Horizontal directivity patterns differ between vowels extracted from running speech

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Abstract: Directivity patterns for vocalizations radiating from the human mouth have been examined regularly, but phoneme-specific changes in radiation have rarely been identified. This study reports half-plane horizontal directivity up to 20 kHz with 15° angular resolution for /ɑ/, /e/, /i/, /o/, and /u/ extracted from running speech, compared with long-term averaged speech. An effect of vowel category on the directivity index was observed, with /ɑ/ being most directional. Angle-dependent third-octave band weighting functions, useful for simulating real-world listening conditions, highlighted disparities in directivity between running speech and individual vowels. These findings point to rapidly changing dynamic directivity patterns during speech.

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1. Introduction

Many studies have reported directivity patterns for human vocalizations radiating from the mouth (Dunn and Farnsworth, 1939; Flanagan, 1960; Moreno and Pfretzschner, 1978; Marshall and Meyer, 1985; McKendree, 1986; Chu and Warnock, 2002; Bozzoli *et al.*, 2005; Jers, 2007; Katz and d'Alessandro, 2007; Cabrera *et al.*, 2011; Monson *et al.*, 2012a; Boren and Roginska, 2013; Halkosaari *et al.*, 2015). Understanding speech and voice directivity is of use for telecommunication (Halkosaari *et al.*, 2005), architectural design (McKendree, 1986; Bozzoli *et al.*, 2005; Chu and Warnock, 2002), vocal performance applications (Marshall and Meyer, 1985; Jers, 2007; Katz and d'Alessandro, 2007; Cabrera *et al.*, 2011; Boren and Roginska, 2013), and other general acoustical modeling of speech (Flanagan, 1960; Moreno and Pfretzschner, 1978; Chu and Warnock, 2002; Strelcyk *et al.*, 2014; Blandin *et al.*, 2016). It has been well established that, in general, low-frequency acoustical energy radiates more omnidirectionally around a talker's head, while radiation becomes increasingly directional toward the front of a talker as frequency increases (e.g., Chu and Warnock, 2002; Monson *et al.*, 2012a).

We previously demonstrated that changes to directivity patterns are induced by increasing or decreasing vocal production level, or by switching between voiceless fricatives (Monson *et al.*, 2012a). Thus directivity patterns may be dynamic during running speech, displaying temporal changes at least at the time scale of individual phonemes. However, this assertion has only been tested for voiceless fricatives extracted from running speech (Monson *et al.*, 2012a). Although some differences in directivity patterns have been reported for individual vowels (Katz and d'Alessandro, 2007; Marshall and Meyer, 1985), these studies examined sung and sustained vowels produced in isolation. It is not clear what differences in directivity, if any, would persist for less exaggerated vowels produced during running speech, additionally subject to the influence of co-articulation.

One primary interest in assessing speech directivity here is to replicate realistic listening conditions for perceptual experiments by simulating speech radiating to a listener standing off-axis from a talker. This can be done using angle- and frequency-dependent weighting functions that can be applied to on-axis speech recordings (e.g., Strelcyk *et al.*, 2014). However, previously published third-octave band weighting functions (Chu and Warnock, 2002) were limited due to (1) data collection in the horizontal plane being obtained by rotating the talker, resulting in nonuniform speech material in each direction, and (2) a lack of data beyond 8 kHz. Furthermore, it is of interest to examine how well third-octave band directivity patterns capture the frequency-dependence of human speech radiation.

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In the present study we address these outstanding issues by comparing directivity patterns for vowels extracted from running speech and for long-term averaged speech, simultaneously recorded in each direction in the horizontal plane. We hypothesized that individual vowels in running speech would exhibit unique directivity patterns. We tested this hypothesis by comparing horizontal directivity indices (DIs) calculated for the vowels /ɑ/, /e/, /i/, /o/, and /u/ extracted from running speech. We also compared third-octave band weighting functions up to 20 kHz for speech and individual vowels. Finally, we examined changes in speech radiation patterns as a function of frequency, using a finer spectral resolution of 21.5 Hz.

2. Methods

2.1 Speech directivity corpus

Details of the speech corpus have been previously reported (Monson *et al.*, 2012a, 2012b). In brief, anechoic speech samples were recorded from 15 native speakers of American English (8 female; age range 20 to 71 yrs, mean age = 28.5 yrs), uttering 20 six-syllable phrases with alternating syllabic strength and low semantic predictability (e.g., "amend the slower page"). Subjects were instructed to speak the phrases in a normal conversational manner. Simultaneous multi-channel recordings (24 bit, 44.1 kHz sampling rate) were made using 13 half-inch type 1 precision microphones (Larson Davis 2551, Provo, UT), positioned in 15° increments in a semicircle located 60 cm from the talker's mouth, at the level of the mouth, surrounding the right side of the talker from 0° (directly in front of the talker) to 180° (directly behind the talker). Although a distance of 1 m is often used for directivity studies (e.g., McKendree, 1986; Bozzoli *et al.*, 2005; Chu and Warnock, 2002), 60 cm was chosen here to reflect a typical distance for natural conversation. The angular resolution of 15° was similar to or better than that of most other studies published at the time of the original data collection (Marshall and Meyer, 1985; McKendree, 1986; Chu and Warnock, 2002; Bozzoli *et al.*, 2005; Cabrera *et al.*, 2011). To facilitate natural vocal production, the talker's head was not constrained, but talkers were instructed and observed to maintain a consistent head location.

2.2 Vowel extraction

Vowel beginning and ending time points were determined manually using the recordings at 0°. Steady-state portions of vowels were extracted at each direction, for each subject, and 10-ms raised cosine fade-in and fade-out was applied. Overall root-mean-squared sound pressure level (SPL) and third-octave band levels were determined for each vowel sample at each direction for each subject. The number of samples of each vowel produced by each subject was as follows: /ɑ/ = 6 samples; /e/ = 12 samples; /i/ = 10 samples; /o/ = 6 samples; and /u/ = 6 samples. Mean SPLs and third-octave band levels for each of the five vowel categories and each subject at each direction were then calculated by averaging across individual vowel samples within a vowel category. For comparison, SPL and third-octave band levels were also determined at each direction for the entire speech waveform for each subject. To calculate weighting functions and directivity patterns, all levels were adjusted to values relative to the level measured at 0°. Average directivity patterns and weighting functions were obtained by averaging across subjects.

To examine the frequency dependence of radiation patterns at a finer spectral resolution, the long-term averaged spectrum (LTAS) for running speech for each subject at each direction was calculated using a 2048-point fast-Fourier transform and Hamming window with 50% overlap (see also Monson *et al.*, 2012b), yielding an LTAS with 21.5-Hz resolution. A mean speech LTAS for each direction was then obtained by averaging across subjects. LTAS directivity patterns were obtained by adjusting LTAS spectral levels to values relative to the LTAS level measured at 0°.

2.3 Statistical analysis

Using the half-plane data, a horizontal DI was calculated for each vowel for each subject as

$$\mathrm{DI}_m(\omega) = 10\log_{10}\frac{|H_{m,0}(\omega)|^2}{\frac{1}{N}\sum_{n=0}^{N-1}|H_{m,n}(\omega)|^2},$$

where H is the sound pressure, m is the subject number, n is the direction, and N is the total number of directions (Tylka and Choueiri, 2014). This DI represents the ratio of acoustical energy radiated toward 0° to the average energy radiated in all directions.

Thus an increase in the DI indicates more directional radiation toward 0°. Statistical analysis consisted of a one-way repeated-measures analysis of variance to assess the effect of vowel on the DI. Audio editing and acoustical analysis were performed using MATLAB. Statistical analysis was conducted in R.

3. Results

Differences between vowel directivity patterns were most prominent at 1 kHz and beyond, whereas energy at 500 Hz and below exhibited highly similar directivity patterns (Fig. 1). At 1 kHz, /o/ and /ɑ/ were the most directional. The 4-kHz octave band exhibited a marked distinction between directivity for /o, u/ and that for /ɑ, e, i/, with the latter group being more directional. An examination of vowel spectra for each direction revealed that all vowels generated acoustical energy levels above the room and electronic noise floor at all frequencies and all directions, except for frequencies beyond 10 kHz at directions beyond 135°. (Data points in the noise floor were omitted for the 8- and 16-kHz octave bands in Fig. 1.) The noise floor for the 16-kHz octave band measured approximately 10 dB SPL, indicating that all vowel spectral energy produced in this octave band dropped to less than 10 dB SPL at directions beyond 135° (see Fig. 1).

Mean overall DIs (± standard deviation) for each vowel were as follows: /ɑ/ $= 3.9 \pm 1.1$ dB; /i/ $= 3.3 \pm 0.8$ dB; /e/ $= 3.1 \pm 0.7$ dB; /u/ $= 2.9 \pm 0.7$ dB; and /o/ $= 2.8 \pm 0.7$ dB. An effect of vowel on the DI was observed ($F = 9.14$, $p < 0.001$). Pairwise comparisons (Bonferroni corrected) revealed significant differences between /ɑ/ and /u/ ($p < 0.05$), and between /ɑ/ and /o/ ($p < 0.05$), with no differences between other vowel pairs. We observed relatively low within-subject variability in DIs for individual vowel tokens from the same vowel category (mean within-subject variance for the vowel categories ranged between 0.1 and 0.5 dB), however, as indicated by standard deviations reported above, between-subject variability was relatively high (see also Fig. S1 in the supplemental material[1]).

Third-octave band weighting functions (i.e., levels relative to 0°) for off-axis radiation of vowels and speech were similar for frequency bands below 1 kHz and at smaller recording angles, with differences emerging as frequency and recording angle increased (Fig. 2; for comparison, previously published data are also shown). For example, at 90° the differences between speech and individual vowels ranged from 2.5 to 5 dB for third-octave bands at 2 kHz and beyond (see also Table S1 in the supplemental material[1]). Table 1 provides these weighting functions for speech.

Analysis with finer spectral resolution revealed fluctuating increases and decreases in directionality as frequency increases, with more rapid and subtle fluctuations observed beyond 2 kHz (Fig. 3). Whereas third-octave bands captured changes in directivity pattern reasonably well at lower frequencies, some of these subtle changes at higher frequencies were lost in the third-octave averaging process. Both analyses demonstrate directionality changes nonlinearly with increasing frequency.

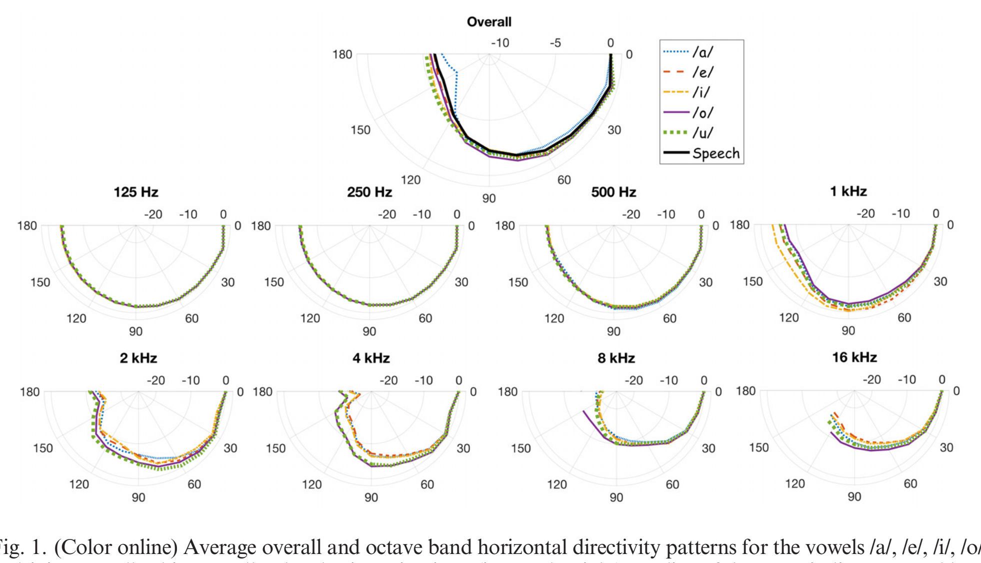

Fig. 1. (Color online) Average overall and octave band horizontal directivity patterns for the vowels /a/, /e/, /i/, /o/, and /u/ across all subjects. Talker head orientation is 0° (i.e., to the right). Radius of the curve indicates sound level relative to the level at 0°.

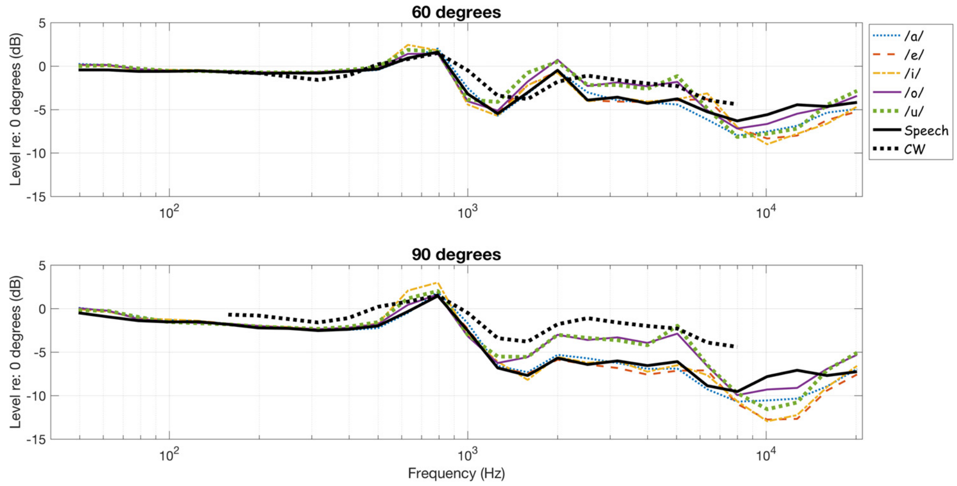

Fig. 2. (Color online) Third-octave band levels relative to 0° for individual vowels and long-term averaged speech radiating at 60° and 90° off-axis in the horizontal plane. CW—average speech data reported by Chu and Warnock (2002).

4. Discussion

Previous work has demonstrated that voiceless fricatives extracted from running speech differ in their directivity patterns (Monson *et al.*, 2012a). The present findings reveal that vowels extracted from running speech also display unique radiation characteristics. Specifically, we found that the vowel /ɑ/ is more directional than /o/ and /u/, suggesting that the relatively small changes in aperture (mouth opening) size and vocal tract configuration made during speech influence radiation of sound from the mouth. These results indicate radiation patterns are temporally dynamic and rapidly change at least at the time scale of individual phonemes during the course of running speech.

Differences among spoken vowel directivity patterns were driven by acoustical energy in the 1-kHz octave band and beyond. The most striking differences were observed in the 4-kHz octave band, where a clear pattern separated the vowels /ɑ, e, i/

Table 1. Third-octave band levels relative to 0° for running speech.

		Angle (degrees)												
		0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Center Frequency (Hz)	**79**	0.0	0.7	−0.2	0.0	−0.6	−1.0	−1.4	−1.7	−2.2	−2.5	−2.7	−2.7	−2.7
	99	0.0	0.7	−0.2	−0.5	−0.6	−1.1	−1.5	−1.8	−2.5	−2.9	−3.1	−3.2	−3.2
	125	0.0	0.8	−0.1	−0.4	−0.6	−1.0	−1.5	−2.0	−2.6	−3.1	−3.4	−3.5	−3.6
	157	0.0	0.8	−0.2	−0.5	−0.7	−1.3	−1.8	−2.3	−3.0	−3.4	−3.8	−4.0	−4.0
	198	0.0	0.8	−0.2	−0.6	−0.9	−1.5	−2.2	−2.8	−3.5	−4.0	−4.2	−4.4	−4.4
	250	0.0	0.7	−0.2	−0.5	−0.8	−1.5	−2.3	−3.0	−3.9	−4.4	−4.8	−4.9	−5.0
	315	0.0	0.7	−0.1	−0.5	−0.8	−1.6	−2.5	−3.5	−4.6	−5.4	−5.8	−6.1	−6.1
	397	0.0	0.6	−0.1	−0.4	−0.6	−1.4	−2.4	−3.5	−4.8	−5.8	−6.4	−6.7	−6.7
	500	0.0	0.6	0.0	−0.2	−0.4	−1.0	−2.0	−3.2	−4.6	−5.6	−6.1	−6.2	−6.2
	630	0.0	0.7	0.5	0.7	0.9	0.5	−0.3	−1.7	−3.6	−5.0	−5.3	−5.1	−4.9
	794	0.0	0.4	0.4	0.9	1.6	1.7	1.5	0.2	−2.0	−4.1	−4.5	−3.9	−3.4
	1000	0.0	−0.3	−1.4	−2.8	−3.2	−2.8	−2.6	−3.3	−5.4	−8.3	−9.2	−7.8	−7.0
	1260	0.0	−0.6	−1.2	−3.0	−5.5	−7.2	−6.8	−6.6	−7.8	−10.9	−14.2	−12.7	−11.3
	1587	0.0	−0.6	0.0	−0.8	−3.0	−6.0	−7.7	−7.3	−7.5	−9.4	−13.8	−14.8	−12.7
	2000	0.0	−1.2	0.3	0.4	−0.5	−2.7	−5.7	−7.1	−7.3	−7.6	−10.9	−14.2	−12.6
	2520	0.0	−1.8	−0.9	−2.6	−3.9	−4.1	−6.4	−9.4	−10.9	−11.4	−13.6	−16.9	−15.3
	3175	0.0	−1.8	−0.5	−1.2	−3.6	−5.0	−6.0	−9.1	−12.7	−13.7	−16.0	−19.8	−17.7
	4000	0.0	−1.6	−1.1	−2.3	−4.3	−5.6	−6.6	−9.0	−13.3	−15.5	−17.1	−22.4	−19.7
	5040	0.0	−1.3	−0.3	−1.0	−3.8	−5.3	−6.1	−8.5	−11.7	−14.7	−17.7	−22.0	−21.3
	6350	0.0	−1.3	−1.5	−2.6	−5.3	−7.0	−8.9	−11.1	−14.7	−17.0	−20.5	−24.7	−24.8
	8000	0.0	−0.9	−1.6	−3.2	−6.3	−7.8	−9.5	−12.8	−16.3	−19.1	−21.8	−25.3	−26.7
	10 079	0.0	−1.1	−1.9	−3.4	−5.6	−6.2	−7.8	−10.6	−14.2	−17.2	−22.0	−24.9	−27.4
	12 699	0.0	0.0	−0.6	−2.6	−4.5	−5.1	−7.1	−10.0	−13.9	−17.6	−21.5	−24.3	−27.5
	16 000	0.0	−0.7	−0.5	−2.2	−4.7	−5.3	−7.7	−11.1	−15.6	−19.1	−23.1	−22.2	−26.3
	20 159	0.0	−0.1	−0.7	−1.1	−4.2	−5.7	−7.3	−9.7	−14.8	−17.4	−21.1	−17.0	−21.9

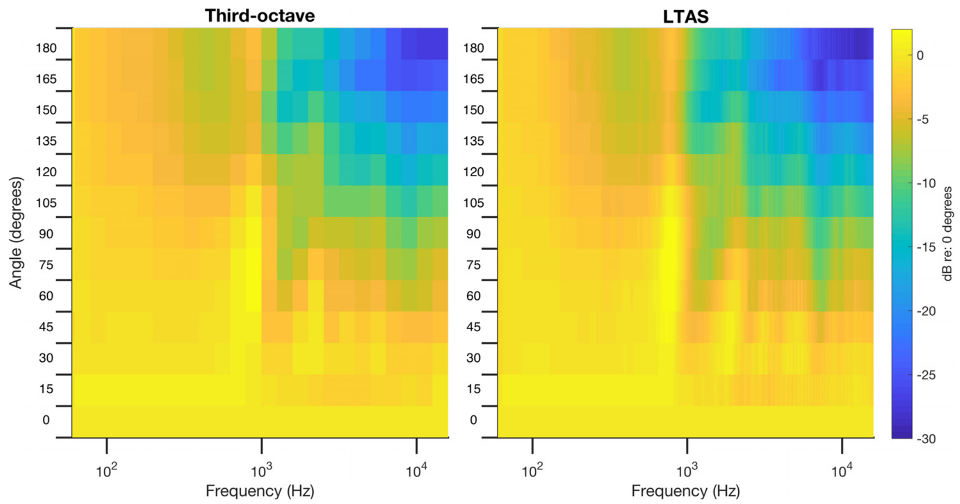

Fig. 3. (Color online) Spectral levels relative to 0°, calculated using third-octave band analysis and the LTAS with 21.5-Hz resolution. Levels are for speech radiating from 0° to 180° in the horizontal plane.

(more directional) from the vowels /o, u/ (less directional). Directivity patterns for spoken vowels depart somewhat from those previously reported for sung and/or sustained vowels. Whereas Marshall and Meyer (1985) found sung /e/ to be more directional than /ɑ/ or /o/, we observed spoken /ɑ/ to be the most directional of the five vowels studied here. Our results appear more in line with those reported by Katz and d'Allesandro (2007), whose data reveal generally decreasing directionality from sung /a/ to /i/ to /o/. However, differences between spoken vowels were more subtle than those reported for sung vowels.

Third-octave band weighting functions for off-axis speech showed some similarity to those reported by Chu and Warnock (2002) (see Fig. 2), but with notable differences at higher frequencies. These disparities might be attributable to the fact that their horizontal plane data collection did not occur simultaneously, or with identical speech material. Given our findings that directivity patterns change at the level of phonemes, differences in phonetic content between recordings might have influenced their analysis. Our functions also extend beyond their results to include lower and higher frequency bands. These functions can be used to design filters to apply to on-axis vocal recordings to simulate off-axis speech radiation that occurs in real-world listening conditions. As such, we expect they will be of value for speech perception experiments and other applications for the creation of virtual acoustic environments. We note that since third-octave band weighting functions do not capture some of the subtle changes in directivity for the highest frequencies (see Fig. 3), a more suitable modeling approach (i.e., finer resolution as shown here) may be necessary if these subtleties are of interest. Our angular resolution is limited to 15°, and changes in directivity are observed at a finer resolution than this (Katz and d'Alessandro, 2007). Furthermore, modeling the rapid phoneme-level temporal changes in directivity for virtual environments will require substantial computation and is likely warranted only if these rapid changes have perceptual consequences for the listener, which is currently unknown.

Acknowledgments

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[1]See supplementary material at https://doi.org/10.1121/1.5044508 for the supplementary figure and table.

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Supplementary Table S1. Third-octave band levels relative to 0° for individual vowels.

n.f. – values were in the noise floor

		Angle (degrees)												
/ɑ/		**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Center Frequency (Hz)	**79**	0.0	0.8	-0.2	-0.4	-0.5	-0.6	-0.8	-1.1	-1.2	-1.5	-1.4	-1.4	-1.3
	99	0.0	0.8	-0.3	-0.6	-0.6	-0.9	-1.4	-1.8	-2.1	-2.1	-2.4	-2.5	-2.0
	125	0.0	0.7	-0.1	-0.3	-0.5	-0.9	-1.2	-1.7	-2.2	-2.5	-2.6	-2.7	-2.7
	157	0.0	0.8	-0.1	-0.4	-0.6	-1.2	-1.7	-2.2	-2.9	-3.3	-3.6	-3.8	-3.8
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	250	0.0	0.8	-0.1	-0.5	-0.8	-1.5	-2.2	-2.9	-3.7	-4.2	-4.6	-4.8	-4.8
	315	0.0	0.7	-0.2	-0.5	-0.8	-1.6	-2.5	-3.5	-4.5	-5.1	-5.5	-5.7	-5.7
	397	0.0	0.7	-0.1	-0.4	-0.7	-1.5	-2.5	-3.6	-4.9	-5.8	-6.3	-6.6	-6.6
	500	0.0	0.6	0.0	-0.2	-0.5	-1.2	-2.3	-3.6	-5.2	-6.3	-6.7	-6.7	-6.6
	630	0.0	0.7	0.5	0.7	0.9	0.4	-0.5	-2.0	-4.1	-5.7	-6.0	-5.8	-5.6
	794	0.0	0.5	0.6	1.2	2.0	2.3	1.9	0.6	-1.7	-4.0	-4.4	-3.7	-3.3
	1000	0.0	-0.3	-1.4	-2.5	-2.6	-1.9	-1.7	-2.5	-4.6	-7.8	-8.9	-7.5	-6.7
	1260	0.0	-0.7	-1.3	-3.2	-5.7	-7.1	-6.6	-6.3	-7.6	-10.7	-14.2	-12.8	-11.3
	1587	0.0	-0.6	0.0	-0.9	-3.2	-6.0	-7.3	-6.9	-7.1	-9.1	-13.3	-14.2	-12.5
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	2520	0.0	-2.0	-0.7	-2.0	-3.1	-3.3	-5.7	-9.1	-10.4	-10.6	-13.1	-16.1	-14.3
	3175	0.0	-1.9	-0.6	-1.4	-4.0	-5.3	-6.3	-9.8	-13.8	-14.1	-16.5	-20.9	-18.0
	4000	0.0	-2.0	-1.0	-1.9	-4.2	-5.3	-6.9	-9.4	-13.7	-16.9	-18.1	-23.7	-20.4
	5040	0.0	-1.4	-0.5	-1.6	-4.7	-5.8	-7.3	-9.4	-12.1	-14.9	-16.0	-16.6	-17.1
	6350	0.0	-1.6	-1.9	-3.4	-6.5	-8.5	-10.0	-11.9	-14.2	-15.5	-16.6	-16.2	-17.2
	8000	0.0	-1.1	-2.4	-4.9	-8.4	-10.5	-11.5	-13.1	-15.4	-16.7	-17.4	-16.3	-18.1
	10079	0.0	-1.0	-2.4	-5.0	-7.7	-9.2	-10.9	-12.8	-15.3	-16.6	-17.2	-15.2	-17.7
	12699	0.0	-1.5	-2.9	-4.7	-7.1	-8.4	-10.7	-12.9	-15.0	-16.6	-17.5	*n.f.*	*n.f.*
	16000	0.0	-1.3	-2.0	-3.5	-5.5	-7.1	-9.3	-11.0	-13.5	-14.5	*n.f.*	*n.f.*	*n.f.*
	20159	0.0	-1.3	-2.5	-3.4	-5.4	-6.7	-7.7	-8.9	-10.8	-11.5	*n.f.*	*n.f.*	*n.f.*
		Angle (degrees)												
/e/		**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Center Frequency (Hz)	**79**	0.0	0.8	-0.2	-0.3	-0.4	-0.7	-1.0	-1.2	-1.5	-1.6	-1.8	-1.8	-1.7
	99	0.0	0.9	-0.1	-0.4	-0.4	-0.8	-1.3	-1.6	-2.0	-2.2	-2.4	-2.5	-2.4
	125	0.0	0.8	-0.1	-0.4	-0.5	-1.0	-1.4	-1.8	-2.3	-2.6	-2.8	-3.0	-3.0
	157	0.0	0.8	-0.1	-0.5	-0.6	-1.2	-1.7	-2.3	-2.9	-3.3	-3.6	-3.8	-3.8
	198	0.0	0.8	-0.1	-0.5	-0.7	-1.4	-2.0	-2.6	-3.3	-3.7	-4.0	-4.2	-4.2
	250	0.0	0.8	-0.1	-0.5	-0.7	-1.4	-2.1	-2.8	-3.6	-4.2	-4.6	-4.8	-4.9
	315	0.0	0.7	-0.1	-0.5	-0.7	-1.5	-2.4	-3.3	-4.4	-5.1	-5.6	-5.9	-6.0
	397	0.0	0.7	0.0	-0.3	-0.6	-1.3	-2.3	-3.3	-4.6	-5.6	-6.2	-6.6	-6.6
	500	0.0	0.7	0.0	-0.2	-0.4	-1.1	-2.0	-3.2	-4.7	-5.6	-6.0	-6.1	-6.1
	630	0.0	0.7	0.5	0.7	0.9	0.5	-0.4	-1.7	-3.6	-4.9	-5.1	-4.9	-4.7
	794	0.0	0.5	0.4	0.9	1.6	1.8	1.4	0.1	-2.2	-4.3	-4.6	-3.9	-3.5
	1000	0.0	-0.3	-1.3	-2.6	-3.1	-2.8	-2.4	-3.3	-5.6	-8.5	-9.2	-7.9	-7.0
	1260	0.0	-0.6	-1.0	-2.7	-5.3	-6.9	-6.6	-6.4	-7.5	-10.7	-14.3	-12.9	-11.4
	1587	0.0	-0.6	0.3	-0.1	-2.2	-5.2	-7.4	-7.3	-7.2	-8.6	-12.6	-14.6	-12.5
	2000	0.0	-1.5	-0.1	0.1	-0.6	-2.7	-5.9	-7.5	-7.5	-7.7	-10.7	-13.7	-12.5
	2520	0.0	-1.9	-0.8	-2.4	-4.1	-4.3	-6.5	-10.1	-11.3	-11.5	-13.7	-16.5	-14.8
	3175	0.0	-1.8	-0.5	-1.5	-4.1	-5.7	-6.9	-10.1	-14.2	-14.9	-17.0	-20.8	-18.4
	4000	0.0	-1.9	-0.9	-2.0	-4.3	-6.0	-7.9	-9.9	-14.0	-17.3	-18.4	-23.3	-21.5
	5040	0.0	-1.3	0.2	-0.7	-3.9	-5.0	-7.1	-9.1	-11.7	-14.0	-15.2	-15.9	-17.0
	6350	0.0	-1.1	-0.5	-1.1	-3.8	-5.6	-7.2	-9.2	-11.8	-12.7	-13.0	-12.5	-14.6
	8000	0.0	-1.1	-1.6	-3.7	-7.2	-9.6	-11.0	-13.0	-15.4	-16.9	-17.4	-16.6	-18.9

	10079	0.0	-0.8	-1.9	-4.8	-8.6	-10.8	-13.0	-15.1	-17.9	-19.1	-20.7	-18.8	-21.9
	12699	0.0	-1.1	-2.2	-4.8	-8.0	-10.3	-12.9	-15.2	-17.4	-18.7	-19.6	-16.4	-20.2
	16000	0.0	-1.9	-2.3	-4.0	-6.4	-8.0	-9.6	-11.0	-13.6	*n.f.*	*n.f.*	*n.f.*	*n.f.*
	20159	0.0	-1.5	-2.6	-3.3	-5.4	-7.0	-7.8	-8.6	-10.2	*n.f.*	*n.f.*	*n.f.*	*n.f.*
	Angle (degrees)													
/i/		**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Center Frequency (Hz)	**79**	0.0	0.7	-0.2	-0.4	-0.5	-0.9	-1.1	-1.4	-1.7	-1.8	-1.9	-2.0	-2.0
	99	0.0	0.9	-0.2	-0.5	-0.4	-0.8	-1.1	-1.4	-1.7	-1.7	-1.9	-1.9	-1.9
	125	0.0	0.8	-0.1	-0.4	-0.4	-0.9	-1.3	-1.7	-2.2	-2.5	-2.7	-2.9	-2.9
	157	0.0	0.8	-0.1	-0.4	-0.6	-1.2	-1.8	-2.3	-2.9	-3.4	-3.6	-3.9	-3.9
	198	0.0	0.8	-0.1	-0.5	-0.7	-1.4	-2.0	-2.6	-3.3	-3.7	-4.1	-4.3	-4.3
	250	0.0	0.8	-0.1	-0.5	-0.7	-1.4	-2.1	-2.8	-3.7	-4.3	-4.7	-4.9	-5.0
	315	0.0	0.7	-0.2	-0.5	-0.8	-1.6	-2.4	-3.3	-4.4	-5.2	-5.7	-6.0	-6.1
	397	0.0	0.7	-0.1	-0.4	-0.6	-1.3	-2.2	-3.3	-4.5	-5.5	-6.2	-6.6	-6.6
	500	0.0	0.7	0.0	-0.2	-0.3	-0.9	-1.7	-2.7	-4.0	-5.0	-5.5	-5.8	-5.9
	630	0.0	0.8	1.0	1.8	2.6	2.7	2.3	1.4	0.1	-0.7	-0.9	-0.8	-0.6
	794	0.0	0.0	-0.5	0.3	2.1	3.2	3.5	2.7	1.1	-0.3	-0.5	0.1	0.5
	1000	0.0	-0.4	-2.0	-3.8	-4.6	-3.7	-3.1	-3.7	-5.7	-8.5	-8.9	-7.5	-6.7
	1260	0.0	-0.6	-1.2	-3.1	-5.9	-7.3	-6.2	-5.7	-6.8	-9.9	-13.0	-11.4	-9.9
	1587	0.0	-0.6	0.3	-0.2	-2.2	-5.7	-8.4	-7.7	-7.2	-8.8	-13.0	-13.9	-11.8
	2000	0.0	-1.9	-0.9	-0.7	-0.8	-2.3	-5.5	-7.4	-7.5	-7.3	-10.4	-13.6	-12.1
	2520	0.0	-1.9	-0.7	-2.3	-4.0	-4.1	-6.2	-9.6	-10.9	-10.9	-12.9	-16.4	-14.4
	3175	0.0	-1.8	-0.3	-1.0	-3.6	-5.1	-6.0	-9.1	-13.3	-13.9	-15.8	-20.0	-17.3
	4000	0.0	-2.0	-0.8	-1.7	-4.0	-5.4	-7.1	-9.4	-13.4	-16.4	-17.6	-23.4	-20.1
	5040	0.0	-1.3	0.0	-0.7	-3.5	-5.0	-6.3	-8.9	-11.4	-14.0	-15.6	-16.7	-17.8
	6350	0.0	-1.3	-0.3	-0.4	-3.2	-5.4	-7.7	-9.7	-12.7	-13.5	-14.4	-14.4	-16.2
	8000	0.0	-1.1	-1.6	-3.6	-6.9	-9.1	-10.7	-12.9	-15.7	-17.4	-18.7	-18.6	-20.6
	10079	0.0	-1.1	-2.4	-5.3	-9.1	-11.2	-13.1	-15.3	-18.1	-19.6	-21.4	-19.8	-22.7
	12699	0.0	-1.4	-2.8	-5.3	-8.1	-10.0	-12.6	-14.7	-16.7	-18.0	*n.f.*	*n.f.*	*n.f.*
	16000	0.0	-1.5	-2.1	-4.1	-6.6	-8.2	-9.2	-10.1	-12.3	*n.f.*	*n.f.*	*n.f.*	*n.f.*
	20159	0.0	-1.0	-2.3	-3.1	-4.7	-6.1	-6.7	-7.5	-8.9	*n.f.*	*n.f.*	*n.f.*	*n.f.*
	Angle (degrees)													
/o/		**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Center Frequency (Hz)	**79**	0.0	0.9	-0.1	-0.3	-0.3	-0.6	-1.1	-1.4	-1.6	-1.7	-2.0	-2.0	-1.9
	99	0.0	1.1	-0.1	-0.6	-0.6	-0.7	-1.4	-1.7	-1.8	-1.6	-2.0	-2.1	-1.4
	125	0.0	0.8	-0.1	-0.3	-0.6	-1.1	-1.4	-2.0	-2.7	-2.9	-3.1	-3.4	-3.4
	157	0.0	0.8	-0.1	-0.4	-0.6	-1.2	-1.7	-2.3	-2.9	-3.4	-3.7	-4.0	-4.0
	198	0.0	0.8	-0.1	-0.5	-0.7	-1.4	-2.0	-2.6	-3.3	-3.7	-4.0	-4.2	-4.3
	250	0.0	0.8	-0.1	-0.5	-0.8	-1.5	-2.2	-2.9	-3.7	-4.2	-4.5	-4.7	-4.8
	315	0.0	0.7	-0.1	-0.5	-0.7	-1.5	-2.4	-3.4	-4.5	-5.3	-5.7	-6.0	-6.1
	397	0.0	0.7	-0.1	-0.3	-0.5	-1.3	-2.2	-3.3	-4.6	-5.6	-6.3	-6.7	-6.7
	500	0.0	0.7	0.1	-0.1	-0.2	-0.9	-1.8	-3.0	-4.4	-5.5	-5.9	-6.1	-6.1
	630	0.0	0.7	0.7	1.1	1.5	1.2	0.5	-0.8	-2.7	-4.0	-4.3	-4.1	-3.9
	794	0.0	0.3	0.1	0.5	1.4	1.8	1.6	0.5	-1.7	-3.7	-4.0	-3.3	-2.9
	1000	0.0	-0.3	-1.5	-3.1	-3.9	-3.6	-3.0	-3.5	-5.6	-8.5	-9.5	-8.0	-7.2
	1260	0.0	-0.4	-0.9	-2.6	-5.1	-6.7	-6.3	-6.0	-7.2	-10.2	-13.2	-11.9	-10.5
	1587	0.0	-0.5	0.3	-0.1	-1.8	-4.2	-5.5	-5.5	-5.8	-7.8	-11.9	-12.8	-11.1
	2000	0.0	-1.4	0.1	0.6	0.7	-0.4	-2.9	-4.5	-5.2	-5.6	-9.1	-12.4	-11.1
	2520	0.0	-1.7	-0.2	-1.5	-2.2	-1.7	-3.6	-6.6	-8.1	-8.3	-10.5	-14.4	-12.7
	3175	0.0	-1.8	-0.1	-0.2	-1.9	-3.0	-3.3	-6.4	-10.1	-10.6	-12.6	-17.5	-15.0
	4000	0.0	-1.7	-0.5	-0.9	-2.3	-3.1	-3.8	-5.8	-10.2	-12.5	-13.6	-17.8	-15.9
	5040	0.0	-0.8	0.1	0.2	-1.9	-2.1	-2.9	-4.5	-6.9	-8.8	-9.1	-9.4	-10.6
	6350	0.0	-1.1	-1.8	-3.2	-5.3	-6.5	-6.8	-8.0	-9.7	-10.4	*n.f.*	*n.f.*	*n.f.*
	8000	0.0	-0.8	-1.6	-4.2	-7.3	-9.4	-10.2	-11.8	-13.5	-14.2	*n.f.*	*n.f.*	*n.f.*
	10079	0.0	-0.4	-1.4	-3.7	-6.8	-8.6	-9.6	-10.7	-11.9	-12.4	*n.f.*	*n.f.*	*n.f.*
	12699	0.0	-0.9	-1.4	-3.2	-5.7	-7.4	-9.4	-11.1	-12.8	-13.5	*n.f.*	*n.f.*	*n.f.*

	16000	0.0	-0.9	-1.7	-3.2	-5.2	-6.7	-7.4	-7.9	-9.6	*n.f.*	*n.f.*	*n.f.*	*n.f.*
	20159	0.0	-0.3	-1.7	-2.1	-3.8	-5.5	-5.8	-6.5	-7.8	*n.f.*	*n.f.*	*n.f.*	*n.f.*
	Angle (degrees)													
/u/		**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**	**180**
Center Frequency (Hz)	**79**	0.0	1.0	0.0	-0.3	-0.2	-0.4	-0.8	-1.1	-1.2	-1.3	-1.4	-1.5	-1.4
	99	0.0	0.9	-0.1	-0.5	-0.6	-1.0	-1.4	-1.9	-2.4	-2.6	-2.8	-2.8	-2.7
	125	0.0	0.8	-0.1	-0.5	-0.6	-1.1	-1.6	-2.1	-2.6	-3.0	-3.1	-3.4	-3.5
	157	0.0	0.8	-0.1	-0.4	-0.6	-1.3	-1.8	-2.4	-3.0	-3.5	-3.8	-4.0	-4.1
	198	0.0	0.8	-0.1	-0.5	-0.7	-1.4	-2.0	-2.6	-3.3	-3.8	-4.1	-4.3	-4.3
	250	0.0	0.8	-0.1	-0.5	-0.8	-1.5	-2.3	-3.0	-3.8	-4.4	-4.8	-5.1	-5.1
	315	0.0	0.7	-0.1	-0.5	-0.7	-1.5	-2.4	-3.2	-4.3	-5.0	-5.5	-5.8	-5.9
	397	0.0	0.7	0.0	-0.3	-0.5	-1.2	-2.1	-3.2	-4.4	-5.4	-6.0	-6.4	-6.4
	500	0.0	0.7	0.1	0.0	-0.1	-0.7	-1.6	-2.6	-3.9	-4.9	-5.3	-5.5	-5.5
	630	0.0	0.8	0.8	1.3	1.8	1.7	1.1	0.0	-1.6	-2.7	-2.8	-2.6	-2.3
	794	0.0	0.4	0.3	0.8	1.7	2.2	2.0	0.9	-1.2	-3.0	-3.1	-2.4	-2.0
	1000	0.0	-0.3	-1.4	-2.9	-3.8	-3.5	-3.0	-3.6	-5.6	-8.5	-9.4	-8.0	-7.0
	1260	0.0	-0.4	-0.6	-2.0	-4.1	-5.6	-5.4	-5.2	-6.4	-9.5	-12.8	-11.3	-9.9
	1587	0.0	-0.4	0.9	0.8	-0.8	-3.4	-5.5	-5.3	-5.3	-7.0	-11.3	-12.5	-10.4
	2000	0.0	-1.6	-0.2	0.3	0.5	-0.5	-3.0	-4.7	-5.3	-5.5	-8.7	-12.5	-10.7
	2520	0.0	-1.8	-0.1	-1.1	-2.1	-1.8	-3.3	-5.9	-7.7	-7.8	-9.9	-13.9	-12.8
	3175	0.0	-1.8	-0.4	-0.4	-2.2	-3.1	-3.7	-6.1	-9.9	-10.6	-12.5	-16.7	-14.9
	4000	0.0	-1.6	-0.5	-1.0	-2.6	-3.1	-4.2	-6.1	-10.1	-12.7	-14.0	-19.1	-16.7
	5040	0.0	-1.1	0.5	0.5	-1.1	-1.7	-1.8	-4.1	-6.1	-8.4	-9.3	-10.5	-11.3
	6350	0.0	-1.2	-1.6	-2.8	-4.9	-5.7	-6.5	-7.9	-10.5	-11.7	-12.7	-12.3	-14.5
	8000	0.0	-1.1	-2.2	-4.8	-8.2	-9.2	-9.8	-12.3	-15.0	-16.7	-18.3	-17.9	-20.1
	10079	0.0	-0.7	-1.4	-3.8	-7.9	-9.6	-11.7	-13.9	-16.4	-17.8	-19.2	-17.6	-20.2
	12699	0.0	-1.3	-2.0	-4.3	-7.3	-9.0	-10.8	-12.5	-14.6	-15.9	-16.6	*n.f.*	*n.f.*
	16000	0.0	-1.0	-1.2	-2.6	-4.8	-6.2	-7.4	-8.1	-10.3	-10.4	*n.f.*	*n.f.*	*n.f.*
	20159	0.0	0.0	-0.8	-1.4	-3.2	-4.9	-5.3	-5.9	-7.3	-7.3	*n.f.*	*n.f.*	*n.f.*

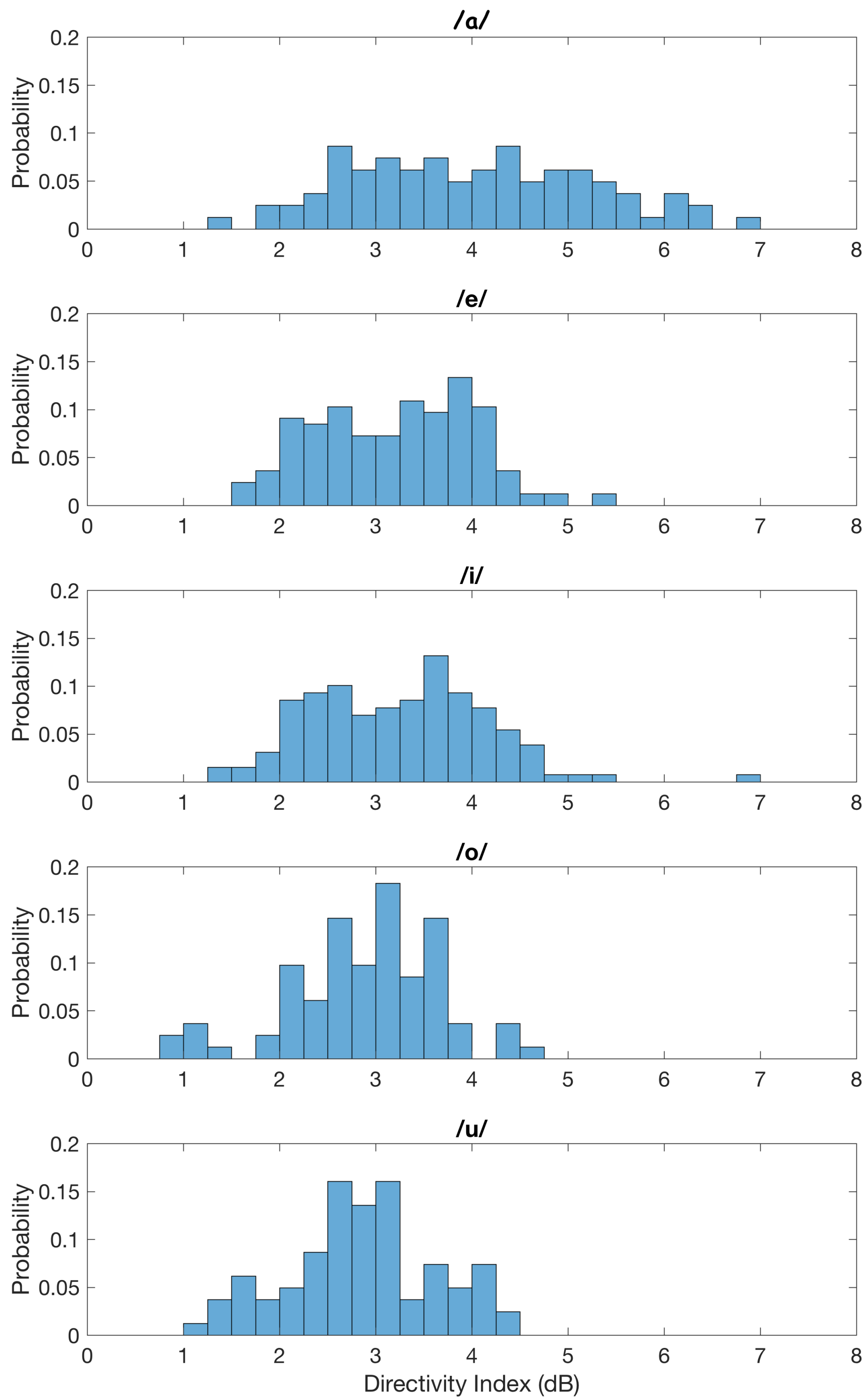

Figure S1. Distributions for the directivity index for each vowel, aggregated across all individual vowel samples from all subjects.