Comparative Analysis of Orbicularis Oculi Electromyogram and Voice Fundamental Frequency Variation in the Context of Acoustic Startle Response

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***Abstract*—This paper presents a comparison of two methods for measuring the acoustic startle response: orbicularis oculi (eyeblink) electromyogram (EMG), which is the conventional measure, and voice fundamental frequency (F_0) variations as a consequence of laryngeal muscle innervations. A comparative analysis of the two approaches was performed using statistical methods, as well as system identification modeling using ARX, ARMAX, Output Error and Box-Jenkins models. For this purpose, an experiment was designed in which fourteen participants sustained constant phonation and acoustic startle stimuli of varying parameters were delivered at random time points during the phonation. Physiological signals, including eyeblink EMG, were acquired in parallel to voice recording. The comparative analysis showed that by increasing intensity of acoustic stimulus, response peak amplitudes of both: F_0 variations and rectified and smoothed EMG responses increased as well. Therefore, voice F_0 may be useful for startle response analysis when eyeblink EMG measurement is unavailable or impractical.**

Keywords—acoustic startle response; EMG eyeblink reflex; orbicularis oculi muscle; voice fundamental frequency; system identification modeling

I. INTRODUCTION

The startle response is defined as a defensive reaction to sudden or threatening stimuli, which is associated with negative affect [1]. The startle response is reflexive in its nature and is therefore particularly suitable for paradigms that require consistent and highly controllable experimental conditions. Negative emotional experiences (like fearful and anxiety states) during startle elicitation often affect the startle response parameters [2]. Consequently, fear-potentiated startle can be used as the outcome measure in fear conditioning and extinction paradigms, which are widely used in PTSD studies [3], [4]. A short latency [5] and slower habituation of fear-potentiated startle response [6] were observed in PTSD patients during the extinction phase [4], [7]. As startle is influenced by emotions, such as fear, and since emotion and cognition are largely intertwined [8], startle paradigms may also be used as building blocks for experimental investigation of more complex cognitive-emotion processes in the brain. A research proposed in this paper can therefore be applied in PTSD prediction and diagnostic studies [3], [4], as well as in various multidisciplinary scientific areas like affective computing [9], cognitive infocommunications, etc [10], [11].

Electromyographic (EMG) analysis of the orbicularis oculi (eyeblink) muscle contraction during the acoustic startle response is the preferred method for startle response detection and analysis, among other methods like vertical electrooculography or the magnetic search coil method [12]. Due to its popularity, the effects of auditory stimuli on the eyeblink EMG have been studied extensively [13], [7]. Optimal stimulus parameters have been described in the literature, as well as the optimal methods for recording and analysis of these responses [14].

The goal of this paper was a comparative analysis of voice fundamental frequency (F_0) and eyeblink EMG responses to auditory startle stimuli. A comparison was performed using statistical methods, as well as system identification modeling. The F_0 startle response analysis was in its basic form proposed by Sapir and colleagues [15], but compared to laryngeal muscle response, which was measured with invasive EMG electrodes. Stimuli used in this prior work [15] were distributed in the range of 25 to 85 dB(A) SPL, while in the current paper stimuli intensity are in the range of 55 to 105 dB(A) SPL.

II. STARTLE RESPONSE BACKGROUND

The normal human startle response is seen as a brief muscle flexion, mostly noticeable in the upper half of the body. It can be elicited by unexpected and intense auditory, somaesthetic, visual or vestibular stimulus [13]. The short latency of startle response is due to a simple reflex circuit that consists of only a few synapses, in which afferent (sensory) and efferent (motor) neurons are connected at the level of the brainstem [16].

A. Orbicularis Oculi Muscle

Because of its consistency, the startle reflex activity of the orbicularis oculi muscle is the most commonly used index for

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analysis of the normal auditory startle reflex. The latency of the eyeblink reflex is much shorter than the latency of EMG activity in other muscle groups which are innervated via cranial nerves. Given these features, some authors suggest that the eyeblink may actually represent a separate reflex from the generalized auditory startle reflex which can be elicited simultaneously [13]. The most important advantage of eyeblink response in comparison to other muscle responses is the fact that it does not readily habituate, which means that it can frequently be observed in the absence of any other manifestations of the startle response [12].

B. Laryngeal Muscles

The startle response in laryngeal muscles has not been explored as much as the eyeblink response, but studies have shown that EMG response can be recorded on the cricothyroid muscle of the larynx when presenting a loud acoustic startle probe. Contractions of the cricothyroid muscle elicited by an acoustic startle probe cause the reflexive vocal folds elongation, which consequently results in rapid short-term increase in F_0 response magnitude [15]. Other studies reference somaesthetically elicited EMG responses on the laryngeal vocalis and interarytenoid muscles that are similar to those of the orbicularis oculi auditory startle response [17]. Additional studies also report similar results for laryngeal muscle innervations in the case of an airblast [18], as well as electrical stimuli [19].

III. EXPERIMENTAL DATA ACQUISITION AND PROCESSING

A. Experiment Setup

Fourteen volunteer college students, ages 23-25, were chosen as participants for the experiment (eleven male and three female subjects). All were free of any speech, hearing, or other medical impairments. Prior to their participation, all participants provided written informed consent.

The participants were seated during the experiment and were asked to remain as still as possible to reduce artifacts in EMG recording from activation of other muscles. The subjects were asked to maintain constant phonation of the vowel ‘a’ and acoustic startle probes were delivered at random time points during the phonation. Parameters of the startle stimuli varied randomly throughout the experiment. All parameter combinations that were used in the experiment are given in Table 1. In the experiment, safety conditions were considered according to the United States Occupational Safety and Health Act standards (OSHA standard number 1910.95) [20].

TABLE I. EXPERIMENTAL STIMULI VARIATIONS

Set	**Stimulus variations depending on stimulus parameters**					
	Set order	***Intensity* [dB(A) SPL]**	***Duration* [ms]**	***Rise time* [ms]**	***Stimulus Type*** ^{a}	***Num. of occur. in set***
Varying intensity set	I	105	50	0	W.N.	3
		95	50	0	W.N.	3
		85	50	0	W.N.	3
		75	50	0	W.N.	3
		65	50	0	W.N.	3
		55	50	0	W.N.	3
Varying duration set	II	95	50	0	W.N.	2
		95	30	0	W.N.	2
		95	10	0	W.N.	2
Varying rise time set	III	105	50	0	W.N.	1
		105	50	10	W.N.	1
		105	50	20	W.N.	1
Varying stimulus type set	IV	95	50	0	W.N.	1
		95	50	0	C.N.	1
		95	50	0	P.T.	1

[a] Stimulus type: W.N. = white noise (20 – 20000 Hz); C.N. = colored noise (440 – 880 Hz); P.T. = 440 Hz pure tone

The subjects were presented with 30 startle trials per session and each participant completed two sessions, for a total of 840 recorded startle responses. The rate of occurrence of stimuli within a session was approximately 3 stimuli per minute. The sequence of various stimuli within each set (specified in Table 1) was chosen randomly, but ensuring a prescribed number of occurrences in the set. The described procedure was aimed at minimizing the effects of habituation.

Startle stimuli were delivered to subjects through a Sennheiser PC 360 headset. Intensity of the acoustic probes was calibrated using the BK 4128 Head and Torso Simulator. The bioelectric signals were recorded using the BIOPAC MP150 device, with modules for: electrocardiogram (ECG), electromyogram (EMG) placed on the orbicularis oculi muscle of the right eye, respiration rate, skin temperature and skin conductance. The stimuli were delivered and responses were recorded in digital format with synchronized SuperLab 4.5 and AcqKnowledge 4.3 software. The voice was recorded through the microphone of the Sennheiser PC 360 headset and sampled at a frequency of 44100 Hz. The EMG signal and all other bioelectric signals were sampled at a frequency of 1250 Hz.

In this paper, only the analysis of the F_0 and eyeblink EMG responses to the stimuli of varying intensity is presented. The total number of recorded observations was 504 (14 subjects × 2 sessions × 6 stimuli intensities × 3 occurrences). More detailed results have been presented in work by Mijić [21].

B. Data Processing

The voice fundamental frequency was extracted from the voice recordings using a Robust Algorithm for Pitch Tracking (RAPT) [22]. F_0 was extracted at a frame analysis rate of 100 frames per second. The F_0 response curve was debiased by subtracting the F_0 value at the time instance of stimuli onset, thus obtaining the absolute F_0 variation curve.

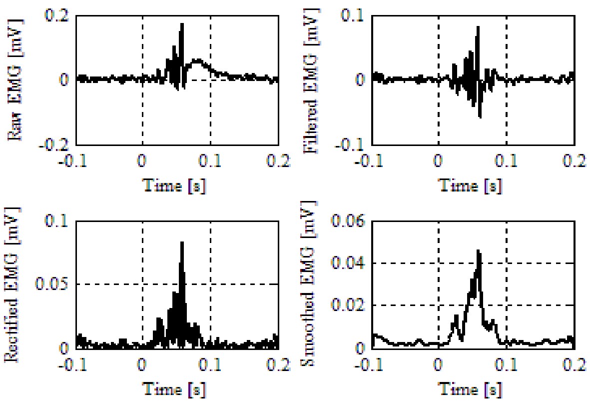

Fig. 1. A step-by-step example of eyeblink EMG data processing.

The eyeblink EMG data were first filtered with a cascade of high order notch FIR filters to eliminate the electrical noise at 50 Hz and its harmonics. It was then band-pass filtered between 28 and 500 Hz and finally rectified and smoothed with a moving average filter (10 sample averaging span) as recommended in the human eyblink EMG Guidelines [12]. The step-by-step example of this process can be seen in Fig. 1.

C. *Trial Rejection and Outlier Data Removal*

In order to ensure the consistency of recorded F_0 responses, trials for which phonation did not last at least 0.5 second before the stimulus onset and at least 1 second after the stimulus onset were rejected. Additionally, some recordings were discarded due to pitch doubling and halving. This resulted in a total of 256 valid F_0 responses.

In the case of eyeblink EMG responses there were three cases in which trials and/or participants were rejected based on EMG Guidelines [12]:

- Spontaneous blinks just prior to stimulus onset – these greatly affect the stimulus response;
- Non-responding participant – a participant with an unusually low percentage of response occurrence;
- Excess noise in the signal (possibly from other muscle activity, or improperly placed electrodes).

The final dataset was formed by applying the above described EMG rejection rules to the 256 valid F_0 responses, resulting in the final set of 176 responses.

IV. STATISTICAL ANALYSIS OF THE STARTLE RESPONSE PARAMETERS

Both F_0 and eyeblink EMG data underwent the same analysis procedures with some varying details specific to the individual responses. The first step in our analysis was averaging the response observations within common groups of responses according to stimulus intensity, resulting in some preliminary conclusions about the relationship between stimulus intensity and response parameters. The second step was based on extracting response parameters of individual trials within groups of observations and calculating distribution values of the given data samples for each group.

The extracted response parameters, shown in Fig. 2., are:

- *Response peak* – the greatest value of the response within the prescribed time window after the stimulus onset (0 to 500 ms for F_0; 20 to 120 ms for blink EMG [12]).
- *Response peak time* – the temporal value of the response peak occurrence relative to the time instance of the stimulus onset.
- *Response rise time* – the time between response onset and response peak.
- *Response latency* (*onset time*) – the first time instance after the stimulus onset, for which the response exceeds a given threshold for a specific duration. The threshold is calculated as the sum of the mean value and standard deviation of the signal baseline. The baseline is defined as a segment of the response right before stimulus onset (for F_0 it is 0.25 s prior to the stimulus onset and for EMG it is 0.1 s prior to the onset).
- *Response duration* – the time required for the response to settle to the same threshold value, relative to the response onset time.

A. *Eyeblink EMG Data*

The results of averaged EMG signal analyses are presented in Fig. 3. using 6 graphs, each showing the averaged value of all responses to a particular stimulus intensity. The average number of responses per each intensity group is 29. The time origin coincides with the stimulus onset and the timespan displayed in the figures (-0.1 to 0.2 s) was chosen to show EMG behavior before and after the stimulus onset. It can be seen that the average response intensity becomes greater with the higher intensity of the stimulus.

After processing and estimating response parameters of individual trials for each intensity group, it can be observed that the EMG response occurs regularly at 105 dB and 95 dB, irregularly at 85 and 75 dB, and almost never at 55 and 65 dB, and that the response peak values are dependent on stimulus intensity. To validate these observations, descriptive statistical methods, computing means, and testing their significance by

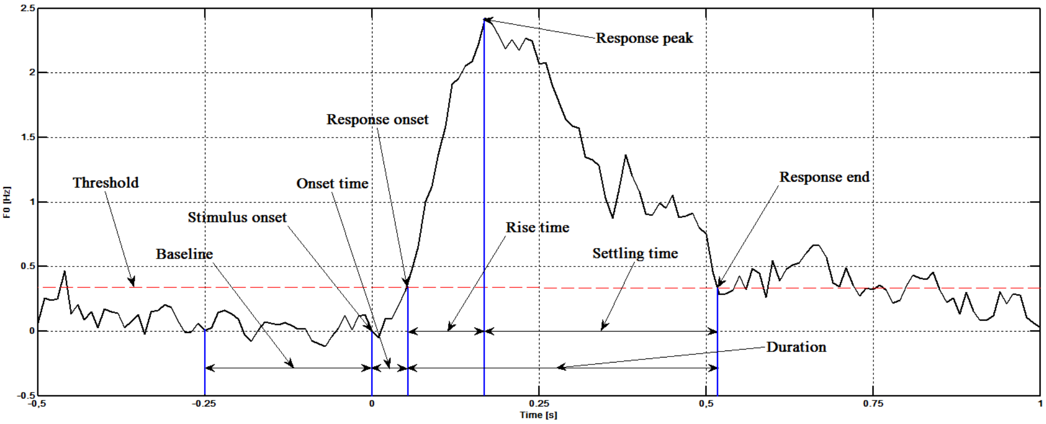

Fig. 2. A display of important response parameters (F_0 response example).

t-tests [23] were used. There was no statistically significant difference at α level of 0.05 between the mean peak value of the 105 dB responses and the 95 dB responses (*p* = 0.33). On the other hand, the difference between the 105 dB responses and the means of the lower intensity responses was statistically significant (*p* values 0.018 and lower). This is congruent with the averaged response analysis presented in Fig. 3.

The results of the analyses of EMG responses are presented in Table 2, which shows the means of the EMG response parameters averaged across stimulus intensity. It can be observed that all response parameters were dependent on stimulus intensity; however for lower intensity stimuli, time parameter means were meaningless, due to a lack in response. The peak value increased with stimulus intensity, while the peak time, rise time and duration decreased with stimulus intensity. The means and standard deviations of the observed parameters were similar to those reported in the literature [24].

B. Voice F_0 Data

The results of averaged F_0 response analyses (with the removed bias) are presented in Fig. 4. The time origin again coincides with the stimulus onset and the timespan is adjusted to -0.5 to 1.0 s due to inherently different time properties of the F_0 response [15]. The average response showed similar properties as the average eyeblink EMG response and the response parameter relations to the stimulus intensity were also similar.

As with the eyeblink EMG analyses, descriptive statistical methods were used to further explore these responses. The t- tests showed that the difference of the mean peak value of the 105 dB responses to the 95 dB responses was not statistically significant at α level of 0.05 (*p* = 0.0632). On the other hand, the difference between 105 dB responses and the means of the lower intensity responses was statistically significant (*p* = 0.0009 [85 dB], *p* = 0.0039 [75 dB], *p* = 0.0012 [65 dB] and *p* = 0.0034 [55 dB]).

Table 3 gives the means of the F_0 response parameters for individual trials, averaged within stimulus intensity sets. At the higher stimuli intensity levels (105, 95 and 85 dB), it can be observed that the value of the voice F_0 response peak was almost directly proportional to stimulus intensity. Similar conclusions, but for lower intensities (25 to 85 dB), were reported by Sapir and colleagues [15]. Furthermore, the onset time of the F_0 response also increased with stimulus intensity but not linearly.

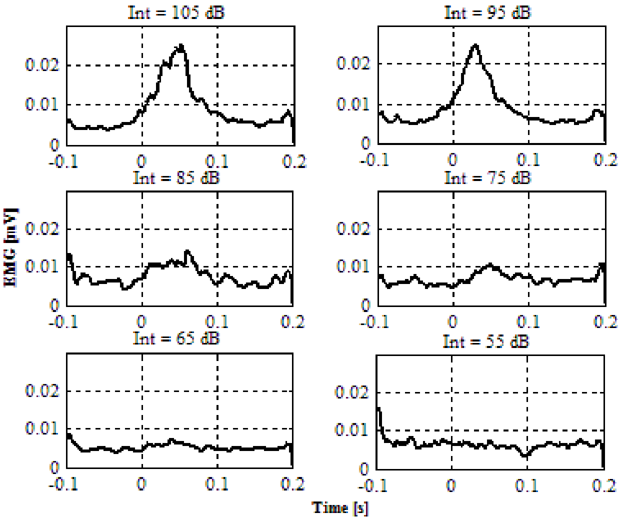

Fig. 3. Eyeblink EMG response plot averaged across stimulus intensity.

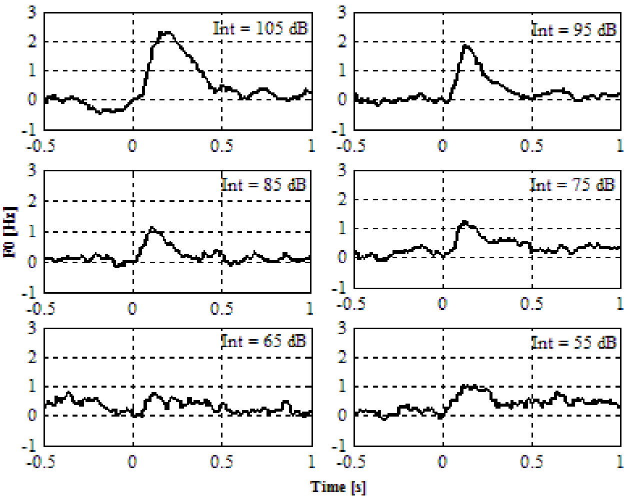

Fig. 4. F_0 response plots averaged across stimulus intensity.

TABLE II. MEANS OF EYEBLINK EMG RESPONSE PARAMETERS AVERAGED ACROSS STIMULUS INTENSITY

Stimulus intensity [dB(A) SPL]	**EMG response parameters**				
	***Peak* [uV]**	***Peak time* [ms]**	***Onset time* [ms]**	***Rise time* [ms]**	***Duration* [ms]**
105	33.93	29.83	20.62	9.21	16.73
95	20.65	33.52	20.78	12.74	32.00
85	20.53	48.35	22.11	26.24	70.75
75	15.89	44.87	21.93	22.94	69.62
65	9.83	59.33	25.38	33.96	90.53
55	11.37	76.99	26.73	50.26	139.76

TABLE III. MEANS OF F_0 RESPONSE PARAMETERS AVERAGED ACROSS STIMULUS INTENSTIY

Stimulus intensity [dB(A) SPL]	**F_0 response parameters**				
	***Peak* [Hz]**	***Peak time* [ms]**	***Onset time* [ms]**	***Rise time* [ms]**	***Duration* [ms]**
105	3.49	214.29	86.86	127.43	278.00
95	2.73	213.95	66.84	147.11	262.11
85	1.99	201.67	56.33	145.33	300.67
75	2.18	207.35	61.47	145.88	225.88
65	1.97	228.89	64.44	164.44	304.44
55	2.11	224.12	104.71	119.41	217.65

For the F_0 response another point has to be taken into account, because of the specifics of these responses. The eyeblink EMG response values are all relative to the value of 0V, but F_0 values vary during the phonation in the range of frequencies, which are specific to speaker gender and phonation pitch. For that reason, in the context of F_0 response, it is not sufficient to analyze the absolute F_0 deviation relative to the baseline value at the instant of the stimulus onset because a deviation of 5 Hz at the baseline frequency of 200 Hz is not the same measure of change as a deviation of 5 Hz at 120 Hz.

Therefore the relative deviation of the F_0 response peak (relative to the baseline frequency of phonation) across stimulus intensities was also calculated as follows: 2.9% (at 105 dB), 2.4% (at 95 dB), 1.7% (at 85 dB), 1.6% (at 75 dB), 1.4% (at 65 dB) and 1.5% (at 55 dB). We found that the behavior of the relative change of F_0 response peak values was similar to those of the absolute peak deviation values.

V. STARTLE RESPONSE SYSTEM IDENTIFICATION

System Identification (SI) is a useful tool when predicting system outputs to particular input, given a number of recorded input/output observations. Although SI is primarily used for prediction of future behavior of a system, SI methods can offer insight into the basic properties of the system itself. In this paper, black box SI methods including the Autoregressive model with exogenous input (ARX), the Autoregressive moving average model with exogenous input (ARMAX), the Output error model (OE) and the Box-Jenkins model (BJ) [25], were used for modeling both eyeblink EMG and voice F_0 responses.

The structure of the BJ model is given in Fig. 5., where one of the inputs ($x[n]$) is reserved for the actual recorded or synthetic input of the system and the other one ($e[n]$) is used for modeling the observation error of the recording. In this paper, the synthetic inputs are used in a form of an impulse, i.e. the Kronecker's delta function. Impulses are positioned at the stimulus onset time instance, with amplitude equal to 1 for all intensities. Consequently, the contribution of the acoustic startle stimuli to the overall response can be modeled within the $B(q)/A(q)$ block, while the $C(q)/D(q)$ block is intended for modeling all other unspecified processes contributing to the response.

The summed influence of both inputs gives us the prediction of the recorded observation of the system $y[n]$:

$$y[n] = x[n]\frac{B(q)}{A(q)} + e[n]\frac{C(q)}{D(q)}. \tag{1}$$

The BJ model is the most general of the models used and the other 3 models are special cases that share some common polynomials as their components. This makes the BJ model the most computationally complex, but often also the best performing model. The performance of SI modeling is presented in this paper by using normalized root mean square error fit (NRMSE), often referred to as percentage fit.

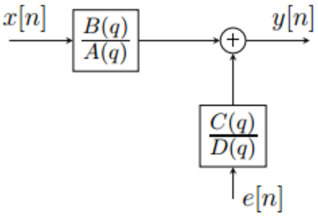

Fig. 5. The structure of a Box-Jenkins model.

The responses were modeled in groups according to stimulus intensity. Both F_0 and EMG responses were down-sampled for modeling to 20 Hz and 100 Hz respectively. Each group underwent the following modeling procedure for each model type, thus resulting with the total of 24 separate modeling processes (6 intensity groups × 4 model types) for each type of response (F_0 and EMG). Analysis of a wide range of model polynomial orders were performed for each modeling process, which are estimated using recommended methods [26], in order to find the optimal polynomial model orders that have the maximum NRMSE. The 10-fold cross validation was performed on all response observations in order to validate the modeling performance. The optimal orders were similar for both responses (EMG and F_0) and for most of the models used (order 2-3 for BJ and 5-8 for all others models). Results of the models with only the optimal polynomial orders are presented in this section.

The performance results of the SI modeling of the eyeblink EMG across different models and groups of observations are presented in Table 4. It can be seen that OE and BJ models outperformed other models for the highest intensity stimulus (105 dB). Similarly, the performance results of the SI modeling of the F_0 response across different models and groups of observations are presented in Table 5. It can be seen that the BJ model of the F_0 startle response outperformed other models, especially for the 105 dB stimulus.

VI. CONCLUSION

A comparative analysis of two manifestations of the acoustic startle response, eyeblink EMG and voice F_0 variation, resulted in the conclusion that the associations between those two measures are significant. We found that both types of responses increased peak values with increased stimulus intensity. The analysis of time related parameters, on the other hand, resulted in different conclusions for the two responses. Furthermore, t-tests of both responses showed statistically significant differences between the mean peak values of the 105 dB responses and the mean peak values of the lower intensity sets.

The system identification modeling produced mixed results, because some model outputs failed to capture the response dynamics or temporal characteristics of the recorded responses. Generally, we found that better results were achieved at the higher level intensity stimuli. The complex BJ models provided relatively high fits, especially for modeling the F_0 responses, while the OE models show satisfactory performance in the case of the highest-intensity eyeblink EMG responses.

TABLE IV. EYEBLINK EMG SYSTEM IDENTIFICATION MODELING PERFORMANCE DATA (FIT [%])

Model Type	**Stimulus intensity [dB(A) SPL]**					
	105	***95***	***85***	***75***	***65***	***55***
ARX	-9.61	-24.66	-19.58	-24.08	-0.34	8.89
OE	25.90	-14.18	-0.77	-4.75	2.34	5.19
ARMAX	2.49	-13.13	-5.23	3.45	6.52	6.25
BJ	18.48	-16.11	0.96	0.22	-0.22	8.37

TABLE V. F_0 SYSTEM IDENTIFICATION MODELING PERFORMANCE DATA (FIT [%])

Model Type	**Stimulus intensity [dB(A) SPL]**					
	105	***95***	***85***	***75***	***65***	***55***
ARX	2.36	3.08	4.36	3.79	5.25	5.96
OE	8.03	8.17	4.54	7.60	3.08	8.74
ARMAX	4.61	9.27	14.85	14.17	12.02	14.78
BJ	30.55	11.10	12.40	16.08	11.34	11.74

The results presented in this paper illustrate the validity of startle response analysis based on acoustic parameters like F_0, and provide a good foundation for further research in this area. One direction of future work could be related to the enhancement of system identification modeling of F_0 response which will include eyeblink EMG response as predictor variable. This modeling approach is justified due to shared neural underpinnings of the startle response across orbicularis oculi and laryngeal muscles up to and including the brainstem.

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