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Auditory–Motor Mechanisms of the Lombard Effect

Allison S. Aaron,[a] Manuel Díaz Cádiz,[a] Sarah Cocroft,[a] and Cara E. Stepp[a,b,c]

[a] Department of Speech, Language & Hearing Sciences, Boston University, MA [b] Department of Otolaryngology—Head & Neck Surgery, Boston University School of Medicine, MA [c] Department of Biomedical Engineering, Boston University, MA

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ABSTRACT

Purpose: The Lombard effect, a speaker's increase of vocal intensity in the presence of noise, is a common phenomenon. However, its underlying auditory mechanisms are unclear.
Method: Participants produced speech before (baseline), during, and after exposure to systematically varied levels of speech-shaped noise. Lombard responses (i.e., elevated vocal intensity from baseline) were measured in an ecologically valid task (noise presented prior to voicing onset; Experiment 1) and in a task modeled after vocal motor learning paradigms (noise triggered by voice onset; Experiment 2). Loudness discrimination was assessed in the participants in Experiment 1.
Results: Compared to baseline, vocal intensity was elevated during noise in both experiments, suggesting contributions of both feedback and feedforward mechanisms to Lombard responses. Vocal intensity during noise was greater when noise was presented prior to voicing onset, as compared to when noise was triggered by voice onset. Intensity was decreased from baseline after noise exposure in Experiment 1 but not Experiment 2. Loudness discrimination thresholds did not explain the variance in Lombard responses.
Conclusions: Lombard responses are driven by both auditory feedback and the updating of feedforward mechanisms. Acuity did not explain the variance in Lombard responses, motivating future studies to investigate other contributing factors.
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The Lombard effect, defined as the increase of a speaker's vocal intensity in the presence of noise (Lombard, 1911), is a common phenomenon that occurs in many communicative contexts. Other acoustic characteristics of the Lombard effect include an increase in fundamental frequency (f_o), flattening of the spectral tilt with greater energy in higher frequencies, and an upward shift of the first formant (Junqua, 1996; Lane & Tranel, 1971; Lu & Cooke, 2008; Summers et al., 1988). Converging evidence suggests that environmental and speaking contexts are underlying factors that influence the relationship between the level of background noise and the magnitude of the Lombard effect (Bottalico et al., 2016; Garnier & Henrich, 2014; Lane & Tranel, 1971). Lombard responses (i.e., speakers' elevated vocal intensity from baseline) are influenced by background noise characteristics (Hadley et al., 2021) and are specifically sensitive to speech frequencies (Lu & Cooke, 2009; Stowe & Golob, 2013) as well as the ratio of informational to energetic content within the noise (Meekings et al., 2016). Lombard response magnitudes are also modulated by communicative intent (Garnier et al., 2010, 2018) and linguistic content of the speech (Patel & Schell, 2008).

Although Lombard responses have been well studied, the role that speaker characteristics may play in driving this common speech motor behavior remains poorly understood. There are limited studies that have investigated person-specific differences in Lombard responses. Two ambulatory monitoring studies reported substantial variation in the magnitudes of elevated vocal intensity during daily life communication in environmental noise across individuals with typical voices (Whittico et al., 2020) and a group of preschool teachers (Lindstrom et al., 2011). Differences in Lombard responses have also been found within the singing domain: Lombard response magnitudes varied across individual singers when singing with increasing levels of background musical accompaniment (Bottalico et al., 2016). Prior studies

Correspondence to Allison S. Aaron: aaaron@bu.edu. ***Disclosure:*** *The authors have declared that no competing financial or nonfinancial interests existed at the time of publication.*

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have found variable Lombard responses in individuals with Parkinson's disease. Although the majority of individuals with Parkinson's disease increase their vocal intensity from baseline during speaking in noise (Adams et al., 2020), response magnitudes can vary across participants (Richardson et al., 2014; Stathopoulos et al., 2014). Furthermore, there was noticeable individual variation in the associated laryngeal aerodynamic and respiratory kinematic adjustments that speakers used to increase vocal intensity. It is possible that these response variations across and within studies reflect a range of auditory function across participants; individual variation in Lombard responses has been linked to hearing ability since it was first described (Lane & Tranel, 1971; Lombard, 1911). Individuals with hearing loss require more noise to evoke a Lombard response, as compared to those with typical hearing (Lane & Tranel, 1971). However, beyond this link to peripheral hearing function, the mechanistic auditory processes (i.e., auditory–motor integration and auditory acuity) underlying the Lombard effect for typical speakers with hearing abilities within normal limits are not well understood.

When individuals speak in noisy environments, they make vocal motor adjustments that maintain audibility of their speech within the noise. Conceptually, these adjustments depend upon the real-time monitoring of two dually presented auditory streams: their own voice and the background noise. Vocal motor adjustments in noise may result solely from a quick reflexive process, or they may also involve the updating of motor plans over time. Computational models of articulatory motor control (Houde & Nagarajan, 2011; Parrell et al., 2019; Tourville & Guenther, 2011) and vocal motor control (Weerathunge, Alzamendi, et al., 2022) can guide our interpretation of the sensorimotor mechanisms driving speech production. Models suggest that there are parallel systems for neural control of speech production: feedback and feedforward control systems (Tourville & Guenther, 2011; Weerathunge, Alzamendi, et al., 2022). During speech development, children use the feedback systems to monitor for errors in their speech, and that feedback is used to update their feedforward motor commands. Contrarily, adults rely heavily on the feedforward system for speech because it is faster and more efficient than feedback control; feedback error corrections occur after ~150 ms of vocalization onset, whereas feedforward contributions dominate in the first 120 ms of vocalization (Burnett et al., 1997; Burnett & Larson, 2002; Larson et al., 2001).

Altered auditory feedback paradigms have been used to study the feedforward control system by predictably manipulating a speaker's auditory feedback in near real time and observing how they respond. When a speaker is exposed to repeated trials of predictable perturbations of feedback (e.g., experimental shifts in acoustic f_o, amplitude, or formants), they typically oppose the perturbation by adjusting their own voice, producing an "adaptive response" (Burnett & Larson, 2002; Houde & Jordan, 1998; Jones & Munhall, 2000; Patel et al., 2015). Adaptive responses in the voice domain can be measured by extracting acoustic output (e.g., f_o or amplitude) during an early time analysis window in each trial (prior to the neural processing of auditory feedback), indirectly measuring the integration of feedback from previous productions into feedforward commands for vocal motor control (Hawco & Jones, 2009; Larson et al., 2001). Adaptation studies have investigated the process of updating the feedforward mechanism for vocal motor control in both speakers with typical voices (Dahl et al., 2024; Jones & Munhall, 2000; Lester-Smith et al., 2020; Patel et al., 2015; Scheerer et al., 2016) and individuals with voice disorders (Abur et al., 2018, 2021; Hilger, 2020; Stepp et al., 2017). These studies can inform our understanding of the auditory–motor mechanisms underlying the Lombard effect.

There is conflicting evidence within the literature regarding the contributions of the feedback and feedforward control systems for Lombard responses. At its origin, Lombard responses were assumed to represent a "reflex" (Lombard, 1911), suggesting that they were driven solely by auditory feedback control. There is some evidence to support this assumption, given the historical presence of the Lombard effect in communication for a variety of animals (Brumm, 2004; Halfwerk et al., 2016; Holt & Johnston, 2014; Scheifele et al., 2005), some of whom lack cortical brain regions (Luo et al., 2018). This rationale aligns with the neural mapping of subcortical regions to the feedback control systems, as described in models of speech production (Tourville & Guenther, 2011; Weerathunge, Alzamendi, et al., 2022). There are also several studies that have shown that nonhuman infants (e.g., ducklings, hatchlings, bats) demonstrate a Lombard response within the first 10 days of life (Dorado-Correa et al., 2018; Leonard & Horn, 2005; Luo et al., 2017); this could be interpreted as indirect evidence that the Lombard response does not require the development of motor learning ability.

On the other hand, the Lombard response may also be mediated by the updating of feedforward control. In mammals, the main processes associated with the Lombard effect (e.g., vocal production, auditory processing, and auditory–motor integration) require both subcortical and cortical involvement (Luo et al., 2018; Z-Rivera et al., 2026). According to the schematic network model for the Lombard effect proposed by Luo et al. (2018), "the Lombard effect is elicited by a subcortical network, which can be modulated by cortical brain areas in mammals." This model can be interpreted in conjunction with models of speech production (Tourville & Guenther, 2011; Weerathunge, Alzamendi, et al., 2022), which associate cortical processing in speech production with feedforward control. Therefore,

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the evidence that Lombard responses in humans are influenced by cognitive processes, such as communicative intent (Garnier et al., 2010) and linguistic content (Patel & Schell, 2008), supports a role for updating of feedforward control in Lombard responses. Additionally, humans can be trained to inhibit the Lombard effect (Pick et al., 1989; Therrien et al., 2012), which further supports higher level cortical involvement and, thus, some role for updating feedforward control in Lombard responses.

There is preliminary empirical evidence that may reflect the process of updating feedforward control in Lombard responses. Two studies observed a persistence of speakers' vocal responses following removal of background noise; one study found elevated mean f_o from baseline for individuals with typical voices (Hill et al., 1988), and one study found elevated vocal intensity from baseline in individuals with voice disorders (Castro et al., 2022). In altered auditory feedback paradigms, one way to measure adaptation is by examining the first few trials after the predictable perturbations of feedback are removed (Jones & Munhall, 2000; Miller et al., 2023; Purcell & Munhall, 2006). If the adaptive response is maintained during these trials, this presumably can be interpreted as evidence that the speaker has used the auditory feedback to update their feedforward motor commands. Similarly, if Lombard responses persist after the removal of background noise (Castro et al., 2022), this may signify that individuals have adapted to the changing acoustical environment, supporting the involvement of updating the feedforward control system for speaking in noisy environments.

A single study to date has explored the underlying feedback and feedforward mechanisms of Lombard responses (Castro et al., 2024) via the extended use of SimpleDIVA, a neurocomputational model designed to fit and interpret behavioral speech data (Kearney et al., 2020). Castro et al. (2024) used this modeling approach to fit their prior behavioral data (Castro et al., 2022); they found that Lombard responses from individuals with hyperfunctional voice disorders exhibited similar values of auditory gain but lower values of feedforward learning rates, as compared to responses from speakers without hyperfunctional voice disorders. This finding suggests that the difference in Lombard responses for speakers with and without voice disorders may be explained by typical speakers relying more heavily on the use of feedback to update feedforward control over time, as compared to those with voice disorders. However, the prior Lombard studies only investigated if Lombard responses persisted across full vowel productions, rather than in an early analysis window to infer updating of feedforward commands. Based on altered auditory feedback literature, adaptation for Lombard responses could be measured through the systematic investigation of repeated vocal responses in an early time window (i.e., prior to 120 ms after vocalization onset) before auditory feedback responses occur (Burnett et al., 1998; Miller et al., 2023; Purcell & Munhall, 2006). Additionally, the interpretation of the prior Lombard study (Castro et al., 2022) is limited, as the speakers only produced sustained vowels, which does not model a naturalistic communicative context.

To elucidate whether speakers update their feedforward control during speaking in real-life noisy environments, a Lombard task could be structured as an auditory–motor paradigm. In a typical noisy environment, speakers are first exposed to constant background noise, and then they initiate speech production. In those scenarios, it is unclear if the speaker is only predicting how their voice will be heard in the noise before they start speaking or if they are also making online adjustments of their voice while speaking. Prior research suggests that prespeech auditory processing plays a role in auditory feedback monitoring during the preparatory phase prior to vocalization (Baddeley & Hitch, 2019; Daliri & Max, 2016; Li et al., 2024). However, based on theoretical models of speech and vocal motor control (Tourville & Guenther, 2011; Weerathunge, Alzamendi, et al., 2022), speaking during and after exposure to a loud environment presumably requires online monitoring of both background noise and one's own voice (i.e., feedback control) and then responding with vocal–motor adjustments (i.e., integrating feedback into feedforward commands). If we expect auditory feedback monitoring in noisy environments to occur before and during vocalization, Lombard responses in the early analysis window during exposure to constant background noise might represent both feedback responses and an updating of feedforward control. Therefore, Lombard responses might be greater during exposure to constant noise than during noise that is only presented during speaking. Thus, vocal motor control of Lombard responses should be observed both during exposure to constant background noise, to measure Lombard responses in a naturalistic speaking context, and during noise that is only presented during speaking, to reduce the effects of feedback responses from the preparatory phase prior to vocalization.

Regardless of the degree to which Lombard responses are mediated by auditory feedback versus feedforward control, both mechanisms presumably rely on a speaker's ability to sense that their acoustic environment has changed. Despite the clear connection between hearing loss (i.e., hearing thresholds measured by audiometric testing) and the magnitude of Lombard responses (Lombard, 1911), individuals with typical hearing thresholds may have a wide range of auditory discrimination abilities (Kohrman et al., 2020). Thus, hearing thresholds alone may not fully explain the underlying auditory mechanisms that drive the Lombard effect (Lane & Tranel, 1971). As individuals are speaking during and after exposure to noisy acoustic environments, they likely require some level of auditory acuity (i.e., the

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ability to discriminate between sounds) to discriminate between the voice signal and environmental modifications before auditory–motor integration (via auditory feedback control or updates to feedforward control) is used to change the vocal motor output (Lindblom, 1990; Tourville & Guenther, 2011; Weerathunge, Alzamendi, et al., 2022). This relationship could be a graded response in which better auditory acuity is associated with larger Lombard responses. Alternatively, it is possible that Lombard responses may be the outcome of a simpler auditory process; individuals with sufficient auditory acuity ability will demonstrate a Lombard response, and those with reduced acuity will not. This lack of theoretical clarity motivates our investigation of the role of auditory mechanisms in Lombard responses.

The aims of the current study were to (a) investigate the involvement of auditory feedback and feedforward mechanisms in the Lombard effect and (b) compare individual auditory acuity ability to the magnitude of Lombard responses. For Aim 1, we induced the Lombard effect via speech production tasks across two experiments: In Experiment 1, we designed a version of the Lombard task to model a naturalistic communicative environment, with speech-shaped noise presented throughout successive speaking trials, including prior to the initiation of speech (i.e., constant noise throughout each trial). In Experiment 2, a new group of participants completed the original Lombard task from Experiment 1 and a second version of the Lombard task that more closely modeled an altered-auditory feedback design. In this version, the noise was triggered by the onset of voicing in each trial to test whether Lombard responses were observed in an early analysis window even when speech-shaped noise was not presented prior to speech initiation. Our hypothesis was that Lombard responses (i.e., increased vocal intensity when speaking in noise as compared to a baseline period prior to its introduction) would be driven by both auditory feedback and feedforward control mechanisms. This would be demonstrated by a significantly elevated average vocal intensity from baseline during and after exposure to noise across both a full sentence (i.e., when speakers have full access to auditory feedback and feedforward control) and in an early time window of speech production (i.e., when speakers primarily have access to feedforward control). We expected to observe Lombard responses in the early window during a Lombard task with constant noise (Experiment 1) and during a Lombard task with voice onset–triggered noise (Experiment 2). Furthermore, we theorized that Lombard responses in the early analysis window would be larger in the task with constant noise, as compared to the task with voice onset–triggered noise.

For Aim 2 of this study, we investigated auditory acuity via loudness discrimination tasks in quiet and noise in speakers with typical voices (i.e., the original group of participants from Experiment 1). We based our second hypothesis on a conceptual model that the Lombard effect is driven in graded fashion by the individual speaker's ability to sense changes in their own voice relative to their environment; we hypothesized that individuals with lower loudness discrimination thresholds (i.e., better discrimination ability) in quiet and in noise would have greater Lombard responses.

Experiment 1: Methods

Participants

Thirty adults (15 cisgender women, 14 cisgender men, and one agender individual who was assigned male at birth) aged 18–33 years (M = 24 years, SD = 4.3) with typical voices participated in this study. No individuals had a history of neurological, voice, speech, language, or hearing disorders. None of the participants reported more than 1 year of formal organized singing experience that had occurred within the past 3 years. Participants who reported participation in a high school choir as their only organized singing experience in the past 3 years were not excluded. All participants reported that they were fluent speakers of English. All participants completed written consent in compliance with the Boston University Institutional Review Board (No. 2625). To be included in this study, participants were required to pass a hearing screening. The hearing screening was conducted using headphones on a GSI 18 audiometer (Grason-Stadler). Hearing thresholds were set at 25 dB HL at 250, 500, 1000, 2000, and 4000 Hz (American Speech-Language-Hearing Association [ASHA], 2018). No participants wore hearing aids.

Acoustic Equipment Calibration

Prior to the experiment, the setup was calibrated using a 1-kHz pure tone from a handheld recorder (Olympus LS-10) positioned 7 cm from an omnidirectional ear-set microphone (MX153, Shure). The microphone gain was adjusted with a preamplifier (RME QuadMic II), and the signal was digitized with a soundcard (RME Fireface UCX). The processed signal was conditioned with another pre-amplifier (Behringer Xenyx Q802). Auditory stimuli were presented via Sennheiser HD 280 Pro headphones and calibrated using an artificial ear (Brüel & Kjaer Type 4153) connected to a sound-level meter (Brüel & Kjaer Type 2250-L with a Type 4192 1/2" pressure-field microphone). The headphone output was calibrated to be 75 dB SPL, which served as a reference intensity value for the experimental tasks.

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Experimental Protocol

Participants completed the experiment in a sound-attenuated booth at Boston University in a single session. These participants were part of a larger study; experimental tasks for the present study (i.e., the Lombard task and loudness discrimination tasks) lasted approximately 1 hr. Participants sat before a computer monitor while wearing the Shure ear-set microphone placed at approximately 45° from the midline and 7 cm away from the corner of the mouth to record all speech signals (Patel et al., 2018). Participants wore the headphones throughout the experimental tasks. The main experimental tasks included (a) the Lombard task with constant noise and (b) the loudness discrimination tasks; the order in which these two main tasks were completed was counterbalanced to reduce order effects.

Lombard Task With Constant Noise

Participants completed the Lombard task with constant noise to model a naturalistic communicative context. Participants were instructed to read aloud custom sentences of six-syllable length as they appeared on the screen in front of them. They produced 108 total trials (one sentence per trial) of repeated blocks of six pseudorandomized sentences (see the Appendix). The duration and pace of the sentence reading were controlled by visual cues on the screen. Each trial was recorded for 4 s, and the interstimulus interval was jittered between 1 and 3 s to avoid rhythmic cues. Given that the Lombard effect is influenced by communicative interaction (Garnier et al., 2010; Lindblom, 1990), it was important to induce a communicative context (Garnier et al., 2018) and convince the participant that the experimenter was indeed listening throughout. The experimenter was positioned facing the participant on a video call stationed outside of the booth. Participants were told that these recordings would be used for another experiment and that the experimenter would be evaluating the recordings for quality. There were also pseudorandomized pauses in the experimental script following 5% of the trials, during which the experimenter briefly communicated with the participant regarding irrelevant "minor technical adjustments" before instructing the participant to continue the task.

As illustrated in Figure 1, the experimental trials were divided into four sequential phases: baseline (four blocks totaling to 24 trials), ramp (five blocks totaling to 30 trials), hold (five blocks totaling to 30 trials), and after-effect (four blocks totaling to 24 trials). The number of trials per phase was modeled after a typical altered-auditory feedback paradigm (e.g., Abur et al., 2021) designed to measure contributions of feedback and feedforward mechanisms. To elicit Lombard responses, speech-shaped noise (Demonte, 2019) was systematically presented to the participants via headphones using the Eventide Eclipse V4 Harmonizer, which was controlled via MIDI commands sent from a custom MATLAB script. No noise was presented through the headphones during the baseline phase. During the ramp phase, the speech-shaped noise was then presented through the headphones at increasing levels across 30 trials. For the first trial of the ramp phase, the noise level was ~26.7 dB SPL, and the noise increased each trial by 1.7 dB SPL until it reached the maximum intensity level of 75 dB SPL. The 75 dB SPL of noise was maintained throughout the hold phase. This maximum noise level was based on previous studies that aimed to induce a robust Lombard effect and avoid hearing discomfort, vocal fatigue, and auditory fatigue (Alghamdi et al., 2018; Castro et al., 2022; Junqua, 1996; Lu & Cooke, 2009; Summers et al., 1988). The speech-shaped noise was then removed for all trials of the after-effect phase. Participants also completed a control run of this experiment, during which they read aloud the sentences, but no noise was presented through the headphones in any phase. The control run was used to account for any natural intensity variability across extended speech production tasks. The order in which the Lombard task with constant noise and the control run were completed was counterbalanced.

Loudness Discrimination Tasks

Two loudness discrimination tasks were used to measure loudness discrimination thresholds: one in quiet and another in noise. Prior to the initiation of the tasks, participants were asked to record a sustained /ɑ/ at a comfortable pitch and loudness for 3 s. A steady 500-ms portion from the middle of their own vowel production was extracted and used as the speaker-specific baseline stimulus for the tasks (Abur et al., 2021). The use of self-produced stimuli allowed us to specifically test individuals' discrimination of internally generated sounds, a relevant task for speech production. The baseline stimulus was normalized to an initial vocal intensity of 70 dB SPL. Throughout the tasks, the vocal intensity of the amplitude-normalized stimulus was then systematically shifted using the Eventide Eclipse V4 Harmonizer.

In each experimental trial, participants were presented with three altered versions of the baseline stimulus via headphones. Each one was 500 ms in duration with interstimuli intervals of 500 ms. In each trial, the amplitude of two of the three stimuli was perturbed identically in a randomized direction (i.e., shifted up or shifted down from 70 dB SPL). The remaining stimulus was perturbed by the same magnitude in the opposite direction. The order of stimuli pairing was randomized in an "AXB" format so that either the first two stimuli (AX) or the last two stimuli (XB) were identical (Repp, 1981; Richardson

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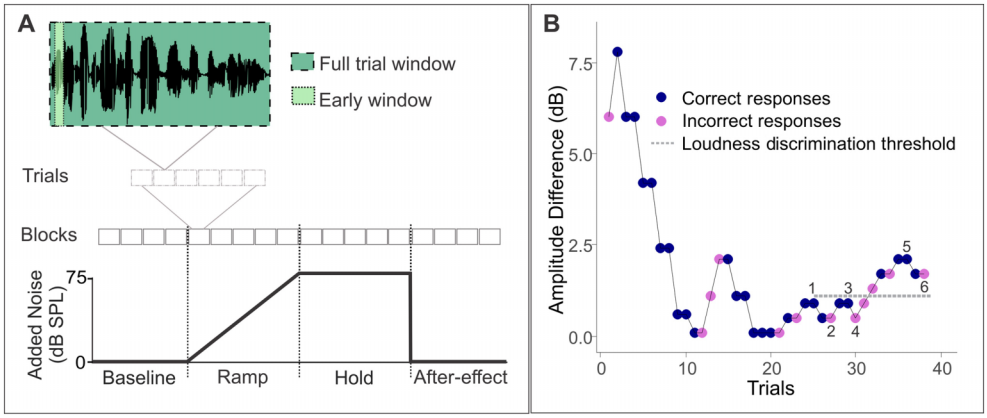
Figure 1. Methodology for Experiment 1. Panel A represents the Lombard task in constant noise by experimental phase and block. Example of vocal intensity extracted from the full trial analysis window (in dark green) and the early analysis window (in light green) for one trial. Panel B represents example results of the "AXB" loudness discrimination task for one participant. Data points represent the amplitude difference between stimuli as trials progressed. The amplitude difference decreased following two correct responses or increased following one incorrect response. The dotted gray line indicates the estimated loudness discrimination in dB, as estimated by the average amplitude difference between stimuli across the last six reversals (numbered in Panel B).



& Sussman, 2019; Weerathunge, Voon, et al., 2022). Participants were instructed to decide whether the "first" or "last" stimulus of a trial was different from the other two stimuli using labeled keys on a keyboard. They were informed that the stimulus with the different loudness would always be either the "first" or "last" stimulus. In the first trial, the amplitude difference between the stimuli was 6 dB (i.e., 73 and 67 dB SPL). The amplitude difference for the following trials was determined by an adaptive up–down method (Levitt, 1971; Macmillan & Creelman, 2004). Two consecutive correct responses resulted in a "down step" (the amplitude difference decreased by 1.8 dB) on the following trial. One incorrect response resulted in an "up step" (the amplitude difference increased by 1.8 dB) on the following trial. After two reversals (i.e., an "up step" followed by a "down step" or vice versa), the step size was reduced to 1.0 dB, and after six reversals, the step size was reduced to 0.4 dB for higher resolution estimation of the loudness discrimination threshold (Dai, 1995). The scalar values for the change in amplitude differences across trials were 1.8, 1.0, and 0.4 dB. Based on pilot testing, all parameters permitted a high-resolution estimate without exceeding the maximum number of trials (60 trials). For the loudness discrimination in noise task, the same baseline voice stimulus at 70 dB SPL was presented in 70 dB SPL of speech-shaped background noise. This noise level was based on pilot testing to design a difficult yet achievable paradigm, to avoid hearing discomfort and fatigue (Junqua, 1996), and to approximately match the maximum intensity of 75 dB SPL in the hold phase of the Lombard task. The background noise was turned on 500 ms before the onset of the first stimulus of a trial and off 500 ms after the offset of the last stimulus in the same trial.

Participants completed eight practice trials before each discrimination task to ensure understanding of the task objectives. Both tasks were considered complete after 10 reversals or 60 trials (Aaron et al., 2025; Abur et al., 2021; Weerathunge, Voon, et al., 2022). Only one participant reached 60 trials before 10 reversals; this occurred only during the loudness discrimination in noise task, in which the total number of reversals was nine. The average total number of trials was 33.1 (SD = 6.7) for loudness discrimination in quiet and 34.7 (SD = 8.3) for loudness discrimination in noise. On average, the loudness discrimination in quiet task lasted 3.7 min (SD = 0.7), and the loudness discrimination in noise task lasted 4.2 min (SD = 1.4). Because the loudness discrimination in quiet task was presumably easier than the loudness discrimination in noise task, the loudness discrimination in quiet task was always completed first, and the loudness discrimination in noise task was completed second.

Data Analysis

For acoustic analysis of the Lombard responses, the acoustic waveform of the microphone signal for each trial was visualized with a custom MATLAB graphical user interface (GUI; Version 2022a, MathWorks, Inc.). For each trial, a trained researcher set a trial-specific silence threshold, such that the beginning and end of each sentence and all speech segments were detected. The vocal intensity (root-mean-square [RMS]) was then extracted from the speech segments within the two analysis windows: the full trial analysis window (i.e., from sentence onset to offset) and the early analysis window (i.e., the 20- to 100-ms section post-onset; see Figure 1). Prior analysis protocols for measuring adaptive f_o responses during sustained vowels have used the

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40- to 120-ms section (Abur et al., 2021; Kapsner-Smith et al., 2024) to assess the feedforward control system contributions after the voice stabilized but before auditory feedback responses are expected to occur (Burnett et al., 1997; Burnett & Larson, 2002; Larson et al., 2001). However, based on pilot testing, we chose to analyze the 20- to 100-ms section to maximize the analysis of voiced speech segments (i.e., prior to voiceless consonants and natural pauses) within the sentence stimuli of the present study.

For each participant, the following normalization processes were completed for both the full trial and early analysis windows of Lombard responses. To account for any differences in Lombard responses across the six stimuli, the average intensity (dB) of each stimulus in the baseline phase served as the reference value and was subtracted from all trials with corresponding stimuli. This process reduced the potential influence of phoneme and linguistic content on the observed Lombard responses (Elie et al., 2024; Patel & Schell, 2008). The intensity (dB) of each trial in the control condition was then subtracted from the corresponding trial in the Lombard condition to account for any natural amplitude variability across extended speech production tasks.[1] To visualize temporal changes across the blocks of six sentences, the normalized amplitude was averaged over every six trials. Average individual Lombard responses during the hold and after-effect phases were calculated for both the full trial and early analysis windows. Loudness discrimination thresholds were calculated for both loudness discrimination in quiet and in noise tasks (see Figure 1) by estimating each participant's average amplitude difference across the last six reversals (Abur & Stepp, 2020).

Statistical Analysis

To investigate the involvement of auditory feedback and feedforward mechanisms in the Lombard effect (Aim 1), we constructed a linear mixed-effects model using the lmer function from the lme4 package in RStudio (Version 4.5.1) to measure the main effects of analysis window (the full trial and early analysis windows) and experimental phase (baseline, ramp, hold, and after-effect) as well as the interaction between analysis window and experimental phase on Lombard responses. Participant was entered as a random intercept. The model specification was the following: lmer(LombardResponse ~ AnalysisWindow × ExperimentalPhase + [1 | Participant]). Effect sizes for significant effects were calculated as semipartial R^2 using the r2beta function from the r2glmm package in RStudio. To test our hypotheses on the involvement of auditory feedback and feedforward mechanisms in the Lombard effect, four post hoc pairwise comparisons of estimated marginal means were computed to determine whether Lombard responses in the hold and after-effect phases were significantly different from baseline in both analysis windows. We used the emmeans function from the emmeans package in RStudio (RStudio Team, 2020) with Tukey correction to adjust for multiple comparisons. Effect sizes for significant comparisons were calculated as Cohen's d values and designated as small (0.2), medium (0.5), and large (0.8; Witte & Witte, 2017).

To compare auditory acuity ability to Lombard responses (Aim 2), we constructed a multiple linear regression model to determine whether measures of loudness discrimination thresholds (in quiet and in noise) significantly predicted average Lombard responses in the full trial analysis window during the hold phase. The model specification was the following: lm(LombardResponse ~ DiscriminationQuiet + DiscriminationNoise). Statistical analyses were conducted in RStudio (RStudio Team, 2020). Significance for all statistical testing was set a priori at $\alpha = .05$.

Experiment 1: Results

Lombard Responses With Constant Noise

Lombard responses across experimental phases of the Lombard task (i.e., baseline, ramp, hold, after-effect) and for both analysis windows (i.e., full trial and early analysis windows) are illustrated in Figure 2. The results of the linear mixed-effects model revealed a statistically significant main effect of analysis window on Lombard responses, $F(1, 6231) = 9.137$, $p < .001$, semipartial $R^2 < .001$; a statistically significant main effect of experimental phase on Lombard responses, $F(3, 6231) = 518.009$, $p < .001$, semipartial $R^2 = .135$; and a statistically significant interaction between analysis window and experimental phase, $F(3, 6231) = 5.114$, $p < .001$, semipartial $R^2 = .005$.

Post hoc contrasts of estimated marginal means were calculated to compare average Lombard responses in the hold and after-effect phases to the baseline phase for both analysis windows. Lombard responses in the hold phase were significantly elevated from baseline in both the full trial ($M = 4.17$ dB, $SD = 2.86$, $p < .001$) and early analysis ($M = 2.97$ dB, $SD = 4.46$, $p < .001$) windows, both with large effect sizes ($d = 1.46$ and 1.07, respectively). Lombard responses in the after-effect phase were not significantly different from baseline in the full trial, but they were significantly decreased in the early analysis window ($M = -0.63$ dB, $SD = 4.0$), with a small effect size ($p < .001$, $d = -0.21$).

[1]Studies investigating the effects of prolonged speaking tasks on acoustic measures for individuals with typical speakers have found that f_o typically increases over time (Boominathan et al., 2010; Remacle et al., 2012; Stemple et al., 1995). Expected trends for changes in vocal intensity are less clear (Vilkman et al., 1999; Vintturi et al., 2001).

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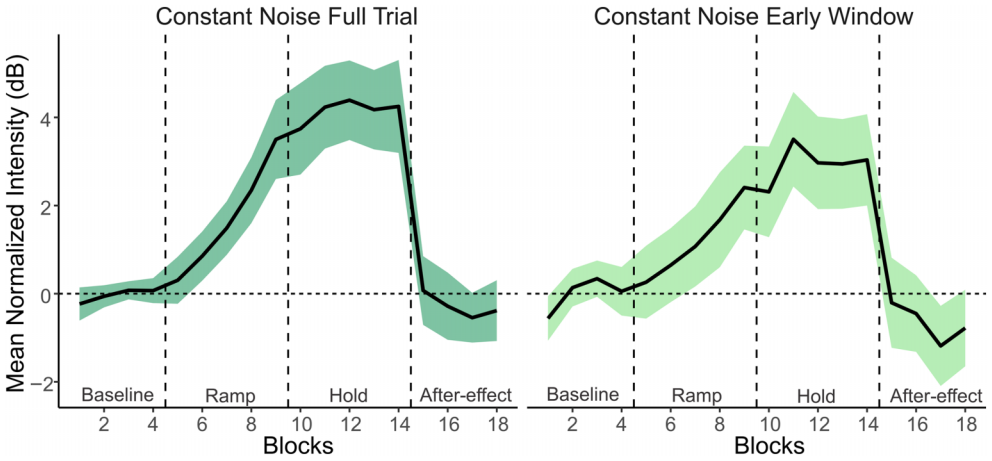
Figure 2. Lombard responses from Experiment 1. Lombard responses (baseline-normalized mean intensity over six trials) across 108 trials of the Lombard task with constant noise in two analysis windows from Experiment 1. The left panel represents the Lombard responses in the full trial analysis window, and the right panel represents the Lombard responses in the early analysis window. Shaded dark green areas represent 95% confidence intervals for the full trial window, and shaded light green areas represent 95% confidence intervals for the early analysis window. Mean values are outlined in black.



Auditory Acuity and Lombard Responses

On the loudness discrimination in quiet task, the average loudness discrimination threshold was 1.82 dB (SD = 0.75 dB), and on the loudness discrimination in noise task, the average threshold was 2.30 dB (SD = 1.06 dB). Loudness discrimination thresholds for the two tasks are visualized in Supplemental Material S1. Multiple linear regression was used to test if loudness discrimination in quiet and loudness discrimination in noise thresholds significantly accounted for the variance in Lombard responses during the hold phase. The overall regression was not statistically significant, $F(2, 5) = 1.113$, $p = .4$, adjusted $R^2 = .03$, $SE = 1.66$. The loudness discrimination thresholds in quiet ($t = 1.44$, $p = .21$) and in noise ($t = -1.31$, $p = .25$) did not significantly explain the variance in Lombard responses during the hold phase. Figure 3 compares individual loudness discrimination thresholds for both discrimination tasks per participant with their average Lombard response from the full trial analysis window during the hold phase. Comparisons of the loudness discrimination thresholds with Lombard responses from the early analysis window, which also did not explain the variance in Lombard responses, can be found in Supplemental Material S2.

Experiment 2: Methods

Participants

Twenty additional speakers (10 cisgender women, seven cisgender men, two transgender women, and one genderfluid individual who was assigned male at birth) aged 19–27 years (M = 22.4 years, SD = 2.0) with typical voices participated in Experiment 2. None of these individuals had participated in Experiment 1. Eligibility criteria for Experiment 2 were identical to Experiment 1, including hearing screening requirements (see Experiment 1 for details).

Lombard Tasks With Constant Noise and Voice Onset–Triggered Noise

Acoustic equipment calibration and participant setup for Experiment 2 was identical to Experiment 1 (see Experiment 1 for details). Experimental tasks for Experiment 2 lasted approximately 45 min to 1 hr. Speakers completed the same Lombard condition (Lombard task with constant noise) and control run as described in Experiment 1. Similarly to Experiment 1, participants completed eight practice trials prior to initiating the main tasks.

In Experiment 2, participants completed an additional second condition of the Lombard task that was designed to more closely model an altered auditory feedback paradigm. In this new condition of the Lombard task (Lombard task with voice onset–triggered noise), the speech-shaped noise in each trial was triggered by the speakers' voicing onset. That is, the noise was presented immediately after the speaker initiated each sentence (see Figure 4). This allowed us to remove the presence of speech-shaped noise prior to voice onset, thus controlling for an effect of speakers anticipating how their voice would sound in the noise prior to vocalization.

To prepare for the new Lombard task with voice onset–triggered noise condition, a participant-specific threshold was calculated as 10% of the average maximum RMS amplitude of the practice trials. This default threshold

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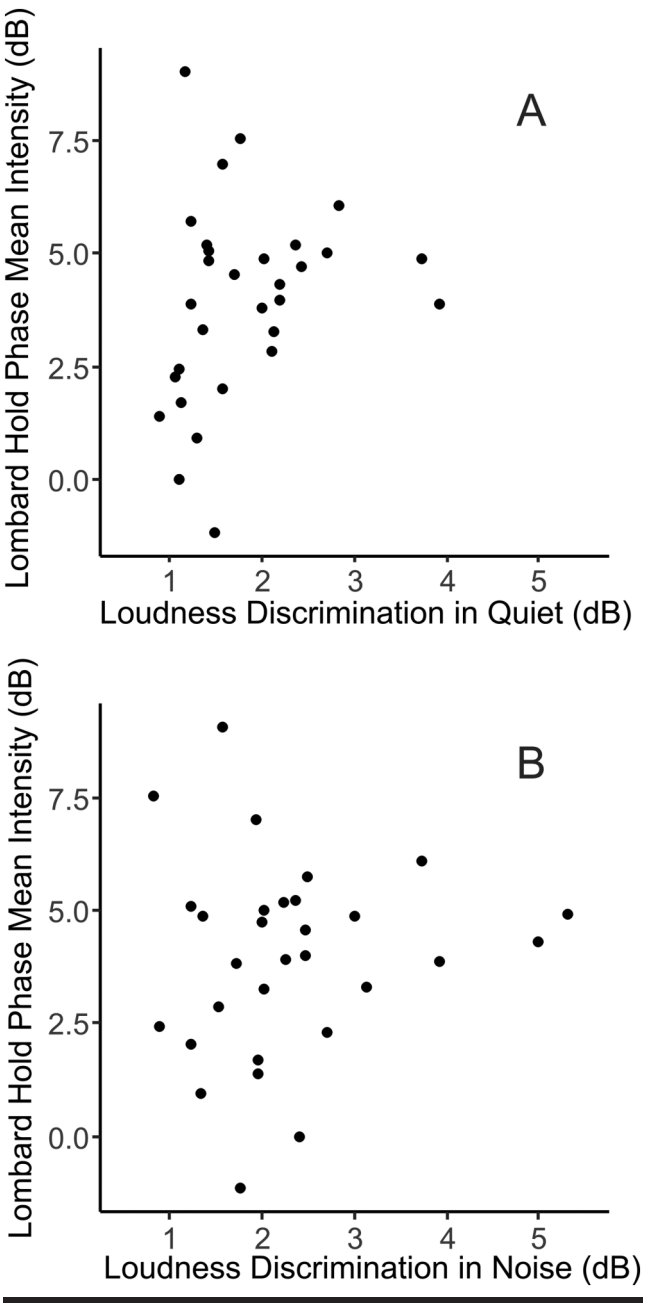
Figure 3. Scatter plots of participant values of mean intensity in dB during the full trial analysis window of the hold phase of the Lombard task and loudness discrimination thresholds (dB) in quiet (Panel A) and in noise (Panel B) from Experiment 1.

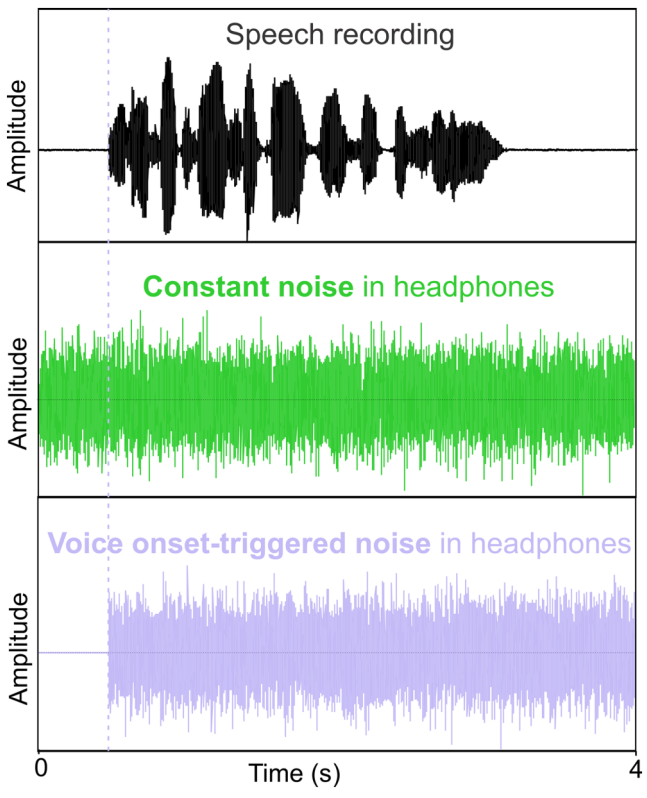


sufficiently detected voicing onset during pilot testing and for all experimental participants. In the Lombard task with voice onset–triggered noise condition, the participant-specific threshold was used to trigger the speech-shaped noise to be presented via headphones at the onset of voicing for the trials in the ramp and hold phases. For each trial with noise, once the threshold was met, the speech-shaped noise was presented until the end of the trial. The order of the two Lombard task conditions was counterbalanced, and the control run was always completed between them.

Data and Statistical Analysis

Data analysis of Lombard responses was completed using an identical protocol to Experiment 1. To calculate the delay durations of noise onset from voice onset for each trial with voice onset–triggered speech-shaped noise, a trained researcher used a custom MATLAB GUI (Version 2022a) to visualize both the microphone and headphone acoustic waveform signals for the trials in the ramp and hold phases of the Lombard task with voice onset–triggered noise. The researcher manually marked the onset of both signals for each trial, and the delay per trial was calculated (noise onset − voice onset). On average, the duration between the voice onset and the triggering of the speech-shaped noise per trial was < 40 ms (M = 38 ms, SD = 16). This finding confirms that the participant-specific thresholds that were

Figure 4. Methodology of Experiment 2. Schematic of Lombard task with constant noise and voice onset–triggered noise. For the two Lombard task conditions, the waveform of the speech recording from the microphone signal is represented in black (top panel). The waveform of the headphone signal from the constant noise condition is represented in green (middle panel), and the waveform of the headphone signal from the voice onset–triggered noise condition is represented in purple (lower panel).



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calculated from the practice trials sufficiently detected voicing onset for all experimental trials across participants.

Given the results of Experiment 1, we focused Experiment 2 analyses on Lombard responses in the early analysis window. For statistical analyses of Experiment 2, we constructed a linear mixed-effects model using the lmer function from the lme4 package in RStudio (RStudio Team, 2020) to measure the main effects of Lombard task condition (constant noise and voice onset–triggered noise) and experimental phase (baseline, ramp, hold, and after-effect) as well as the interaction between condition and experimental phase on Lombard responses. Participant was entered as a random intercept. The model specification was the following: lmer(LombardResponse ~ Condition × Experimental Phase + [1 | Participant]). Effect sizes for significant effects were calculated as semipartial R^2 using the r2beta function from the r2glmm package in RStudio.

Four post hoc comparisons of estimated marginal means were constructed using pairwise contrasts with a Tukey correction to adjust for multiple comparisons. We used the emmeans function from the emmeans package in RStudio (RStudio Team, 2020) to compare early window Lombard responses in the hold and after-effect phases to baseline for both the constant noise condition and the voice onset–triggered noise condition. Additionally, we constructed a fifth post hoc comparison to compare early analysis window Lombard responses in the hold phase across the two Lombard noise conditions. Effect sizes for significant comparisons were calculated as Cohen's d values and designated as small (0.2), medium (0.5), and large (0.8; Witte & Witte, 2017).

Experiment 2: Results

Lombard responses across experimental phases (i.e., baseline, ramp, hold, after-effect) and for both Lombard task conditions (i.e., constant noise and voice onset–triggered noise) are illustrated in Figure 5. Results of the linear mixed-effects model revealed a statistically significant main effect of condition on Lombard responses, $F(1, 4211) = 16.84$, $p < .001$, semipartial $R^2 < .001$, and a statistically significant main effect of experimental phase on Lombard responses, $F(3, 4211) = 95.19$, $p < .001$, semipartial $R^2 = .054$. There was also a statistically significant interaction between analysis window and experimental phase, $F(3, 4211) = 13.02$, $p < .001$, semipartial $R^2 = .008$.

Post hoc contrasts of estimated marginal means were calculated to compare average Lombard responses in the hold and after-effect phases to the baseline phase for both constant noise and voice onset–triggered noise conditions. In the constant noise condition, Lombard responses in the hold phase were significantly elevated from baseline in the early analysis window ($M = 3.19$ dB, $SD = 4.77$, $p < .001$), with a large effect size ($d = 0.82$). In the voice onset–triggered noise condition, Lombard responses in the hold phase were significantly elevated from baseline in the early analysis windows ($M = 1.6$ dB, $SD = 4.10$, $p < .001$), with a small effect size ($d = 0.42$). There was no statistically significant difference from baseline in the after-effect phase for either Lombard noise condition. We also performed a post hoc comparison of Lombard responses in the early analysis window in the hold phase from the constant noise condition with responses in the hold phase from the voice onset–triggered noise condition. Lombard responses in the hold phase were significantly larger in the constant noise condition as compared to the voice onset–triggered noise condition ($p < .001$), with a small effect size ($d = 0.40$).

Discussion

In the naturalistic Lombard task with constant noise (Experiment 1), Lombard responses were elevated during the hold phase in both the full trial and early analysis windows, drawing into question assumptions that Lombard responses are solely driven by feedback control. In Experiment 2, we compared vocal intensity in an early analysis window across two Lombard conditions: the constant noise condition (i.e., the identical Lombard condition from Experiment 1) and the voice onset–triggered noise condition (i.e., a new Lombard condition for which speech-shaped noise was not present prior to speech initiation). Vocal intensity was elevated in the early analysis window of the hold phase for both Lombard conditions in Experiment 2, confirming that speakers update their feedforward control across successive utterances during speaking in noisy environments. As hypothesized, Lombard responses were greater in the constant noise condition, as compared to the voice onset–triggered noise condition, suggesting that both prevoicing anticipation and updating of feedforward control contribute to Lombard responses. Contrary to our hypothesis, vocal intensity was decreased from baseline in the after-effect phase in Experiment 1. This finding was not replicated in Experiment 2. Loudness discrimination thresholds did not explain individual variation in Lombard responses. These findings are consistent with a hypothesis that Lombard responses may be partially driven by the process of updating feedforward control, and they are inconsistent with a hypothesis that auditory acuity mediates the magnitude of Lombard responses in a graded fashion.

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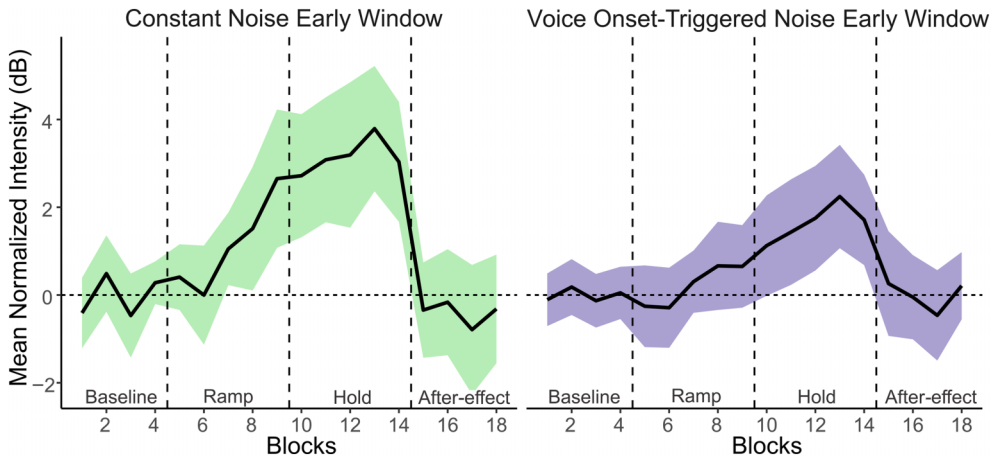
Figure 5. Lombard responses from Experiment 2. Lombard responses (baseline-normalized mean intensity over six trials) in the early analysis window across 108 trials of the Lombard task in two conditions (constant noise and voice onset–triggered noise) for Experiment 2. Shaded green areas represent 95% confidence intervals for the constant noise condition (left panel). Shaded purple areas represent 95% confidence intervals in the voice onset–triggered condition (right panel). Mean values are outlined in black.



Involvement of Feedback and Feedforward Mechanisms in Lombard Responses

Lombard Responses in the Hold Phase

In Experiment 1, Lombard responses in the hold phase were significantly elevated from baseline in both the full trial and early analysis windows for the constant noise condition. This finding suggests that Lombard responses may be driven not only by feedback mechanisms (Hage et al., 2013; Roy et al., 2011; Sakata & Brainard, 2006; Tyack & Janik, 2013) but also by feedforward control mechanisms (Castro et al., 2024; Luo et al., 2018). Based on prior auditory–motor adaptation research, a compensatory response in an early analysis window (i.e., before auditory feedback comes online; Burnett et al., 1997; Burnett & Larson, 2002) suggests that a speaker has updated their feedforward motor commands from prior vocalizations. This finding supports the hypothesis that speaking in noisy acoustic environments may involve the updating of feedforward control. The results of this study align with the literature supporting the theoretical construct that the Lombard effect is mediated by higher level processes (Castro et al., 2022; Garnier et al., 2010; Lindblom, 1990; Patel & Schell, 2008).

Adaptation studies typically present the speaker with altered auditory feedback starting at the onset of each vocalization to induce a perceived speech error for the speaker (Houde & Jordan, 1998). However, for the Lombard task in constant noise in Experiment 1, speakers were exposed to speech-shaped noise prior to the onset of speaking per trial (~1 s before vocalization). It is possible that the speakers in Experiment 1 were anticipating how their voice would sound in the noise prior to initiating each vocalization. This decision to introduce the noise prior to the onset of vocalization was motivated by a desire to model a typical communicative scenario. However, the distinction between adaptation paradigms and the Lombard task with constant noise should be considered when interpreting the findings of Experiment 1.

In Experiment 2, we found that vocal intensity was elevated in the early analysis window for the Lombard task with constant noise condition and the voice onset–triggered noise condition. Thus, we can confirm that Lombard responses from Experiment 1 were not driven solely by an auditory feedback-driven prevoicing anticipation based on the presentation of noise prior to speech onset. Furthermore, the finding that Lombard responses were greater in the constant noise condition, as compared to the voice onset–triggered noise condition, enables further interpretation. We confirmed our hypothesis that two simultaneous processes might be driving Lombard responses: (a) Speakers use the auditory feedback of the speech-shaped noise that is present prior to speech initiation to anticipate how their voice will sound in the noise (Daliri & Max, 2016; Li et al., 2024), and (b) speakers update their feedforward control for future vocalizations during speaking in noisy environments.

Lombard Responses in the After-Effect Phase

In the Lombard task with constant noise condition from Experiment 1, average Lombard responses for the after-effect phase were significantly decreased from baseline in the early analysis window. This finding from Experiment 1 differed from the prior Lombard study in individuals with voice disorders that demonstrated a persistence of Lombard responses from baseline following the removal of noise

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(Castro et al., 2022). We hypothesized that vocal intensity would be elevated from baseline in the early window of the after-effect phase. Instead, we observed an overshoot and stabilization of a lower intensity than the baseline throughout the after-effect phase. This pattern of lower intensity values during the after-effect in Experiment 1 was observed only in the early analysis window and not in the full trial analysis window, suggesting that the pattern may be explained by the involvement of updating feedforward control.

This significant finding in Experiment 1 was not replicated in the constant noise condition or in the condition with voice onset–triggered noise in Experiment 2. However, we observed a similar trend in the early window of the constant noise condition of Experiment 2 with a noticeable overshoot of lower intensity in the after-effect phase compared to baseline (see Figure 5). The lack of significant replication in Experiment 2 might be explained by the difference in sample size between the experiments (i.e., 30 speakers completed Experiment 1, and 20 speakers completed Experiment 2). Thus, it is possible that the statistical tests were not sufficiently powered to replicate the more subtle difference in responses during the after-effect from the baseline phase in Experiment 2.

Regardless of the lack of significant finding in Experiment 2, neither experiment in the present study replicated the persistence of (elevated) Lombard responses as observed in the prior study (Castro et al., 2022). This difference may be explained by discrepancies in the experimental designs. The present study measured Lombard responses at the sentence level, whereas the prior study used sustained vowels. Furthermore, Castro et al. (2022) found persistence of Lombard responses in individuals with voice disorders after participants took a 5-min vocal rest following noise exposure; the present study measured responses in speakers with typical voices starting immediately after noise removal (i.e., baseline-normalized average vocal intensity of the 24 sentences in the after-effect phase).

The present study also did not replicate the expected after-effects observed in classic f_o adaptation work (Jones & Munhall, 2000). Because the six stimuli within each block varied, we are unable to investigate whether Lombard responses persisted within the first one to three trials of the after-effect, as observed in prior f_o adaptation work. Thus, the lack of after-effects may be explained by either a methodological limitation or an inconsistency with prior work. One possible explanation is that noise-induced vocal motor adjustments more commonly occur in everyday life compared to f_o shifts. Therefore, the process of de-adaptation may be stronger and closer to automatized, allowing speakers to very rapidly return to baseline. More research is needed to thoroughly interpret the exact timeframe of de-adaptation of Lombard responses following noise exposure.

Auditory Acuity and Lombard Responses

We observed substantial variability of full-trial Lombard response magnitudes in the hold phase for Experiment 1 (SD = 2.86 dB), which aligns with the individual variability of Lombard responses observed in prior work (Bottalico et al., 2016; Lindstrom et al., 2011; Stathopoulos et al., 2014; Whittico et al., 2020). In conflict with our hypothesis, variation in loudness discrimination ability did not significantly explain the variation of Lombard response magnitudes in this study. Prior work suggests that some level of auditory function is necessary to engage the mechanisms driving Lombard responses (Lane & Tranel, 1971; Lombard, 1911). However, this study suggests that auditory discrimination may be involved but not in a graded fashion.

In this study, we only compared one type of auditory processing ability with Lombard responses. We compared Lombard responses with loudness discrimination, rather than another perceptual feature (e.g., pitch or articulation). This decision was motivated by an effort to compare acuity within the same domain as the primary outcome measure of Lombard responses (i.e., vocal intensity). However, it is possible that the acoustic features (i.e., intensity, pitch, or formants) that are most susceptible to change during speaking in noisy environments are person specific. Lombard responses are not limited to increased vocal intensity but involve segmental and prosodic modifications as well (Garnier & Henrich, 2014; Summers et al., 1988; Whitling et al., 2015; Whittico et al., 2020). Given the multiparametric nature of the Lombard effect, a more comprehensive evaluation of discrimination ability for pitch and articulation would be required to discern the true underlying factors driving Lombard responses.

Between-participant variation in peripheral hearing may also explain the lack of significant correlation. In this study, we included individuals who passed an audiometric hearing screening (ASHA, 2018). However, we did not investigate peripheral hearing as an outcome measure to compare with Lombard responses. It is possible that a more in-depth analysis of peripheral hearing (e.g., comparing hearing thresholds to Lombard responses) would better account for the variance in Lombard responses. Furthermore, additional evaluation of the central auditory system may have identified individual participant variation in central auditory processing that might explain variation in Lombard responses. Future work should use auditory temporal processing tests (Eggermont, 2015; Walker et al., 2002) or speech-in-noise tests (Billings et al., 2024; Taylor, 2003) to comprehensively evaluate the variation of Lombard responses observed in individuals with typical hearing thresholds.

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It is also possible that a relationship between acuity and Lombard responses was masked by the measurement noise observed within the individual Lombard responses (see Figure 2 for confidence intervals). In a recent study investigating test–retest reliability of behavioral assays of auditory–motor control of voice, researchers found that f_o adaptive responses for the pitch adaptation paradigm showed poor test–retest reliability (Kapsner-Smith et al., 2024). Since this Lombard task was closely modeled after pitch adaptation paradigms, it is possible that the Lombard responses may be too noisy to detect person-specific relationships with acuity. Future work should measure test–retest reliability of Lombard magnitudes to investigate the reliability of person-specific Lombard response magnitudes.

Clinical Implications

Speaking in noisy acoustic environments is a common occurrence in daily life. Thus, investigation of the mechanisms underlying the Lombard effect can inform clinical voice care. This article investigated Lombard responses in speakers with typical voices, providing a foundational understanding for typical vocal motor behaviors. A recent study found preliminary evidence for differences in the Lombard effect in individuals with vocal hyperfunction; after speaking in noise, Lombard responses for those with vocal hyperfunction persisted after removal of the noise compared to controls (Castro et al., 2022), suggesting a potential deficit in integrating feedback into feedforward commands (Castro et al., 2024). Furthermore, a subset of individuals with vocal hyperfunction was shown to have atypical auditory–motor responses during an altered auditory-feedback paradigm (Abur et al., 2021; Stepp et al., 2017). Recent research has also shown that current voice therapy approaches may inherently improve auditory–motor control in individuals with vocal hyperfunction (Abur et al., 2021), suggesting a need for standardized clinical practices to measure auditory–motor function.

Together, these prior findings and the findings of this study suggest that the Lombard task can be designed as an altered auditory-feedback adaptation paradigm to measure sensorimotor adaptation in individuals with vocal hyperfunction. Future clinical applications of the Lombard task could include its use as an ecologically valid voice diagnostic tool and the development of individualized auditory and auditory–motor treatment for those with sensorimotor integration deficits underlying their vocal hyperfunction. However, the Lombard task must first be directly compared to typical adaptation paradigms to better determine whether atypical auditory–motor adaptation is related to atypical Lombard responses.

Limitations and Future Directions

There were a few limitations to the design and interpretation of the Lombard tasks in this study. Despite our attempts to design a Lombard task that modeled naturalistic communication with built-in experimenter interactions, the task was completed within a lab setting, and the participants wore headphones throughout. Additionally, in real-life communication in noise, there are likely higher level communicative predictions about how the listener will perceive a speaker's message. In this study, the speaker was not communicating a particular message to the experimenter/listener; instead, they were just reading aloud sentences. The present study is not designed to inform us about the nature of these communicative predictions that likely occur in more ecologically valid scenarios. These experimental features limit our ability to directly apply findings to that of a typical conversational interaction.

One limitation of the acuity tasks was that the loudness discrimination tasks were not counterbalanced. Because the loudness discrimination in quiet was presumed to be easier than the loudness discrimination in noise task, participants always completed the loudness discrimination task first in quiet and then in noise. Despite the researchers' a priori expectation that the loudness discrimination in quiet would be better than the loudness discrimination in noise task, about one third of the total participants performed better on the loudness discrimination in noise task. Thus, the finding that better discrimination ability was not associated with greater Lombard responses may have been influenced by uncontrolled individual factors, such as an individual's ability to learn or a heightened ability to attend to complex stimuli, and therefore, perform better on the second discrimination task.

Speaking in background noise is a common occurrence for many speakers in their daily lives. Thus, the Lombard task used in this experiment has the potential to elicit a comprehensive understanding of the role of auditory–motor function and dysfunction in speaking in noisy environments. These findings motivate future studies to investigate other auditory and/or somatosensory factors that may explain variation in Lombard responses. However, this task has yet to be compared to the standard lab-grade altered auditory feedback adaptive paradigms used in speech motor control research. Furthermore, future work is needed to compare the Lombard task to classic adaptation paradigms.

Conclusions

This study investigated the underlying auditory mechanisms associated with Lombard responses in speakers with typical voices. As expected, Lombard responses were

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elicited during the Lombard task. Lombard responses were significantly elevated from baseline in an early analysis window during speaking in noise for both Lombard conditions (when noise was presented prior to voicing and when noise was triggered by voicing onset), suggesting that Lombard responses are driven by both feedback and the updating of feedforward mechanisms. Loudness discrimination thresholds did not account for the variance in Lombard responses. These findings motivate future studies to investigate other auditory factors that may explain variation in Lombard responses. Future research should compare the Lombard task with altered auditory feedback adaptation paradigms to further validate the Lombard task as a naturalistic protocol to inform clinical voice care in individuals with voice disorders.

Data Availability Statement

The data sets generated and/or analyzed during the current study are not publicly available due to commitments to protect participant confidentiality but are available from the senior author, Cara E. Stepp (cstepp@bu.edu), through formal mechanisms on reasonable request.

Acknowledgments

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Appendix

List of Six Lombard Stimuli Pseudorandomized per Experimental Block

1. We saw a wee fly on my food on Monday.
2. We showed Nell my shiny new shoe bin.
3. The leafy tree should grow three feet this year.
4. The classy Casey scarfed down the beefy burger.
5. They ordered miso soup and sushi to eat.
6. I think wishy washy Buffy may never decide.

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