**Abstract**

Electrolaryngography (Lx) and electroglottography (EGG) are non-invasive methods used to assess human vocal fold vibration and investigate speech and singing. This paper provides a systematic review of evidence-based studies using Lx/EGG in the analysis of the singing voice, identifying and critically appraising the thematic content and the research methodologies of the relevant investigations. Lx/EGG represents a powerful tool for the analysis of the singing voice in medical settings, and in support of research and teaching. Current research in this area is paving the way towards a better comprehension of singing performance.

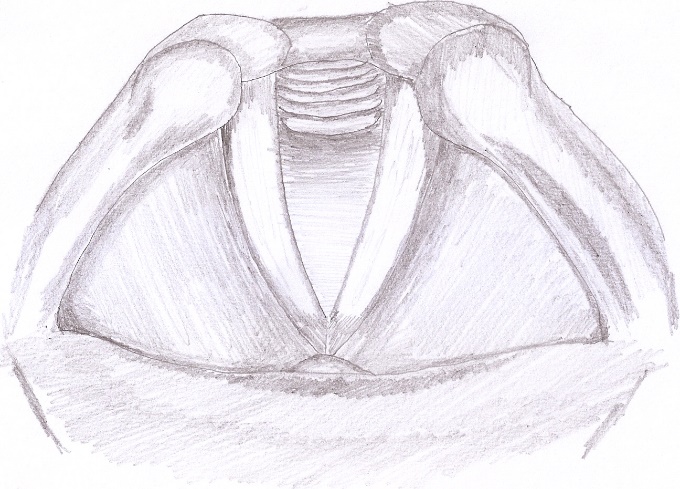
**Keywords**:

Electrolaryngography, electroglottography, singing, systematic review.

Electrolaryngography (Lx) and electroglottography (EGG) are non-invasive techniques for assessing human vocal folds, through the application of electrodes placed externally on either side of the neck. Developed by Fabre, the basic principle of EGG was reported in Fabre (1940) and fully explained in Fabre (1957). The tool was further developed by Fourcin and Abberton (1971), who presented a slightly different version, the Lx, and by Rothenberg (1992), who designed the multichannel EGG, featuring a vertical array of two pairs of electrodes to track the vertical movements of the larynx.

Based on the principle that human tissue is a good electrical conductor while air is not, the Lx/EGG electrodes monitor the closing and opening of the vocal folds (see Figure 1), by measuring variations in the electrical impedance of the larynx. A constant, high frequency current in the 0.3-3MHz range is sent through the neck of the participant using the electrodes: the impedance/admittance variation of the current, caused by the contacting and de-contacting of the vocal folds, is measured (Fourcin & Abberton, 1971), which reflects the amount of contact between the vocal folds (Scherer, Druker, & Titze, 1988) and is graphically represented in the waveform produced.

Posterior

Vocal fold Trachea

Glottis

Ventricular fold

Anterior

*Figure 1.*Schematic representation of the vocal folds[[1]](#footnote-1) in open position, which are located within the larynx at the top of the trachea. The gap between them is called the glottis.

The Lx/EGG waveform allows the objective measurement of a number of aspects of vocal fold vibration occurring during phonation[[2]](#footnote-2). The most common quantitative parameters include:

* Amplitude (Amp): peak-to-peak amplitude of each cycle
* Fundamental period (T0): duration of one vibratory cycle
* Fundamental frequency (*f*o): calculated as
* Vocal fold closed phase (CP): the time in each cycle for which the vocal folds remain in contact
* Vocal fold open phase (OP): the time in each cycle for which the vocal folds remain apart
* Vocal fold contact quotient (CQ): an estimation of the time for which the vocal folds are in contact. This parameter was also referred to as “closed quotient” (Fourcin & Abberton, 1971; Howard, 1995) or as “quasi closed-quotient” (Hacki, 1996); nevertheless, the term “contact quotient”, introduced by Davies, Lindsey, Fuller and Fourcin (1986) in relation to EGG, recognises that it does not reflect a full glottal closure (Herbst, Schutte, Bowling, & Švec. in press).
* Vocal fold open quotient (OQ): an estimation of the time for which the vocal folds remain apart.

CQ and OQ were firstly measured in the ‘70s by Fourcin and Abberton using a threshold-based technique, identifying the (de)contacting instants in the Lx/EGG waveforms when crossing a given threshold, ranging between 20 and 80% of the peak-to-peak amplitude (Howard, 2009). Some researchers have also used the derivative of the EGG signal (DEGG) to investigate the maximum glottal opening and closing instants based on the positive and negative peaks of the DEGG, as shown in Figure 2 (Teaney & Fourcin, 1980; Henrich, d’Alessandro, Doval, & Castellengo, 2004). Results suggest that DEGG may be a valuable tool for the identification of peculiar glottal configurations (Bernadin, Morris, Okerlund, Ellerbe, & Kessela, 2015). DEGG is preferable to most threshold-based analysis in the case of sustained sounds (Henrich et al., 2004), although it can be difficult to identify the start of the open phase when multiple peaks occur due potentially to the influence of mucus strands (Colton & Conture, 1990), or abnormalities in vocal fold tissue structure affecting EGG regularity (Baken & Orlikoff, 2000; Kitzing, 1990).

*Figure 2.*Lx waveform of a semi-professional soprano extracted from Speech Studio software, showing amplitude and period of a vocal fold vibratory cycle[[3]](#footnote-3) normalized in the range 0-1, and two different methods to calculate the contact quotient: a 35% threshold-based technique with (de)contacting events marked in dark grey, and an Lx derivative-based method with (de)contacting events highlighted in light grey.

Other studies compared different approaches used to measure the closed quotient (CQ) for the analysis of the singing voice, suggesting the importance of distinguishing the methods used when reporting and comparing the data. The CQ values derived from EGG differ from those obtained from inverse filtering, a technique that filters the resonant effects of the vocal tract from the acoustic waveform output of the voice to estimate the glottal volume velocity waveform (Lã & Sundberg, 2015; Mecke, Sundberg, Granqvist, & Echternach, 2012), from those derived from high-speed digital imaging, (Mecke et al., 2012), and videokymiographic endoscopy (Herbst et al., in press; Herbst & Ternström, 2006). A new method for analysing and displaying EGG and DEGG signal has been developed: the EGG wavegram, an alternative technique to measuring contact quotient, independent from any arbitrary threshold criterion, provides insights into vocal fold dynamics in speech and singing, by measuring time-varying *f*o and consecutive glottal cycles (Herbst, Fitch, & Švec, 2010b). Recently, a novel EGG-based clustering method has been developed as an alternative to the standard time-domain based analysis, which proved to be a valuable approach to systematically differentiate EGG shapes of modal and falsetto voices (Selamtzis & Ternström, 2014) and in relation to the acoustic signal (Selamitz & Ternström, 2016). Lastly, EGG recording during dynamic lung MRI has been made possible by Özen et al. (2016), to analyse the respiratory dynamics in breathing and phonation (Traser et al., 2017a) and the regional ventilation during phonation in singers (Traser et al, 2017b).

Narrative reviews describe limitations related to the appropriate size and placement of electrodes and the effect of neck thickness. It has been shown that the proper placement of the electrodes is essential to ensure accurate and reliable recordings of vocal fold vibration (Abberton et al., 1989). The electrodes should be placed in the thyroid region behind the vocal folds to maximize recording of the electrical impedance variation. Research has found that the signal resulting from Lx/EGG may be too weak or noisy to be reliable in certain populations, including, children (Howard, 2009), sopranos (Pabst & Sundberg, 1993), and when a thick layer of subcutaneous tissue is present in the neck (Askenfelt, Gauffin & Sundberg, 1980; Colton & Conture, 1990; Haji, Horiguchi, Baer & Gould, 1986). Literature also describes its application to investigate and treat speech and voice problems as well as analysing the normal function of the voice source in clinics and research laboratories, and supporting vocal pedagogy in the singing studio (Abberton, Howard, & Fourcin, 1989; Baken & Orlikoff, 2000, Childers & Krishnamurthy, 1985; Colton & Conture, 1990; Howard, 1999, 2009; Lã, 2012; Miller & Schutte, 1999; Rothenberg, 1992).

A comprehensive evaluation of the studies that investigate the singing voice using Lx/EGG has not previously been conducted. This paper provides a systematic review of the empirical studies that use Lx/EGG for singing voice analysis, to identify and critically appraise the methodology and thematic application of current research.

# Methods

This review has been performed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher, Luberati, Tetzlaff, & Altman, 2009). The PRISMA flowchart is shown in Figure 3.

## Literature search strategy

This review includes empirical investigations that make use of Lx/EEG to analyse aspects of the singing voice. The following criteria established the pertinence of each study:

1. *Inclusion criteria*:
   1. Only English-language studies are considered
   2. Analysis of the characteristics of the singing voice is provided
   3. Lx/EEG equipment is employed
   4. Major investigations and case-studies are presented and retrievable
   5. Any studies using singers are included, including those developing atypically
2. *Exclusion criteria*:
   1. Review publication (e.g., meta-analyses)
   2. A full report is not provided: the publication summarises the study, but protocols and analysis are not provided

## Data extraction

Two researchers (SD and HD) defined and piloted a data extraction form, independently extracting the entire data set and comparing results. Inter-rater reliability was 100%. The data form includes authorship, year, place and study design of the publication, number and type of participants, apparatus, Lx/EGG derived parameters analysed in the study, research questions, main thematic content, summary of the main findings and conclusions.

Full-text articles assessed for eligibility  
(n = 82)

Full-text articles excluded, with reasons:

1a (n=3); 1b (n=4); 1c (n=3); 2a (n=3); 2b (n=10)

Studies included in the current review  
(n = 104)

Full-text articles excluded, with reasons:

1a (n=2); 1b (n=4);

1c (n=2); 1d (n=5);

2a (n=10); 2b (n=15)

2334 Titles/abstracts identified through database searching:

* Google Scholar (n=2294)
* PubMed (n=16)
* Web of Science (n=24)

Records after duplicates removed

(n=2003)

Records screened

(n=2003)

Records identified through database searching  
(n = )

Records excluded

(n=1921)

83 additional records identified through

* recurring journals (n=9)
* reference list of the selected articles (n= 34)
* publication list of recurring authors (n=18)
* emailing recurring authors (n=22)

*Figure 3.* PRISMA flow chart (Moher et al., 2009).

## Procedure

The literature search was based on a four-step approach. Firstly, large online databases were searched for relevant articles (PubMed, Web of Science, and Google Scholar), using the following terms: electrolaryngograph singing, electrolaryngograph singer, electrolaryngograph chorister, electroglottograph singing, electroglottograph singer, electroglottograph chorister. The journals in which articles appear most frequently were identified (*Journal of Voice*, *Journal of Acoustical Society of America*, *Logopedics Phoniatrics Vocology*, and *Folia Phoniatrica and Logopaedica*) and all their issues reviewed online for additional similar publications. The reference lists of the above articles were also searched for related studies. Finally, the resulting list of articles was reviewed to identify the authors recurring multiple times (Matthias Echternach, Nathalie Henrich, Christian Herbst, David Howard, Filipa Lã, Donald Miller, Johan Sundberg, and Sten Ternström). Their complete list of publications was investigated and they were contacted via email for retrieval of unpublished articles, which were included if the criteria were met.

## Data synthesis

The protocol created a shortlist of 104 publications, which were critically appraised according to the methodology and the thematic category. These articles were summarized in Excel and are reported in Appendix.

# Results

## Thematic categories

As shown in Figure 4, the research questions addressed within the literature revealed nine recurring broad categories, in which the application of Lx/EGG played a valuable role in advancing understanding of the singing voice.

*Figure 4.* Analysis of the selected articles showing the number of publications according to the thematic content identified on the bases of the research questions addressed.

### **Singing Styles (27 studies).** Research have used Lx/EGG to investigate and compare the different characteristics of various singing styles such as Western and Peking operatic singing, Music Theatre (MT), Pop, Rock, Jazz, Blues, Soul, Swedish Dance Band, Bizantine chant, Japanese, legit, belting, and a cappella singing, mostly in the adult population. Based on Lx/EGG signals, MT and belting style seem to be characterized by significantly higher CQ than opera singing (Björkner, 2008; Estill, 1988; Evans, 1995; Evans & Howard, 1993). Belt also shows longer CP and glottal adduction than employed in a neutral style of singing (Bestebreurtje & Schutte, 2000; Sundberg & Thalén, 2015). However, a larger study did not report different CQ values across legit and belt style, with results close to 50% in both styles (Lebowitz & Baken, 2011).

Other differences between Western Classical singing and non-classical styles, such as belting, Pop, Rock, Folk and Broadway musicals, include laryngeal position and vocal fold patterns (Schutte & Miller, 1993). A comparative investigation of the voice source characteristics used to perform single tones in Pop, Rock, Jazz and Blues showed that the voice source is close to flow and neutral phonation in Classical style, close to neutral in Pop and Jazz, and in pressed phonation in Blues (Thalén & Sundberg, 2001). Zangger Borch and Sundberg (2010) and Sundberg, Thalén and Popeil (2012) made use of DEGG as part of an inverse filtering approach, to further investigate, respectively, Pop, Rock, Soul and Swedish Dance Band styles and substyles of belting.

A few studies also investigated the idiomatic characteristics of operatic and early music styles by means of Lx/EGG data analysis. The case study conducted by Howard (1992) reported the presence of some vibrato in the opera and early music style, but none in the Elizabethan style. Daffern (2008) highlighted a number of distinguishing characteristics of operatic music and early music, demonstrating that singers in the early music group used a smaller vibrato extent and employed vibrato in fewer tones than operatic singers. Howard, Brereton and Daffern (2009) also reported different CQ values between operatic, early music mainstream and clear smooth sweet chaste, as defined by in Bethel (2009), performed by a single singer, whilst CQ behavior did not seem to characterize operatic and early music performance specialism in two groups (Daffern & Howard, 2010). Recently, Sundberg, Lã and Gill (2016) found significant differences between vowels for CQ at four different pitches in male opera singers. By analysing EGG derived CQ and larynx position, opera singers show the ability to compensate for the effects of changes in the lung volume capacity (Thomasson, 2003a, b).

Yodelling singing, characterized by rapid and repeated changes in pitch, presents low CQ for the upper pitch (Echternach & Richter, 2010), whilst Noh singing, a traditional Japanese style, features low OQ, high speed quotient and utilisation of three phonation types identified as pressed, vocal-ventricular mode and growl voice (Yoshinaga & Kong, 2012). Byzantine chant performance, analysed through the application of EGG for pitch track, presents microintervallic differences with the equal temperament scales introduced by the Patriarchal Music Committee (Delviniotis, Kouroupetroglou, & Theodoridis, 2008). Peking opera singing features a vibrato rate of 3.5 Hz, which is notably slower than Western Classical singing, although the contribution of the Lx data to this analysis is unclear (Sundberg, Gu, Huang, & Huang, 2012).

EGG is also used to investigate the non-linear dynamic characteristics of the human vocal fold vibratory system analysing the period-doubling occurrences found in some Asian vocal cultures (e.g., Tibetan voice and Mongolian Kargyraa voice) and in the Sardinian bassus style. Bailly, Henrich, Webb, Müller, Licht, and Hess (2007) and Bailly, Henrich and Pelorson (2010) found the periodic variation of glottal cycle duration and the active involvement of the ventricular folds, vibrating at half of the glottal-cycle frequency, during phonation.

Finally, a few studies have investigated *a cappella* SATB performance, reporting a grouping of CQ values for each member of a quartet (Howard, 2003), and a smooth distribution of CQ values between the parts in support of choral blending (Howard, 2007c).

**Registers and voice classification (25 studies)**. Empirical investigations have used Lx/EGG to analyse the sung vocal range, and the associated registers and register transitions commonly identified in Western music and often labelled the chest (or modal), head, and falsetto register. Based on EGG signals, Kitzing (1982) highlighted some physiological characteristics of falsetto, featuring increased *f*o. These results suggest the decrease of the muscular tension during voice break, corroborating previous electromyography derived findings (Hirano, Vennard, & Ohala, 1970).

Roubeau, Chevrie-Muller and Arabia-Guidet (1987) revealed a large variation of EGG data across voice registers in male and female, trained and untrained voices. Visual inspection of the shape and size of the Lx waveforms of professional countertenors revealed the presence of characteristics of both falsetto singing, featuring relatively small CQ, and modal singing, exhibiting large CQ (Welch, Sergeant, & MacCurtain, 1988). A later study confirmed different voice source behaviors between modal and falsetto singing related to the size and shape of the Lx waveform, although some bass/baritones and tenors also exhibited “modal” shapes in falsetto singing (Welch, Sergeant, & MacCurtain, 1989). Register shifts between chest and falsetto were clearly marked in the EGG wavegrams of a classically trained baritone (Herbst, Hess, Müller, Švec, & Sundberg, 2015). The pilot study conducted by Miller and Schutte (1993) with two professional female singers objectively described the highest register, identified by different terminologies such as the flageolet, flute, bell or whistle register, reporting a reduced vocal fold oscillation based on EGG analysis. Early studies identified distinct patterns between EGG waveforms and sub- and supraglottal pressure variations in a bass-baritone voice (Miller & Schutte, 1984) and in soprano high notes (Schutte & Miller, 1986). EGG has also contributed to the definition of male head register and the *passaggio* in opera singing (Miller & Schutte, 1994).

A number of studies focus on laryngeal function during the transition between registers. Neumann, Schunda, Hoth and Euler (2005) reported the lack of consistent patterns in CQ during the transition between head and chest registers in male operatic singers. Echternach, Dippold, Sundberg, Arndt, Zander and Richter (2010) and Echternach, Sundberg, Zander and Richter (2011) found irregularities in vocal fold oscillation during the transition between falsetto and modal register, in addition to higher OQ and lower CQ respectively. The EGG recordings confirm changes in the voice source characteristics during this transition, by means of a greater CQ, and less dominant fundamental in modal register (Salomão & Sundberg, 2009). The transition between chest and middle registers features a slight decrease in the CQ values (Miller & Schutte, 2005; Morris, Okerlund, & Craven, 2016), and is associated with changes in the vocal tract length, measured using Lx and a microphone, suggesting that the larynx lowers after the transition (Amarante Antrade, 2012).

Other studies further investigate registers in terms of the laryngeal vibratory mechanisms that characterize human voice production. The performance of a *glissando* and held notes of trained and untrained voices clearly indicates three distinct laryngeal transitions, corresponding to four laryngeal mechanisms graded from low to high and labelled M0-M3; the transition to a higher mechanism is characterized by a pitch jump, a decrease of EGG amplitude, and a change in the DEGG signal (Roubeau, Henrich, & Castellengo, 2009). The DEGG derived OQ seem to be significantly correlated with two main laryngeal mechanisms: M1 referring to chest, modal and male head register; and, M2 related to falsetto for males and head register for females (Henrich, Castellengo, d’Alessandro, & Doval, 2005). OQ was also found to be strongly related to *f*o in M2. These findings were corroborated by Henrich, Wolfe and Smith (2014), who revealed that DEGG derived CQ in M1 increased in that of M2 in professional operatic singers when performing the same vowel at the same pitch. The transition to the whistle register in 12 sopranos featured a single laryngeal transition related to two laryngeal mechanisms, M2 and M3, associated with the head and whistle register, whose laryngeal transition range varied among the singers between the interval D#5 and D6 (Garnier, Henrich, Crevier-Buchman, Vincent, Smith, & Wolfe, 2012). The characteristic interval leap between chest and falsetto seems to be dimorphically distributed across gender with female singers featuring smaller physiological values (e.g., *f*o fluctuations, CQ and peak-to-peak amplitude) during the leap interval, and less individual variation compared with male singers (Miller, Švec, & Schutte., 2002).

Lastly, a few studies have analysed voice classifications through Lx/EGG. An early study conducted by Pabst and Sundberg (1993) analysed the role of the vertical larynx position through multichannel EGG, reporting its variation across voice classifications and within singers as the result of the effect of pitch, vowel and lung pressure. Rosenau (1999) found relatively small differences in CQ between German singing and speaking voices of four voice classes, identified as bass, baritone, mezzo, and soprano. Miller, Schutte and Doing (2001) evaluated the gradual *diminuendo* from the loudest to the softest phonationof sustained high notes in one robust and one lyric tenor, performing a *messa di voce*. EGG analysis shows distinct capabilities of the two voices: the lyric voice being able to gradually diminish with minimal change to the glottis, whilst the robust voice features an abrupt transition passing from high closed quotient in loud production to incomplete glottal closure in soft production. Recently, the analysis of the DEGG signal provided insight into voice classification for male singers also showing that tenors seem to have significantly higher OQ/log(*f*o) gradient than baritones in chest and head registers, and baritones showed higher gradient in falsetto than in chest and head registers (Yan, Ng, Chan, Wang, & Liao, 2012).

**Tuning and resonance strategies (6 studies)**. Research has also employed Lx/EGG to analyse tuning, in particular with reference to pitch drift. By generating a vocal pitch trace from the Lx signal which was shown to 66 children whilst they were speaking and singing, Welch (1983, 1985) postulated and tested a schema theory to explain tuning in children. Results indicate that singing in tune can be learned when information of the pitch error is provided and practiced. Furthermore, Howard (2007a, b), based on Lx-derived *f*o analysis, reported that an *a* *cappella* SATB quartet tended to tune to a non-equal-tempered system and varied their intonation with modulation.

Using Lx/EGG, three studies have also investigated formant tuning strategies, also termed resonance strategies, which refers to the adjustment of the resonance frequencies of the vocal tract to approximate certain harmonics in the voice source. Miller and Schutte (1990) observed the systematic use of resonance strategies in relation to the complexity of the musical phrase by a professional singer. Sundberg, Lã and Gill (2011, 2013) used DEGG to inform inverse filtering techniques to analyse tuning strategies in professional male singers.

### **Vibrato (5 studies)**. Since an early electroglottographic study conducted by Hicks and Teas (1987) revealed little about the physiological characteristics of vocal vibrato at the level of the voice source, later studies provide further understanding. Based on the application of Lx/EGG, research shows that vibrato is produced by trained amateur singers using laryngeal musculature (Laukkanen, Vilkman, & Unto, 1992); it features laryngeal amplitude modulation in trained singers irrespective of the degree of training, (Dromey, Reese, & Hopkin, 2009); and, mean vibrato extent reduced with practice in an SATB student quartet (Daffern, in press). Using the point of glottal closure in the EGG signal to align audio and supraglottal pressure signals, Schutte and Miller (1991) observed a complex varying pattern in sound pressure level (SPL) modulation within a vibrato cycle in tenor high notes.

### **Child and/or Adolescent Development (10 studies)**. The application of Lx/EGG has proved valuable for improving our knowledge of the development of the voice source from childhood, by recording vocal fold activity in relation to age, training and sex. An early study with 25 male singers aged 11-17 revealed a negative correlation between serum testosterone and *f*o and a decrease in *f*o from age 15 reaching a lowest value of 148 Hz (Pedersen, Kitzing, Krabbe, & Heramb, 1982). CQ values suggest that voice source activity tends to be more efficient in young choristers compared with untrained children (Welch & White, 1993). A later study observed three phases in the *f*o behavior of a group of five-year-old children, featuring an initial phase with a glide upwards, a middle phase with a greater frequency stability and a termination phase characterized by greater instability (White, Sergeant, & Welch, 1996). A large study conducted by Pedersen (1997), including EGG-derived *f*o analysis, reported a significant correlation between serum estrone and *f*o, and between the development of voice range profiles and serum testosterone in boys and serum estrone in girls.

Barlow and Howard (2002) found a significant effect of vocal training on CQ in 126 trained and untrained children. This preliminary analysis was confirmed by a larger sample size, demonstrating that training, gender and age have predictable and measurable effects upon the voice source (Barlow, 2003; Barlow & Howard, 2005, 2007).

Data on child and adolescent singing voices for different styles is still scarce. A few studies shed some light on the differences between classical and musical theatre (MT) style in female adolescent singers, reporting higher CQ when singing in MT compared with classical style (Barlow, LoVetri, & Howard, 2007; Barlow & LoVetri, 2008).

**Practice (7 studies)**. Lx/EGG has a key role in the investigation of the effects of training on the singing voice; seven studies suggest the pedagogical usefulness of including Lx/EGG derived objective parameters, such as mean *f*o, CQ and OQ, in biofeedback devises for singing coaching and practice. Rossiter, Howard and Comins (1995) observed a significant increase in mean *f*o after a short period of vocal tuition, whilst the pilot investigation conducted by Rossiter and Howard (1997) suggests that the relationship between mean voice *f*o and the full *f*o range tends to be constant even when *f*o range changes with training.

An early pilot study indicated that OQ is a distinct parameter of vocal training, as it decreases with experience and training (Howard & Lindsey, 1987). This study was further expanded by Howard, Lindsey and Allen (1990) reporting that trained voices are characterized by significantly higher CQ values compared with those of untrained singers. This study was corroborated by Howard (1995) showing that the CQ/log(*f*o) gradient is positively correlated with the number of years of formal training that singers received. Results of a longitudinal study show the quantifiable effect of one year of singing training on the voice source of a boy chorister (Williams, Welch, & Howard, 2005).

### **Voice quality (11 studies)**. Research have analysed the relationships between Lx/EGG signals and vocal qualities, including pressed and supported/unsupported voice, breathiness, resonance, vocal loudness and perceptual evaluation of singing performance, demonstrating the importance of objective laryngeal parameters (e.g., OQ and CQ) to understanding voice quality. Scherer and Titze (1987) highlighted a decrease in OQ from breathy to normal and pressed voice in a professional singer; Verdolini, Druker, Palmer and Samawi (1998) reported that CQ values distinguish resonant from pressed voice, healthy voices and participants with nodules, but do not consistently differentiate resonant from breathy voice. Research found that supported voices were characterized by lower OQ (Griffin, Woo, Colton, Casper, & Brewer, 1995) and steeper EGG slope during the closing phase (Sonninen, Hurme, & Sundberg, 1993) than unsupported voices. Four qualities of a baritone voice, labelled “naive falsetto”, “countertenor falsetto”, “lyrical chest”, and “full chest”, are achieved through distinct glottal configurations (Herbst, Ternström, & Švec, 2009). The “voix mixte” quality of a countertenor voice features lower CQ than “head” quality (Howard, Welch, & Penrose, 2001).

Sundberg, Titze and Scherer (1993) found that, at low peak flow values generally representative of low subglottal pressure, an increase in SPL was achieved through a lengthened closed phase, which was also characteristic of a change from breathy to pressed phonation. Laukkanen, Mickelson, Laitala, Syrja, Salo and Sihvo (2004) investigated voice quality using HearFones, a commercial product designed to enhance auditory feedback during phonation, and results demonstrate that CQ is significantly higher with HearFones than without. Furthermore, Sonninen, Laukkanen, Karma and Hurme (2005) observed that ratings of optimum voice quality are related to an intermediate EGG slope. Buder and Wolf (2003) suggest that CQ is also a useful objective parameter to evaluate the vocal health of singing voices, as researchers found that a singer reporting a history of vocal problems presented glottal insufficiencies as assessed by CQ values in the head register, being higher than those of a second singer with similar physical and training characteristics, but reporting no voice disorders. Conducting acoustic analysis on electroglottographic waveforms, jitter, shimmer, harmonic-to-noise ratio, amplitude and pitch range were found to change consistently within individuals pre- and post- performance, however the impact of performance to increase or decrease these parameters varied between tenors (Kitch, Oates, & Greenwood, 1996). These EGG/Lx based findings suggest that singers adjust their laryngeal and/or glottal configuration to achieve specific voice qualities, and that CQ and OQ are useful to investigate breathiness, pressed voice and vocal health.

### **Clinical Research (9 studies)**. EGG represents a valuable tool to measure the effect of vocal exercises traditionally understood only in intuitive terms and frequently used by therapists and logopedists to treat hyperfunctional voices and by singing teachers for vocal warmup. A study conducted by Elliot, Sundberg and Gramming (1997) observed a lower vertical larynx position, previously associated with healthy voices (Shipp & Izdebski, 1975), during a standard vocal exercise compared with the rest position. Cordeiro, Montagnoli, Nemr, Menezes and Tsuji (2012) focus on lip and tongue trills and report higher CQ during the performance of the lip exercises, compared with the tongue trill condition. Guzman, Rubin, Muñoz and Jackson-Menaldi (2013) investigated the influence of resonance tubes and phonation with vibrato on the voice source, as possible therapeutic tools for phonatory hyperfunction: although a causal effect was not demonstrated, findings showed a decrease in the CQ during the tube and vibrato phonation, suggesting potential value of the treatment.

Lx/EGG have also been used to investigate the direct influence of hormonal fluctuations on the singing voice. Chernobelsky (1998) analysed the effect of the menstrual cycle and reported hypotension, as indexed in the EGG waveform, in different phases of the cycle in singers and only around menses in non-singers, suggesting that singers should be informed of these findings, as compensation for hypotension requires an effort that could lead to the development of voice disorders.

Investigations led by Filipa Martins Baptista Lã over the last two decades analysed the correlation between hormonal variations and the singing voice through the application of Lx, and provide contrasting results with those observed in the 1980s, which reported such a negative effect of the oral contraceptive pill (OCP) on the voice that professional singers were advised to avoid them (Brodnitz, 1971; Dordain, 1972; Gelder, 1974). The double blind randomized placebo controlled study conducted by Lã, Davidson, Ledger, Howard and Jones (2007a) revealed that the menstrual cycle and oral contraception influence both the psychological and physiological components of the singing voice by improving the perceived and measurable vocal control, regulating the vocal fold vibration pattern. The findings were confirmed by the randomized controlled experiment conducted by Lã, Ledger, Davidson, Howard and Jones (2007b), reporting that a third generation OCP such as Yasmin improves the regularity of the vibration patterns of the vocal folds, and suggesting that singers should continue to take OCP during their menstrual cycle. Further analysis of the data applied to the audio or the Lx signal, depending on the reliability of the output, also showed a slower vibrato rate during OCP than during a natural cycle, and a lack of effects when singers performed a higher note in relation to the vibrato extent (Lã, Howard, Sa-Couto, & Freitas, 2012). Results were corroborated by a larger study with 20 singers, demonstrating that current OCPs do not have a negative effect on the voice quality of professional singers, based on regularity of vocal fold vibrations (Lã, Howard, Ledger, Davidson, & Jones, 2009).

Finally, a case study by Lã and Sundberg (2012) has improved understanding of the effect that pregnancy has on vocal quality, previously based on singers’ reports (Abramson, Steinberg, Gould, Bianco, Kennedy, & Stock, 1984), observing a decrease in vocal fold motility and increased vocal adduction during pregnancy.

In summary, Lx/EGG are valuable tools for improving knowledge in this field of research, but future investigations featuring larger longitudinal studies and different OCPs are needed.

### **Real-time Biofeedback (4 studies)**. Research have analysed the usefulness of Lx/EGG as a supplementary aid in vocal teaching and assessment. Rossiter, Howard and DeCosta (1996) compared the vocal development of two untrained participants undertaking six singing lessons, one taught traditionally and one with the aid of ALBERT (Acoustic and Laryngeal Biofeedback Enhancement in Real Time), software providing live feedback of Lx parameters among others. Results indicate that using the biofeedback system was associated with greater increases of CQ compared with those observed without biofeedback, suggesting this tool could be useful in vocal teaching.

Garner and Howard (1999) described the design of a real-time feedback system employed during various singing lessons, based on the display of the *f*o and CQ derived from Lx. Herbst, Howard and Schlömicher-Their (2010a), also suggested EGG real-time feedback can be a crucial element for skill acquisition during vocal training. Barlow and Brereton (2008) also identified the requirements for a biofeedback system for young singers, suggesting that efficient real-time feedback should assess a wide range of performance parameters, including Lx measurements.

## Study design

Empirical investigations have been mostly conducted with adult participants (age >18): 86 studies involved adults; 14 studies focussed on children (featuring prepubertal voice), and/or adolescents (with pubertal voice); and 4 studies do not specify the age of participants. Literature in the adult population features an average of 9.9 participants (SD=41.1) and is mostly characterized by case-studies analysing vocally trained singers, whilst only a few studies represent full experiments, as shown in Figure 5. A limited number of studies (n. 5) focussed on untrained participants.

*Figure 5.* Number of participants and training level across the selected studies analysing the singing voice of the adult population.

The body of work analysing the singing voices of children and/or adolescents through Lx/EGG involves a larger sample size (Mean=126.2 participants; SD=41.0) than that investigating adult populations. Six studies focused on trained singers, 3 on untrained, and 4 with both trained and untrained, suggesting an interest in analysing the singing voice of children and adolescents across training levels.

*Figure 6.* Number of participants and training level across the selected studies focussed on the singing voice of children and/or adolescents.

Lastly, investigation of the singing performance standards of the participants in the selected articles demonstrates the use of the following categories of singers, as shown in supplementary Table 1: professional singers, semi-professional singers, singing students, experienced performers, unexperienced singers, choristers, singing teachers, famous chanters, primary school students, non-singers, non-experts, amateurs. These results, in light of systematic categorization of the professional level of participants described by Bunch and Chapman (2000), suggest an ambiguity in the literature and the need for more consistency in the taxonomy of singers used in scientific research.

# Conclusions

The current review shows that Lx/EGG is a commonly-used tool for the analysis of the laryngeal vibratory system that governs the singing voice, improving our understanding of a number topics, including different singing styles, registers, voice classifications, tuning, resonance strategies, vibrato, vocal development, practice effects, voice quality, analysis techniques, and its use in clinical research and vocal pedagogy. Specifically, Lx/EGG were largely used for the purpose of facilitating the identification of the moment of glottal closing and the recording of the laryngeal position, although often used in connection with audio recordings to contextualise findings.

Lx/EGG has been shown to be valuable for investigating breathiness, pressed voice and vocal health, and in analysing the effect of specific vocal exercises and training, with its usefulness identified as an aid in vocal teaching through real-time feedback systems. Research also demonstrates the successful application of Lx/EGG to analyse the effects of hormonal fluctuations on singing voices and effectively contributing to the identification of the idiomatic characteristics of multiple singing styles. Specifically, the extraction of CQ values has been used to differentiate registers and singing styles such as belt, and MT from operatic style. Lx/EGG derived *f*o analysis has proven valuable for the investigation of vibrato, tuning and ensemble singing performances.

Lx/EGG combined with other methods, such as electrophotoglottography, EMG, inverse filtering, measures of sub- and supra-glottal pressure and airflow, have advanced knowledge of the physiological mechanisms underpinning the singing voice, revealing the contribution of the voice source. These research techniques and knowledge can usefully inform traditional psychomusicological approaches to singing performance, to better grasp the intentions, priorities and perceptions of the performers as well as the audience. The small sample size characterizing many empirical investigations and the ambiguity in the taxonomy of singers limit the possibility to generalise some findings across populations and illustrate the need for further work. Nevertheless, the wealth of literature emerging from Lx/EGG research is highly valuable and leading towards a fuller understanding of the singing voice*.*

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# Appendix

*Table 1. Summary of empirical investigations using Lx/EGG for the analysis of the singing voice*

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Author(s) | Year | Thematic category | Participant(s) | | | | |
|  |  |  | Number | Age | Training experience | Professional experience+ | Gender |
| Amarante | 2012 | Registers | 11 | Adults | T | Pro | M |
| Bailly et al. | 2007 | Styles | 1 | Adult | T | Pro | M |
| Bailly et al. | 2010 | Styles | 1 | Adult | T | Pro | M |
| Barlow | 2003 | Vocal development | 127 | Ch, Adol | T, U | NS, St | F, M |
| Barlow & Brereton | 2008 | Real-time biofeedback | 418 | Ch, Adol | T, U | NS, St | F, M |
| Barlow & Howard | 2002 | Vocal development | 127 | Ch, Adol | T, U | NS, St | F, M |
| Barlow & Howard | 2005 | Vocal development | 256 | Ch, Adol | T, U | NS, St | F, M |
| Barlow & Howard | 2007 | Vocal development | 256 | Ch, Adol | T, U | NS, St | F, M |
| Barlow & LoVetri | 2008 | Vocal development | 20 | Adol | T | St | F |
| Barlow et al. | 2007 | Vocal development | 10 | Adol | T | St | F |
| Bestebreurtje & Schutte | 2000 | Styles | 1 | Adult | n.a. | n.a. | F |
| Bjorkner | 2008 | Styles | 10 | Adults | T | Pro | n.a. |
| Buder & Wolf\* | 2003 | Vocal quality | 2 | Adults | T | Pro | F |
| Chernobelsky | 1998 | Clinic | 40 | Adults | T, U | NS, St | F |
| Cordeiro et al. | 2012 | Clinic | 10 | Adults | n.a. | Pro | F, M |
| Daffern | 2008 | Styles | 16 | Adults | T | Pro | F |
| Daffern | in press | Vibrato | 4 | Adults | T | St | F, M |
| Daffern & Howard | 2010 | Styles | 16 | Adults | T | Pro | F |
| Delviniotis et al. | 2008 | Styles | 13 | Adults | n.a. | Famous chanters | M |
| Dromey et al. | 2009 | Vibrato | 17 | Adults | T | St | F |
| Echternach & Richter | 2010 | Styles | 12 | Adults | T, U | Pro, Teach, Amateurs | F, M |
| Echternach et al. | 2010 | Registers | 18 | Adults | U | n.a. | M |
| Echternach et al. | 2011 | Registers | 20 | Adults | U | n.a. | M |
| Elliot et al. | 1997 | Clinic | 7 | Adults | T | n.a. | F, M |
| Estill | 1988 | Styles | 1 | n.a. | T | n.a. | n.a. |
| Evans | 1995 | Styles | 9 | Adults | T | Inc | In |
| Evans & Howard | 1993 | Styles | 1 | Adult | T | Teach | F |
| Garner & Howard | 1999 | Real-time biofeedback | n.a. | Adults | T | SP | M |
| Garnier et al. | 2012 | Registers | 12 | Adults | T | Nonexperts, St, Pro, | F |
| Griffin et al. | 1995 | Vocal quality | 8 | Adults | T | Pro | F, M |
| Guzman et al. | 2013 | Clinic | 36 | Adults | T | n.a. | F, M |
| Henrich et al. | 2005 | Registers | 18 | Adults | T | n.a. | F, M |
| Henrich et al. | 2014 | Registers | 7 | Adults | T | SemiPro, Pro | M |
| Herbst et al. | 2009 | Vocal quality | 1 | Adult | T | Pro | M |
| Herbst et al. | 2010a | Real-time biofeedback | 1 | Adult | U | Chorister | F |
| Herbst et al. | 2015 | Registers | 1 | Adult | T | SemiPro | M |
| Herbst et al. | in press | Techniques | 13 | Adults | T, U | Amateurs, Pro | F, M |
| Hicks & Teas | 1987 | Vibrato | 10 | Adults | T | n.a. | F, M |
| Howard | 1995 | Practise | 26 | Adults | T, U | Amateurs, Pro | F |
| Howard | 2003 | Styles | 4 | Adults | n.a. | Exp | F, M |
| Howard | 2007a | Tuning | 4 | Adults | n.a. | Exp | F, M |
| Howard | 2007b | Tuning | 4 | Adults | T | St | F, M |
| Howard | 2007c | Styles | 4 | Adults | n.a. | Exp | F, M |
| Howard & Lindsey | 1987 | Practise | 4 | Adults | T, U | Exp | M |
| Howard et al. | 1990 | Practise | 18 | n.a. | T, U | Pro, Exp, Unexp | M |
| Howard et al. | 2001 | Vocal quality | 1 | Adult | T | Pro | M |
| Howard et al. | 2009 | Styles | 1 | Adult | T | Pro | F |
| Kitch et al. | 1996 | Vocal quality | 10 | Adults | T | Exp | M |
| Kitzing | 1982 | Registers | 2 | Adults | T, U | Pro, NS | M |
| Lã & Sundberg | 2012 | Clinic | 1 | Adult | T | SemiPro | F |
| Lã et al. | 2007a | Clinic | 1 | Adult | T | St | F |
| Lã et al. | 2007b | Clinic | 7 | Adults | T | St | F |
| Lã et al. | 2009 | Clinic | 20 | Adults | T | Pro, SemiPro | F |
| Lã et al. | 2012 | Clinic | 1-9 | Adults | T | SemiPro | F |
| Laukkanen et al. | 1992 | Vibrato | 1 | Adult | T | Amateur | F |
| Laukkanen et al.\* | 2004 | Vocal quality | 20 | Adults | T, U | Pro | F, M |
| Lebowitz & Baken | 2011 | Styles | 20 | Adults | T | Pro | F |
| Miller & Schutte | 1984 | Registers | 1 | Adult | T | Pro | M |
| Miller & Schutte | 1990 | Tuning | 1 | Adult | T | Pro | M |
| Miller & Schutte | 1993 | Registers | 2 | Adults | T | Pro | F |
| Miller & Schutte | 1994 | Registers | 1 | Adult | T | Pro | M |
| Miller & Schutte | 2005 | Registers | n.a. | Adults | T | Pro | F |
| Miller et al. | 2001 | Registers | 2 | Adults | T | Pro | M |
| Miller et al. | 2002 | Registers | 11 | Adults | T, U | Exp | F, M |
| Morris et al. | 2016 | Registers | 15 | Adults | T | St, Pro, Teach | F |
| Neumann et al. | 2005 | Registers | 11 | Adults | T | Pro | M |
| Pabst & Sundberg | 1993 | Registers | 7 | Adults | T | Pro, NonPro, Teach, St | F, M |
| Pedersen et al. | 1982 | Vocal development | 25 | Ch, Adol | T | St | M |
| Pedersen | 1997 | Vocal development | 95 | Ch, Adol | n.a. | St | F, M |
| Rosenau | 1999 | Styles | 4 | Adults | T | Pro | F, M |
| Rossiter et al. | 1995 | Practise | n.a. | Adults | U | Unexep | M |
| Rossiter & Howard | 1997 | Practise | 2 | n.a. | U | Unexep | M |
| Rossiter et al. | 1996 | Real-time Biofeedback | 2 | n.a. | U | Unexep | M |
| Roubeau et al. | 1987 | Registers | 10 | Adults | T, U | n.a. | F, M |
| Roubeau et al. | 2009 | Registers | 79 | n.a. | T, U | n.a. | F, M |
| Salomão & Sundberg | 2009 | Registers | 13 | Adults | T | Chor | M |
| Scherer & Titze | 1987 | Vocal quality | 1 | Adult | T | Pro | M |
| Schutte & Miller | 1986 | Registers | 2 | Adults | T | Amateur, Pro | F |
| Schutte & Miller | 1991 | Vibrato | 1 | Adult | T | Pro | M |
| Schutte & Miller | 1993 | Styles | n.a. | n.a. | n.a. | n.a. | F |
| Sonninen et al. | 1993 | Voice quality | 9 | Adults | T | Pro | F, M |
| Sonninen et al.\* | 2005 | Vocal quality | 7 | Adults | T | Pro | F, M |
| Sundberg et al. | 1993 | Vocal quality | 10 | Adults | n.a. | Pro, NPro | M |
| Sundberg et al. | 2011 | Tuning | 8 | Adults | T | St, Pro, | M |
| Sundberg et al. | 2012a | Styles | 7 | Adults | T | Pro | M |
| Sundberg et al. | 2012b | Styles | 1 | Adult | T | Pro | F |
| Sundberg et al. | 2013 | Tuning | 8 | Adults | T | St, Pro, | M |
| Sundberg et al. | 2016 | Styles | 8 | Adults | T | St, Pro | M |
| Sundberg & Thalén | 2015 | Styles | 6 | Adults | T | Pro | F |
| Teachey et al. | 1991 | Practise | 30 | Adults | U | SemiPro, Pro | F, M |
| Thalén & Sundberg\* | 2001 | Styles | 1 | Adult | T | Pro | F |
| Thomasson | 2003a | Styles | 9 | Adults | T | Pro | M |
| Thomasson | 2003b | Styles | 9 | Adults | T | Pro | M |
| Verdolini et al. | 1998 | Vocal quality | 12 | Adults | T | Trained participants | F, M |
| Welch | 1983 | Tuning | 66 | Ch | U | PSSt | F, M |
| Welch | 1985 | Tuning | 66 | Ch | U | PSSt | F, M |
| Welch & White | 1993 | Vocal development | 48 | Ch | T | 5y subjects, chor | F, M |
| Welch et al. | 1988 | Registers | 9 | Adults | T | Pro | M |
| Welch et al. | 1989 | Registers | 19 | Adults | T | Pro | M |
| White et al. | 1996 | Vocal development | n.a. | Ch | T | PSSt | F, M |
| Williams et al. | 2005 | Practise | n.a. | Adol | T | Chor | M |
| Yan et al. | 2012 | Registers | 29 | Adults | T | Pro | M |
| Yoshinaga & Kong | 2012 | Styles | 4 | Adults | T | Pro | F, M |
| Zangger Borch & Sundberg\* | 2010 | Styles | 1 | Adult | n.a. | Teach, Pro | M |

*Note.* +Information reported as in the paper. \*Studies including in addition participants taking part to a listening test. Adol: adolescents featuring prepubertal voice; Adult(s): participants after age 18; Ch: children featuring prepubertal voice; Chor: choristers; Exp: experienced singers; F: female(s); M: male(s); n.a.: complete information not available; NPro: non-professional singers; Pro: professional singers; PSST: primary school students; SemiPro: semi-professional singers; St: singing students; Teach: singing teacher(s); Unexpe: unexperienced singers.

1. Vocal folds are constituted by muscles shaped as folds and are approximately 9 to 13 mm and 15 to 20 mm long in adult females and males, respectively (Sundberg, 1987, p. 6). [↑](#footnote-ref-1)
2. ‘*Phonation* means sound generation by means of vocal fold vibration’ (Sundberg, 1987, p. 9) [↑](#footnote-ref-2)
3. Each closure with return to the open position of the vocal folds is referred to as a cycle and the number of vibratory cycles occurring each second determines the *f*o being produced, which corresponds to the pitch which is heard (Sundberg, 1987, p. 10-11). Considering an operatic soprano range, for instance, their vocal folds will vibrate from approximately 220 – 988 times a second, corresponding to an A3 (220Hz) and B5 (988Hz) (Hirano, 1981, p. 89; Sataloff, 2005, p. 82). [↑](#footnote-ref-3)