JASA EXPRESS LETTERS

https://doi.org/10.1121/10.0001446

Ambulatory monitoring of Lombard-related vocal characteristics in vocally healthy female speakers[a)]

Thomas H. Whittico,[b)] Andrew J. Ortiz, Katherine L. Marks,[b)] Laura E. Toles,[b)] Jarrad H. Van Stan,[b)] Robert E. Hillman,[b)] and Daryush D. Mehta[b)]

Center for Laryngeal Surgery and Voice Rehabilitation, Massachusetts General Hospital, Boston, Massachusetts 02114, USA

thwhittico@gmail.com, aortiz15@mgh.harvard.edu, kmarks@mghihp.edu, ltoles@mghihp.edu, jvanstan@mghihp.edu, hillman.robert@mgh.harvard.edu, mehta.daryush@mgh.harvard.edu

Abstract: Speakers typically modify their voice in the presence of increased background noise levels, exhibiting the classic Lombard effect. Lombard-related characteristics during everyday activities were recorded from 17 vocally healthy women who wore an acoustic noise dosimeter and ambulatory voice monitor. The linear relationship between vocal sound pressure level and environmental noise level exhibited an average slope of 0.54 dB/dB and value of 72.8 dB SPL at 50 dBA when correlation coefficients were greater than 0.4. These results, coupled with analyses of spectral and cepstral vocal function measures, provide normative ambulatory Lombard characteristics for comparison with patients with voice-use related disorders.

[Editor: Anders Lofqvist] Pages: EL552–EL558

Received: 21 April 2020 **Accepted:** 1 June 2020 **Published Online:** 24 June 2020

1. Introduction

It has been well established that speakers tend to modify their voice production characteristics in the presence of increased background noise levels, thus exhibiting the classic Lombard effect.[1–3] The Lombard effect (or Lombard response) typically refers to an involuntary increase in vocal intensity in loud environments but has been associated more broadly with other voice and speech modifications, including increased fundamental frequency,[4] increased spectral energy in higher frequencies,[5] and an increased degree of hyperarticulation.[6] Speakers have even been shown to exhibit the Lombard effect despite being educated about the effect and given explicit instruction to suppress their typical response to increases in background noise levels.[7] Factors that play a role in modulating the Lombard effect include the degree of hearing loss of the speaker,[3] type of background noise (spectral energy distributions, babble noise, stationary noise, etc.),[5] presence of a communicative partner,[3,8] and distance between the speaker and listener(s).[9,10]

Investigators often quantify the Lombard effect in terms of a linear correlation between the changes in a speaker's acoustic voice characteristics and concomitant changes in the background noise level (played to the speaker through headphones so as not to corrupt the measurement of acoustic voice features). The typical slope of the resulting regression line between vocal sound pressure level (SPL) and background noise levels has been observed to be in the range of 0.3–1 dB/dB;[3,4,8,9,11–15] i.e., a speaker's vocal SPL behavior can reach up to a one-to-one intensity ratio to compensate for increases in background levels. Some studies theorize that a compensatory ratio of 0.5 dB/dB can be explained due to the boost in self-perception of voice by both air and bone conduction pathways. The starting point of the Lombard effect—the background noise level above which vocal SPL starts to increase—has been measured in the range of 46–57 dBA.[9,16,17] When an individual's change in vocal fundamental frequency (f_o) is compared with environmental noise levels, the slope of the resulting regression line exhibits a rate of approximately 1 Hz/dB.[4] Of note, studies reporting slopes often do not report the statistical correlation of the underlying regression line (with exceptions[18]). Most studies have assessed the Lombard effect in laboratory conditions during which the level of background noise is artificially controlled. However, the establishment of baseline Lombard-related characteristics for typical vocal behavior would be enhanced by the ability to continuously measure vocal function measures as

[a)]Portions of this work were presented at the 6th Occupational Voice Symposium, London, UK, March 2019 and in the master's dissertation of T.H.W.

[b)]Also at: Massachusetts General Hospital Institute of Health Professions, Boston, Massachusetts 02114, USA. ORCID: 0000-0002-6535-573X.

https://doi.org/10.1121/10.0001446

individuals go about their normal daily activities in environments with naturally occurring changes in loudness levels.

The purpose of the current study was to determine daylong Lombard-related characteristics exhibited by vocally healthy women. Traditional voice measures of SPL and f_o were computed over the course of a day using a neck-surface accelerometer sensor that is robust to acoustic noise and has been used extensively in ambulatory voice monitoring studies.[19–22] Two additional measures of vocal function were derived from the accelerometer signal: cepstral peak prominence (CPP) and the difference between the log-magnitude of the first two spectral harmonic levels (L_1–L_2). Accelerometer-based CPP and L_1–L_2 have been shown to correlate highly with respective measures derived from acoustic[23] and aerodynamic[24] voice signals and can be interpreted to reflect underlying voice production mechanisms related to signal periodicity and glottal closure patterns.

2. Methods

The study sample consisted of 17 adult female speakers with no history of voice disorders. The healthy vocal status of the subjects was confirmed based on criteria of no history of or current voice difficulty, a typical voice quality, and a normal laryngeal endoscopic evaluation as administered by a clinician. All subjects passed a pure-tone hearing screening, which consisted of positive responses to air-conduction stimuli in both ears at 25 dB HL (hearing level) at 500, 1000, and 2000 Hz. The mean (standard deviation, SD) age of the participants was 27.5 (10.8) years, with a range of 19–55 years. Ten of the subjects were students majoring in vocal performance; the occupations of the remaining seven subjects were voice teacher, nurse, restaurant server, physical therapist, graphic designer, hospice chaplain, and stay-at-home parent.

Subjects were instructed to wear two ambulatory monitoring devices for estimating vocal features and environmental noise level, respectively, during waking days. As in previous work,[19] a uniaxial accelerometer sensor (BU-27135, Knowles Electronics, Itasca, IL) was affixed to the anterior neck-skin surface of the subject and wired to a Google/Samsung Nexus S smartphone, which recorded the accelerometer signal at a sampling rate of 11.025 kHz (16-bit quantization). At the beginning of each day, participants recorded an /a/ vowel from a loud-to-soft level while holding a microphone (H1 Handy Recorder, Zoom Corporation, Tokyo, Japan) 15 cm from the lips. Thus, accelerometer-based SPL was obtained by applying the regression line mapping accelerometer signal magnitude (in dB) to acoustic SPL (in dB SPL at 15 cm).[25] A Spark 705 P personal noise exposure meter (Larson Davis, Depew, NY) was provided to record environmental noise levels using an omnidirectional microphone with a flat frequency response ($\pm$0.2 dB) over a 20 Hz–20 kHz range. The microphone was covered with a windscreen and clipped on one of the subject's shoulders near the ear.

The accelerometer signal and microphone noise levels were analyzed using two temporal levels of data processing: (1) short-duration frames for computing voice features and environmental noise levels and (2) longer-duration windows for computing average statistics of each feature. At the frame level, voice activity detection was applied to the accelerometer signal as documented in prior work to detect voicing in 50 ms, non-overlapping frames.[26] Following previously established algorithms,[27] four vocal features were computed for each voiced frame: SPL (dB SPL at 15 cm), f_o (Hz), CPP (dB), and L_1–L_2 (dB). Environmental noise levels were recorded by the noise exposure meter over 1 s, non-overlapping frames to yield measures of equivalent sound pressure level (L_{eq}) in units of A-weighted decibels (dBA). Since the noise exposure meter captured both environmental and speech acoustics, synchronization of the vocal features and L_{eq} data from the two monitoring devices could be achieved by maximizing the cross-correlation between accelerometer-based voice SPL and the L_{eq} time series during a series of three sustained vowels and standard reading passage (Rainbow passage) produced at the beginning of the day by the subject. Subsequently, L_{eq} values were masked out during frames when subjects produced speech phrases to capture environment-only noise levels. Speech phrases were defined as contiguous voiced frames concatenated with neighboring unvoiced segments less than 0.5 s in duration.[26]

At the longer-duration window level, the frame-based voice features and environmental L_{eq} values were averaged over 30 s, non-overlapping windows. The following statistical features of central tendency were computed for all windows containing at least 150 ms of voicing (0.5% phonation time): median voice SPL, median voice f_o, median voice CPP, median voice L_1–L_2, and median environmental L_{eq}. Figure 1 illustrates daylong histograms and regression lines for one subject relating each of the four vocal function measures to environmental L_{eq}. The regression lines were assessed using Pearson's correlation coefficient (r), slope, and value at median L_{eq} values of 50 dBA (a quiet environmental L_{eq}). These three Lombard-related characteristics were computed for each vocal function measure for each day a subject was monitored.

https://doi.org/10.1121/10.0001446

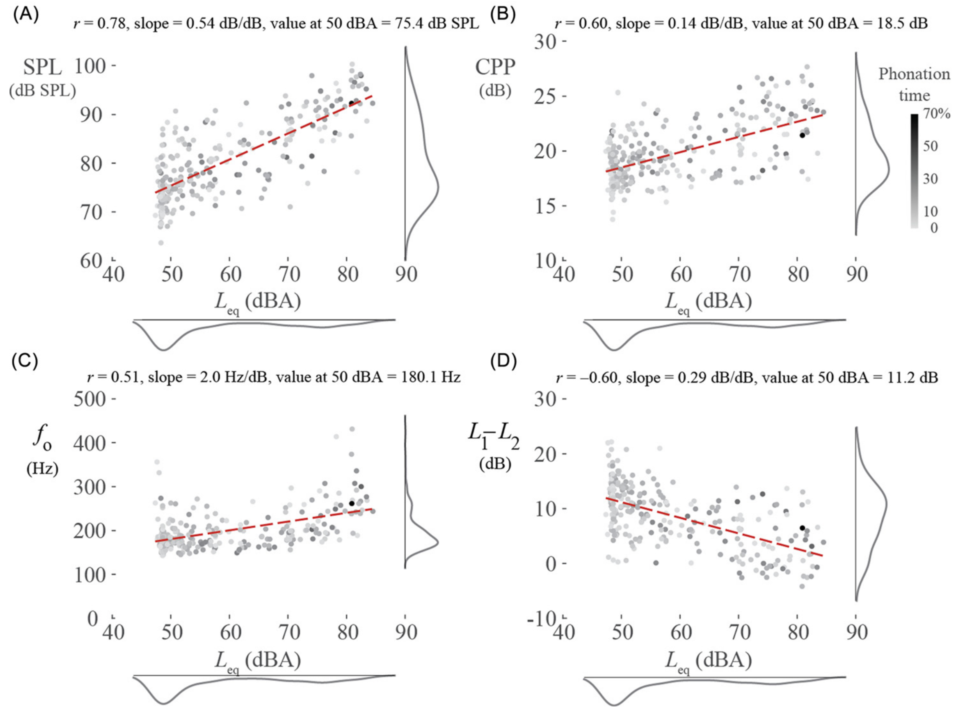

Fig. 1. (Color online) Example of four scatter plots and marginal distributions depicting the relationship between equivalent environmental noise level (L_{eq}) and the four Lombard-related vocal function measures of (A) sound pressure level (SPL), (B) cepstral peak prominence (CPP), (C) fundamental frequency (f_o), and (D) the difference between the first two harmonic levels (L_1–L_2). Pearson's correlation coefficient (r), regression line slope, and regression value at 50 dBA are shown. Markers are shaded accorded to phonation time within each 30 s window.

3. Results

Ambulatory monitoring data with the ambulatory voice monitor and acoustic noise exposure meter were available for two to four days per subject with a mean (SD, range) recording time per day of 11.9 (2.0, 7.9–16.2) hours. The percent phonation time, on average, was 6.3% (3.3 percentage points, 0.8%–12.0%). These phonation time statistics are reported to provide as reference for the current study sample and for comparison with other studies that report various phonation times depending on occupational and social context.[26,28,29] As an overview of average environmental noise levels across all days, the median L_{eq} was 58.3 (5.0, 48.6–69.0) dBA, and the average 95th percentile L_{eq} was 77.3 (5.8, 58.6–90.1) dBA. In terms of data support for the Lombard analysis, the average daily number of 30 s windows with at least 0.5% was 546 (243, 67–1159).

Figure 2 displays the correlation coefficients for all monitored days organized by subject identifier. As expected, the vocal feature exhibiting the strongest daylong Lombard effect—i.e., the maximum absolute correlation with median L_{eq}—was voice SPL [$r(266) = 0.78$, $p < 0.001$], followed by CPP [$r(544) = 0.74$, $p < 0.001$], L_1–L_2 [$r(457) = 0.63$, $p < 0.001$], and f_o [$r(266) = 0.51$, $p < 0.001$]. As an initial value to aid in quantifying the prevalence of significant Lombard-related effects, days exhibiting absolute correlation coefficients of at least 0.4 (medium effect size) were counted. For the voice SPL–L_{eq} relationship, 14 out of the 17 subjects (25 of the 48 total days) exhibited such a correlation ($r > 0.4$) during at least one day. For the CPP–L_{eq} relationship, 12 subjects (20 days) exhibited a significant effect. Eight subjects (11 days) exhibited a significant relationship between L_1–L_2 and L_{eq}, and only two subjects (two days) exhibited a significant f_o–L_{eq} relationship.

Figure 3 displays the regression-line slope for each subject's monitored day. When a significant Lombard-related effect was exhibited ($r > 0.4$), the mean slope relating each median vocal feature to median L_{eq} was computed to be 0.55 dB/dB for voice SPL, 0.19 dB/dB for CPP, –0.27 dB/dB for L_1–L_2, and 2.8 Hz/dB for f_o. Positive or negative slopes indicate the directionality of the rate of change of the respective vocal feature with respect to increases in background noise levels. In particular, the negative slope for L_1–L_2 is expected because decreases in L_1–L_2 are known to correlate with increases in vocal intensity.[24,30]

Figure 4 displays the value of the regression lines for each subject's monitored day at a median L_{eq} of 50 dBA. When a significant Lombard-related effect was exhibited ($r > 0.4$), the mean value at 50 dBA was computed to be 72.8 dB SPL for SPL, 18.7 dB for CPP, 10.1 dB for

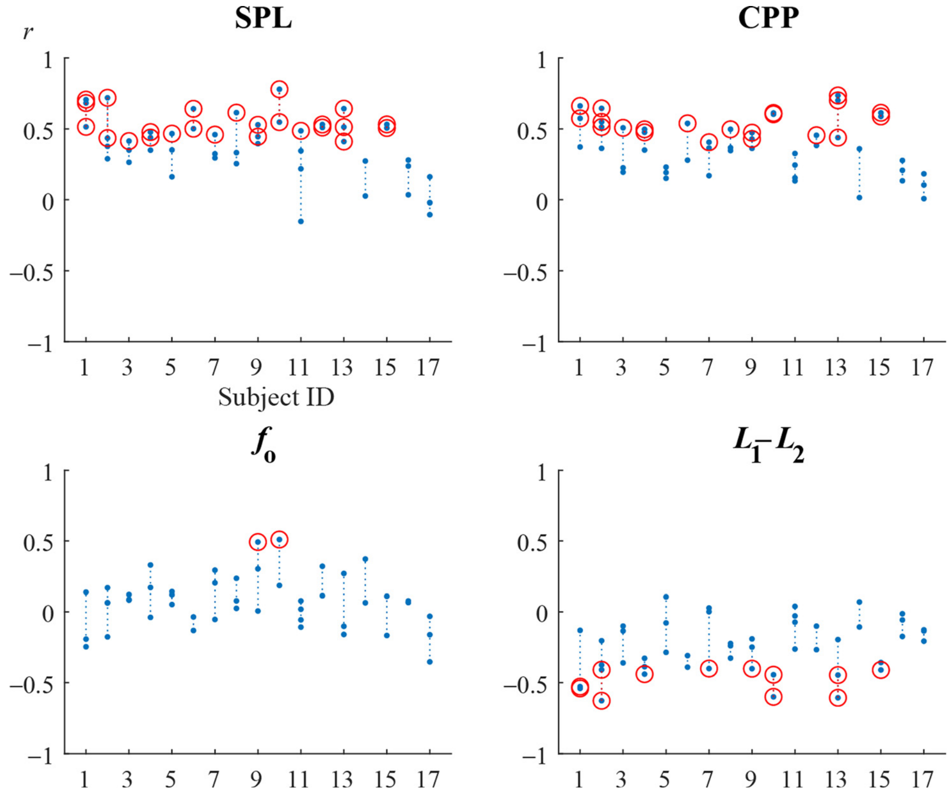

Fig. 2. (Color online) Per-day correlation coefficient (r) between the four Lombard-related vocal function measures (SPL, f_o, CPP, and L_1–L_2) and environmental noise level. Days with $r > 0.4$ are circled. Vertical dotted lines connect minimum and maximum values per subject for visualization purposes.

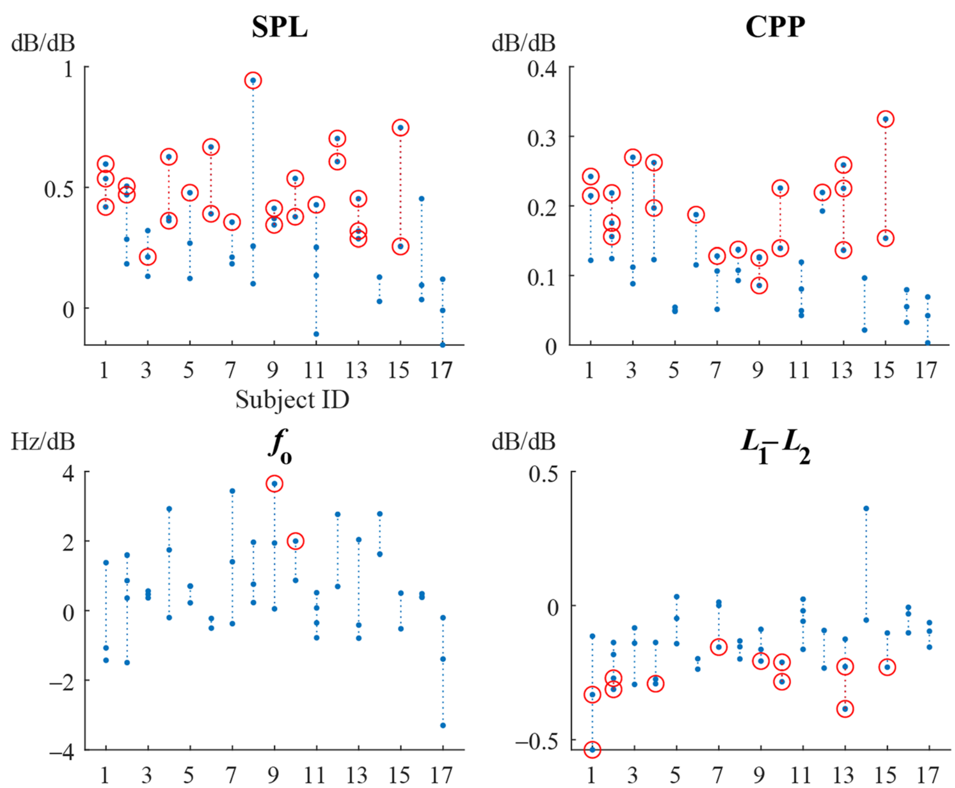

Fig. 3. (Color online) Per-day slope of the regression line between the four Lombard-related vocal function measures (SPL, f_o, CPP, and L_1–L_2) and environmental noise level. Days with $r > 0.4$ are circled.

JASA EXPRESS LETTERS

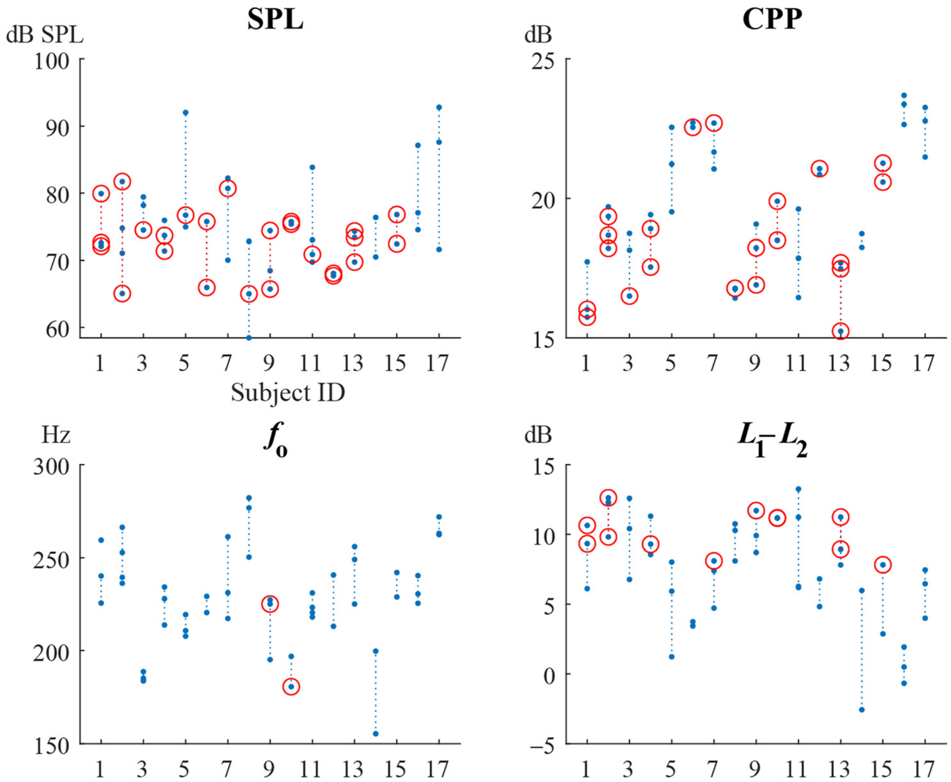

Fig. 4. (Color online) Per-day values at 50 dBA for the four Lombard-related vocal function measures (SPL, f_o, CPP, and L_1–L_2) and environmental noise level. Days with $r > 0.4$ are circled.

L_1–L_2, and 202.8 Hz for f_o. These vocal features can be considered voice characteristics produced in quiet, indoor environments. The regression lines can then be used to predict voice characteristics exhibited by the subjects in progressively louder settings. Table 1 displays the average vocal characteristics one would expect from individuals exhibiting the Lombard effect in soft, moderate, and loud ambulatory settings.

4. Discussion

The Lombard effect has been typically studied in controlled laboratory settings that playback pre-defined sound stimuli in the background as individuals speak. A few studies have attempted to characterize Lombard-related characteristics in naturalistic environments using ambulatory voice and ambient sound monitoring using the previously commercially available VoxLog device (Sonvox AB, Umeå, Sweden).[18,31,32] One such study found that preschool teachers varied widely in how they adjusted their vocal SPL and f_o in the context of naturally occurring changes in classroom noise levels.[31] Pearson's correlation coefficients ranged from 0.07 to 0.87 when relating average values of vocal SPL to average environmental SPL computed over three-minute, non-overlapping windows. The correlation coefficients between average values of their vocal f_o and environmental SPL were also highly individualized, ranging from 0.11 to 0.78. In the current study, the voice SPL–L_{eq} correlation coefficient was greater than 0.4 for over half of the monitored days and varied overall from −0.15 to 0.78; in contrast, the f_o–L_{eq} correlation was much less strong, with only two subjects exhibiting correlation coefficients greater than 0.4. To further quantify physiological voice mechanisms in addition to the traditional measures of SPL and f_o, CPP and L_1–L_2 were computed from the neck-surface vibration signal to reflect underlying

Table 1. Predicted average Lombard-related vocal characteristics based on subjects exhibiting significant correlations ($r > 0.4$) with everyday environmental noise levels.

Environmental level	SPL (dB SPL)	CPP (dB)	f_o (Hz)	L_1–L_2 (dB)
Soft (50 dBA)	72.8	18.7	202.8	10.1
Moderate (65 dBA)	79.9	21.6	245.2	6.1
Loud (80 dBA)	87.1	24.4	287.5	2.2

https://doi.org/10.1121/10.0001446

harmonics-to-noise and glottal closure phenomena during phonation. Results indicate that these voice quality–related measures can also vary in a systematic manner across a day of monitoring; the extent to which CPP and L_1–L_2 correlate with environmental noise levels may provide insights into whether an individual is modulating vocal loudness in ways that are more likely to maintain or negatively impact vocal health (i.e., the potential for phonotrauma).

One application of the normative data in the current study is the evaluation of the Lombard effect in speakers with voice disorders who are hypothesized to exhibit particularly adverse vocal behaviors in acoustically challenging environments. Szabo Portela *et al.*[32] found that, overall, individuals diagnosed with phonotrauma (and their matched healthy controls) experienced higher environmental noise levels in their daily life than individuals diagnosed with a functional voice disorder marked by vocal fatigue (and their matched healthy controls). In that study, an approach was taken to first categorize L_{eq} values in three distinct bins: low ($\leq$55 dBA), moderate (55–70 dBA), and loud ($>$70 dBA) environmental noise levels. On a group basis, all patients and their matched controls exhibited an increase in voice SPL and f_o across these three bins; however, no between-group differences existed in the manner in which this Lombard effect was produced. It is hypothesized that adding measures such as CPP and L_1–L_2 will aid in additional characterization of Lombard-related phonatory adjustments that may be associated with different types of voice disorders. Any clinical implications of the Lombard effect would benefit from approaches that account for any inherent correlations, e.g., between voice SPL and CPP, through partial correlation analysis, etc.

Anecdotally, some of the louder environments experienced by individuals in the current study were due to being outdoors, at a live music venue, at a restaurant/bar, or indoors with music being played through free-field speakers. A limitation of this study is not knowing the exact environment where someone is speaking, the distance to a listener, or the acoustic spectrum of the background noise. Although the A-weighting of the noise dosimeter filtered out spectral energy that would not be audible by the speaker, measuring additional properties of the environmental acoustics (such as spectral distributions[5] and time-varying dynamics) could aid in pinpointing how and why individuals react to background noise levels. Additional methods to characterize both environmental acoustics and vocal behavior may include the detection of singing periods (especially for vocal performers)[33] and the computation of higher-order statistics of the distribution of measures over a given window, such as the standard deviation, skewness, kurtosis, etc. (versus simply median statistics, as in this study).

5. Conclusion

In individuals with healthy vocal function, the Lombard effect was observed to a moderate degree as individuals interacted with typical noise levels in their naturalistic environments. The vocal feature with the highest correlation with environmental noise level was SPL, followed by CPP, L_1–L_2, and f_o. The average regression line slope for SPL was 0.54 dB/dB, which agrees with laboratory studies and expected compensatory mechanisms due to self-perception of voice. The average slope for L_1–L_2 was inversely proportional to that of CPP, whereas the f_o relationship was highly variable. The average value of median SPL at a 50 dBA environmental noise level was 72.8 dB SPL. These normative results provide an important point of reference for investigating the vocal behavior of patients with disorders that are related to voice use (e.g., phonotraumatic vocal hyperfunction).

Acknowledgments

This work was supported by the National Institutes of Health (NIH) National Institute on Deafness and Other Communication Disorders (NIDCD) under Grant No. P50 DC015446. The article's contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH. R.E.H. has a financial interest in InnoVoyce LLC, a company focused on developing and commercializing technologies for the prevention, diagnosis, and treatment of voice-related disorders. R.E.H.'s interests were reviewed and are managed by Massachusetts General Hospital and Partners HealthCare in accordance with their conflict of interest policies.

References and links

[1]E. Lombard, "Le signe de l'élévation de la voix" ("The sign of the elevation of the voice"), Ann. Otolaryngol. **37**, 101–119 (1911).

[2]S. A. Zollinger and H. Brumm, "The Lombard effect," Curr. Biol. **21**, R614–R615 (2011).

[3]H. Lane and B. Tranel, "The Lombard sign and the role of hearing in speech," J. Speech Lang. Hear. Res. **14**, 677–709 (1971).

[4]P. Bottalico and A. Astolfi, "Investigations into vocal doses and parameters pertaining to primary school teachers in classrooms," J. Acoust. Soc. Am. **131**, 2817–2827 (2012).

[5]J. H. L. Hansen and V. Varadarajan, "Analysis and compensation of Lombard speech across noise type and levels with application to in-set/out-of-set speaker recognition," IEEE Trans. Audio Speech Lang. Process. **17**, 366–378 (2009).
[6]J. Šimko, Š. Beňuš, and M. Vainio, "Hyperarticulation in Lombard speech: Global coordination of the jaw, lips and the tongue," J. Acoust. Soc. Am. **139**, 151–162 (2016).
[7]H. L. Pick, G. M. Siegel, P. W. Fox, S. R. Garber, and J. K. Kearney, "Inhibiting the Lombard effect," J. Acoust. Soc. Am. **85**, 894–900 (1989).
[8]M. Garnier, N. Henrich, and D. Dubois, "Influence of sound immersion and communicative interaction on the Lombard effect," J. Speech Lang. Hear. Res. **53**, 588–608 (2010).
[9]K. S. Pearsons, R. L. Bennett, and S. Fidell, "Speech levels in various noise environments," Environmental Health Effects Research Series, U.S. Environmental Protection Agency, Report No. EPA-600/1-77-025 (1977), pp. 1–70.
[10]D. Pelegrin-Garcia, B. Smits, J. Brunskog, and C. H. Jeong, "Vocal effort with changing talker-to-listener distance in different acoustic environments," J. Acoust. Soc. Am. **129**, 1981–1990 (2011).
[11]M. Södersten, S. Granqvist, B. Hammarberg, and A. Szabo, "Vocal behavior and vocal loading factors for preschool teachers at work studied with binaural dat recordings," J. Voice **16**, 356–371 (2002).
[12]M. Hodgson, G. Steininger, and Z. Razavi, "Measurement and prediction of speech and noise levels and the Lombard effect in eating establishments," J. Acoust. Soc. Am. **121**, 2023–2033 (2007).
[13]H. Sato and J. S. Bradley, "Evaluation of acoustical conditions for speech communication in working elementary school classrooms," J. Acoust. Soc. Am. **123**, 2064–2077 (2008).
[14]P. Bottalico, "Lombard effect, ambient noise, and willingness to spend time and money in a restaurant," J. Acoust. Soc. Am. **144**, EL209–EL214 (2018).
[15]G. E. Puglisi, A. Astolfi, L. C. Cantor Cutiva, and A. Carullo, "Four-day-follow-up study on the voice monitoring of primary school teachers: Relationships with conversational task and classroom acoustics," J. Acoust. Soc. Am. **141**, 441–452 (2017).
[16]E. M. Yiu and P. P. Yip, "Effect of noise on vocal loudness and pitch in natural environments: An accelerometer (Ambulatory Phonation Monitor) study," J. Voice **30**, 389–393 (2016).
[17]P. Bottalico, I. I. Passione, S. Graetzer, and E. J. Hunter, "Evaluation of the starting point of the Lombard effect," Acta Acust. Acust. **103**, 169–172 (2017).
[18]M. Nusseck, B. Richter, C. Spahn, and M. Echternach, "Analysing the vocal behaviour of teachers during classroom teaching using a portable voice accumulator," Logoped. Phoniatr. Vocol. **43**, 1–10 (2018).
[19]D. D. Mehta, M. Zañartu, S. W. Feng, H. A. Cheyne II, and R. E. Hillman, "Mobile voice health monitoring using a wearable accelerometer sensor and a smartphone platform," IEEE Trans. Biomed. Eng. **59**, 3090–3096 (2012).
[20]P. Bottalico, S. Graetzer, A. Astolfi, and E. J. Hunter, "Silence and voicing accumulations in Italian primary school teachers with and without voice disorders," J. Voice **31**, 260.e11–260.e20 (2017).
[21]P. S. Popolo, J. G. Švec, and I. R. Titze, "Adaptation of a Pocket PC for use as a wearable voice dosimeter," J. Speech Lang. Hear. Res. **48**, 780–791 (2005).
[22]H. A. Cheyne, H. M. Hanson, R. P. Genereux, K. N. Stevens, and R. E. Hillman, "Development and testing of a portable vocal accumulator," J. Speech Lang. Hear. Res. **46**, 1457–1467 (2003).
[23]D. D. Mehta, J. H. Van Stan, and R. E. Hillman, "Relationships between vocal function measures derived from an acoustic microphone and a subglottal neck-surface accelerometer," IEEE/ACM Trans. Audio Speech Lang. Proc. **24**, 659–668 (2016).
[24]D. D. Mehta, V. M. Espinoza, J. H. Van Stan, M. Zañartu, and R. E. Hillman, "The difference between first and second harmonic amplitudes correlates between glottal airflow and neck-surface accelerometer signals during phonation," J. Acoust. Soc. Am. **145**, EL386–EL92 (2019).
[25]J. G. Švec, I. R. Titze, and P. S. Popolo, "Estimation of sound pressure levels of voiced speech from skin vibration of the neck," J. Acoust. Soc. Am. **117**, 1386–1394 (2005).
[26]D. D. Mehta, J. H. Van Stan, M. Zañartu, M. Ghassemi, J. V. Guttag, V. M. Espinoza, J. P. Cortés, H. A. Cheyne II, and R. E. Hillman, "Using ambulatory voice monitoring to investigate common voice disorders: Research update," Front Bioeng. Biotechnol. **3**, 155–168 (2015).
[27]J. H. Van Stan, D. D. Mehta, A. J. Ortiz, J. A. Burns, L. E. Toles, K. L. Marks, M. Vangel, T. Hron, S. Zeitels, and R. E. Hillman, "Differences in weeklong ambulatory vocal behavior between female patients with phonotraumatic lesions and matched controls," J. Speech Lang. Hear. Res. **63**, 372–384 (2020).
[28]I. R. Titze, E. J. Hunter, and J. G. Švec, "Voicing and silence periods in daily and weekly vocalizations of teachers," J. Acoust. Soc. Am. **121**, 469–478 (2007).
[29]H. Watanabe, T. Shin, M. Oda, J. Fukaura, and S. Komiyama, "Measurement of total actual speaking time in a patient with spastic dysphonia," Folia Phoniatr. (Basel) **39**, 65–70 (1987).
[30]E. B. Holmberg, R. E. Hillman, and J. S. Perkell, "Glottal airflow and transglottal air pressure measurements for male and female speakers in soft, normal, and loud voice," J. Acoust. Soc. Am. **84**, 511–529 (1988).
[31]F. Lindstrom, K. P. Waye, M. Södersten, A. McAllister, and S. Ternström, "Observations of the relationship between noise exposure and preschool teacher voice usage in day-care center environments," J. Voice **25**, 166–172 (2011).
[32]A. Szabo Portela, S. Granqvist, S. Ternström, and M. Södersten, "Vocal behavior in environmental noise: Comparisons between work and leisure conditions in women with work-related voice disorders and matched controls," J. Voice **32**, 126.e23–126.e38 (2018).
[33]A. J. Ortiz, L. E. Toles, K. L. Marks, S. Capobianco, D. D. Mehta, R. E. Hillman, and J. H. Van Stan, "Automatic speech and singing classification in ambulatory recordings for normal and disordered voices," J. Acoust. Soc. Am. **146**, EL22–EL27 (2019).