IS THERE A STARTING POINT IN THE NOISE LEVEL FOR THE LOMBARD EFFECT?

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Abstract

The Lombard Effect is an involuntary tendency to raise the voice with an increase in the background noise. The aim of this study was to determine the starting point of the Lombard Effect in terms of background noise level (Ln). Twenty subjects read a passage with the goal of being understood by a listener at 2.5 m. Background pink noise emitted by a loudspeaker varied from 20 dBA to 65 dBA in 5 dB increments. Using a regression model, the data was segmented, and slopes estimated around, a change point(s) in the relationship between the response variable, within-subject normalized SPL, and the explanatory variable, Ln. The rate of change in speech level below 43.3 dBA of noise was about 0.24 dB/dBA while the rate of change above 43.3 dBA was 0.65 dB/dBA. Hence, 43.3 dBA of noise indicates the point of change in the speaker's adaptation to the background noise level.

Keywords: Lombard effect, Speech in Noise, Noise Annoyance, Vocal Effort.

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1 Introduction

The level of a speaker's vocal effort depends on the acoustics of the space, the level of the background noise and the type of communication. Vocal effort can be expressed by the equivalent continuous A-weighted sound pressure level (SPL) of speech measured at a distance of 1 m from the mouth in anechoic conditions [1]. In the presence of noise, speech can be masked, and its production can be modified by what is called the Lombard effect [2]. The Lombard effect is the involuntary response by talkers to the presence of background noise; the vocal level, and therefore the vocal effort, increase as the magnitude of communication disturbance increases. It can be assumed that vocal discomfort will increase as the magnitude of the noise disturbance increases. Historically, the increase in the vocal level as a function of the noise level in an environment has been considered to be a linear phenomenon that is constrained by the maximum power level that a talker is able to produce (*i.e.*, the "ceiling'" [3]), without much consideration of the noise level at which the Lombard effect first appears.
Studies have addressed the Lombard effect in various conditions [3,4,5,6], and various slopes have been reported for the relationship between the noise level and voice level. These slopes vary according to boundary conditions such as the speech situation (reading *vs*. holding a conversation), the noise type (including machinery noise, office noise, speech noise, wide band noise, white noise, and pink noise), the style of speech (normal or shouting), the speaker-listener distance, and the acoustics of the room.

Lazarus [5] stated that the speech level rises with the noise level with a slope of 0.3-0.6 dB per noise level rise of 1 dB for all disturbing noise exceeding 40-50 dB(A). However, up to a noise level of 30-40 dB(A), the noise level has a minimal effect on the speech level [6,7,8], and in the presence of very high noise levels, there is saturation in the voice level due to physiological limitations [9,10]. In sum, although much attention has been paid to the Lombard effect, information about the existence of the starting point in terms of noise level, and the slope for the low noise levels, are still lacking.
In this study, the objective was to determine whether there is a particular point at which the Lombard effect, as traditionally described, commences. The research question was: *Is there a starting-point in the level of the noise for the Lombard effect?* It was hypothesized that there would indeed be a starting point for the Lombard effect and that this point would occur in the region of 35-45 dB(A), as predicted on the basis of previous studies [6,7,8].

2 Experimental method

In this study, the effects of noise on vocal effort (quantified as SPL) were evaluated, where noise varied between 20 and 65 dB(A). Ethical approval was obtained from Michigan State University's Human Research Protection Program (IRB #13-1149) for the recruitment and audio recording of 10 male and 10 females (18-34 yrs; mean 22 yrs). These subjects reported no history of speech impairment and were audiometrically assessed between 250 Hz and 6 kHz to confirm normal hearing ≤ 20 dB HL.
Subjects were recorded in a sound-attenuated booth both without noise (background noise was equal to 20 dB(A)) and with artificial pink noise (at levels from 25 to 65 dB(A), with an incremental step of 5 dB). In order to simulate a real communication setting, subjects were seated facing a human listener, positioned at a 2.5 m distance. The 10 noise conditions were presented in a randomised order.
The subjects were instructed to read a text (a 6-sentence excerpt from the Rainbow passage [11]), which was attached to a small stand placed at a 1 m distance from the speakers. Subjects were issued the following instructions: ‘Each time, I [the listener] would like you to pretend that you are telling the story to me. Make sure that I understand you equally well each time.’ The listener was present in the booth during the entirety of the experiment.

3 Room acoustic and measurement procedures

The experiment took place in a sound-attenuated booth (2.5 m x 2.75 m x 2.0 m). Speech was acquired by a head-mounted microphone (HMM Glottal Enterprises M-80), which was connected to a PC via a Scarlett 2i4 Focusrite soundboard. The recording software was Audacity 2.0.6.
Speech was recorded in ten noise conditions: natural background noise at 20 dB(A) and nine levels of added pink noise: from 25 to 65 dB(A) in 5dB increments. The noise levels for the ten conditions were measured with a NTI Measurements microphone M2211 (Class 1 frequency response) and analyzed by means of the NTI XL2 Audio and Acoustic Analyzer (level range 10 -110 dB(A)). The measurements were performed by placing the microphone in the position of the subject's ears. Pink noise was emitted by a directional speaker (KRK Systems studio monitor model Rokit5 G3) placed at 2.5 m from the subject and directed at the subject. The gain of the playback software of the studio monitor was modified in order to obtain increments of 5 dB over the background noise.
Reverberation time was measured in the sound booth from the impulse responses (IRs) generated by balloon pops [12]. Four IRs were recorded in two source positions and two microphone positions by means of NTI Measurements microphone M2211 (Class 1 frequency response) and analyzed by means of the NTI XL2 Audio and Acoustic Analyzer. The reverberation time (T20) at mid-frequencies in the room was 0.05 s, and the trend over the octave band was almost flat.

4 Analysis

MATLAB (2014b) was used for speech signal analysis. For each condition, the mean value of the SPL was obtained per subject. For each subject, the average of SPL among the conditions was computed and subtracted from each mean SPL value for that subject to derive ΔSPL. This within-subject centering was performed in order to evaluate the variation in the subject's vocal behavior in the different conditions from their typical vocal behavior.
Statistical analysis was conducted using R version 3.1.2. A piecewise linear (also called segmented or broken-line) model was fit to the response variable SPL with the predictor, noise level, using the segmented package in R [13]. In such models, the fitted lines are constrained to be connected at the estimated change-point, *i.e.,* the change-point in the relationship between the response and the predictor. At the change-point, it is assumed that the mean of the parameter is constant between the two slopes. If the first slope is equal to zero, the change-point can be considered a starting point. Firstly, a linear model is fit. Subsequently, using the segmented function, maximum-likelihood methods are used to determine the slopes of the regression lines and the location of the change-point. No initial guess for change-point locations or the number of change-points is supplied. The confidence intervals for the change-point are estimated using the standard error from the Delta method for the ratio of two random variables [13].

5 Results

ΔSPL was measured at each of the 10 noise levels between 20 and 65 dB(A), as shown in Fig. 1. A piecewise linear model was fit to the response variable, ΔSPL and the predictor, Ln. The slope of the lower segment, was 0.24, and the upper, 0.65, with a change-point identified in Ln at 43.3 dB(A) (CI 95% lower: 41.0, CI 95% upper: 45.6) with R^2 equal to 0.94. The change-point, Ln = 43.3 dB(A), can be considered to reflect the starting point for the Lombard effect as traditionally known. Model estimates with associated standard errors and p values are given in Table I.

Table 1 – Summary of output for the piecewise linear model with response variables ΔSPL as a function of Ln.

Response	Predictor	Estimate	Std. Error	t value	p	Ln Domain / dB(A)
ΔSPL / dB(A)	(int.) Ln	-12.44 0.24	0.70 0.02	-17.89 10.46	< 0.001 < 0.001	$20 \leq Ln \leq 43.3$
	(int.) Ln	-30.25 0.65	1.33 0.02	-22.88 -27.09	< 0.001 < 0.001	$43.3 \leq Ln \leq 65$

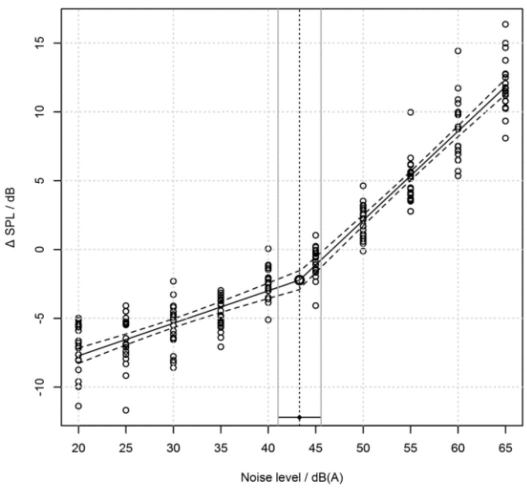

Figure 1 - Voice level (Δ SPL / dB) is shown as a function of the level of the noise in dB(A). The Lombard effect change-point is marked by a large black circle on the vertical dark dashed line. Confidence intervals for this change-point are marked by the so-called rug (1-d representation of the change-point) at the foot of the figure and the lighter vertical lines. 95% confidence intervals for the two fitted slopes are indicated by dashed black lines.

6 Conclusions

The results of this study, which are comparable to those reported in previous studies, support the claim that vocal level, and therefore effort, increase as background noise increases. The hypothesis of a starting point for the Lombard Effect could not be confirmed. However, as background noise increased, a change-point could be identified in the slope of the increase in vocal level (Lombard Effect), at a noise level equal to 43.3 dB(A). The slope of the Lombard effect can be estimated as an increase in the voice level of 0.65 dB(A) per 1 dB(A) increase for noise levels higher than 43.3 dB(A). Hence, the change-point of the Lombard effect may be estimated at a noise level equal to 43.3 dB(A), which is consistent with Lazarus's claim [6] that only when the noise level exceeds 40 dB is there a non-minimal effect on the speech level. However, recall that the estimate of the slope for noise levels prior to the change-point - between 20 dB(A) and 43.3 dB(A) - was an increase of 0.24 dB(A) in the speech level per 1 dB(A) noise increase.

In future studies, the step increase could be refined from a coarse 5 dB step to better estimate the change-point, and the talker's response to pink noise could be compared with their responses to various other types of noise with different spectral shapes.

In conclusion, speakers use different levels of vocal effort depending on the acoustics of the space, the level of the background noise and the type of communication. An understanding of the nature of the speaker's response to the environment can throw light on speech communication and vocal limitations caused by overuse of the voice [14, 15].

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