengthening of the vocal tract with a tube lowers the maximum pitch to which the two singers of that study can extend the $R1{:}f_0$ tuning and also shifts down the laryngeal transition to the *whistle* register. However, recent results have shown that sopranos can still utilize resonance strategies over their highest range by tuning their second vocal tract resonance ($R2$) to f_0 once f_0 exceeds the possible range of $R1$ (Garnier *et al.*, 2010). Therefore the weaker vibration of the vocal folds at very high pitch might not necessarily be a consequence of the absence of tuning of a vocal tract resonance.

In a second "damping" theory, it is proposed that high frequencies are produced and controlled by adjusting the vibrating length of the vocal folds by means of varying degrees of compression of the arytenoids (Pressman and Kelenen, 1955; Van den Berg, 1963; Thurman *et al.*, 2004; Titze and Hunter, 2004). Many authors report the absence of complete closure of the vocal folds at very high pitch (Thurman *et al.*, 2004; Svec *et al.*, 2008; Tsai *et al.*, 2008). However, most of them observed a vibration of the whole length of the folds, including the posterior chink (Keilmann and Michek, 1993; Svec *et al.*, 2008).

In a third aero-acoustic theory, it is suggested that vocal folds vibrate in a "vortex-induced" fashion similar to that of lip whistling (Berry *et al.*, 1996; Herzel and Reuter, 1997). In lip whistling, the air flow is modulated by the oscillatory motion of an air jet through the constricted lips (Wilson *et al.*, 1971). The modulation frequency, i.e., the pitch of the lip whistle, is controlled by the second resonance of the vocal tract, behaving as an upstream resonator. Somewhat similarly, extreme high vocal pitches are hypothesized to be produced by an oscillating jet at a narrowed glottis. Pitch may be controlled by the second resonance of the vocal tract, behaving in this situation as a downstream resonator. Further supporting this hypothesis are the only horizontal surface movements of the vocal folds (Keilmann and Michek, 1993) reported in the *whistle* register, the rotation of water on the folds observed at the same frequency as their oscillation (Berry *et al.*, 1996) as well as the close proximity between $R2$ and f_0 observed in singers able to sing above D6 (Garnier *et al.*, 2010).

Further understanding of the physiological nature of the transitions in the high soprano range is needed. This study investigates the high range of 12 sopranos with different levels of expertise, to characterize how their glottal behaviors and their voice spectra vary with pitch and intensity, the frequencies at which fundamental changes occur and whether these transitions are influenced by vocal training. Interesting phenomena observed from the EGG signal are then investigated further through high-speed glottal video imaging of one of these singers. These observations, in conjunction with parallel measurements of vocal tract adjustments (Garnier *et al.*, 2010), enable discussion of the physiological nature of the transitions in the high soprano range and how they relate to changes in resonance tuning.

II. MATERIALS AND METHODS

A. Acoustic and EGG measurements on 12 singers

1. The subjects

The subjects of the study were 12 sopranos, aged from 18 to 29 years and selected for their ability to produce high pitches. Subjects NE1 to NE4 were non-expert singers, AD1 to AD4 were advanced students, and PR1 to PR4 were professionals. Additional details are presented in Garnier *et al.* (2010).

2. The protocol

In a first part, singers were asked to produce at least three *glissandi* over their whole tessitura using the vowel [a]. They began at pitches around C4–E4.

In a second part, singers sustained a single note for 4 s, again on the vowel [a]. They were asked to maintain constant pitch and loudness and to limit vibrato. Three tokens of each note were produced for measurement. They started on the pitch A4 and continued, on an ascending diatonic scale, to the highest pitch they could produce. For 5 of the 12 singers, the maximum pitch that could be sustained for more than a second was the same as the highest pitch that they could produce briefly at the end of the ascending *glissando* (see Fig. 1). For the others, the *glissando* briefly achieved pitches higher than those that could be sustained by one or two tones (for NE2, NE3, NE4, and PR2) or by three to six tones (for AD1, AD2, and AD3). Only eight singers could sustain notes above C6, and only five singers could sustain notes above E6. Four of the singers (NE1, AD3, AD4, and PR4) exhibited a pitch range around E5–G5 (from two tones to an octave), over which they were able to produce intentionally two very different voice qualities with distinct measured properties. In this paper, these qualities are called *full head* and *fluty resonant*, but the analysis uses their acoustic properties rather than subjective assessments or names. Over this range in which the two qualities overlap, these four singers produced three tokens of each note in each of the qualities.

In a third part, these four singers were asked to produce *decrescendi* on the vowel [a] for several notes in the range where the two different qualities were possible. The loudest part of the *descrescendo*, at its beginning, was produced with the *full head* quality. At least three examples of each note were recorded. One singer also produced *crescendi* in this overlap range.

3. The measurements

The audio signal was recorded with a 1/4-in pressure microphone (Brüel and Kjær 4944-A), placed 30 cm away from the singers' lips, then amplified (conditioning amplifier Brüel and Kjær Nexus 2690) and digitized with 16-bit resolution at a rate of 44.1 kHz using a FireWire audio interface (MOTU 828). The sound pressure level was calibrated using the 1 kHz internal reference signal of the conditioning amplifier.

The EGG signal was simultaneously recorded with a two-channel electroglottograph (Glottal Enterprises EG2), using medical gel to improve electric contact between the skin and the electrodes. Electrodes were placed on both sides of the thyroid cartilage while the singer was singing in her comfortable middle range. The best placement of the electrodes was found by monitoring the EGG waveform with an oscilloscope. Medical tape was used on each electrode, instead of the usual Velcro neck strap, to prevent the electrodes from moving down throughout the experiment. No automatic gain control was used.

During the second part of the protocol, vocal-tract resonance frequencies were measured by broad-band excitation at the mouth, while audio and EGG signals were simultaneously recorded. These vocal-tract resonance measurements are presented in a companion article (Garnier *et al.*, 2010) and will be referred to when examining how laryngeal transitions relate to resonance adjustments.

Using MATLAB software, the following four parameters were extracted from the EGG signal, using an 80 ms sliding rectangular window with no overlap:

(1) The fundamental frequency (f_0), calculated using an autocorrelation method.
(2) The amplitude of the EGG signal.
(3) The glottal OQ, defined as the ratio between the duration of the glottal open phase and the fundamental period. OQ was computed from the closing (positive) and opening (negative) peaks detected in the derivative of the EGG signal (DEGG) (Henrich *et al.*, 2004).
(4) The contact speed quotient (Qcs), defined as the ratio in amplitude of closing and opening peaks of the DEGG signal. This quotient describes the relative difference in speed of contact between glottal opening and closing. It reflects the degree of asymmetry of the EGG waveform.

The calibrated sound pressure level (SPL) and voice spectrum were measured from the audio signal, using an 80 ms sliding rectangular window with no overlap. The levels of voice harmonics (AH_i, in dB) were then extracted from the voice spectrum to estimate r = mean (AH_1, AH_2) − mean$(AH_3, AH_{i \leq 10\ \mathrm{kHz}})$, a parameter quantifying the difference between the average level of the two first harmonics and that of the other harmonics below 10 kHz.

For the sustained pitches of the second session, the mean value of glottal parameters was computed over the 4 s of phonation, whereas the mean SPL and mean r value were computed only from the first second of the audio signal before the vocal tract was excited by the external broadband signal.

Previous studies showed how, on *glissandi*, the change in laryngeal mechanism from M1 to M2 is characterized by a sudden decrease in glottal contact (translating into a decrease in amplitude of the EGG signal), a sudden increase in OQ and a sudden change toward more symmetrical waveform of the EGG signal (Roubeau *et al.*, 1987, 1991; Henrich, 2001; Henrich *et al.*, 2005; Roubeau *et al.*, 2009).

In the *glissandi* produced in this study, we verified that these sudden changes in the EGG signal, typical of the M1–M2 transition (the *primo passaggio*), and often accompanied by a pitch jump, always occurred below E4. Consequently, sopranos were always using mechanism M2 in their middle range (~F4–G4), corresponding to the bottom of the range considered for analysis in this paper and its companion study (Garnier *et al.*, 2010). It follows that the transitions above F4 described in this article, and especially those far above F4, cannot be interpreted as the M1–M2 transition.

B. Endoscopic investigation on one singer

Singer NE1 undertook further endoscopic investigations of *glissandi* and *decrescendi* in her high-pitch range, to relate features of the EGG signal in this range to visual observations of the glottis. Endoscopy was not available for the other 11 singers.

High-speed video recording of the vocal fold vibration was carried out at the Georges Pompidou European Hospital (HEGP) in Paris using a high speed camera (Weinberger SL Kamera 2000) connected to a SpeedCam + Lite acquisition system. Two thousand frames were recorded per second with a resolution of 256 × 256 pixels. The EGG signal (Portable Laryngograph) was recorded in synchrony with the audio signal (AKG C410 microphone) on the computer. Both signals were preamplified with a Diana interface (SQLab).

III. RESULTS

Figure 1 indicates the pitch range explored for each soprano, from F4 (above the M1–M2 transition) to the upper limit of her vocal range. It summarizes different information on vocal transitions in this high range: (1) variations in amplitude of the EGG signal, (2) regions of pitch jumps or voice instabilities, and (3) ranges where different resonance tuning strategies were used. In this figure (as well as in Figs. 2 and 3), data for each token on each subject are included to indicate intra-subject variability.

A. Changes and transitions observed during *glissandi*

1. *A laryngeal transition characterized by a decrease in EGG amplitude*

The vertical axis in Fig. 1 is the amplitude of the EGG signal. This was always weaker at the top of the singers' vocal range than in the medium range (~*F4*). This decrease in amplitude may be interpreted as a decrease in glottal contact. Another possible contributing factor is the rising larynx that most sopranos reported feeling at high pitch and described in several studies (Shipp and Izdebski, 1975; Sonninen *et al.*, 1999). In any case, this decrease in amplitude indicates a transition between two stable laryngeal behaviors. The lower and upper limits of the laryngeal transition respectively were identified by visual inspection as the pitches immediately before and after the decrease in amplitude. The pitch range of the transition was the difference between the upper and lower limits.

On average, the amplitude of the EGG signal was reduced by a factor of 4.2 ± 1.5 during this transition (for comparison, Roubeau *et al.*, 1987 reported a decrease by only 1.8 during the M1–M2 transition for women.)

Although this laryngeal transition always occurred at pitches above those of the M1–M2 transition, it could start as low as G4 (for singers NE3, NE4, and PR4) or as high as D5-D#5 (for singers AD4 and PR1), the average starting pitch being A#4 ± 3 semitones. Expertise did not appear to influence the lower pitch limit of the transition. The upper pitch limit of the transition also varied considerably among singers: non-expert singers tended to complete the laryngeal transition at lower pitches (~D#5) than advanced and professional singers (from F#5 to D#6), except for singers NE2 and AD3. The laryngeal transition sometimes occurred very rapidly with increasing pitch (e.g., NE1) or could be spread over an octave (e.g., PR4).

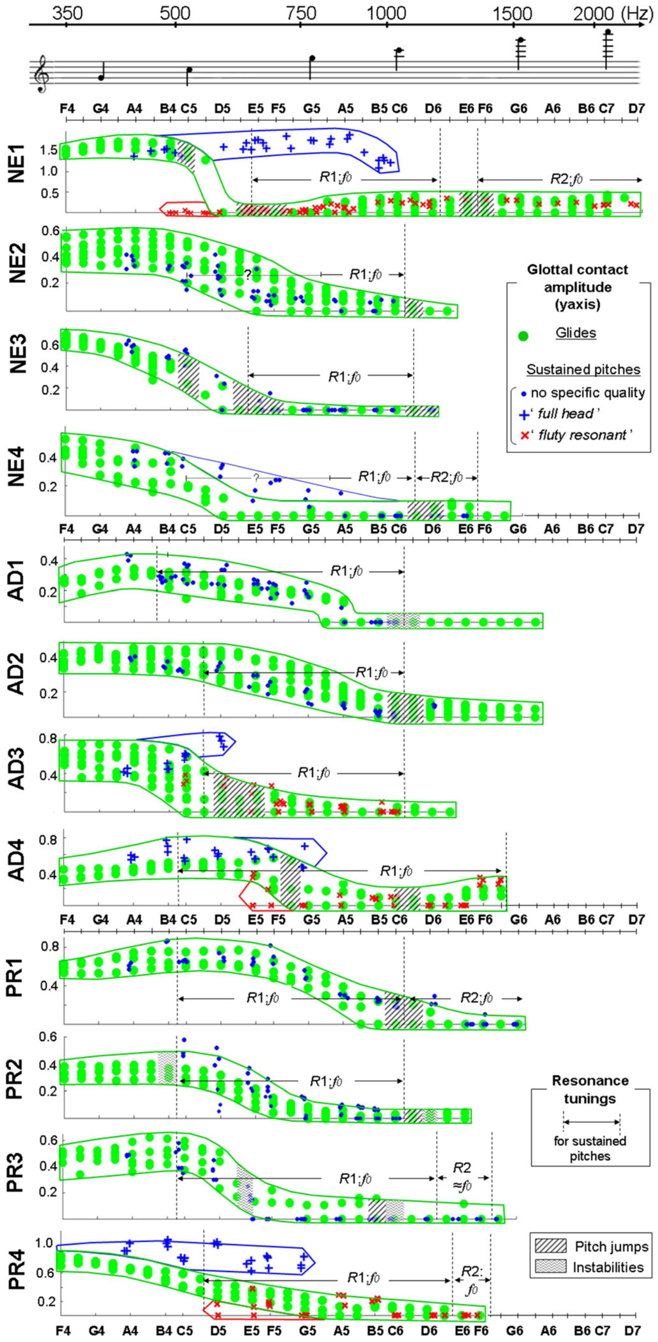

FIG. 1. (Color online) Summary of the observations on the 12 singers. Large pale circles represent, in the arbitrary units of the electroglottograph (no automatic gain control was used), the variation in glottal contact amplitude with increasing pitch on *glissandi*. (The multiple points at each pitch are from different *glissandi* and indicate the reproducibility.) Small dark dots represent this variation for sustained pitches produced without any specific intended quality, while dark + and × symbols represent this variation for sustained pitches produced with, respectively, a *full head* or a *fluty resonant* intended quality. Dashed or waved areas indicate pitch ranges where pitch jumps and instabilities were observed on *glissandi*. Horizontal arrows indicate the ranges of sustained notes over which vocal tract resonances were tuned to the first voice harmonic (f_0) (reported from Garnier *et al.*, 2010).

In most cases, there were one or more pitches in the transition range for which no variation in glottal contact was detected by EGG, i.e., the EGG signal showed no periodic waveform. In a few cases, however (on some of the *glissandi* produced by singers NE2, AD2, PR1 to PR4), glottal contact variation was maintained throughout the transition. For 10 of the 12 singers, a small-amplitude, periodic EGG signal could be detected above the transition. No substantial change in the amplitude of the EGG signal was then observed with increasing pitch (see Fig. 1).

2. *Variations in open quotient (*OQ*)*

In Figs. 2 and 3, several acoustic and glottal parameters are plotted as functions of pitch for four singers to illustrate different behaviors observed. Two contrasting behaviors were observed in the *OQ*:

In 10 singers (PR2-4, AD1,3-4, NE1-4), *OQ* increased smoothly with increasing f_0 over the pitch range throughout which the amplitude of the EGG signal decreased [see Figs. 2(b) and 3]. However, the parameters did not always vary in complete synchrony: For different singers, *OQ* started increasing at pitches that were slightly higher or lower than those of the decrease in contact amplitude. The maximum values of *OQ*, higher than 0.8 and mostly around 0.9, were reached at the upper limit of the laryngeal transition. Above the transition, *OQ* tended to decrease continuously with ascending pitch for seven singers [see Figs. 2(b) and 3] and remained constant for one (singer AD3).

For two singers (PR1, AD2), *OQ* decreased with f_0 over the first part of the transition interval [see *glissandi* chart of Fig. 2(a)]. It then reached a local minimum four semitones before the amplitude of the EGG signal reached its lowest level and then continuously increased with pitch over the remaining transition interval and above.

3. *Variation in contact speed quotient (*Qcs*)*

The contact speed quotient consistently decreased smoothly with ascending f_0 for 10 of the singers over the pitch range in which the amplitude of the EGG signal decreased (see Fig. 2), indicating that the EGG waveform was becoming more symmetrical. The variation in *Qcs* was not completely synchronous with the variation in amplitude of the EGG signal or with the variation in *OQ*. Above the laryngeal transition, no significant change in *Qcs* was observed with increasing f_0 (see Figs. 2 and 3). For two singers (NE2 and PR1), *Qcs* continued to decrease slightly with increasing f_0.

4. *Variations in the EGG waveform*

Apart from NE1, for whom the laryngeal transition was abrupt, no singer showed any discontinuous variation in laryngeal parameters during the transition. As a consequence, the EGG signal presented intermediate waveforms between the typical M2 waveform observed below the transition and the EGG waveform observed above it (see Fig. 4).

5. *Variation in SPL*

For most singers, SPL was typically 10-15 dB greater above the laryngeal transition than below. For some singers

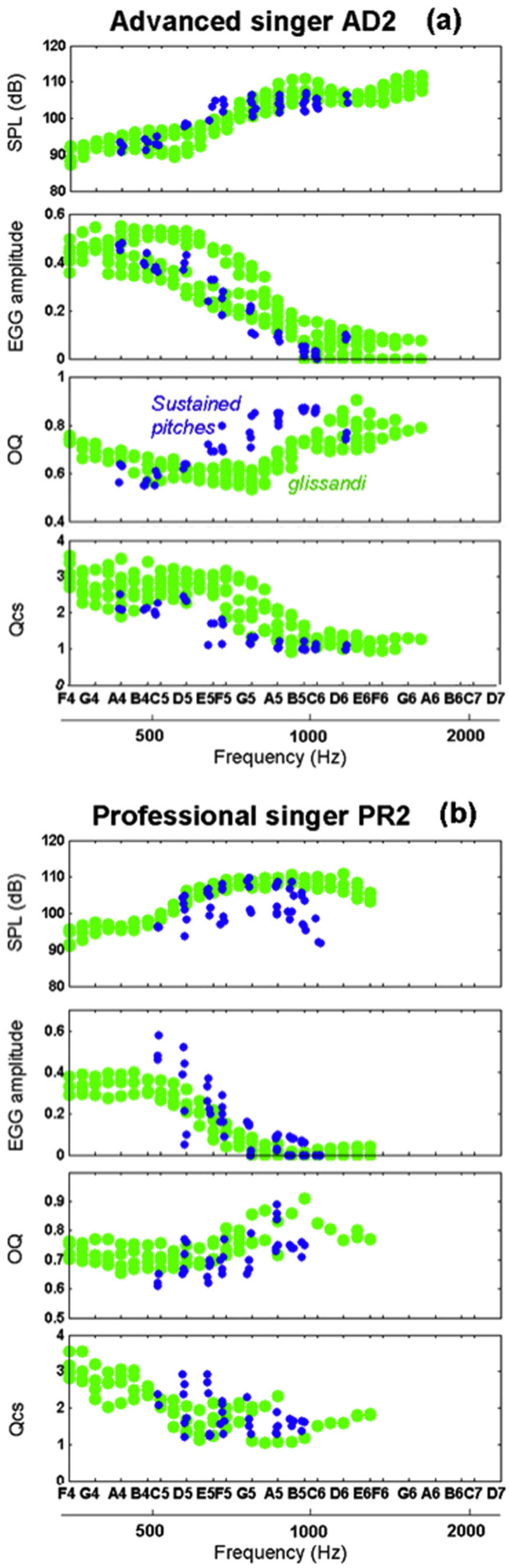

FIG. 2. (Color online) The variation of sound pressure level (SPL), amplitude of the EGG signal, open quotient (*OQ*), and the contact speed quotient (*Qcs*) with increasing pitch for the advanced singer AD2 (a) and the professional singer PR2 (b), measured on continuous *glissandi* (light grey) or sustained pitches (dark).

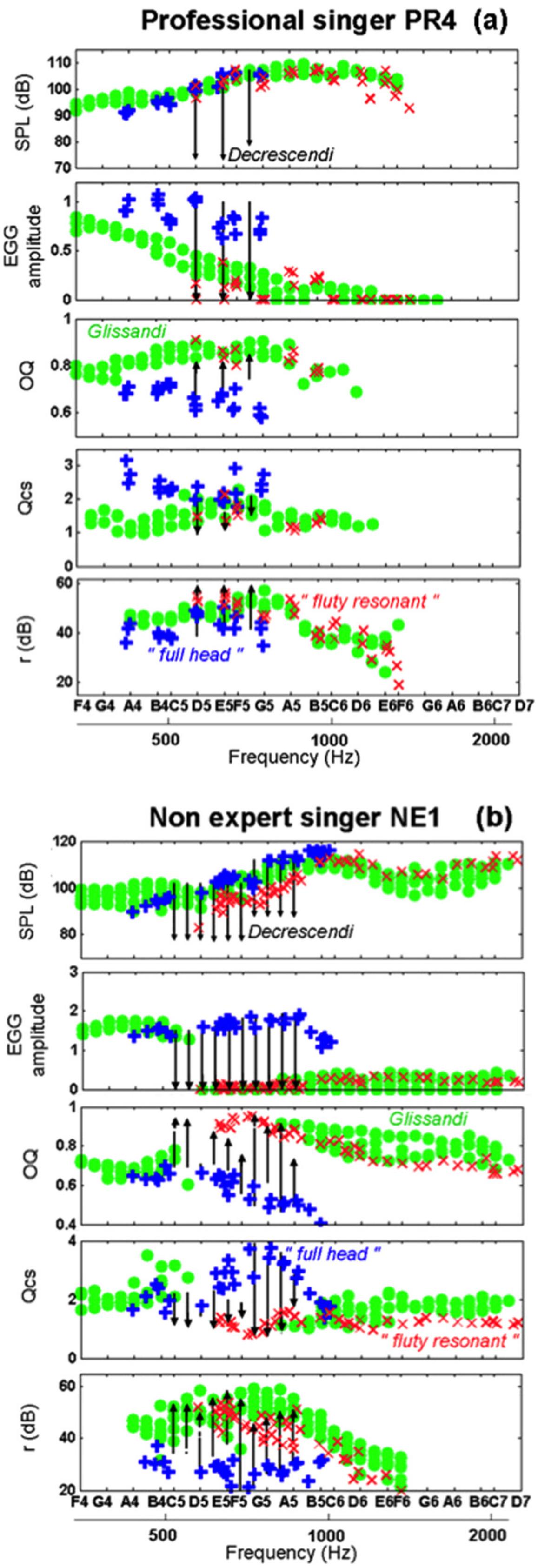

FIG. 3. (Color online) The variation of SPL, amplitude of the EGG signal, open quotient (*OQ*), contact speed quotient (*Qcs*), and enhancement of the two first voice harmonics (*r*) with increasing pitch for the professional singer PR4 (a) and the nonexpert singer NE1 (b). They were measured on continuous *glissandi* (big pale dots), on sustained pitches in *full head* quality (dark bold +) or in *fluty resonant* quality (× symbols), and on continuous *decrescendi* (black lines).

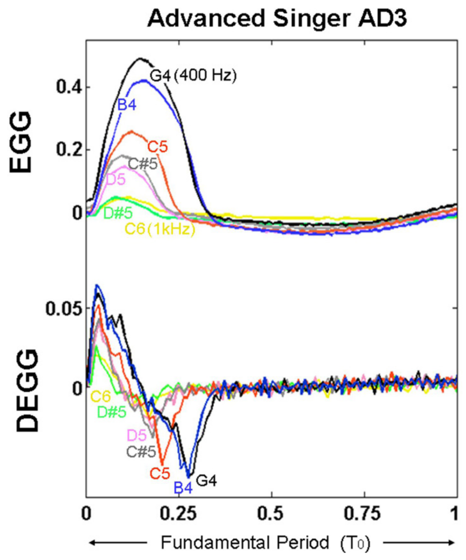

FIG. 4. (Color online) Waveforms of the EGG and DEGG signal measured for singer AD3 before, during, and after her laryngeal transition, which occurred between B4 and D#5.

(NE2, AD1, AD2, PR1-PR4), it increased during the transition and reached its maximum value at the end of it [see Figs. 2 and 3(a)]. For other singers, it started increasing around C5-D5, which was either above (AD3, NE1, NE3 and NE4) or below (AD4) the starting pitch of the transition [see Fig. 3(b)].

For all singers, SPL reached its maximum value in the range A5–C6 and then decreased at higher pitch. For some singers, the decrease was small [see Fig. 3(a)]. For others, the decrease could be as much as 10 dB between C6 and G6 [see Fig. 3(b)]. Singers who sang above E6 demonstrated a second increase of SPL with f_0 over their top range where no significant change was observed in glottal parameters [see Figs. 2(a) and 3(b)].

6. *Pitch breaks, pitch jumps, and instabilities*

Although singers were instructed not to avoid breaks, the professional and advanced singers exhibited fewer pitch breaks or jumps than did non-expert singers. A reason may be that part of vocal training consists in learning how to smooth and hide register transitions. Therefore, voice instabilities during the *glissandi* were considered in addition to pitch breaks or jumps. They were quantified by computing df_0/dt as a function of f_0 and identifying local extrema.

Figure 1 summarizes for each singer the pitch range(s) over which pitch jumps (striped shading) or instabilities (wavy shading) were observed during the different *glissandi*. There were three main pitch ranges where instability occurred:

(1) around B4–C5. This concerned only three singers. Systematic jumps were observed for two non expert singers (NE1 and NE3) and the professional singer PR2 exhibited consistent instability.

(2) around E5 (from D5 to F#5 depending on the singer). This concerned five singers: non-experts (NE1, NE3),

advanced and professional singers (AD3, AD4, and PR3).

(3) around C#6 (from B5 to E6 depending on the singer). Ten of the 12 singers showed pitch jumps or instability in this region.

One singer (PR4) exhibited no pitch breaks, jumps, or instabilities in the pitch range studied. Half of the singers (NE2, NE4, AD1, AD2, AD3, and PR1) exhibited instability in only one pitch range, which coincided with the upper limit of the M2–M3 laryngeal transition (i.e., the pitch from which the amplitude of the EGG signal stopped decreasing). This upper limit varied among singers, observed as low as D5 and as high as D6 (Fig. 1). Three singers (AD4, PR2, and PR3) showed instabilities in two pitch ranges, and two singers (NE1 and NE3) exhibited instabilities in three pitch ranges. In four of these five singers, the instabilities also occurred at the upper limit of the laryngeal transition.

Taking all these cases together, 10 of the 12 singers exhibited a region of pitch instability near the upper limit of the laryngeal transition, around D5-F#5 (for NE1, AD3, AD4, and PR3) or around C6-D6 (for NE2, NE3, NE4, AD1, AD2, and PR1). Singers PR2 and PR4 behaved differently from the other singers: PR4 presented no instabilities at all over her high range, and PR2 exhibited jumps at C6, far above her laryngeal transition pitch range.

Consequently, it appears to be more relevant to relate voice instabilities to ranges or events in the glottal behavior instead of considering only the pitch at which they occur. As mentioned in the above text, they commonly occurred at the upper limit of the laryngeal transition (for 10 singers of 12). They sometimes occurred below the transition, when the amplitude of the EGG signal started decreasing (around B4-C5 for NE1 and PR2). They often also occurred far above the laryngeal transition, in a range (from C#6 to F6) where the glottal behavior showed no significant change (NE1, NE3, AD4, PR2, and PR3).

7. Direct endoscopic observations

A descending *glissando* from D7 (2350 Hz) to E4 (330 Hz) produced by singer NE1 was analyzed with high-speed video, audio, and EGG recordings, as illustrated in Fig. 5. It presented several pitch jumps and changes in voice quality.

A glottal contact was detected on the upper pitch range of the glide, down to D#6. A small pitch jump was observed near F6 corresponding to no particular change in vibration pattern nor in the EGG waveform. A stretched glottis could be seen on the high-speed images. At these high pitches, the glottal cycle could be characterized with a maximum of two images, which showed either a vocal fold contact or a small-amplitude opening (see the two images taken near 1.65 s and presented at the bottom left of Fig. 5).

Between D#6 and G5, no glottal contact could be detected by EGG. This range corresponded to constriction in the epilaryngeal tube, clearly noticeable on the high-speed sequence. The maximum constriction coincided with an abrupt pitch decrease recorded in the audio signal at 2.2 s.

Below G5, glottal contact was again detected and its amplitude suddenly increased around E5 together with a pitch jump.

B. Sustained pitches and changes in voice quality

For six singers (PR3, PR2, AD1, NE2, NE3, NE4), the behavior of the glottal parameters was the same for sustained pitches as for *glissandi* [see Fig. 2(b)].

For two singers, however, some differences were observed between *glissandi* and sustained pitches. Interestingly, these two singers were AD2 and PR1, whose variations of *OQ* differed from those of the other singers during *glissandi*. For AD2, the variation of *OQ* on sustained pitches became similar to that observed in most of the singers: It increased with pitch over the laryngeal transition, i.e., the pitch range where the amplitude of the EGG decreases [see Fig. 2(a)].

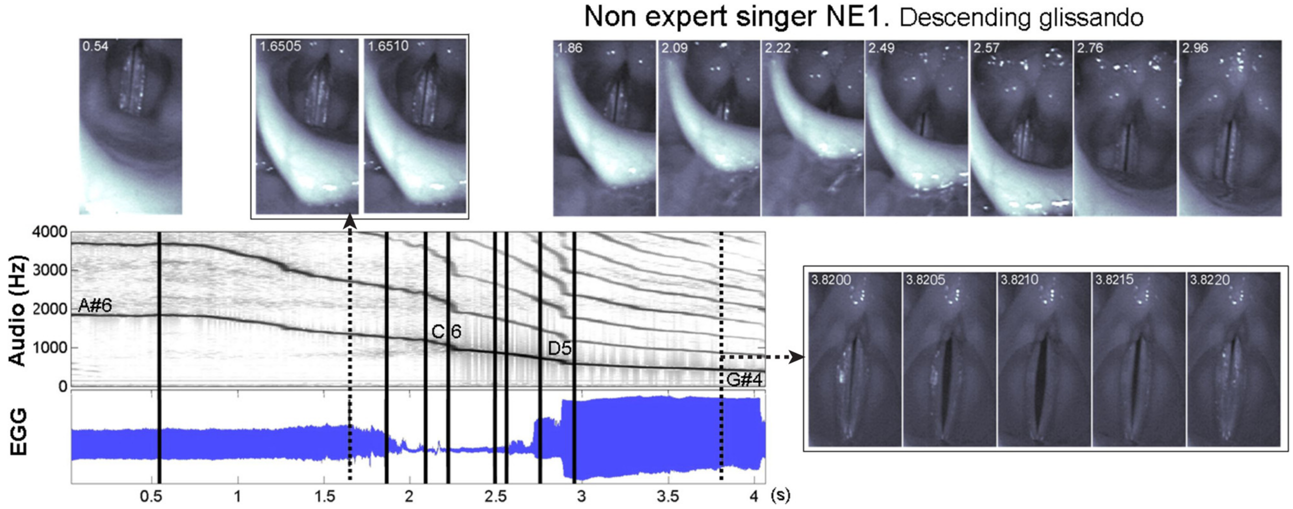

FIG. 5. (Color online) A descending *glissando* produced by singer NE1. Vertical lines on the spectrographic sound analysis indicate the corresponding instants of the endoscopic images. Two glottal-cycle sequences (dashed lines) illustrate the stable behavior observed before and after the laryngeal transition (high pitch, two images; lower pitch, five images).

The four remaining singers (PR4, AD3, AD4, NE1) showed an overlap range over which they could produce two different qualities with distinctly different EGG signals, referred to here as *full head* and *fluty resonant*. For all these four singers, the comparison of sustained pitches produced in both qualities showed clear and consistent differences in glottal parameters: The EGG amplitude and the contact speed quotient (Qcs) were significantly lower in the *fluty resonant* quality than in the *full head* one, whereas OQ values were significantly higher in the *fluty resonant* quality than in the *full head* one (see Fig. 3). Comparison of sustained pitches produced in both qualities showed clear and consistent differences in spectral content and SPL for two of the four singers (NE1 and AD4): Their *fluty resonant* quality tended to be 10 dB weaker than the *full head* one, with the higher harmonics being especially weak with respect to the first two [see Fig. 3(b)]. For the two other singers (PR4 and AD3), the two qualities were produced with similar SPL values [see Fig. 3(a)]. Harmonics above the first two were also weak in the *fluty resonant* quality, but to a lesser extent than for NE1 and AD4.

Last, the values of glottal parameters OQ and Qcs in *full head* sustained productions (see × symbols on Figs. 1 and 3) were similar to those observed on *glissandi* (see pale dots in Figs. 1 and 3) prior to the laryngeal transition, i.e., before the amplitude of the EGG signal starts decreasing. On the other hand, values in *fluty resonant* sustained productions (see + symbols in Figs. 1 and 3) were similar to those observed on *glissandi* above the transition, i.e., after the amplitude of the EGG signal had reached its lower level.

Consequently, it appears that for these singers, *full head* quality is produced in M2 within the overlap range (M2–M3 transition shifted higher in pitch), whereas *fluty resonant* quality is produced in M3 instead (M2–M3 transition lowered).

C. Decrescendi

The four singers who demonstrated an overlap range of the two glottal behaviors were asked to produce *decrescendi* on a few sustained notes within that range.

An abrupt decrease in the amplitude of the EGG signal was observed, with continuously decreasing SPL, followed by the disappearance of any observable EGG waveform [see second panel in Fig. 6(a)].

For NE1, AD3, and PR4, this sudden decrease in amplitude was systematically accompanied by pitch jumps [see $df_0(t)/dt$ in Fig. 6(a)], whereas jumps occurred only in some

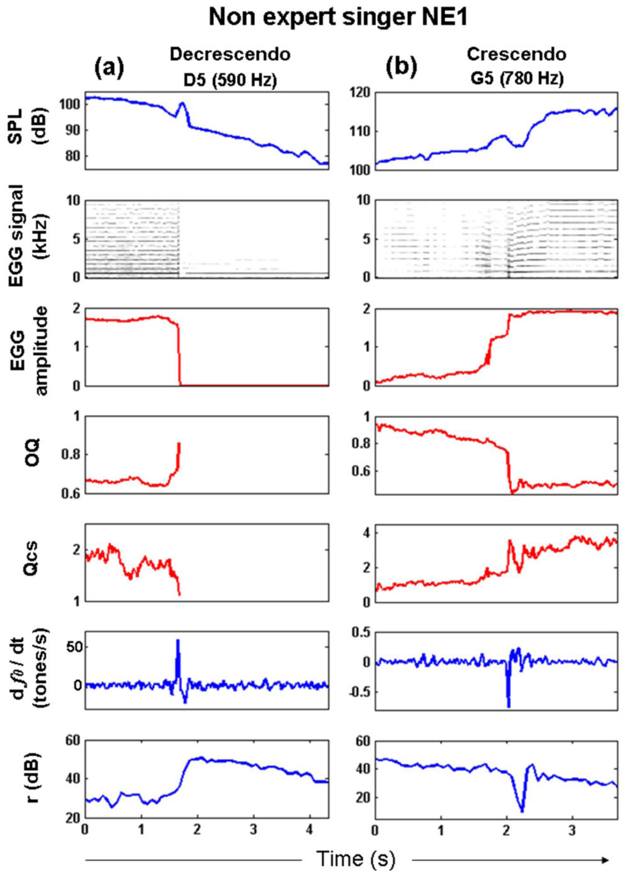

FIG. 6. (Color online) Example of the variation of measured acoustic and glottal parameters during a *decrescendo* and *crescendo* produced on D5 and G5 respectively by singer NE1.

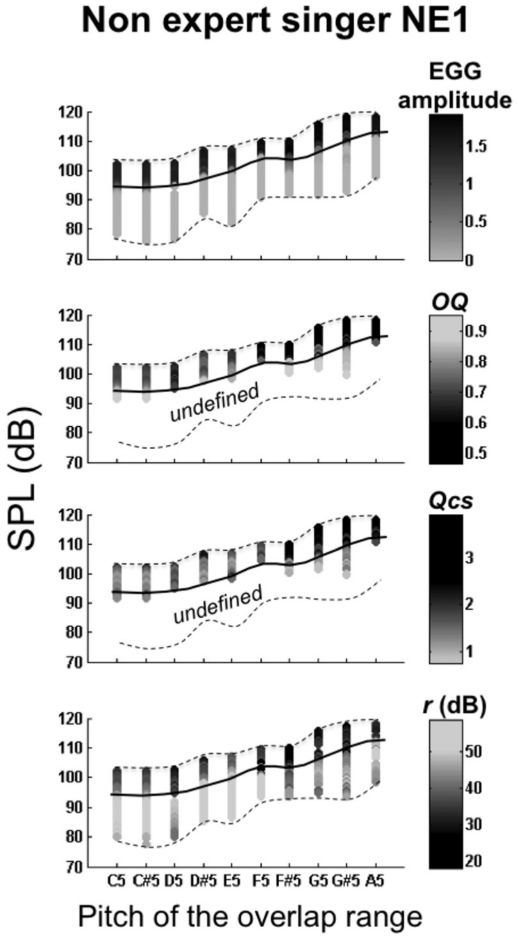

FIG. 7. The variation of amplitude of the EGG signal, open quotient (OQ), contact speed quotient (Qcs), and enhancement of the two first voice harmonics (r) with decreasing SPL and several pitches of the overlap range for the non expert singer NE1. The dotted lines indicate the limits of the SPL range explored for each decrescendo. The solid line indicates, for each pitch, the SPL from which the amplitude of the EGG signal suddenly decreased and became null. In that range where no glottal contact was observed any longer, the glottal parameters OQ and Qcs could consequently not be defined.

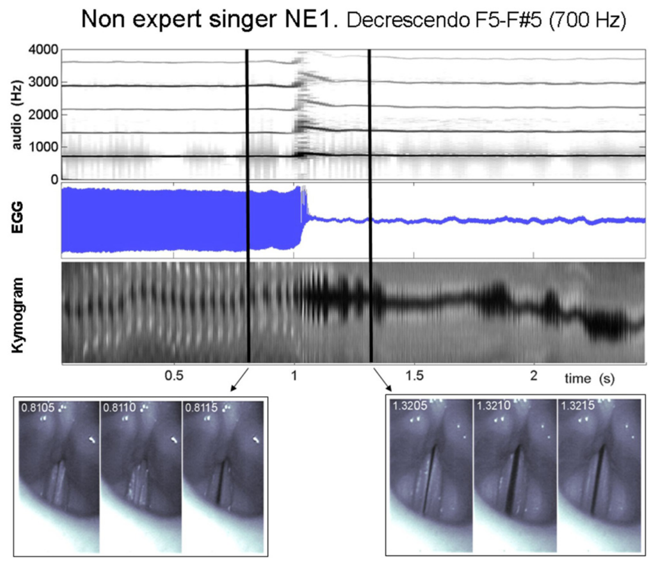

FIG. 8. (Color online) A *decrescendo* produced by singer NE1 on pitch F5–F5#. Top panel: spectrographic sound analysis. Middle upper panel: EGG signal. The vertical dark lines indicate the shot instants. Middle lower panel: kymographic analysis of a median line. Bottom panel: two glottal-cycle sequences illustrating the stable behavior before and after the pitch break.

cases for AD4. Pitch jumps were greater for *decrescendi* on higher notes.

For all four singers, the sudden decrease in amplitude of the EGG signal was also accompanied by a sudden decrease in the proportion of acoustic power in voice harmonics above the first two [see lowest panel of Figs. 6(a) and 7]. This explains the sudden change in perceived voice quality, from *full head* at high SPL to *fluty resonant* at lower SPL.

As was observed for the *glissandi* over the laryngeal transition, *OQ* increased over the SPL range for which the EGG signal decreased, whereas *Qcs* tended to decrease (see *Qcs* in Figs. 6 and 7).

Values of glottal and acoustic parameters at the beginning of the *decrescendo*, i.e., at high SPL, are comparable with those measured on *glissandi* around G4–A4, below the laryngeal transition and with those measured on *full head* sustained pitches over the overlap range. On the other hand, values of glottal and acoustic parameters measured at lower SPL of the *decrescendi*, after the amplitude of the EGG signal decreased (and just before it disappeared for *OQ* and *Qcs*), are comparable with those measured on *glissandi* around A5–B5, above the laryngeal transition and with those measured on *fluty resonant* sustained pitches over the overlap range (see Fig. 3).

Comparison of *decrescendi* produced on different pitches within the overlap range of the four singers, indicates that the transition in glottal behavior and in voice quality occurred at higher SPL when the pitch increased (see Fig. 7).

In a separate session, singer NE1 produced crescendi over the overlap range of the two glottal behaviors. Observations were consistent with those made on *decrescendi*: in *crescendi*, the amplitude of the EGG signal increased suddenly with increasing SPL, accompanied by pitch jumps and sudden variation in *OQ*, *Qcs*, and temporary enhancement of the voice harmonics above the first two [see Fig. 6(b)]. The transition in glottal behavior did not occur at lower SPL on *crescendi* than on *decrescendi*. Thus for this laryngeal transition and for this singer, there did not appear to be any hysteresis of the sort reported for the M1-M2 transition (Roubeau *et al.*, 2004). As a consequence, NE1 did not show any overlap range in SPL within which she could choose, for a given pitch, to use one glottal behavior and its associated voice quality instead of the other.

The glottal behavior of singer NE1 on a *decrescendo* on pitch F5–F5# (700 Hz) that produced a pitch break, and a change in voice quality was assessed with combined high-speed laryngoscopy, audio, and EGG. Figure 8 plots the spectrographic analysis, the EGG signal, a kymogram of a median line, and the images from two glottal cycles within the sequence. Voice quality went from *full head* to *fluty resonant*. The spectrographic analysis and the EGG signal showed a noticeable laryngeal transition, with a pitch jump (F5 to F5#) and a brief subharmonic pattern (about 30 ms). The kymographic analysis and the glottal images showed no glottal contact after the pitch break nor did the EGG signal (no contact detected after 1.1 s).

IV. DISCUSSION

A. The laryngeal nature of the whistle register

The EGG and direct endoscopic investigations suggest that there is only one main laryngeal transition in the high soprano range that occurs above the M1–M2 transition or *primo passaggio*.

Some similarities between the laryngeal transition reported here and the M1–M2 transition support the idea that the higher transition corresponds to the fundamental change between laryngeal mechanisms M2 and M3 proposed by Roubeau *et al.* (2009). Indeed, as is observed for the M1–M2 transition (Henrich, 2001; Henrich *et al.*, 2005; Roubeau *et al.*, 2009), the amplitude of the EGG signal decreased significantly with ascending pitch during the M2–M3 transition, while *OQ* increased and the EGG waveform became more symmetrical. The M2–M3 transition was accompanied by a substantial change in voice spectrum, with reduced energy in harmonics above the first two producing a *flutier* quality. Similarly to the M1–M2 transition, these results show that there can be an overlap pitch range for the two M2 and M3 glottal behaviors observed below and above the transition. This overlap range was observed around E5 and could cover up to one octave (C5–C6), which corresponds to the typical range of the upper register (Miller, D.G., 2000; Miller, R., 2000; Echternach *et al.*, 2010). Similarly to the M1–M2 overlap range, *decrescendi* produced over the overlap range of M2 and M3 showed a sudden change from one glottal behavior to the other, accompanied by pitch jumps or voice instabilities at the transition as well as noticeable changes in voice spectrum.

However, the M2–M3 transition differs from the M1–M2 in several aspects; this rather supports the idea that while the M2-M3 laryngeal transition corresponds to a change in glottal behavior, that change is not always an abrupt and fundamental change in vocal fold biomechanics like that observed at the M1–M2 transition. Indeed minor modifications in vocal fold amplitude of vibration and contact were observed before and after the transition on the high-speed video of one singer. An epilaryngeal constrictive movement was observed at the top of the M2 range released when transitioning to the M3 laryngeal behavior. Furthermore, in the EGG signals, continuous transition from M2 to M3 behavior was often observed to occur over a range of several notes, which is not the case for M1-M2 laryngeal transition.

Further electromyographic, aerodynamic and endoscopic data would be needed to understand better the biomechanical principles of this main change in laryngeal behavior in the high soprano range.

B. Whistle register and resonance adjustments

As reviewed in the Introduction, previous studies have supported the idea that the transition to *whistle* register is caused by a change in the acoustic load on the vocal folds produced by changes in vocal tract resonance (Miller and Schutte 1993; Rothenberg 1988). In this study, however, only few singers showed a correspondence among (1) pitch jumps or instabilities, (2) the end of $R1{:}f_0$ tuning (presented in the companion paper Garnier *et al.*, 2010), and (3) the end of the M2–M3 laryngeal transition. For most singers, the change in glottal behavior and voice quality occurred around C5–E5, far below the upper limit of the $R1{:}f_0$ tuning (around C6–D6). It was also observed that some singers can extend the $R1{:}f_0$ tuning up to F#6, whereas they always changed glottal behavior and voice quality below C6 (Garnier *et al.*, 2010). Because the M2–M3 laryngeal transition coincides with the upper limit of a regime of resonance tuning for only a small proportion of singers, it appears that this laryngeal transition is not caused by the end of $R1{:}f_0$ resonance tuning. The physiological reasons for this change in laryngeal behavior remain unidentified.

C. Pitch jumps and breaks in the high soprano range

Additional pitch jumps or instabilities occurred over the high soprano range at pitches other than the end of the M2-M3 laryngeal transition. In particular, singers who demonstrate the M3 behavior from as low as D5–E5 can also have pitch jumps or instabilities around C6–D6, although no noticeable change was observed in their glottal behavior in that range. The pitch range C6–D6 corresponds to the range from which singers start tuning $R2$ to f_0 instead of $R1$ (Garnier *et al.*, 2010) and from which the SPL starts increasing again. The pitch jumps and instabilities observed around these pitches are very likely to be induced by acoustical interactions between the tract and the glottal source.

D. Implications for voice quality and voice classification

Because the starting pitch of the M3 behavior is not caused by the limits of a vocal tract tuning regime, some singers demonstrated the ability to lower or raise the M2–M3 transition to some extent, similarly to the transition pitch of M1 and M2 (Roubeau *et al.*, 2004; Henrich, 2006; Roubeau *et al.*, 2009). Consequently, there can be an overlap range (as much as one octave in this study) over which singers can choose to use M2 or M3 depending on the intended voice quality.

The qualities described here as *fluty resonant* (with reduced glottal contact) and *full head* quality (with M2 vibratory pattern) were not associated with different strategies of resonance tuning. Despite reduced glottal contact, sounds produced with the M3 behavior were often resonant and rarely breathy. They could be very loud: up to 115 dB SPL at 30 cm. Furthermore, our results indicate that sopranos, irrespective of their vocal expertise, can start using the laryngeal mechanism M3 from as low as C5–D5, which is one octave lower than what is usually reported for the whistle register (Van Deinse, 1981; Walker, 1988; Miller and Schutte, 1993; Herzel and Reuter, 1997; Thurman *et al.*, 2004; Henrich, 2006). Consequently, the mechanism M3 should not be considered as a marginal type of voice production found only in a few singers at extreme pitches.

These results suggest that *light*, *soubrette*, or *coloratura* sopranos—those who demonstrate a *fluty* sound above E5 and who are able to produce extreme pitches with agility—might correspond to the category of singers who use the M3 mechanism from as low as D5–E5. On the other hand, sopranos classified as *full lyric* or *dramatic*—those who demonstrate a full and rich sound above E5—are likely to correspond to the category of singers who use the M2 mechanism in their upper register. These considerations imply that *light* or *coloratura* sopranos might benefit from slightly different training methods than *lyric* or *dramatic* sopranos.

E. Voice registers and transitions in the high soprano range

A singing voice register can be considered as a distinct region of homogeneous voice quality that can be maintained over some ranges of pitch and loudness (Titze, 1994). Voice quality depends not only on the laryngeal mechanism but also on the vocal tract configuration and its influence on vocal fold vibration.

D. G. Miller (2000) suggested that the female voice is divided, above the M1–M2 transition, into three registers: *middle*, *upper*, and *flageolet* registers, all underlined by similar *falsetto* (~M2) pattern of vocal fold vibration, and differing in vocal tract adjustment.

The present study and its companion paper support that proposed division: two main changes in vocal tract adjustment were observed in the high soprano range. One indicates the lower limit of $R1{:}f_0$ tuning, which, for some singers and vowels, starts in the vicinity of C5 (Joliveau *et al.*, 2004a,b; Garnier *et al.*, 2010; Henrich *et al.*, 2011), i.e., the typical region of the middle/upper transition (Miller, D.G, 2000). The second, which occurs typically around C6, is the upper limit of $R1{:}f_0$ tuning (Garnier *et al.*, 2010).

This second resonance transition did not always coincide with a weakening of vocal fold vibration, in contrast with the observation of D. G. Miller (2000) and Rothenberg (1988). In the present study, there was always a finite transition interval over which the amplitude of the EGG signal decreased significantly. However, the low-amplitude EGG waveform (corresponding to the M3 glottal behavior) was often reached below the upper limit of $R1:f_0$ tuning. Furthermore, for singers who could sing above the end of the $R1:f_0$ tuning, this low-amplitude waveform was still observed up to the top of their vocal range despite the use of another resonance tuning ($R2:f_0$) in that range (Garnier *et al.*, 2010). These observations indicate that the M3 glottal behavior is not just a weakened version of the laryngeal mechanism M2, due to an absence of resonance tuning. This implies the existence of a laryngeal transition in the high range that is independent from resonance transitions.

With two resonance transitions and the M2–M3 laryngeal transition, there could theoretically be four registers in the high soprano range, above the *primo passaggio*. This is in accord with R. Miller (2000), who considers a *lower middle* register over the Eb4–C#5 range, followed by an *upper middle* register up to F#5 (the average pitch of the *secondo passaggio*), then an *upper* register over the F#5-C#6 range, followed by a *flageolet* register above C#6 (supposed to be equivalent to the *whistle* register of other authors). The pitches of these register transitions match completely those of the resonance and laryngeal transitions characterized in this study on 12 sopranos. Comparison of our results with Miller's approach to the soprano registers suggests that his *lower middle* and *upper middle* registers are very likely to correspond to voice productions with the laryngeal mechanism M2 and that these registers may be distinguished by the absence or presence of $R1:f_0$ tuning below or above C#5, respectively [see Fig. 9(a)]. Likewise, his *upper* and *flageolet* registers probably correspond to voice productions with the laryngeal mechanism M3, supported by $R1:f_0$ or $R2:f_0$ resonance tuning above C#6, respectively [see Fig. 9(a)]. The *secondo passaggio* of sopranos would then be associated with the M2–M3 laryngeal transition, and would not necessarily coincide with the lower limit of the $R1:f_0$ resonance tuning (Miller, D.G., 2000; Echternach *et al.*, 2010).

In practice, however, the pitch region of the M2–M3 laryngeal transition was not always found in the middle of the C5-C6 range [i.e., Fig. 9(a) and strategy 2 in Fig. 9(b)], so that there may be two further strategies, in addition to R. Miller's average picture of the soprano registration. Indeed, the M2–M3 laryngeal transition was found as low as C5–D5 in some sopranos, close to the lower limit of the $R1:f_0$ resonance tuning [strategy 1 in Fig. 9(b)]. For others, the M2–M3 laryngeal transition was found as high as C6, close to the upper limit of the $R1:f_0$ resonance tuning [strategy 3 in Fig. 9(b)]. Furthermore, some singers showed the ability, over a subset of the C5–C6 range, to use either the M2 or the M3 laryngeal mechanism, depending on the desired voice quality (*full head* or *fluty resonant*).

These observations imply that sopranos may sometimes feel only two register transitions, instead of three, over their high range, above the *primo passaggio*, and that the register transitions may be of different nature (resonance and/or laryngeal) across singers.

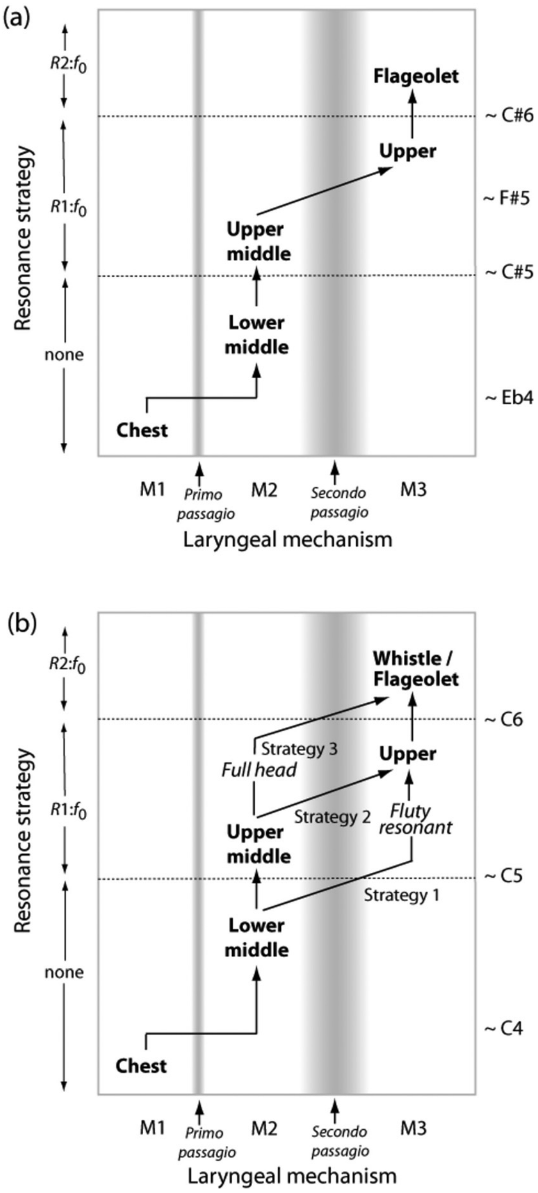

FIG. 9. (a) Idealized schematic indicating the different registers considered by R. Miller (2000) for the soprano voice, and how they may be related to combinations of laryngeal mechanism (M1, M2, M3) and vocal tract adjustment (no tuning, $R1:f_0$, $R2:f_0$). (b) Representation of the three different strategies observed on the 12 sopranos of this study to produce the C5-C6 range. As a result, sopranos may feel different number and nature of register transitions over their high range, above the *primo passaggio*.

These observations also question the pitch range of the *middle upper* and the *upper* registers of R. Miller (2000). Indeed if these registers are associated with the same laryngeal and resonance properties over their whole range, then our results support the idea that the *middle upper* register could be extended to higher pitches (up to C6) and that the *upper* register could be extended to lower pitches (down to C5).

V. CONCLUSION

Three regions of pitch jumps or instabilities were observed in the high soprano range, above the M1–M2 transition or *primo passaggio*. However, EGG and direct endoscopic investigations revealed only one main laryngeal transition in that range, the transition between the M2 and M3 laryngeal mechanisms proposed by Roubeau *et al.* (2009). The range of this laryngeal transition varied among the 12 singers. Its lower limit was between G4 and D#5 (A#4 on average). The upper limit, varying between D5 and D#6, was usually lower for expert singers. Some singers demonstrated an overlap range (within the C5–C6 upper range) within which they could choose to use either the M2 or the M3 glottal behavior, depending on the desired voice quality. Voice breaks (discontinuities in pitch) coincided with the upper limit of the M2–M3 transition during *glissandi* or *decrescendi*, as well as with changes between resonance tuning strategies (no tuning, $R1{:}f_0$ and $R2{:}f_0$; see Garnier *et al.*, 2010). However, for most singers, the M2–M3 laryngeal transition did not coincide with one of these changes of resonance tuning.

ACKNOWLEDGMENTS

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