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SPEECH LEVEL ADJUSTMENT TO REVERBERATION TIME AND EARLY REFLECTIONS

Pasquale Bottalico, Simone Graetzer, Eric J. Hunter

Communicative Sciences and Disorders, Michigan State University, East Lansing, Michigan, USA.
{pb@msu.edu, sgraetz@msu.edu, ejhunter@msu.edu}

Abstract

Talkers adjust their vocal effort according to room acoustic conditions. The present paper addresses how vocal effort, which can be quantified in terms of Sound Pressure Level (SPL), is affected by not only room acoustics, but also speaking style and short-term vocal fatigue. The speech levels produced by 20 subjects in the presence of babble noise were measured in anechoic, semi-reverberant and reverberant rooms. Each room was modified acoustically by increasing the strength of the early sound reflections in the talker position. The subjects reported their perceived vocal effort, comfort, control, and vocal clarity. Results indicated that SPL and self-reported effort increased in the loud style and decreased when reflective panels were present and when reverberation time increased. Talkers experienced the least short-term vocal fatigue in the semi-reverberant room.

Keywords: Vocal effort, reverberation time, vocal fatigue, acoustic clarity, loud voice.

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1 Introduction

The interaction between a person, a room and an activity leads to different experiences or sensations relating to voice production. This interaction determines the acoustic comfort, which contributes to well-being. It also affects vocal comfort, which is a psychological magnitude that is determined by those aspects that reduce the vocal effort [1], e.g., the speaker-listener distance and the background noise level. Vocal comfort appears to decrease with the speaker's perceived fatigue and the sensation of needing to increase the voice level [2]. A speaker may unconsciously balance vocal effort and vocal comfort to maintain their own clarity and intelligibility.

Vocal control can be defined as the capacity to regulate one's own vocal behavior. The sensation of control relates to the ability to adjust the voice consciously. In adverse conditions, or when the talker is aware that the listener may have difficult perceiving their speech due to a hearing impairment or a different native language, talkers attempt to control their voice production in order to meet the needs of listeners [3,4].

Vocal effort is a physiological entity accounting for changes in voice production that can be expressed by the A-weighted SPL (dB) at 1m from the mouth [5]. It relates to factors such as the characteristics of the listener [4], the speaker-listener distance, the background noise level, and other acoustic characteristics of the room [6,7], and also linguistic factors such as vowel quality [8], and the speaker’s level of fatigue [9,10]. Vocal fatigue is often experienced by speakers who use their voice for long periods and and/or with increased vocal effort, such as teachers. Titze [1] identified two physiological aspects of such fatigue: laryngeal muscle fatigue and laryngeal tissue fatigue. The minimization of vocal fatigue is particularly important when (1) the speaker is at high risk of vocal injury, such as in teaching environments [11], when classroom acoustics are poor [12]; and (2) when vocal function is impaired by loading and/or incomplete muscle recovery [13]. SPL, in particular, has been found to be affected by vocal loading, possibly inducing vocal fatigue [9]. Reverberation time has been found to influence voice power level and vocal intensity in continuous speech. The effects on voice power level of reverberation time and speaker-listener distance were investigated by Pelegrín-García *et al.* [6]. They found that the vowel power level increased as a function of the speaker-listener distance (1.5 to 12 m), and at every distance was at its highest in an anechoic chamber, relative to a lecture hall, a long and narrow corridor and a reverberation room.

The aim of the present study was to evaluate the effects of room acoustics, voice style (corresponding to normal and raised levels) and chronological task order or “experimental presentation order” on vocal effort (SPL) and self-reported vocal effort, control, comfort and clarity. The two independent room acoustic parameters were the reverberation time and the external auditory feedback. The main research questions were: (1) is it possible to decrease speakers’ vocal effort by increasing their external auditory feedback, and (2) if there is such an effect, how does it interact with the effects of reverberation time and speech style?

Experimental method

The speech of 20 talkers was recorded in 3 rooms with different reverberation times in the presence of classroom babble, with and without reflective polycarbonate panels at 0.5 m from the talkers’ mouths. Ethics approval for the experiment was granted by the Michigan State University Human Research Protection Program (IRB 13-1149). 20 subjects, 10 males and 10 females, participated in the experiment. The subjects, who were non-smoking English-speaking MSU students, were aged between 18 and 30 ys. (mean age 20.8 ys.) and had self-reported normal speech and hearing.

The subjects were instructed to read a text of approximately 30 s in duration in the presence of classroom babble noise, with and without reflective panels at 0.5 m from the mouth. The text was a 6 sentence excerpt from the Rainbow passage printed and attached to a stand at 1 m from the subject. Two speech styles were elicited - normal and loud - for which the instructions were as follows: “Speak in your normal voice” (Normal); “Imagine you are in a classroom and you want to be heard by all of the children” (Loud).

The first of the 3 rooms was an anechoic room with dimensions 3.4×4.6×2.4 m (IAC 107840). The second was a semi-reverberant room, 8.5×7.3×4.6 m. The third room was a reverberant room with dimensions 7.7×6.4×3.6 m (IAC 107840). In each room, the subject was asked to read in 4 conditions, for a total of 12 tasks per subject: (1) with a normal vocal effort and without reflective panels; (2) with a loud vocal effort and without reflective panels; (3) with a normal vocal effort and with reflective panels; and (4) with a loud vocal effort and with reflective panels. The order of administration of the tasks was randomized.

Subjects answered 4 questions after each task: (1) Effort: How effortful was it to speak in this condition? (2) Control: How well were you able to control your voice in this condition? (3) Comfort: How comfortable was it to speak in this condition? (4) Clarity: How clearly did you perceive your own voice in this condition? Subjects responded by making a vertical tick on a continuous horizontal line of 100 mm in length (on a visual analogue scale or VAS). The score was measured as the distance of the tick from the left end of the line. The extremes of the lines were ‘not at all’ (left) and ‘extremely’ (right).

Equipment and Room acoustic parameters

Speech was recorded by a head-mounted omnidirectional microphone placed at a distance of 5-7 cm from the mouth (Glottal Enterprises M80, Glottal Enterprises, U.S.A). The microphone was connected to a PC via an external sound board (Scarlett 2i4 Focusrite, Focurite, U.S.A.). The signals were recorded with Audacity 2.0.6 with a sampling rate of 44100 Hz.

Room acoustic parameters were obtained from the impulse response measurements in the non-occupied condition for the three rooms [14]. Balloon pops were used as impulses. The T30 for combined 500 Hz and 1 kHz octave bands was 0.04 s (s.d. 0.005) in the anechoic room, 0.78 s (s.d. 0.012) in the semi-reverberant room and 2.37 s (s.d. 0.167) in the reverberant room.

To manipulate the level of external auditory feedback in the position of the talker, 2 reflective panels were placed at 45°, 0.5 m from the subject. The panels were made of transparent polycarbonate material and had a surface area of 56 x 66 cm^2, which was perpendicular to the lines joining the panels and the subject. The presence of the panels generated a strong first reflection of the subject's voice. In order to quantify this effect, pink noise was emitted from the mouth and received by the ears of a Head and Torso Simulator (HATS) with Mouth Simulator (45BC KEMAR). This measurement was repeated in the 3 rooms, each both with and without reflective panels, maintaining a constant source (mouth) power. The ears were connected to an audio analyzer (XL2, NTI audio). Figure 1 shows the difference between the SPL measured per octave band in the anechoic room without panels and the sound levels measured in all room and panel conditions. Higher SPL was recorded in the frequencies relevant to speech in all rooms when panels were present. The higher the reverberation time in the room, the higher the increase in SPL introduced by the panels.

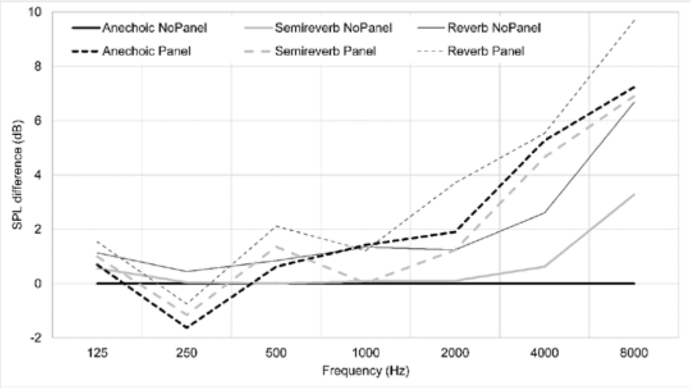

Figure 1 - Differences in SPL measured per octave band between the anechoic room without panels and the sound levels measured in all room and panel conditions.

Classroom babble was emitted by a directional loudspeaker placed 2 m in front of the subject. The power level of the loudspeaker was set in order to obtain an A-weighed equivalent level averaging both ears of 62 dB at the talker position (measured with the HATS). This level represents the background noise present in a classroom during group activities [15].

Analysis

MATLAB 2015b was used for speech signal analysis. For each condition (task), a time history with SPL evaluated at 0.125 s intervals was obtained from the recorded speech. Hence, 12 time histories were obtained per subject. The average among all SPL values was computed per subject, and this mean was subtracted from each value of the 12 time histories performed by that subject. This within-subject centering was performed in order to evaluate the variation in the subject's vocal behavior in the different conditions from the average vocal behavior. After transformation, the parameter was termed ΔSPL. The time information associated with the time histories (which typically ranged from 0 to 30 seconds within a task) was retained for inclusion in the statistical analysis.

Statistical analysis was conducted using R version 3.1.2. Linear Mixed-Effects (LME) models were fit by restricted maximum likelihood (REML). Random effects terms were chosen on the basis of variance explained. Models were selected on the basis of the Akaike information criterion (the model with the lowest value being preferred) and the results of likelihood ratio tests and were built using lme4, lmerTest and multcomp packages. Tukey's post-hoc pair-wise comparisons were performed to examine the differences between all levels of the fixed factors of interest. The p values for these multiple comparisons were adjusted using the default single-step method. The LME output includes the estimates of the fixed effects coefficients, the standard error associated with the estimate, the degrees of freedom, *df*, the test statistic, *t*, and the *p* value. The Satterthwaite method is used to approximate degrees of freedom and calculate p values.

Results

A LME model was run with the response variable ΔSPL (dB) and the fixed factors (1) style, (2) room, (3) panel, (4) gender and (5) chronological task order or 'order' (between task 1 and task 12) with interactions of (6) room and style and (8) room and order. The random effects were the interaction of subject and time (where time was measured in ms per task). Other possible interactions were excluded after likelihood-ratio tests indicated that their inclusion did not improve the model fit ($p > 0.1$). Model results are shown in Table 1, while summary statistics in the 12 conditions are shown in Table 2. The effects of style, room, panel and order, and the interactions between room and style, room and order and style and gender were significant, with the exception of the interaction between order and the anechoic room.

The mean increase in ΔSPL from the normal to the loud style was 8.32 dB. However, the mean increase was greater in female subjects (9.27 dB) than in male subjects (7.33 dB). With regard to room, as shown in Figure 2, difference in ΔSPL between the styles was greater in the anechoic and reverberant rooms (8.59 and 8.41 dB, respectively) than in the semi-reverberant room (7.96 dB). In the normal style, the highest ΔSPL values were measured in the semi-reverberant room, and the lowest in the reverberant room; a higher ΔSPL in this style was measured in the semi-reverberant room (-3.84 dB) than the anechoic (-4.11 dB) and the reverberant room (-4.83 dB). In the loud style, ΔSPL decreased as reverberation time increased: 4.48, 4.13, and 3.58 dB for anechoic, semi-reverberant and reverberant rooms, respectively ($T30 = 0.04$, 0.78, and 2.37 s). Post-hoc comparisons confirmed that, overall, the ΔSPL measured for the reverberant room was lower than both that of the semi-reverberant room ($z = -6.21$, $p < 0.0001$) and the anechoic room ($z = -5.76$, $p < 0.0001$), and that the difference between the anechoic and semi-reverberant rooms was not significant ($z = -0.447$, $p = 0.90$).

Regarding the effect of panels, ΔSPL decreased when panels were present in both style conditions and in all 3 room conditions. The reduction in ΔSPL when panels were present rather than absent was 0.49 dB, as shown in Figure 3.

Table 1 - LME model fit to the response variable ΔSPL (dB) with the predictors (1) style, (2) room, (3) panel and (4) chronological order (‘order’) with interactions of (5) room and style, (6) room and order, (7) style and gender, and the interaction of subject and time as a random effects term. Reference levels are the normal style, the semi-reverberant room, absent panels, and female gender.

Fixed factors	Estimate (dB)	Std. Error (dB)	df	t	p
(Intercept)	-4.92	0.21	24045	-23.12	<0.001
Loud Style	8.95	0.18	34622	49.31	<0.001
Anechoic Room	-0.72	0.30	33683	-2.43	<0.05
Reverb Room	-1.82	0.28	31755	-6.53	<0.001
Panel present	-0.44	0.09	34481	-4.80	<0.001
Order	0.12	0.02	32020	4.86	<0.001
Anech. R. : Loud St.	0.53	0.22	34449	2.38	<0.05
Reverb. R. : Loud St.	0.49	0.22	34506	2.22	<0.05
Anech. R. : Order	0.06	0.04	27167	1.56	0.119
Reverb. R. : Order	0.13	0.04	23883	3.68	<0.001
Normal St.: Male	1.02	0.17	6597	6.15	<0.001
Loud St.: Male	-0.90	0.16	6461	-5.52	<0.001

Table 2 - Summary statistics for the variables ΔSPL (dB), Effort (%), Control (%), Comfort (%) and Clarity (%) in the 12 conditions (2 Styles, 3 Rooms and 2 Panels).

Conditions			ΔSPL (dB)		Effort (%)		Control (%)		Comfort (%)		Clarity (%)	
Style	Room	Panel	Mean	S.E	Mean	S.E	Mean	S.E	Mean	S.E	Mean	S.E
Normal	Semireverb.	Absent	-3.57	0.15	28.8	6.0	78.2	5.0	76.1	4.9	75.1	3.7
Normal	Semireverb.	Present	-4.12	0.15	24.0	4.5	75.8	4.9	72.1	4.9	72.9	4.0
Normal	Anechoic	Absent	-3.93	0.15	25.7	5.7	73.7	6.0	72.7	5.6	66.1	5.0
Normal	Anechoic	Present	-4.29	0.16	19.8	4.5	72.5	6.2	75.3	4.5	71.5	4.1
Normal	Reverb.	Absent	-4.73	0.14	26.4	5.0	77.6	4.3	73.5	4.2	63.5	5.1
Normal	Reverb.	Present	-4.92	0.14	20.0	4.6	79.8	3.3	77.9	3.3	75.6	3.6
Loud	Semireverb.	Absent	4.32	0.18	65.2	6.6	62.8	5.6	53.4	7.0	65.5	5.4
Loud	Semireverb.	Present	3.93	0.19	53.5	5.4	66.8	4.6	52.2	5.6	70.6	4.2
Loud	Anechoic	Absent	4.69	0.19	55.9	6.1	64.7	5.0	49.2	6.1	66.2	5.0
Loud	Anechoic	Present	4.28	0.19	49.6	5.3	69.7	4.7	52.6	5.2	75.4	3.8
Loud	Reverb.	Absent	4.06	0.17	40.1	6.1	66.4	4.6	62.5	5.3	75.7	5.3
Loud	Reverb.	Present	3.10	0.16	45.4	5.4	65.1	5.1	55.3	5.7	72.4	5.8

According to the model, there was a significant effect of chronological task order on ΔSPL and an interaction between order and room. In order to better understand the interaction between chronological task order and room, three simple linear regression models were fit to ΔSPL, one per room, with order as a predictor variable. The models that best fit the data in anechoic, semi-reverberant and reverberant rooms are reported in equations (1), (2) and (3), respectively,

$$\Delta \mathrm{SPL}_{\mathrm{anechoic}} = -1.39 + 0.24 \cdot Order \tag{1}$$

$$\Delta \mathrm{SPL}_{\mathrm{semi\text{-}reverberant}} = -0.60 + 0.13 \cdot Order \tag{2}$$

$$\Delta \mathrm{SPL}_{\mathrm{reverberant}} = -1.73 + 0.20 \cdot Order \tag{3}$$

where Order represent the chronological order of task administration from 1 to 12. The p values associated with the factor of order in the 3 models were lower than 0.0001. When compared with null models, the results of likelihood ratio tests were also significant at $p < 0.0001$ in each case, confirming that the models including the Order term were preferable.

Four separate LME models were run with the subjective response variables Effort, Control, Comfort and Clarity, each with the fixed factors (1) style, (2) room and (3) panel and the random effects term of subject (Table 3). Each response variable is reported in percent. The reference levels were the normal style, the anechoic room, and absent panels. Summary statistics for the self-reported variables are reported in Table 2.

The estimate for self-reported vocal effort in the loud style was 27.48% higher than that in the normal style. In the semi-reverberant and reverberant rooms, estimates were 5.11% and 9.89% lower respectively than the estimate associated with the anechoic room. The estimate for self-reported vocal effort in the presence of the panels was 4.95% lower than that without panels. These values are very similar to the actual differences in means. The effect of panels on self-reported effort is shown in Figure 3. A Spearman's rho test indicated a significant relationship between self-reported effort and ΔSPL ($r_s(240) = 0.51$, $p < 0.0001$).

The model estimate for self-reported vocal control was 10.28% lower in the loud style than in the normal style, while the estimate for self-reported vocal comfort was 20.35% lower in the loud style than in the normal style. The estimate for self-reported vocal clarity in the presence of the panels was 4.38% higher than that without panels ($p = 0.061$). These differences are again very similar to the actual difference in means. Other factors did not have observable effects.

Table 3 - LME models fit by REML for the subjective response variables Effort, Control, Comfort and Clarity including fixed factors style, room, panel and a random effects term: subject. Reference levels are normal style, anechoic room, and absent panels.

	Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
Effort	(Intercept)	31.60	4.39	40	7.19	<0.001
	Loud Style	27.48	2.46	215	11.13	<0.001
	Semireverb R	-5.11	3.01	215	-1.69	0.09.
	Reverb R	-9.89	3.02	215	-3.27	<0.01
	Panel present	-4.95	2.46	215	-2.00	<0.05
Control	(Intercept)	75.5	3.95	42	19.12	<0.001
	Loud Style	-10.28	2.28	218	-4.51	<0.001
	Semireverb R	-0.74	2.8	215	-0.27	0.8
	Reverb R	1.23	2.8	215	0.44	0.7
	Panel present	1.13	2.29	215	0.5	0.6
Comfort	(Intercept)	73.7	4.23	40	17.42	<0.001
	Loud Style	-20.35	2.38	215	-8.55	<0.001
	Semireverb R	-0.96	2.91	215	-0.33	0.74
	Reverb R	3.77	2.92	215	1.29	0.2
	Panel present	-0.22	2.38	215	-0.09	0.93
Clarity	(Intercept)	68.77	3.5	58	19.66	<0.001
	Loud Style	0.17	2.3	215	0.075	0.94
	Semireverb R	-1.23	2.84	215	-0.43	0.67
	Reverb R	0.78	2.85	215	0.275	0.78
	Panel present	4.38	2.32	215	1.88	0.06.

Figure 2 shows the mean self-reported vocal effort in the three rooms, for both normal and loud styles. The perception of vocal effort and reverberation time were inversely proportional and the presence of panels was generally associated with a lower vocal effort. The only exception to this rule was the condition with the loud style in the reverberant room, which may be due to excessive energy in the reflections because of the combination of the reverberant sound field and the increased first reflection associated with the panels.

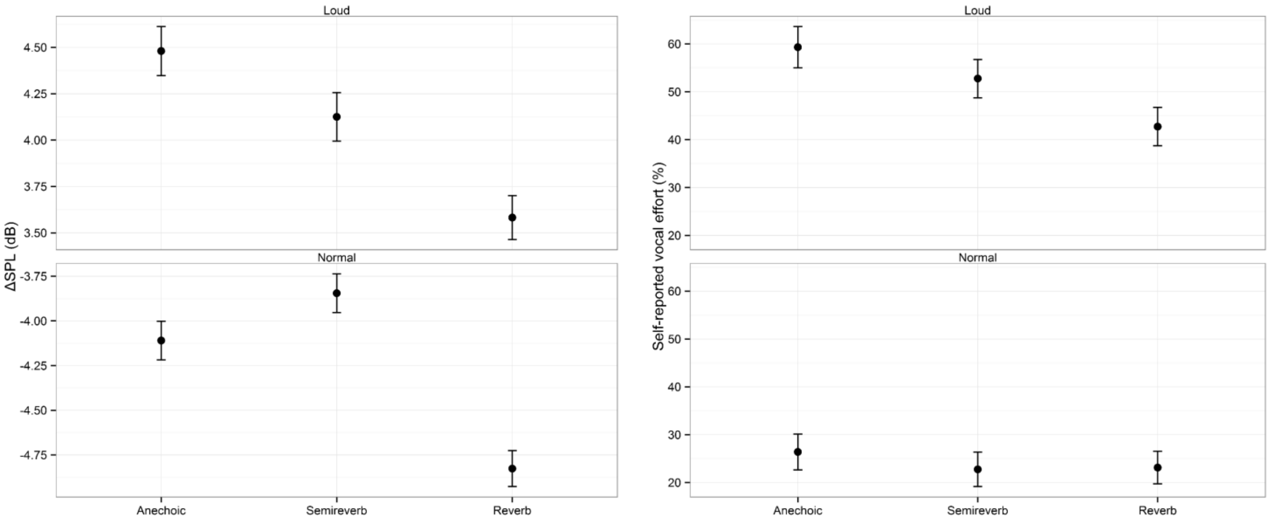

Figure 2 – (Left): Mean ΔSPL in dB across subjects per room for the loud (upper) and normal (lower) styles, where the error bands indicate ± standard error. (Right): Mean self-reported vocal effort in percent across subjects in the three rooms (anechoic, semi-reverberant and reverberant) for normal and loud styles, where the values are derived from the linear model fit. Error bands indicate ± 1 standard error.

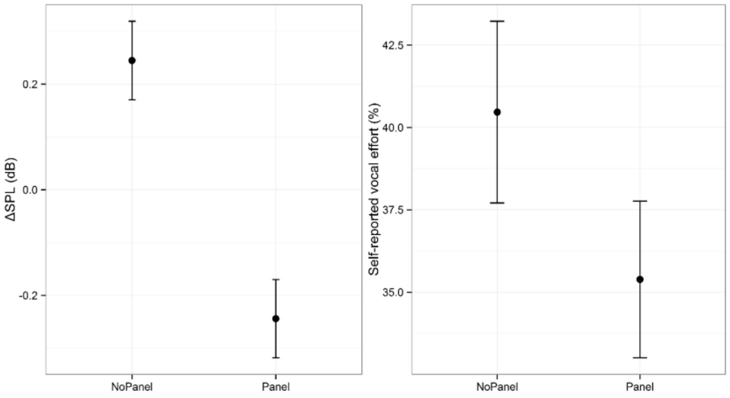

Figure 3 - Mean ΔSPL in dB across subjects per panel condition (Left) and self-reported vocal effort across subjects per panel condition (Right), where error bands indicate ± 1 standard error.

Discussion

Across panel and style conditions, ΔSPL was found to be higher in the anechoic and semi-reverberant rooms than in the reverberant room. Consistent with previous findings [6,7], in this study, as reverberation time increased (between 0.04 and 2.4 s), mean ΔSPL decreased (anechoic: 0.27, semi-reverberant: 0.24, reverberant: -0.49). The interaction between room and style principally related to the relationship between the anechoic and semi-reverberant rooms in the two styles: ΔSPL was higher in the anechoic room than the semi-reverberant room in the loud style but lower in the normal style. In the loud style, the voice intensity was higher and consequently the reflected sound was more intense. In particular, when the energy emitted by the subject was higher, the reflections associated with the panels seem to have been more effective in decreasing the subject’s ΔSPL in the semi-reverberant room. In the loud style, ΔSPL was lower in the semi-reverberant room than in the anechoic room (mean diff = 0.35 dB). In the normal style, ΔSPL decreased from -4.83 dB in the reverberant room to -4.11 dB in the anechoic room and -3.84 in the semi-reverberant room.

The effect of the panel being present was a decrease in the ΔSPL (mean = 0.49 dB), which was observable in all room and style conditions. The placement of the panels near the talker increased the reflected energy (and external auditory feedback) in the talker position, thus increasing the levels of voice support and room gain, as defined by Pelegrín-García [6]. It is consistent with his findings that there was an inverse relationship between SPL and the quantity of reflected energy. In this study, as expected, when panels were present, talkers reported greater clarity of their own voice.

Female subjects showed a larger dynamic range in the voice level between styles (*i.e.*, mean difference between the styles) than male subjects. The larger dynamic ranges associated with females could provide insights into reported gender-associated vocal health risks [13,16,17].

An increase was observed in ΔSPL across the 12 tasks, which may indicate short-term vocal fatigue. This finding is consistent with the tendency for SPL to increase with vocal loading observed by Rantala *et* al. [9] and Laukannen *et al.* [10]. Overall, reverberation time and SPL were inversely related such that as reverberation time increased from 0.78 s (semi-reverberant room) to 2.37 s (reverberant room), there was a decrease in ΔSPL of 0.74 dB. This result was consistent with self-reported effort. The relationship between ΔSPL and short-term vocal fatigue (evaluated by means of the chronological task order) was observed to depend strongly on reverberation time. Lower vocal demands and lower magnitudes of vocal fatigue were experienced by talkers in the room in which the reverberation time was more likely to be found in a typical communication environment, *i.e.*, the semi-reverberant room.

Conclusions

An experiment was conducted to evaluate the effects of reverberation time, the strength of the early reflections, and style (normal, loud) on speech produced in the presence of classroom babble noise. The main conclusions were as follows:

- Panels were associated with a reduction in SPL of 0.49 dB and the effect of the panels was consistent among styles and rooms, however
- The effect of panels was strongest in the reverberant room (-0.61 dB), followed by the semi-reverberant room (-0.48 dB), and the anechoic room (-0.37 dB), and
- The effect of panels was stronger in the loud style (-0.59 dB), than in the normal style (-0.36 dB).
- Panels were generally associated with a lower perceived vocal effort, with the exception of the condition with the loud style in the reverberant room, which may be due to excessive energy in the reflections.

The increase in the external auditory feedback due to reflective panels resulted in an objectively measurable benefit. Thus, it was shown that the placement of reflective surfaces can improve the quality of the sound field for speakers. Importantly, early reflections can be used to reduce vocal effort without modifying reverberation time, which should be one of the goals in classroom design. In order to improve classroom design and to be able to give recommendations concerning the placement of reflective surfaces, it is necessary to test the effect of panels on speech at different distances from the speaker and at different angles. Finally, for a more systematic evaluation of the effects of reflective panels, it will be necessary to perform some experiments with auralization, for improved control of the acoustical parameters.

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