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ORIGINAL PAPER

Effects of Different Lung Volume Conditions on Closed Quotient, Vocal Fundamental Frequency and Relative Intensity in Vocally Untrained Female Speakers

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Abstract
The objective of this study was to determine the relationship between lung volume (LV) conditions and vocal fold vibratory patterns using measurements of closed quotient (CQ), fundamental frequency (F_0) and relative vocal intensity. Forty-three healthy and vocally untrained females were asked to produce the vowel /a/ following breathing instructions that cued for higher, habitual, or lower LV conditions. Closed quotient was measured by electroglottography (EGG) and analyzed using criterion-level method of 25%. An average of CQ, F_0 and relative vocal intensity were obtained. No significant difference was observed in CQ between cued LV conditions; however, there was a trend for CQ to increase in the cued high LV condition. Relative vocal intensity and F_0 differed significantly across all conditions with higher F_0 and relative vocal intensity observed at the high LV condition. These findings suggested that the use of different cued LVs did not have a significant impact on CQ. This may have been due to (1) the phonatory task, (2) variability in responses to the breathing instructions between individuals, and (3) the measurement of CQ. However, F_0 and relative vocal intensity were significantly influenced by the LV. This offers a possible alternative approach in cueing pitch and loudness in singing and voice therapy.

Keywords Lung volume · Closed quotient · Fundamental frequency · Vocal intensity · Electroglottography · Vocal fold vibration

1 Introduction

Voice production involves the activities of the respiratory and laryngeal subsystems. The interaction between these two components plays a crucial role in determining the characteristics of the voice. During normal phonation, the vocal folds are set into vibration by a driving force from the phonatory airflow [1] which is supplied by the lungs. The volume of air in the lungs at any point in time is called *lung volume* (LV) [2] and determines the amount of air that may be used in phonation. Higher LVs are associated with phonation [3]. LV conditions can be labeled based on the percentage of the vital capacity (VC) used during phonation, which has varied across studies. For example, high LV may refer to a volume equivalent to 80% [4] or 90% [5], habitual or typical LV refers to 40% [5] or 60% [4], and low LV refers to 20% [5] or 40% [4] of the VC. In singing pedagogy and speech language pathology, manipulation of LV is implemented through breathing instructions [6]. It is believed that optimal breathing technique is necessary for attaining full potential in singing [7]. Singers are taught to increase loudness and pitch through the use of techniques that adjust subglottal pressure [8], e.g., diaphragmatic breathing [8, 9]. Breathing instructions have also been widely used in voice therapy to reduce vocal hyperfunction [3] and to increase vocal strength in vocal pathologies [10–14]. The frequent use of breathing instructions to achieve desired changes in loudness, pitch, and vocal strength suggests that LV plays a significant role from physiological, pathological, and therapeutic perspectives.

Vocal fold vibration and glottal closure are inherent in the definition and understanding of vocal registers [15, 16]. Controlling or modifying vocal registers has been one of the essential targets in the practice of speech language pathologists (SLP) to treat voice disorders such as puberphonia where pitch modulation and cues for registers are used [17,

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18]. Pedagogically, singers are also trained to achieve a wide range of frequencies to ensure the transition from one to another is accurate and smooth as different singing styles require mastering different vocal registers [19].

Vocal registers have typical glottal closure patterns and vocal fundamental frequency (F_0) ranges [20, 21] that can be quantified using voice source parameters obtained from electroglottography (EGG) or inverse filtering [22]. One of the EGG parameters related to vocal register is the closed quotient (CQ), which is the ratio between the closed phase duration and the fundamental period [20]. In other words, CQ is the ratio of the time interval between the rising and falling parts of the EGG waveform at a given percentage threshold of the peak-to-peak amplitude to the fundamental period [22]. Different threshold levels have been used to calculate CQ [23–25]. A criterion level of 25% has been recommended as it is least influenced by F_0 and vocal intensity and correlates well with perceptual evaluation and videokymography [23, 26]. The CQ can be indicative of the type of vocal register used during phonation [27, 28]. The measurement of CQ is often based on the use of a vowel as the phonatory task [24, 26, 27]. Previous research has demonstrated an average CQ of 0.52 (standard deviation, SD = 0.07) for modal register and 0.44 (SD = 0.11) for falsetto register [26]. The CQ is affected by vocal intensity and F_0 [29, 30]. Within a vocal register, CQ has been found to increase with vocal intensity [29, 30], whereas it may decrease with an increase in F_0 across vocal registers or increase with F_0 within the same register [29, 31]. A significant change in CQ has been observed during the transition from one register to another (e.g., decrease in CQ from modal to falsetto) as compared to within a given register [19, 29].

Previous research has shown that LV conditions affect CQ, F_0, and vocal intensity in untrained speakers. Iwarsson, Thomasson, and Sundberg [3] found that CQ was lower at high (30.7%) than at low (35.9%) LV, suggesting a greater glottal abduction force at high LV. Dromey and Ramig [6] found that F_0 increased significantly in high LV compared with low LV and vocal sound pressure level (SPL) was significantly higher at high LV than at low LV. Watson et al. [4] also found higher F_0 and SPL at high LV compared to low LV. Together these findings imply an inter-relationship in activities between the respiratory subsystem and the larynx in phonation in vocally untrained speakers. The effect of tracheal pull on the larynx has been considered to explain this mechanical link, which is more prominent at high LVs [3, 32]. Tracheal pull refers to the downward contraction of the diaphragm during inhalation, which creates an abductory force on the larynx [4, 5]. Breathiness perceived at high LV has been explained by reduced valving efficiency (i.e., increased abductory force) which leads to a greater glottal leakage [5]. Iwarsson and Sundberg [5] referred to the effects of tracheal pull to explain their findings of a significantly correlation between high LV and a lower larynx position compared with low LV.

To date, the relationship between commonly used breathing instructions that cue different LV conditions and vocal quality in voice therapy and singing, LV and phonation, and CQ and registers have all been investigated in isolation from each other. The link between LV, CQ, F_0, and vocal intensity has yet to be investigated simultaneously. It has been assumed that breathing instructions can cue for various LV conditions, which can lead to a change in vocal qualities such as CQ, F_0, and vocal intensity associated with vocal registers. Testing this assumption by examining changes in the glottal source when different breathing instructions are given may help to unravel the effectiveness of breathing instructions in achieving specific vocal registers in voice therapy and singing pedagogy. The following research questions were therefore investigated:

1. How do CQ, F_0 and vocal intensity change when vocally untrained speakers are given specific breathing instructions that cue for different LVs prior to voice onset?
2. Is there any relationship between CQ, F_0 and vocal intensity in cued LV conditions?

2 Method

2.1 Participants

Forty-three females (mean age = 22.7 years, SD = 3.4) were recruited for the study from a University Health Sciences Faculty. Inclusion criteria were (1) aged 18 to 50 years old, (2) fluent English speaker, (3) non-smoker, and (4) no prior voice or singing training. Participants meeting the following exclusion criteria were omitted from the research: (1) a history of previous or current speech, language or voice disorders, (2) a history of pulmonary disease, (3) a history of head and neck surgery, and (4) use of medications that may affect voice quality. This study used participants with a single gender to control for factors related to gender-related variability in voice production.

All participants completed a voice screening procedure, which consisted of a self-rated questionnaire (Voice Symptom Scale—VoiSS) [33] and an auditory-perceptual evaluation of a recorded sample of conversational speech and reading of the Rainbow Passage [34] in a soundproof room using the GRBAS scale (Grade, Roughness, Breathiness, Asthenia, Strain) [35]. Participants with a score of 16 or higher on the VoiSS or/and a score of G1 or higher on the GRBAS scale were excluded from the study.

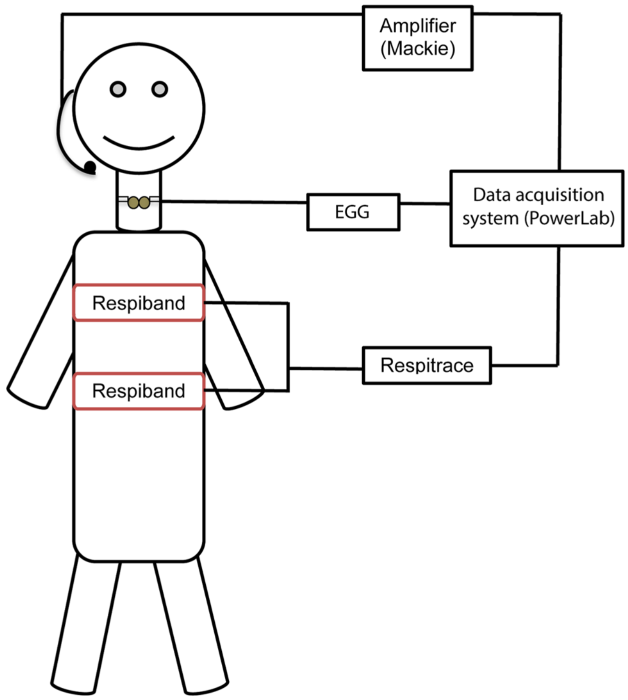

Fig. 1 Measurement setup

2.2 Equipment

The experimental setup is illustrated in Fig. 1. Acoustic signals were recorded by a C520 head-mounted condenser microphone [36] placed at a distance of 5 cm and 45^{o} from the mouth. Microphone signal was recorded by the Layla 24/96 Multitrack Recording System and Adobe Audition software version 1.0 [4] at a sampling rate of 44.1 kHz.

A respiratory inductive plethysmograph (Respitrace™, model 10.9230) [37] with two elastic transducers (Respibands) and a retainer to secure the bands were used to observe movement of the ribcage and abdomen. The upper band was placed just under the armpit (at the level of rib cage), while the lower band was placed below the lowest rib, just above the top of the pelvic bone. The lower band was checked to make sure that it did not encroach the lower rib cage.

An electroglottograph (EGG, EG2-PCX2) [38] was attached at the level of the thyroid cartilage to measure impedance changes due to vocal fold contact. Prior to attachment of EGG electrodes, the neck areas of participants were cleaned using alcohol wipes to remove surface oil that could potentially affect the EGG signal. Electrodes were placed approximately 1.5 cm apart with conducting gel applied between the electrodes and the skin. This was secured with the use of Velcro strip and Coban tape (3 M, United States).

All signals from the head-mounted condenser microphone, Respitrace™, UVM, and EGG were digitized using a 16-channel data acquisition system (PowerLab PL3516) [39], and recorded simultaneously using software LabChart Pro V.8.0.5 [40].

2.3 Breathing Instructions

Three LV conditions were cued prior to the production of the vowel /a/ using three different breathing instructions. In cued high LV condition, participants were required to take in a deep breath before saying /a/. Cued habitual LV condition was achieved by instructing participants to "take in a normal breath" before saying /a/. A second habitual condition was included for all participants to function as a washout between experimental phases. In the resting expiratory level (REL) condition, participants were instructed to take in a breath and do a relaxed sigh before saying /a/. These were thereafter referred to in text as cued habitual, high, habitual washout and REL LV conditions. A relaxed sigh was prompted for participants to reach REL, the LV space where the tidal breathing ends, approximately 40% of the VC [3, 41]. This was consistent with previous studies on LV and phonation [3, 41]. Prior to each trial, participants were provided time to practice with the breathing instructions. Modeling was provided to ensure participants followed and performed the instructions correctly.

2.4 Procedures

Participants were allocated into two groups (Group A or B) through non-randomized sequential allocation on enrollment. They were instructed to produce the vowel /a/ on 3 successive phonations for 3 s each on 3 separate trials for each breathing instruction. No cues or modeling for pitch and volume were provided. Participants in Group A completed the tasks in the sequence of habitual—high—habitual—REL, while participants in Group B completed the tasks in the order of habitual—REL—habitual—high LVs. During data recording, the digital output from EGG and Respitrace (i.e., displacements of ribcage and abdomen) was displayed on a monitor screen and was observed at the time of data collection to ensure that breathing instructions were followed appropriately to prevent any vocalization prior to the start of the task.

2.5 Closed Quotient, F_0, and Relative Vocal Intensity Measurement

The EGG signal was exported from LabChart and analyzed using Phasecomp V.1.3.8 [42]. The first /a/ of each trial was used for analysis. A high-pass filter of 40 Hz was applied to remove any background noise interfering with CQ calculation. The CQ was calculated on a cycle-by-cycle basis using criterion-level method of 25% [23]. Five cycles (each occurring five cycles apart) were selected from each trial sample and the selection of glottal cycles began after 10 complete glottal cycles. Average CQ and F_0 for each sample trial were obtained. Relative vocal intensity was analyzed using Praat 5.4.08 [43]. Absolute intensity was not used, as the head-mounted microphone was not calibrated across participants.

2.6 Statistical Analysis

Statistical analyses were conducted using IBM SPSS Statistics (V 23.0, SPSS, Inc., Chicago, IL, USA). Mean and SD of CQ, F_0 and vocal intensity were computed. Repeated-measures analysis of variance (ANOVA) and paired t test were used to compare the differences in CQ, F_0 and vocal intensity separately across different breathing instructions. Effect size was measured using partial eta squared. Pearson's correlation coefficient (r) was used to examine relation between CQ, F_0, vocal intensity and age.

Ten percent of the samples were re-analyzed to determine the inter-judge reliability and intra-judge reliability for CQ, F_0 and relative vocal intensity measurements. Inter-judge reliability was performed by a trained undergraduate student, while the first author performed intra-judge reliability with a two-week lapse between the first and second analysis. Inter-judge and intra-judge reliability were measured by intraclass correlation coefficients (ICC) [44]. The ICC was calculated using a two-way mixed model, consistency type, and single measure analysis [ICC (3,1)]. To assess the level of correlation, ICC < 0.5 indicates poor correlation, 0.5–0.75 moderate, 0.75–0.9 good, and > 0.9 excellent correlation [45].

3 Results

There were excellent inter-judge reliability (CQ: ICC = 0. 988, $p < 0.001$; F_0: ICC = 0.977, $p < 0.001$; relative vocal intensity: ICC = 0.908, $p < 0.01$) and excellent intra-judge reliability (CQ: ICC = 0. 997, $p < 0.001$; F_0: ICC = 0.997, $p < 0.001$; relative vocal intensity: ICC = 0.957, $p < 0.01$).

3.1 Effects of LV Conditions on CQ, F_0 and Vocal Intensity

Means, standard deviation and range of CQ, F_0 and relative vocal intensity in each LV condition are presented in Table 1. Figures 1, 2 and 3 show the distribution of CQ, F_0 and relative vocal intensity across LV conditions.

3.1.1 Closed Quotient

Repeated-measures ANOVA revealed no statistically significant main effects of LV conditions on CQ ($F = 1.901$, $p = 0.175$, partial $\eta^2 = 0.043$). Closed quotient was the highest in the high LV condition and lowest in the REL (Table 1). In the habitual condition, CQ was higher than that in the REL but lower than in the high LV (Figs. 2, 3 and 4). There were significant overlaps in CQ range across conditions (Table 1).

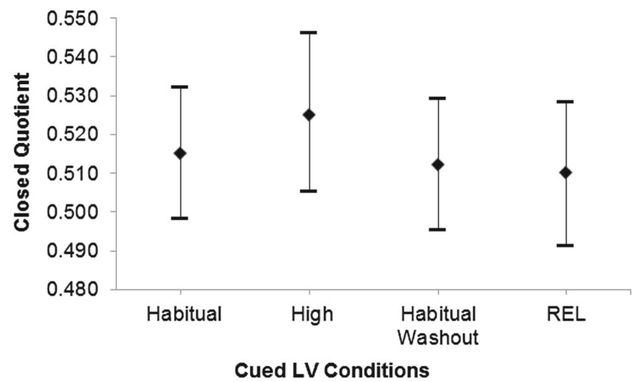

Fig. 2 Closed quotient across different lung volume conditions (indicators for lower confidence interval, mean and upper confidence interval)

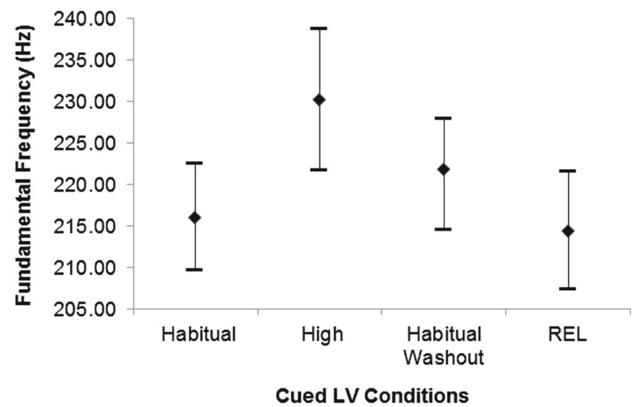

Fig. 3 Fundamental frequency across lung volume conditions (indicators for lower confidence interval, mean and upper confidence interval)

3.1.2 Fundamental Frequency

Significant main effects of LV conditions were observed for F_0 ($F = 5.685$, $p = 0.022$, partial $\eta^2 = 0.119$). There was considerable variability in F_0 across conditions. Paired t-tests revealed a statistically significant difference in F_0 (16 Hz) between the high and REL conditions ($p < 0.001$) and between the habitual and high LV conditions ($p < 0.001$). It was the lowest in the REL condition and increased significantly in higher LV (Table 1 and Figs. 2, 3 and 4). There was no significant difference in F_0 between the habitual and REL conditions ($p = 0.384$).

3.1.3 Relative Vocal Intensity

Significant main effects of LV conditions were observed for relative vocal intensity ($F = 42.417$, $p < 0.001$, partial $\eta^2 =$

Table 1 Means, (Standard Deviation, SD) and [Range] for Closed Quotient, F_0 (in Hertz) and Relative Vocal Intensity (in dB) across different lung volume conditions

Lung volume conditions	Closed quotient	F_0 (Hz)	Relative vocal intensity (dB)
Habitual	0.515 (0.06) [.407–.655]	215.98 (20.75) [164.80–260.63]	56.51 (3.39) [47.21–62.79]
High	0.525 (0.07)c [.345–.654]	230.10 (27.72) [170.31–291.84]	59.25 (3.42) [48.62–67.20]
Habitual washout	0.512 (0.06) [.386–.642]	221.76 (21.76) [164.37–260.65]	57.14 (3.60) [47.55–64.99]
REL	0.510 (0.06) [.392–.625]	214.35 (23.02) [158.22–262.81]	55.54 (3.43) [46.67–65.14]

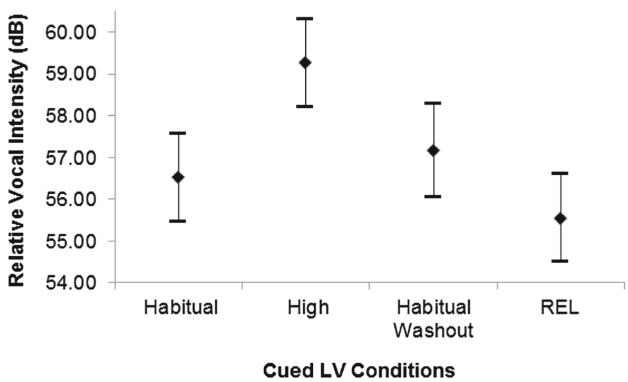

Fig. 4 Relative vocal intensity across lung volume conditions (indicators for lower confidence interval, mean and upper confidence interval)

0.502). This measure was the lowest in the REL, was higher in the habitual than in the REL, and was highest in the high LV condition (Table 1 and Figs. 2, 3 and 4). There were statistically significant differences in vocal intensity between the high and REL ($t = 12.665, p < 0.001$), between the habitual and high ($t = -9.852$, $p < 0.001$), and between the habitual and REL conditions ($t = 3.843$, $p < 0.001$).

3.2 Correlation Between CQ, F_0, and Relative Vocal Intensity

Table 2 presents the correlation between CQ, F_0, and relative vocal intensity. No correlation was observed between CQ and F_0, CQ and vocal intensity, and between F_0 and vocal intensity across all LV conditions. The order of the sequence (Group A vs. Group B) had no significant effects on the mean CQ ($F = 0.056$, $p = 0.814$), the mean F_0 ($F = 2.879$, $p = 0.098$) and the mean relative vocal intensity ($F = 7.860$, $p = 0.078$).

4 Discussion

The present study found significant main effects of LV for F_0 and relative vocal intensity but not for CQ. The average

Table 2 Correlation between CQ, F_0, and relative vocal intensity across LV conditions

Conditions	Parameters	F_0	Intensity
Habitual	CQ	0.219	− 0.152
	F_0	1	0.089
	Intensity	0.089	1
High	CQ	0.196	− 0.020
	F_0	1	0.179
	Intensity	0.179	1
Habitual washout	CQ	0.237	0.000
	F_0	1	0.027
	Intensity	0.027	1
REL	CQ	0.030	0.066
	F_0	1	0.114
	Intensity	0.114	1

range of CQ across all LV conditions (0.510 - 0.525) in the study suggested all participants phonated in a similar register, which was the modal register (mean = 0.52, SD = 0.07) based on existing literature [23, 26].

4.1 Effects of Lung Volume on CQ

This study found no significant differences in CQ across all the LV conditions. However, there was a trend for CQ to increase in high LV (Fig. 2). This was not consistent with Iwarsson et al's findings that CQ decreased with an increase in LV [3, 41]. Two possibilities may explain for this. Firstly, phonatory task might be a factor that affects the response of the vocal folds to changes in LV. The effects of LV on glottal closure could be less pronounced in a vowel in isolation than in a vowel following an aspirated stop like /p/ due to the contextual effects of the aspirated consonant on the adjacent vowel which may change the glottal closure pattern in that vowel [46]. In Iwarsson et al's studies, the voiceless consonant /p/ that precedes the vowel is likely to have promoted glottal abduction prior to the vocal fold vibration [3, 41, 47]. With a voiceless aspirated stop consonant, greater abductory force may be expected during the aspiration and before phonation of the vowel [48–50]. This leads to a delay in voice onset, resulting in an increased voice onset time (VOT) and reduced CQ [51, 52]. By contrast, the present study used the vowel /a/ without a preceding consonant as the phonatory task. The voice onset of a vowel in modal voice quality has been associated with a glottal onset [16]. A glottal onset is described as closure of the vocal folds prior to vibration of the vocal folds [16, 53]. During the production of vowel in isolation, the vocal folds may approximate more quickly, leading to a longer closed phase [54] that is less affected by LV changes. Closure of the true vocal folds requires activation of the thyroarytenoid muscle which has been correlated with greater adduction force [55]. Further research is needed to investigate the changes in voice source parameters in different consonant–vowel combinations in different LV conditions.

Secondly, the trend for a higher CQ in the high LV condition may have also resulted from the "intensity effects" associated with high LV as observed by Stathopoulos and Sapienza in vocally untrained subjects [30]. These authors found that high LV was associated with high vocal intensity, decreased open quotient, and greater laryngeal airway resistance. As vocal intensity increases, an increment in both the activity of the vocal fold adductors and the abductory force associated with greater Bernoulli effect may occur [30, 56]. The decreased open quotient (i.e., longer closed time) observed by Stathopoulos and Sapienza was significant when compared between comfortable and loud intensity in females and between soft and comfortable intensity in males [30]. In the present study, relative intensity was higher for high LV, which is consistent with the findings of Stathopoulos and Sapienza's study [30], i.e., the participants may have used an increased glottal closure for the high intensity at the high LV. Using an increased glottal adduction to obtain a high vocal intensity is a well-known phenomenon [57, 58]. According to Sundberg [59], vocal intensity is determined by the amplitude of the negative peak of the differentiated airflow and increasing the CQ is one of the ways to increase this amplitude.

In addition, gender may also be a factor that contributes to the trend for CQ to rise in high LV in this study. This study used all females. Previous research [60] in vocally untrained speakers has found that vocal attack time (VAT) in sustained /a/ phonation was significantly shorter for females than for males. Gender effects may also explain the inconsistency in CQ findings between this study and Iwarsson, Thomasson, and Sundberg's study in which CQ data were averaged across two genders (18 males and 14 females) [3].

The wide range of CQ observed in all cued LV conditions implies a greater variability of responses in individuals at the cued high LV condition. This was expected as differences in responses to identical breathing instructions have been documented previously [7]. The increased variability also suggests a heightened difficulty in stabilizing vocal fold closure and subsequent vocal fold vibration at higher LV.

Despite visual monitoring of breathing behaviors through ribcage and abdominal displacements, participants in this study may not have initiated phonation at similar LV when provided the same instruction. The difference in the actual LV used for phonation could potentially account for the variability in the results. In the present study, as CQ was analyzed based on the instructions provided rather than the absolute LV measurements, an overlap in the LV used for phonation across the instructions was expected. This potentially led to the wide range of CQ observed across all instructions as documented in Fig. 1, especially at high LV condition. Variability can also be contributed by the change in participants' attention, cognitive load, or posture, which led to changes in breathing pattern such as increased breathing duration [61, 62]. In addition, the challenge in regulating higher subglottic pressure could have played a role in the variability observed [63].

The threshold level used for the criterion-level method applied in this study is another factor that could influence CQ results. Different threshold levels, ranging between 20% and 50%, have been used in the past [23]. Rothenberg (1988), who proposed the criterion-level method, concluded that a threshold level of 35% was ideal for achieving consistent glottal cycles in normal, breathy, and tightly adducted voices [64]. However, as recommended by previous studies, a criterion-level of 25% was used in this study [23, 26]. This choice could have affected the CQ results in this study as CQ was previously reported to decrease with an increasing threshold level [26]. It would therefore be noteworthy to investigate how the different measures of CQ could affect CQ in the production of the vowel in this study.

4.2 Effects of LV on F_0 and Intensity

This study found a greater F_0 and relative vocal intensity in the high LV condition, which was consistent with the findings from previous studies [4, 41, 65, 66]. Two possibilities could be used to explain this finding. Firstly, the increased F_0 at the cued high LV condition may be related to tracheal pull [4, 41, 65, 66], a phenomenon in which the descending expansion of the lungs pulls the tracheobronchial tree downwards, resulting in a greater abductory force on the glottis and resultant lengthening of the true vocal folds. Iwarsson and Sundberg [5] have demonstrated that high LVs are associated with a lower larynx vertical position than low LVs. Tracheal pull results in changes in the larynx configuration, thereby increasing the vertical tension of the vocal fold and the vocal fold length, resulting in a raised F_0 [4, 6, 67]. Secondly, the increased F_0 in high LV condition may also result from the increased subglottal pressure (Ps). In vocally untrained speakers, Iwarsson, Thomasson, and Sundberg [3] found higher Ps in high compared to low LV. Titze [68] demonstrated that in the chest (modal) register, F_0 increased as Ps increased as a result of the amplitude-frequency dependence. In this study, vocal intensity was increased, suggesting a possible increase in Ps as it is one of the most important factors that control vocal intensity [69, 70].

Contrary to the high LV condition, lower F_0 and relative vocal intensity were observed at the cued REL condition. This can be explained by the reduced tracheal pull at lower LV [3, 41]. The maximum mean difference in F_0 between the cued high and REL LV conditions was 16 Hz (approximately 1.2 semitones). This may be detectable by many listeners; however, it did not lead to a change in vocal register as inferred from CQ. A change in F_0 within the same register was also observed. Thus, we concluded that breathing instructions were effective in changing F_0 but may not be sufficient enough to cause a change in vocal register when producing a vowel.

Similarly, lower relative vocal intensity was documented at the cued REL condition. However, despite a statistically significant difference in relative vocal intensity across different conditions, it is notable that the maximal difference in the relative vocal intensity recorded was 4 dB, as documented between the cued high and low LV conditions. This may be detectable by many listeners in a quiet acoustic environment [71, 72]. Therefore, while breathing instructions had a statistically significant impact on the relative vocal intensity, it is likely to have only a perceptually small effect.

4.3 Correlation Between CQ, F_0 and Relative Vocal Intensity

The absence of correlation between F_0, relative vocal intensity and CQ confirmed that the criterion-level method of 25% was not influenced by F_0 and vocal intensity [26]. Despite that, an increasing trend in CQ with F_0 and relative vocal intensity was noted, which was consistent with finding in previous studies [29, 30, 73].

4.4 Limitations and Future Directions

There were a number of limitations in this study. Firstly, there are many factors that affect breathing behaviors. Individuals given the same set of breathing instructions have been observed to respond differently, hence varying the outcomes [7]. Physical and anticipatory changes such as cognitive load, attention and postural changes, can also affect breathing patterns [74, 75], and these were not controlled here. Cognitively demanding conditions have been found to induce an increase in speech pauses with longer duration while increased attention on breathing led to the lengthening of inhalation and exhalation duration [61, 62]. Physical changes such as postural adjustments can also affect speech breathing [76]. These factors all contribute to the variability in responses to the breathing instructions across individuals and thus affect the resultant vocal quality.

Secondly, CQ reveals the duration of vocal fold closure and not the amount of vocal fold contact. Therefore, the use of CQ as a measure of vocal fold closure does not provide information on how much contact exists along the length or width of the vocal folds during phonation. This would require further investigation using other methods, e.g., laryngeal imaging to view the full length of the vocal folds.

Thirdly, this study did not collect glottal airflow data. Using inverse filtering to obtained a flow glottogram would achieve valuable information regarding the patterns of transglottal airflow over time corresponding to changes in LV conditions. This would give more insight into the interaction between the larynx and breathing during phonation in untrained speakers. Glottal airflow data should be collected in any future studies.

Finally, application of these results to singing and spontaneous speech is limited as results were based on the prolongation of a vowel in a training context. Thus, further investigation is required to determine its applicability in singing and spontaneous speech.

Future studies may include different phonatory tasks such as /pa:/ to mark a comparison to previous studies to investigate the effects of task on CQ. Correlation between CQ and perceptual judgment of the type of vocal register should also be investigated to look at the reliability of CQ in determining vocal registers as perceived aurally. Future studies should also include absolute LV measurements to help validate and assess the range of LV used under each breathing instruction. This could provide more details to investigate the effectiveness of breathing instructions in cueing various LV conditions and to discuss the variability between individuals, thus establishing the link between LV and CQ in the production of a vowel.

5 Conclusion

Cued LV conditions had no significant impact on CQ but significantly influenced F_0 and relative vocal intensity. This is most likely the result of the choice of phonatory task. Within the same vocal register, an increasing trend of CQ was noted with increment in both F_0 and relative vocal intensity at high LV condition, which affirmed previous findings [29, 30]. This study therefore suggests a potential use of breathing instructions in cueing pitch and loudness.

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