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Evaluation of the Starting Point of the Lombard Effect

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Summary

Speakers increase their vocal effort when their communication is disturbed by noise. This adaptation is termed the Lombard effect. The aim of the present study was to determine whether this effect has a starting point. Hence, the effects of noise at levels between 20 and 65 dB(A) on vocal effort (quantified by sound pressure level) and on both perceived noise disturbance and perceived vocal discomfort were evaluated. Results indicate that there is a Lombard effect change-point at a background noise level (Ln) of 43.3 dB(A). This change-point is anticipated by noise disturbance, and is followed by a high magnitude of vocal discomfort.

1. Introduction

As a person encounters different communication environments, they adjust their voice [1]. The level of a speaker's adjustment and vocal effort depends on the acoustics of the space, the level of the background noise and the type of communication. The Lombard effect [2] is a vocal response by a speaker to the presence of background noise [3]. This change in voice production has been characterized by a higher vocal intensity, higher fundamental frequency, changes in first-formant frequency and articulation; variations in spectral components, and increased vowel intensity and duration [4, 5, 6, 7, 8].

Of these characteristics, vocal intensity has been tied to vocal effort. Vocal effort can be expressed by the equivalent continuous A-weighted sound pressure level (SPL) of speech measured at a distance of 1 m in front of the mouth in anechoic conditions [9]. Therefore, due to the Lombard effect, the vocal effort increases as the magnitude of disturbance increases. It can be assumed that vocal discomfort will increase as the magnitude of the communication disturbance by noise increases. Historically, the increase in the level of the voice as a function of the level of noise in an environment has been considered a linear phenomenon constrained by the maximum power level that a talker is able to produce ("ceiling effect" [10]), without much consideration of the noise level at which the effect first becomes apparent.

Many studies have addressed the Lombard effect in a variety of conditions [10, 11, 12, 13, 14]. Various slopes of the relationship between the noise level and voice level have been reported. These slopes vary according to boundary conditions such as the speech situation (reading vs conversing), type of noise (machinery noise, office noise, speech noise, wide band noise, white noise, pink noise), the style of speech (normal or shouting), the speaker-listener distance, and the room acoustics. Lazarus [13] 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 minimal effect on the speech level [14, 15, 16], and there is saturation in the voice level due to physiological limitations in very high noise levels [17, 18]. In sum, although close 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, is still lacking.

In this study, the primary aim was to determine whether there is a particular starting point at which the Lombard effect, as traditionally known, commences. The research questions were as follows:

1. Is there a starting-point in the level of the noise for the Lombard effect?
2. Is there a starting-point for self-reported communication disturbance, and how does this relate to the starting-point for the Lombard effect?
3. Is there a starting-point for self-reported discomfort, and how does this relate to starting-points for disturbance and the Lombard effect?

It was hypothesized that there would in fact be a starting point for the Lombard effect and that this point would occur in the region of 35–45 dB(A), based on the results of previous studies [14, 15, 16].

2. Experimental method

In this study, the effects of noise varying between 20 and 65 dB(A) on (1) vocal effort (quantified as SPL), (2) the amount of self-reported disturbance in the communication by noise and vocal control, and (3) the amount of self-reported discomfort, were evaluated.

With protocol approval of the Michigan State University's Human Research Protection Programs Human Subjects Review Board (IRB #13-1149), 10 male and 10 females were recruited to participate. The speech of the 20 talkers (18-34 yrs; mean 22 yrs) was recorded in a sound-attenuated booth both with and without artificial pink noise. These subjects reported no history of speech impairment and were audiometrically assessed between 250 Hz and 6 kHz to confirm normal hearing lower than or equal to 20 dB HL.

In order to simulate a real communication setting, subjects were seated in the booth facing a human listener, positioned at a 2.5 m distance. The 10 noise conditions (see Section 2.1) were presented in a random order. Subjects were asked to read the text to the listener using 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.

The subjects were instructed to read a text (a 6-sentence excerpt from the Rainbow passage [19]), which was attached to a small stand placed at a 1 m distance from the speakers. After each reading of the text, subjects were asked to answer two questions about the experience of talking in the various noise level conditions to evaluate disturbance and discomfort. The questions were as follows:

1. *Disturbance*: Please rate the amount of disturbance you perceived during your communication by noise. (The extremes of the lines were "very low" to the left and "very high" to the right.)

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2. *Discomfort*: How comfortable was it to speak in this condition? (The extremes of the lines were “extremely” to the left and “not at all” to the right.)

These questions were worded in a manner consistent with the relevant ISO standard [20] and administered immediately after the exposure to the noise of the task. Subjects responded to the questions by making a vertical tick on a continuous horizontal line of 100 mm length (a visual analogue scale).

2.1. 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) and 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 5 dB 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 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 s ubject’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 [21]. The 4 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 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.

2.2. Analysis

MATLAB (2014b) was used for speech signal analysis. In each condition the equivalent SPL was measured. The levels were a combination of two sources: the voice and the noise. However the effect of noise on the equivalent level was negligible because the signal (voice) to noise ratio was at least 17 dB. The contribution of the background noise on the overall level (noise and voice) was below 0.08 dB.

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 values for that subject (termed 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.

Self-reported communication disturbance and discomfort were measured on visual analogue scales. The score was measured as the distance of the tick from the left end of the line and converted into a percentage, where 0 indicates no disturbance or discomfort, and 100, maximal disturbance or discomfort.

Statistical analysis was conducted using R version 3.1.2. Three piecewise linear (also called segmented or broken-line) models were fit to the response variables SPL, self-reported discomfort and self-reported disturbance with the predictor, noise level, using the segmented package in R. 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 as a starting point. Firstly, a simple 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 [22]. Because the segmented function [22] accepts as input only simple linear models and not mixed-effect models, the between-subject variability was taken into account by the within-subject centering.

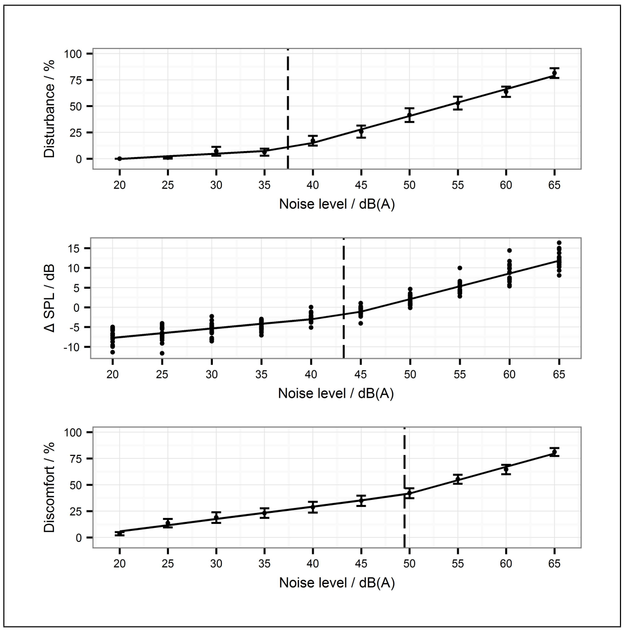

Figure 1. Relationship between the level of the noise in dB(A) and self-reported level of communication disturbance (upper), voice level (center) and self-reported level of discomfort (lower), where the error bands indicate the standard error. The change-points are marked by a vertical dashed line.

3. Results

The ΔSPL was measured at each of the 10 noise levels between 20 and 65 dB(A), as shown in Figure 1. A piecewise linear model was fit to the response variable, ΔSPL SPL 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 an R-squared of 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.

Self-reported communication disturbance was measured at each of the ten noise levels (Figure 1). A piecewise linear model was fit to the response variable, disturbance (%) and the predictor, Ln. The slope of the lower segment was 0.50, and the upper was 2.55, with a change-point in Ln identified at 37.4 dB(A) (CI 95 % lower: 31.7, CI 95 % upper, 43.1) and an R-squared of 0.65.

Table I. Piecewise Linear model output for three models with response variables ΔSPL SPL, Disturbance and Discomfort as a function of Ln.

Response	Predictor	Estimate	Std. Error	t value	p	Ln Domain / dB(A)
Δ SPL / dB(A)	(Int.)	-12.44	0.70	-17.89	< 0.001	20 ≤ Ln≤ 43.3
	Ln	0.24	0.02	10.46	< 0.001	
	(Int.)	-30.25	1.33	-22.82	< 0.001	43.3 < Ln≤ 65
	Ln	0.65	0.02	-27.09	< 0.001	
Disturbance / %	(Int.)	-10.03	6.78	-1.48	0.143	20 ≤ Ln≤ 37.4
	Ln	0.50	0.24	2.06	< 0.05	
	(Int.)	-86.77	13.68	-6.34	< 0.001	37.4 <Ln≤ 65
	Ln	2.55	0.26	9.92	< 0.001	
Discomfort / %	(Int.)	-17.75	6.95	-2.56	< 0.05	20 ≤ Ln≤ 49.5
	Ln	1.17	0.21	5.69	< 0.001	
	(Int.)	-84.82	22.02	-3.85	< 0.05	49.5 < Ln≤ 65
	Ln	2.53	0.38	6.64	< 0.001	

Models estimates with associated standard errors and p values are given in Table I.

Self-reported vocal discomfort was measured at each of the ten noise levels, as shown in Figure 1. A piecewise linear model was fit to the response variable, discomfort (%) and the predictor, Ln. The slope of the lower segment, was 1.18, and the upper, 2.53, with a change-point in Ln identified at 49.5 dB(A) (CI 95 % lower: 41.6, CI 95 % upper, 57.4) with an R-squared of 0.59. The intercepts for the two slopes were -17.75 and -84.82. Model estimates with associated standard errors and p values are given in Table I.

4. Discussion

Based on the reported results, which are comparable to previous work, it can be claimed that vocal level (effort), disturbance, and vocal discomfort increase as background noise increases. The hypothesis of a starting point for the Lombard Effect was not verified. However, as background noise increased, change-points could be identified in the slope of the increase in vocal level (Lombard Effect), disturbance, and discomfort. Regarding the objective measure of vocal effort, a change-point of the Lombard effect was identified at a noise level equal to 43.3 dB(A). Regarding the subjective measures, the change-point for disturbance was lower at a noise level equal to 37.4 dB(A), and for discomfort, was higher at a noise level equal to 49.5 dB(A). Subjects started to become (more) disturbed by noise at a lower noise level than that associated with the change-point of the Lombard effect, while they started to perceive discomfort at a higher noise level.

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 [14] 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 between 20 dB(A) and 43.3 dB(A) was an increase of 0.24 dB(A) per 1 dB(A) noise increase.

5. Conclusions

In this study, the primary aim was to determine whether there is a particular starting point at which the Lombard effect, as traditionally known, commences. Results indicate that there is a change-point in the Lombard effect associated with the level of the background noise. As the noise level increases incrementally from 20 dB(A) to 65 dB(A), initially, talkers begin to be disturbed by the increased noise level. Having perceived the disturbance, talkers begin to strongly increase their speech level due to the Lombard effect. Finally, when the noise exceeds that at the change-point, the talkers experience greater discomfort. While the relationship between the Lombard, disturbance and discomfort change-points was estimated in this study, the exact location was calculated on the basis of a coarse 5 dB step pink noise level increase. In this study, because of the background noise presence on the recording, it was not prudent to asses spectral characteristics of the speech material. Moreover, possible gender effects were probably masked by the within-subject centering.

Future studies could refine the step increase to better estimate the change-points, and compare the talker‘s response to pink noise to their responses to various other types of noise with different spectral shapes, such as babble and traffic noise. Moreover, denoising techniques could be used to analyzed spectral changing in the speech [23].

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 a speaker‘s response to their environment can throw light on speech communication and vocal limitations caused by overuse of the voice [24, 25].

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