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INTRINSIC LARYNGEAL MUSCLE ACTIVITY DURING SUBVOCALIZATION

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Intrinsic Laryngeal Muscle Activity During Subvocalization

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ABSTRACT

Purpose: Subvocalization, the low-grade activity of speech articulator muscles while thinking or reading, may mediate phonological representations of verbal material. However, no literature exists that directly measures whether intrinsic laryngeal muscles (ILMs) are active during subvocalization. The possibility of ILM activation during subvocalization has implications for establishing appropriate baselines when experimental conditions involve linguistic features.

Method: In two separate studies, forty-five cisgender women completed one or two subvocalization tasks (two in the first study, Experiments 1a and 1b, and one in the second, Experiment 2). Fine wire electromyography was used to directly measure ILM activity during an at-rest baseline and the subvocalization tasks. Other muscles were measured via surface electromyography: submental muscle in Experiments 1a and 1b, anterior tibialis in Experiment 2, and upper trapezius in all experiments.

Results: Interrupted time-series analysis was used to directly measure changes in ILM activity from baseline to the subvocalization tasks. A paired two tailed t-test was used to measure mean differences in ILM activity across conditions for each participant. Some individuals displayed statistically significant increases from baseline during subvocalization tasks, whereas others displayed decreases. Cohen's *d* was used to calculate the effect size for each muscle across the three subvocalization conditions. Of the 21 muscles measured across three experiments, 5 yielded a small mean effect size, and the effect sizes for the remaining 16 muscles were negligible. At a group level, only the right cricothyroid showed statistically significant changes (Experiment 1b).

Conclusions: The ILM responses during subvocalization vary in both magnitude and direction. Most but not all changes can be described as negligible. For future studies of ILM activity during

conditions that involve linguistic processing, investigators should consider the idiosyncratic variation during subvocalization when determining the most appropriate baseline task.

KEYWORDS: SUBVOCALIZATION, INTRINSIC LARYNGEAL MUSCLES

1. Introduction

Subvocalization is the low-grade activity of speech articulator muscles while thinking or reading and is a well-documented phenomenon.[1,2] Subvocalization seems to play a role in control processes that mediate a phonological representation of verbal material such as reading.[3] Most widely studied in the context of reading, subvocalization is thought to facilitate reading proficiency, detection of errors, improve comprehension, and recall of material.[2–7] This proposed role of subvocalization in helping to encode read information is consistent with the dual-encoding hypothesis of reading.[8] No studies in this body of literature have examined intrinsic laryngeal muscle activity, either directly via fine-wire electromyography (EMG) or indirectly via surface EMG or direct visualization of the vocal folds.

Another body of literature dedicated to the phenomenon of subvocalization exists in the arena of music processing and perception. People seem to subvocalize during auditory imagery experiences, and subvocalization might facilitate the rehearsal and maintenance of rhythmic patterns.[9,10] Brodsky et al.[11] demonstrate that trained musicians displayed increased surface laryngeal electromyography activity when presented with a silent sightreading task. The authors attribute the increased surface laryngeal EMG activity to increased vocal fold activity and conclude that "notational audition," or the ability to internally "hear" the music, is a byproduct of "covert excitation of the vocal fold." However, this attribution could not be verified.

Similarly, Bruder et al.[12] measured laryngeal activity in eight singers using surface EMG to ostensibly capture activity of the cricothyroid and thyrohyoid muscles, while simultaneously visualizing the larynx via laryngoscopy. EMG recordings were made during a silent baseline condition compared to a subvocalization condition in which singers were instructed to silently imagine singing or speaking. Additionally, this study used a blinded experimental design in which

three expert otorhinolaryngologists rated apparent laryngeal activity during the baseline, imagined speaking, and imagined singing conditions. The singers generated significantly more surface laryngeal EMG activity during the imagined speaking task compared to baseline, though the surface laryngeal EMG activity for the imagined singing task was not statistically significant from baseline. Likewise, laryngoscopic ratings were statistically significantly "more active" during imagined speech, but not different from baseline during imagined singing. Finally, despite these various physiological examinations of subvocalization, to our knowledge the activity of the intrinsic laryngeal muscles has not been directly examined.

Not only is subvocalization evident across a variety of silent tasks, it seems that cognitive demand might be one mediating factor in whether and to what extent subvocalization occurs. For instance, people exhibit increased subvocalization when reading a difficult passage compared to an easier text.[13,14] It remains unknown whether this phenomenon exists in the context of a silent task other than reading. This question has relevance to our previous work examining intrinsic laryngeal muscle (ILM) response during experimentally-induced stress. We previously showed statistically significant increases in ILM activity during both physical and psychosocial stressors.[15,16] The psychosocial stressor task involved a silent speech preparation paradigm, with the addition of multiple stressful elements designed to ensure a robust stress response. While some participants exhibited large increases in both tonic and phasic ILM activity from baseline to stressor, others showed only modest changes. Given the linguistic nature of the psychosocial stressor paradigm, we used a silent baseline task designed to mimic our psychosocial stressor without triggering a stress response. This approach was intentionally conservative; we sought to isolate the stress response and not inflate our measurements with ILM activity stemming from

subvocalization vis-a-vis the underlying linguistic nature of the tasks. We obtained exploratory data in both of these previous studies, but they have not been examined or reported until now.

The present study aims to assess whether silent cognitive and linguistic tasks specifically designed to not induce stress are associated with significant changes in ILM activity. We specifically were interested in exploring the phenomenon of subvocalization in the broadest context of working memory and representation processes, rather than through the relatively narrower lens of its relevance to skilled musicians. Thus, we conducted this study in a general population sample of adult women, with no inclusion criteria related to specific training or skill (e.g., musical background). Three subvocalization task paradigms were compared to an at-rest silent baseline. These data are intended to guide future research paradigms pertaining to laryngeal stress responses (see[15,16]).

2. Materials and Methods

Experiments described here were embedded in two larger original research studies by the first author[15,16] and thus some demographic details about participants have been previously published. Both studies aimed to measure ILM responses when presented with a stressor, first with a physical stressor (the cold pressor task[16]) and then with a psychosocial stressor (modified Trier Social Stress Test[15]). Prior to completing either stressor task, subjects completed both baseline and subvocalization tasks. The present paper analyzes the data collected from those baseline tasks and subvocalization tasks. Experiments 1a and 1b originate from Helou et al.[16], which piloted two different subvocalization conditions, and Experiment 2 is from Helou et al.[15] and included only one subvocalization condition. Both studies were approved by the University of Pittsburgh

Institutional Review Board (Experiments 1a and 1b – PRO11030103; Experiment 2 – PRO012110063).

2.1 Participants

Eight vocally healthy cisgender women were recruited for Experiments 1a and 1b. Forty vocally health cisgender women were recruited for Experiment 2. All participants were between the ages of 18 and 30. Specific exclusion criteria for both studies have been previously reported, and included current pregnancy; current upper respiratory illness; history of voice disorders, neck or throat surgery, autonomic dysfunction, known psychological disorders; asthma; and blood clotting or coagulation disorders. Participants also reported their height and weight, and those with body mass index at or above 31 (i.e., obese individuals) were excluded from participation because (1) excessive fatty tissue in the neck may make it difficult to identify landmarks for hook wire electrode placement and (2) obesity may impact respiration. For Experiment 2, participants were also excluded if they had frequent or high level of comfort with public speaking; known allergy to local anesthetic medications such as Lidocaine; and any known respiratory disorders.

Participants eligible for face-to-face screening were subsequently assessed clinically at the UPMC Voice Center (formerly the University of Pittsburgh Voice Center) to establish (a) tolerance of laryngeal palpation and manipulation and (b) normal laryngeal structure and physiology as judged by a board-certified laryngologist based on laryngoscopic imaging. These studies only included cisgender women to minimize heterogeneity in physiological stress responses, as men and women tend to have different reactions to stress.[17–21]

2.2 Data Collection

All experiments took place in a quiet clinical procedure room at the University of Pittsburgh Voice Center. All unnecessary electronic equipment and lights were turned off and unplugged (if possible) to minimize ambient electronic noise. Participants were seated in an examination chair at a semi-upright angle (120º), where they remained for the duration of the study, except during placement of fine wire electrodes when they were reclined to a ~170º angle.

The bipolar hook-wire electrodes were constructed in-house and gas sterilized. For construction, two strands (bifilar) of 0.002-in diameter insulated stainless steel wire were cut to 5-in lengths. About 3 mm of each wire was stripped of insulation at its endpoint, and this section was used to couple each wire to the data acquisition system using a micrograbber. The opposite tip of each wire was folded over a thin piece of metal to create barbs of 1.1 and 1.6 mm, and 1 mm of insulation at the tip of each barb was removed using a laser. This method offset the uninsulated portions of each wire so as to prevent a short circuit. The bifilar wire was threaded through the lumen of a 1.5-in 27-gauge hypodermic needle and gas sterilized.

2.2.1 *Electromyography Equipment Placement*

Subjects in both studies had 20-mm bipolar Ag/AgCl surface electromyography (SEMG) electrodes placed on the upper portion of the left trapezius (TPZ) muscle, medial to the midpoint of c7 and the acromion. SEMG electrodes were placed on the left submental complex (SUB) in Experiment 1, and on the left anterior tibialis (TIB) as a negative control site for subjects in Experiment 2. Next, a fellowship-trained laryngologist injected 1 to 2 mL of 1% lidocaine with 1:100,000 epinephrine subcutaneously over the cricothyroid (CT) membrane prior to placement of hook-wire electrodes. Hook-wire electrodes were inserted into the right posterior cricoarytenoid (PCA), bilateral thyroarytenoid/lateral cricoarytenoid (TA/LCA) muscle complex, and bilateral

CT muscle by a fellowship-trained laryngologist (co-author Rosen) according to previously published methods.[22] Verification tasks were repeated and recorded at this time to ensure that the electrode uncoupling and recoupling procedures had not disrupted electrode placement.

3. Experimental Procedures

3.1 Experiments 1a and 1b

3.1.1 *Baseline*

Following electrode placement, participants completed a baseline task. Subjects were instructed to "please just lie still and relax without talking. Please don't clear your throat, readjust your head or body, et cetera." SEMG and LEMG data were collected for 90 seconds.

3.1.2 *Experimental Conditions*

After the subjects completed the baseline task, they completed the two experimental conditions. For **Experiment 1a**, participants silently read the *Rainbow Passage*. The investigator instructed the subjects to "read this paragraph silently, under your breath, without talking, until I ask you to stop." After 30 seconds, the investigator instructed subjects to stop. For **Experiment 1b**, the subjects silently counted backwards from 100. The investigator instructed subjects "I want you to count backwards from 100 by 1, again without talking aloud." Again, after 30 seconds the investigator stopped the subject. None of the participants were ever guided or instructed to actually engage in subvocalization behaviors.

3.2 Experiment 2

3.2.1 *Baseline*

Following electrode placement, subjects completed an at-rest baseline condition. The baseline condition involved participants remaining at rest and observing an emotionally neutral audio-visual stimulus for 3 minutes. Participants were instructed to "focus on the video while keeping your body still and quiet." SEMG and LEMG data were collected throughout this time. Halfway through, the investigator verbally encouraged the subjects to maintain attention to the video stimulus.

3.2.2 *Experimental Condition*

In **Experiment 2**, participants were prompted to "imagine a small group of people with whom you are very comfortable and at ease, and to imagine that you are talking with these people about your dream job." Participants were presented with short, bulleted, written prompts to imagine themselves describing (a) what their dream job entails, (b), the "who, what, where, and when" of this dream job, and (c) what they will accomplish in this dream job. Halfway through the 3-minute task, participants were gently encouraged by the investigator to "keep imagining that you are talking about your dream job, while keeping your body still and quiet." The investigator did not directly address or focus their attention on the participant, to avoid possibly inducing a stress response.

4. Results

4.1 Participants

4.1.1 *Experiments 1a and 1b*

Eight participants satisfied all the inclusion criteria and completed all subvocalization tasks. In total, we collected 56 EMG signals (8 participants, each with 7 EMG channels). No data were lost for Experiments 1a and 1b, and all 56 signals are reported herein. No participants phonated or spoke aloud for any of the tasks.

4.1.2 *Experiment 2*

Forty participants satisfied all the inclusion criteria and participated in the study. Of those 40 participants, one could not tolerate the placement of the fine wire electrodes and was dismissed from the study after that experimental stage. Data from four participants were corrupted for unknown reasons and hence could not be analyzed. Thus, complete data sets for 35 individuals are presented herein. In total, we collected 245 EMG signals. At the end of the study, participants repeated the EMG verification tasks to ensure that electrode placement had not become disrupted. To ensure an accurate analysis of the data, we discarded EMG signals that did not respond to their verification task. As a result, we used 204 EMG channels in the following analysis. No participants phonated or spoke aloud for any of the tasks.

Racial/ethnic information for this cohort is as follows: non-Hispanic (n=36); Hispanic (n=1); White/Caucasian (n=28); Black/African American (n=5); Asian (n=4). Data from one participant exceeding the BMI criterion were included in the study; during the screening she was just below the Obese Class I threshold, but by the time she participated in the experiment her weight had increased. This difference was not realized or confirmed by the investigators until after the participant had completed the experiment, and her data are included herein.

4.2 Data Reduction and Analyses

Data reduction and analysis was performed using Matlab 7.8.0 r2009a (MathWorks, Inc., Natick MA, USA). A 20 Hz high-pass filter was applied to all EMG channels in order to remove drift and offset. Notch filters (4 Hz) of 60, 120, and 180 Hz were applied to all data channels, and all EMG data channels were full-wave rectified and low-pass filtered for analysis. To determine whether laryngeal muscle change was statistically significant across conditions, within-subjects analysis of amounts and amplitudes of muscle activation per unit/time via interrupted time-series analysis (ITSA) were performed using the ARIMA model 2 in Matlab. ITSA is intended to identify whether an event (e.g., Repeat Baseline task) is associated with the time-series pattern present in observations prior to the event (e.g., Baseline Rest). ITSA estimates the amount of autocorrelated data in each set of data, subtracts the autocorrelated data from the raw data, and performs a t-test on the remaining non-autocorrelated data (Crosbie, 1993). Rolling windows shifted in 5-sec increments. Individual ITSAs were performed comparing: (1) Baseline Rest epoch to the Baseline Subvoc epoch and (2) and Baseline Subvoc epoch to the SPT epoch. These repeated ITSA analyses yielded a p value and t value for each muscle recorded for each participant. Conceptually, this approach is similar to a meta-analysis, and provides information regarding the magnitude of the total effect size of the phenomenon of interest (i.e., subvocalization). Data were imported into R (version 4.0.0) and plotted.

4.3 EMG Activity from Baseline to Subvocalization Tasks

4.3.1 *Group Level Differences*

To determine whether the changes from baseline to the subvocalization tasks were statistically significant, we used a two tailed paired t-test to compare ITSA means from baseline to the subvocalization task for each muscle at the group level for Experiments 1a, 1b, and 2. Table 1 shows the results. Only one muscle reached the level of statistical significance ($p < .05$) – the right cricothyroid in Experiment 1b. The few statistically significant differences at the group level are likely due to the varied nature of individual responses; i.e., some subjects demonstrated a significant increase and others demonstrated a significant decrease.

Table 1

Group-Level Paired Two Tailed T-Tests Analysis of Baseline to Subvocalization Condition

Muscle	*t*-statistic	*df*	*p* value
Experiment 1a			
Left Cricothyroid	-0.31	5	0.77
Right Cricothyroid	-0.21	5	0.85
Left Thyroarytenoid	-1.62	6	0.16
Right Thyroarytenoid	0.41	6	0.70
Posterior Cricoarytenoid	0.07	3	0.95
Submental	1.37	7	0.21
Trapezius	0.73	7	0.49
Experiment 1b			
Left Cricothyroid	-0.43	5	0.69
Right Cricothyroid	2.73	5	0.04*
Left Thyroarytenoid	-1.48	6	0.19
Right Thyroarytenoid	0.5	6	0.62
Posterior Cricoarytenoid	1.63	3	0.20
Submental	0.87	6	0.41
Trapezius	0.3	7	0.78
Experiment 2			
Left Cricothyroid	0.26	27	0.80
Right Cricothyroid	0.22	24	0.82
Left Thyroarytenoid	0.78	31	0.44
Right Thyroarytenoid	-2.02	26	0.054
Posterior Cricoarytenoid	0.42	21	0.68
Trapezius	-1.52	34	0.14
Tibialis	-0.6	34	0.55

Table 1 shows the results of the paired two tailed t-test for each muscle at the group level across experiments. * indicates ($p < .05$).

4.3.2 *Individual Level Differences*

As previously mentioned, participants displayed variability in both the direction and magnitude of EMG activity from baseline to subvocalization tasks. Table 2 displays the number of subjects who demonstrated statistically non-significant, increased, or decreased EMG activity during the subvocalization conditions compared to baseline. Subjects generally demonstrated more significant changes from baseline in Experiments 1a and 1b than in Experiment 2.

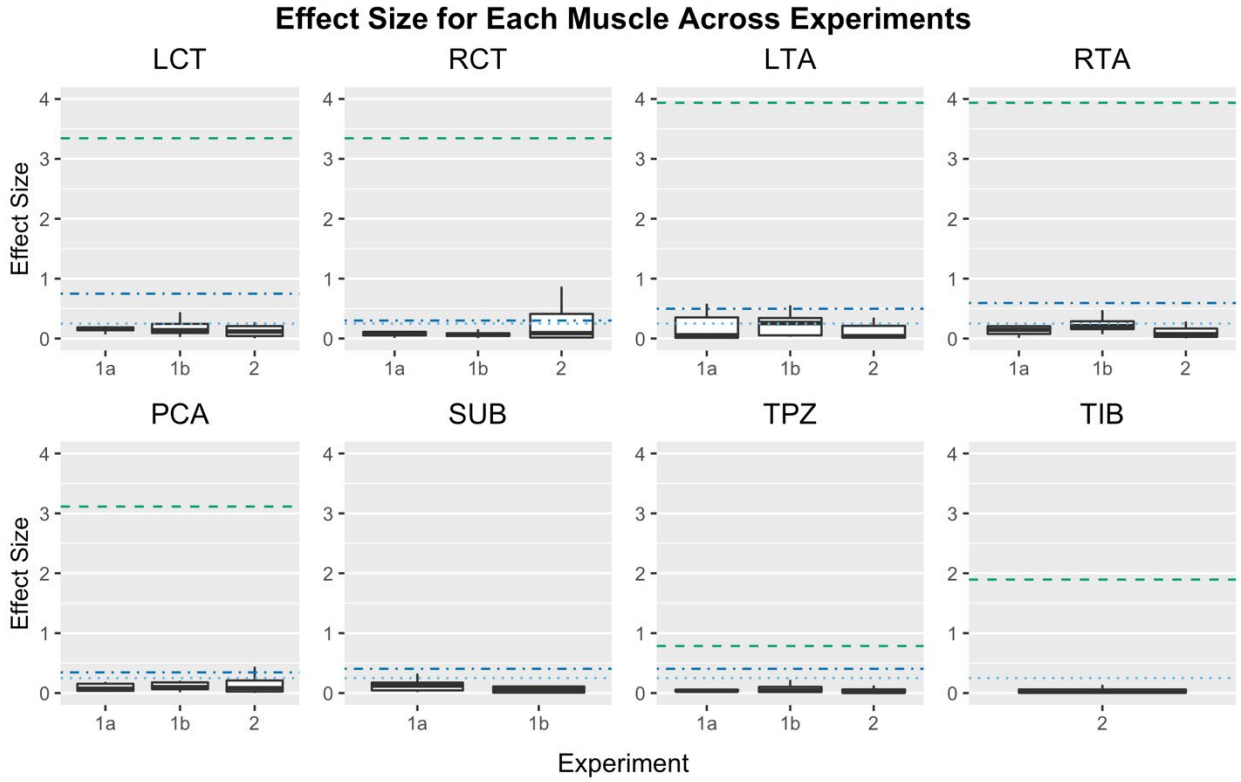
Table 2

The Number of Subjects That Demonstrated a Statistically Significant Change from Baseline

Muscle	Not Significant	Significant Increase	Significant Decrease
Experiment 1a	*n* (%)	*n* (%)	*n* (%)
Left Cricothyroid	0	3 (38%)	5 (63%)
Right Cricothyroid	2 (25%)	5 (63%)	1 (13%)
Left Thyroarytenoid	3 (38%)	2 (25%)	3 (38%)
Right Thyroarytenoid	2 (25%)	3 (38%)	3 (38%)
Posterior Cricoarytenoid	2 (25%)	2 (25%)	4 (50%)
Submental	7 (88%)	1 (12%)	0
Trapezius	1 (13%)	4 (50%)	3 (38%)
Experiment 1b			
Left Cricothyroid	0	3 (38%)	5 (63%)
Right Cricothyroid	4 (50%)	3 (38%)	1 (13%)
Left Thyroarytenoid	0	2 (25%)	6 (75%)
Right Thyroarytenoid	0	6 (75%)	2 (25%)
Posterior Cricoarytenoid	1 (13%)	4 (50%)	3 (38%)
Submental	7 (88%)	1 (13%)	0
Trapezius	1 (13%)	3 (38%)	4 (50%)
Experiment 2			
Left Cricothyroid	24 (86%)	4 (14%)	0
Right Cricothyroid	23 (92%)	1 (4%)	1 (4%)
Left Thyroarytenoid	30 (94%)	1 (3%)	1 (3%)
Right Thyroarytenoid	25 (93%)	0	2 (7%)
Posterior Cricoarytenoid	16 (73%)	3 (14%)	3 (14%)
Trapezius	32 (91%)	1 (3%)	2 (6%)
Tibialis	34 (97%)	0	1 (3%)

Table 2 shows the number of individuals who demonstrated a statistically significant ($p < .05$) change from the baseline task to the subvocalization task based on the interrupted time-series analysis.

Figure 1



Box plots for Cohen's *d* values shown for each muscle across experiments, with value negativity removed. The light blue dotted line represents a small effect size in Communication Science & Disorders.[23] The dark blue dot-dashed line represents mean Cohen's *d* value for the cold pressor (physical stressor) task used in Experiments 1a and 1b.[16] The green dashed line represents mean Cohen's *d* value for the speech preparation task (psychosocial stressor) used for Experiment 2.[15] LCT = left cricothyroid, RCT = right cricothyroid, LTA = left thyroarytenoid, RTA = right thyroarytenoid, PCA = posterior cricoarytenoid, SUB = submental, TPZ = trapezius, TIB = tibialis.

4.4 Effect Sizes

To measure the magnitude of the increases and decreases in muscle activity, we calculated the effect size (Cohen's *d*) for each muscle from baseline to the subvocalization task across all three experiments. We calculated the mean Cohen's *d* value for each muscle in each experiment (see Table 3). For ease of visually appreciating the overall effect sizes, we then removed all value negativity and plotted effect sizes as positive values, for each muscle across the experiments. Figure 1 shows these box plots compressed to accommodate additional reference lines for previously published EMG responses to a physical stressor[16] and a psychosocial stressor,[15] and for the reader to appreciate the relative magnitude of these responses to the established cutoff for "small" effect sizes.[23] Only 5 of the 21 muscles measured pass the threshold for a small effect size; the remaining effect sizes are negligible.

Table 3

Mean and Standard Deviation of Cohen's *d* Values for Each Muscle

Muscle	*M*	*SD*
Experiment 1a		
Left Cricothyroid	.179	.094
Right Cricothyroid	.184	.330
Left Thyroarytenoid	.186	.233
Right Thyroarytenoid	.359*	.680
Posterior Cricoarytenoid	.113	.108
Submental	.128	.103
Trapezius	.06	.062
Experiment 1b		
Left Cricothyroid	.186	.148
Right Cricothyroid	.068	.048
Left Thyroarytenoid	.241	.192
Right Thyroarytenoid	.355*	.429
Posterior Cricoarytenoid	.182	.238
Submental	.090	.120
Trapezius	.074	.077
Experiment 2		
Left Cricothyroid	.250*	.451
Right Cricothyroid	.254*	.302
Left Thyroarytenoid	.165	.262
Right Thyroarytenoid	.129	.173
Posterior Cricoarytenoid	.268*	.490
Trapezius	.052	.069
Tibialis	.084	.182

* indicates a small effect size in CSD research, per Gaeta & Brydges.[23]

5. Discussion

This study directly measured ILM activity to determine if these muscles were meaningfully active during a non-stressful cognitive-linguistic task. These findings provide evidence for ILM activity during subvocalization that varies in magnitude and direction of change, both within and across individuals. Some individuals showed decreased ILM activity during the subvocalization task compared to baseline, while others exhibited increased activity. Given no clear systematic changes, we view the variation as relative noise, perhaps due to truly fluctuating ILM activity or related underlying behaviors such as Valsalva, breathing rate differences, or swallow. Although all steps were taken to prevent extraneous signal noise during baseline and to ensure subjects were engaging appropriately with the subvocalization tasks, we cannot exclude the possibility that some participants were or were not subvocalizing at the appropriate times. Additionally, it remains a possibility that some individuals truly decrease their ILM activity during non-stressful cognitive-linguistic subvocalization tasks.

At the group level, the magnitude of change in ILM activity across conditions was minimal, particularly compared to the activity observed during stressful tasks irrespective of whether cognitive-linguistic tasks elements were also present in the stressor. For comparison, Figure 1 contains the mean effect size observed during a stressor, taken from Helou et al.[15,16] Although a few individuals displayed statistically significant changes in EMG activity from baseline to a subvocalization task, the overall effect size of these changes were minimal, and no participant exhibited larger-than-small effect sizes.

Taken together, the magnitude of ILM activity as a function of subvocalization is relatively small but it does exist for some individuals. Future investigations regarding ILM activity might take these findings into consideration to ensure rigor in their experimental design. On the surface

it seems reasonable to compare a condition of interest to a subvocalization "baseline" to control for any subvocalization activity that might occur during the condition of interest. However, the directionality of ILM activity change is not consistent across individuals. Therefore, comparing the stress response to a subvocalization "baseline" may slightly inflate the measurements of the condition of interest for some participants, but underestimate it for others.

Finally, some limitations of this study are as follows. First, we studied primarily young adult women in this study, most of whom were Caucasian. A more diverse sample would allow us to draw more generalizable conclusions about the phenomenon of subvocalization in the general population. Second, although we selected task instructions that would hopefully be understood by participants without manipulating or inducing subvocalization, the direction that participants read the text "under your breath without talking" might have been too vague or confusing to some participants. It might have been preferable (though logistically more challenging) to measure laryngeal muscle activity under more natural conditions and without the introduction of discrete instructions.

These considerations notwithstanding, the overall magnitude of change (regardless of the direction) yields a small effect (at best), with the overwhelming majority of measurements yielding a negligible effect size. Some investigators may decide to compare a measured stress response to a true baseline, if only for the logic that requiring subjects to complete a subvocalization task inevitably introduces extraneous variance.

6. Conclusion

To our knowledge, this is the first study that directly measured ILM activity via fine-wire EMG for a subvocalization paradigm. Previous studies have used these measures to compare ILM activity during a stress response. As described here, individuals display idiosyncratic differences in the direction and magnitude of ILM activity during a subvocalization task. Despite the variability, the overall effect sizes are negligible-to-small. Future investigations into the ILM may seek to compare a measured stress response to a true baseline or to a subvocalization task for a baseline.

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