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A DATABASE FOR THE COMPARISON OF MEASURED DATASETS OF HUMAN VOICE DIRECTIVITY

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ABSTRACT

More than 200 years ago, early research on human voice radiation showed that speech has directional properties [1,2]. Since then, many speech directivity studies have investigated several specific aspects, for example, phoneme or loudness dependencies, but only a few datasets are freely available. This study presents a database that allows direct comparison and visualization of datasets from 19 different studies. The data is collected from tables, plots, and datasets from the supplemental material of the respective studies. Some studies present directivity patterns averaged over a whole sentence, while others report phoneme-dependent data. Furthermore, these datasets vary in their sampling grids, with many measured in the horizontal plane and just a few measured spherically. Most datasets included in this work present frequency-band averaged values, for example, in one-third octave bands, while a few newer studies provide the raw data in the form of transfer functions. Our database allows the visualization and comparison of directivity patterns of various datasets found in literature in different ways, such as polar plots or amplitudes over frequency. This study can thus simplify the systematic review and support a better understanding of the specific properties of human voice directivity.

Keywords: *human voice, directivity, sound radiation*

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1. INTRODUCTION

Long before the term ”directivity” was technically defined, research studies showed that the radiation emitted by the human voice is directional [1–4]. Human voice directivity has been identified as being relevant to the design of appropriate theater or auditorium shapes and the suggestion of optimal distances between the performer on stage and the audience for optimal speech intelligibility. These studies made an indirect measurement of the directivity of the human voice, which was done by determining the distance up to which a listener can hear a human speaker in different radiation directions. This shows that the basic concepts of human voice directivity and its relevance to speech intelligibility have long been understood, as summarized in more detail by Postma et al. [5]. Postma et al. compared the results of these early studies with a modern one [6], which shows that for frontal and lateral directions, the measurements are in fairly good agreement. However, for backward directions, only Saeltzer's results [4] are within perceptual thresholds .

The first direct measurements of voice directivity were published in 1929 by Trendelenburg [7], who already analyzed phoneme dependencies in human voice directivity patterns of several vowels and fricatives in the horizontal plane. The plots in Trendelenburg's paper show only exemplary frequency bands for some of the subjects at selected phonemes. In contrast, only 10 years later, Dunn and Farnsworth [8] published comprehensive results analyzing the sound radiation for a spoken sentence in octave or one-half octave bands from 63 Hz to 12 kHz. Since then, many studies have addressed specific aspects of human voice radiation, such as the influence of voice level [9], differences between speaking and singing [10], or the influence of face masks [11] or hand postures [12] on voice radiation. While in most studies, the measurements were performed in the horizontal or vertical plane only, a few studies measured the full spherical characteristics of human voice directivity, e.g. [6, 8, 13–15]. In addition, most measurements were performed sequentially, i.e. one after the other for each direction. Thus, the spectrum of the emitted sound can only be analyzed averaged over time, and time-variant effects of the voice directivity, e.g. phoneme dependencies, cannot be resolved. For this, the measurements need to be performed simultaneously for all measurement positions, for example, by using a spherical microphone array [16–18]. And finally, in the publications, there are different ways of presenting the data in the form of polar plots resolving the directivity patterns in the horizontal or vertical planes in frequency bands, or in the form of balloon plots that show the spherical radiation at one frequency. Other studies depict the directivity over frequency in one plane or present the data in tables. Accordingly, the results of the various voice directivity measurements can often hardly be compared. This study provides a general overview and comparison of studies measuring voice directivity patterns determined for human speakers and dummy heads. The supplementary material provides a database and Matlab scripts that allow to compare and visualize the datasets from 19 different studies.

2. LITERATURE REVIEW

2.1 Human Voice Measurements

As a first direct measurement of directivity, **Trendelenburg [7]** analyzed the voice radiation patterns of different phonemes. To obtain reflection-free conditions, the measurements were made on a rooftop, and because of the high background noise in Berlin, at night or early in the morning. **Dunn and Farnsworth [8]** were the first to publish detailed results with numerical data for different frequency bands of voice directivity patterns. The authors analyzed the sound radiation for a spoken sentence in octave or one-half octave bands from 63 Hz to 12 kHz. They measured the directivity along a sphere in steps of 45° in the horizontal and vertical planes. The measurements were performed sequentially by comparing the microphone signals at the respective positions with a measurement with another microphone at a reference position. The data were for each measurement distance repeated eight times and then averaged, with the closest measurements made directly at the mouth opening and the farthest at a distance of 1 m. Due to technical limitations, the authors had to perform the measurements for each frequency band separately, resulting in approximately 5000 measurements. This early study is still a valuable source for research and comparison, showing many specific effects of human voice directivity. For example, the influence of frequency on the main radiation direction, which we have recently studied [41], correlates well to the results from [8]. **Moreno and Pfretzschner [21]** published results on ten male subjects measured while they were speaking on a topic of their choice. Directional patterns were presented in one-third octave bands for both the vertical and horizontal planes. **Marshall and Meyer [9]** determined voice directivities for singers with different voice types (soprano, alto, baritone) and while singing different vowels. Based on their measurements, which show that the main radiation direction is slightly downward, the authors emphasize the importance of floor reflections. **Studebaker [22]** examined voice directivity patterns in the horizontal plane for a female and a male subject. The results of the study generally confirm the findings of previous studies on human voice directivity [8,21] and on directivity patterns determined for a dummy head [20]. **Sugiyama and Irii [23]** analyzed frontal radiation at different distances for 12 subjects. As one part of the study they determined the directivity for ±30 azimuth and elevation and compared it to simulations of a prolate spheroid. In their study, **Kob and Jers [24]** introduced the glissando method, which allows obtaining a broadband excitation signal and has been employed in many recent studies to analyze the directivity of single phonemes, e.g. vowels [14, 15, 33]. The datasets of **Chu and Warnock [6]** provide a comprehensive overview of the directivity of the human voice with values in one-third octave bands measured on a spherical grid in steps 15° azimuth for 9 vertical directions. They include both averaged values and standard deviations over all 40 subjects and values separated for female and male ones. For comparison, the directivity pattern of a B&K head and torso simulator was also determined. Although this study does not resolve phoneme dependencies, it has been the most comprehensive for a long time. The authors have further included a comparison with the results of Dunn and Farnsworth [8] and with those of Moreno and Pfretzschner [21]. The measurements of **Bozzoli et al. [26]** were performed with a horizontal resolution of 5° for two dummy heads and one human speaker in octave bands between 500 Hz and 2 kHz and were in **Bozzoli et al. [27]** extended to 10 subjects and 3 elevations (0° and

Authors	Year	No. of subj.	Dummy head model	Articulation	Data representation	Sampling grid	Distance	Measuring procedure	Data acquisition	Remarks	Database
Trendelenburg [7]	1929	1		selected phonemes	selected freq.	15° hor.		sequential			
Dunn and Farnsworth [8]	1939	1		fluent speech	1/2 oct.	spherical, 45° hor., 22.5° vert.	0.05 m - 1 m	sequential	table	one hemisphere, mouth centering, ≤ 500 Hz 1/1 octave	○
Flanagan [19]	1960		mannequin		1/1 oct.	20° hor.	0.3 m	sequential	plot	mouth centering	○
Olson [20]	1972		self-built		1/1 oct.	45° hor., 5 elevations	0.6 m	sequential			
Moreno and Pfretzschner [21]	1978	10		fluent speech	1/3 oct.	hor. and vert. planes		sequential	plot		○
Marshall and Meyer [9]	1985	1		singing	1/1 oct.				plot	[a] [e] [o] only shown for 2 kHz, not considered	x
Studebaker [22]	1985	2		fluent speech	freq. resp.	45° hor.	1 m	sequential	plot	one hemisphere	
Sugiyama and Irii [23]	1991	12		speech	1/3 oct.	15° hor., 15° vert.	0.5 m	sequential	plot	range of ±30° hor. and vert.	
Kob and Jers [24]	1999	1	ITA	singing							
Huopaniemi et al. [25]	1999		B&K 4128		1/1 oct.		2 m	sequential	plot	2 meas. methods (reciprocal and direct)	x
Chu and Warnock [6]	2002	40	B&K	fluent speech	1/3 oct.	spherical, 15° hor., 9 elevations	1 m	sequential	table	one hemisphere, standard deviations of all data given in paper	○
Bozzoli et al. [26, 27]	2003, 2005	10	B&K 4230, Parma		1/1 oct.	5° hor.				2 meas. series, 1 and 10 subj., 3 elevations meas. in one series	○
Halkosaari et al. [28]	2005		B&K 4128, B&K 4227, HEAD HMS II.3		freq. resp.	selected directions	varying	sequential		near field measurements	
Katz et al. [29]	2006	1		[a] [o] [i] [m] [n] [f] [s] [ch]	1/1 oct.	5° hor.		simultaneous	plot	one hemisphere, not all bands shown in plots	x
Katz et al. [30]	2007	1		[a] [o]	1/3 oct.	5° hor.		simultaneous	plot	one hemisphere, loudness variances, dynamic voice directivity	
Cabrera et al. [31]	2011	8	B&K 4128C	singing	1/1 oct.	15° hor.		simultaneous	plot	one hemisphere	
Monson et al. [10]	2012			fluent speech, [s] [sh] [f] [th], singing	1/1 oct.	15° hor.	0.6 m	simultaneous	table	one hemisphere	○
Kocon and Monson [32]	2018	15		fluent speech, [a [e] [i] [o] [u]	1/3 oct.	15° hor.	0.6 m	simultaneous	table	one hemisphere	○
Brandner et al. [33]	2018	2		singing	freq. resp.	11.25° hor., 11.25° vert.	1.23 m	simultaneous	plot	2 freq. bins, 22.5° steps in hor. and vert. plane	x
Fischer et al. [34]	2019		Kemar 45BC		freq. resp.	4° hor.	0.6 m	sequential	plot	4 freq. bins	x
Brandner et al. [35]	2020	2	B&K 4128		freq. resp.	11.25° hor., 11.25° vert.	1.23 m	simultaneous	plot	2 freq. bins, 22.5° steps in hor. and vert. plane	x
Pörschmann et al. [11]	2020		HEAD HMS II.3		freq. resp.	spherical, 2702 Lebedev grid	2 m	sequential	dataset	5 face masks and reference without mask	○
Leishman et al. [13]	2021	6	Kemar 45BC	fluent speech	freq. resp.	spherical, 5° hor., 5° vert.	1.83 m	vert. simult., hor. sequential	dataset	multiple-capture transfer function technique	○
Pörschmann and Arend [14, 15]	2021, 2023	13		23 phonemes	freq. resp.	spherical, 32 directions	1 m	simultaneous	dataset	spatial Upsampling [36] to 2702 Lebedev grid	○
Pörschmann and Arend [12]	2022	13		articulation of an [a] w/wo hand postures	freq. resp.	spherical, 32 directions	1 m	simultaneous	dataset	spatial Upsampling [36] to 2702 Lebedev grid	○
Pörschmann and Arend [37]	2022	1		fluent speech segmented in frames of 67 ms	freq. resp.	spherical, 32 directions	1 m	simultaneous		spatial Upsampling [36] to 2702 Lebedev grid	
Luizard et al. [38]	2022	1		[a] [i] [o] [m] [v] [s]	1/1 oct.	2° hor.	1.5 m	simultaneous	plot	mouth centering	
Brandner et al. [39]	2022	10		[a] [e] [i] [o] [u]	freq. resp.	11.25° hor., 11.25° vert.	1.23 m	simultaneous	dataset	sustained vowels	x [2]
Pörschmann [40]	2023	13		fluent speech	continuous	spherical, 32 directions	1 m	simultaneous	dataset	spatial Upsampling [36] to 2702 Lebedev grid	○

Table 1. Overview of all studies on voice directivity. The last column indicates in which form the data sets could be made usable in the database. An [x] denotes single data sets suitable for comparative purposes, and a [○] denotes full data sets determined in multiple frequency bands and on a well-defined sampling pattern.

±30°), but the results are shown only for the 1 kHz octave band. **Katz et al. [29]** devoted their study to the measurement of phoneme dependencies, and determined the voice directivities of vowels, fricatives, and nasals in the horizontal plane. Although only exemplary frequency bands for some of the phonemes are published, the study gives an idea of the extent of the differences between the phonemes. This study was extended in **Katz et al. [30]** and slight variations of voice directivity depending on the voice intensity were found. Furthermore, in this study dynamic voice directivity was determined for a singer [1]. **Cabrera et al. [31]** measured the horizontal directivity patterns of 8 opera singers in octave bands and compared the results with measurements by Marshall and Meyer [9] and Chu and Warnock [6]. Similar measurements were carried out by **Monson et al. [10]** for 15 subjects, analyzing patterns of different voice strengths. This study also determined the directivity patterns of voiceless fricatives. The measurements of **Kocon and Monson [32]** also cover the horizontal plane but with a finer one-third octave spectral resolution for different vowels and speech. **Brandner, et al. [33, 35, 39]** determined speech directivities under a variety of different conditions in three different studies. The first [33] measured a human singer as well as the radiation of musical instruments. The second [35] analyzed measurements of two singers and an artificial mouth for different mouth opening sizes. In the third [39] the directivity was determined for 10 subjects articulating sustained vowels. The measurements were performed with a resolution of 11.25° in the horizontal and vertical planes. **Leishman et al. [13]** performed spherical measurements with a resolution of 5° in azimuth and elevation. The datasets were collected from a dummy head and 8 subjects articulating speech. In two subsequent studies **Pörschmann and Arend [14, 15]** we performed simultaneous measurements on a spherical grid with 32 sampling directions. To obtain dense directivity sets from the sparse measurements, we applied spatial upsampling to a dense grid using the SUpDEq (Spatial Upsampling by Directional Equalization) method [36], which was evaluated for speech directivity in [42]. In total, we measured 23 phonemes in the two subsequent studies, each twice for 13 subjects, and found significant differences in the directivity index both within and between the investigated groups of phonemes. Our follow-up study **Pörschmann and Arend [12]** used the same measurement procedure and analyzed the effect of two common head postures on the directivity of the human voice. The results showed that both holding a hand in front of the mouth and cupping the hands around the mouth severely affects the directivity of the human voice. The effect of the postures, e.g. on the directivity index, was stronger than any variance we observed in our other studies [14, 15] between the phonemes studied. In **Pörschmann and Arend [37]** we presented a study on dynamic voice directivity, determining the patterns of a spoken sentence in frames of 67 ms. While the visualization already gives an impression of how the directivity changes over time, there are many open questions about the technical and perceptual required temporal resolution. Recently, **Luizard et al. [38]** published a study determining the voice directivity for various phonemes in the horizontal plane. The resolution of 2° has promising potential for future research studies. Finally, in this study, we provide as **supplementary material [40]** a further dataset, a phonetically balanced sentence articulated by 13 subjects which were recorded in the measurement series of [14] but have not yet been published.

2.2 Dummy Head Measurements

While several of the studies described in the previous section included measurements with a dummy head, others only determined the directivity patterns of dummy heads. These studies are briefly described below. The first measurements of voice directivity with a mouth simulator were made by **Flanagan [19]** using a life-size mannequin with head and torso. In addition, this study compared the measurements with calculations for a spherical source and a piston in a sphere. **Olson [20]** compared the human voice radiation data of Dunn and Farnsworth [8] with measurements performed with a self-built head and mouth simulator, finding good agreement for the data in both the horizontal and vertical planes. **Huopaniemi et al. [25]** analyzed and compared two different methods for measuring directivity, a direct measurement and one using the reciprocity method, both for a B&K 4128 dummy head. The result showed good agreement between the two methods. **Halkosaari et al. [28]** concentrated on the comparison of the directivity characteristics of humans with those of dummy heads, a B&K 4128, a B&K 4227, and a HEAD HMS II.3. As a result, the study aims at providing fundamental information on how artificial mouth measurements for telephone handsets should be designed and in which way the potential difference between the

[1] Visualization at https://youtu.be/elaacIo6g7M

[2] The digital dataset of [39] has not been used for our database due to technical reasons.

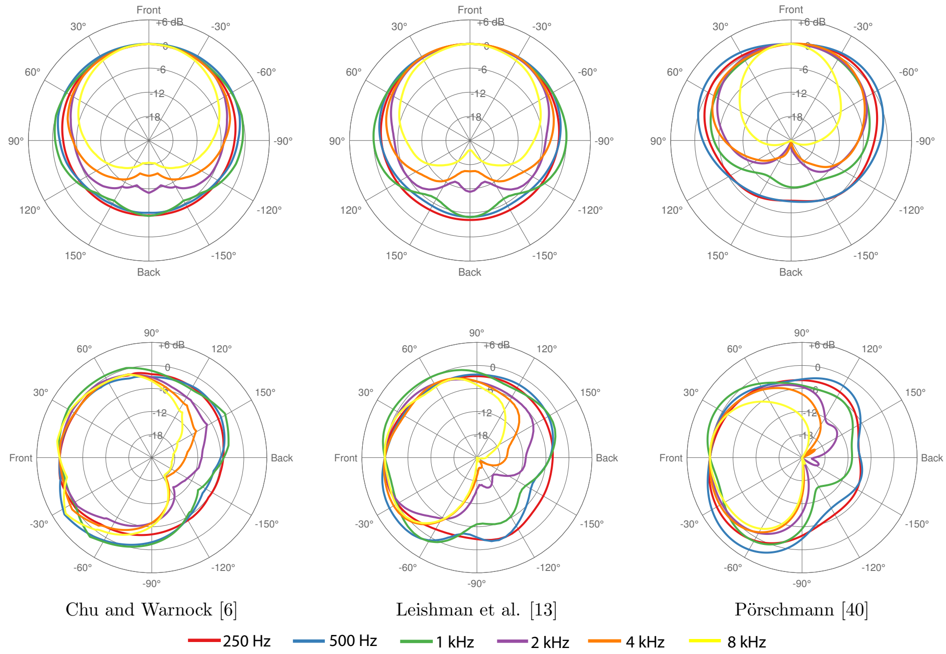

Figure 1. Polar plots of the directivity patterns of three exemplary studies [6, 13, 40] in the horizontal plane (top) and vertical plane (bottom), determined for speech. Shown are the mean values in octave bands with center frequencies between 250 Hz and 8 kHz.

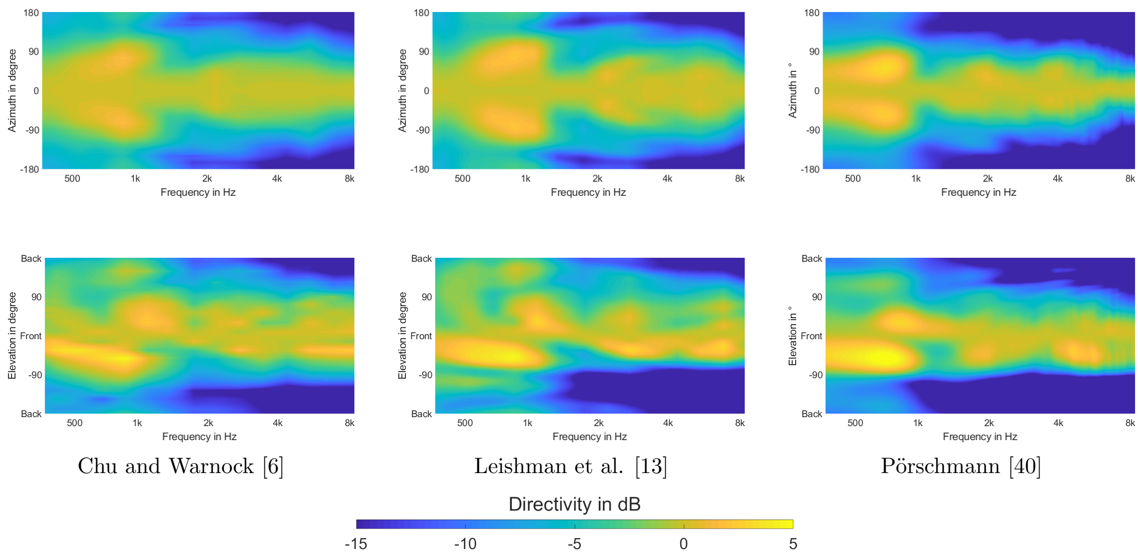

Figure 2. Directivity patterns of three exemplary studies [6, 13, 40] in the horizontal plane (top) and vertical plane (bottom), determined for speech.

directivities can be compensated in the results. **Fischer et al. [34]** determined the directivity pattern of a Kemar 45BC dummy head in the horizontal plane and compared it to a spherical head model. The authors found that the spherical head model produced a spatially smoother directional frequency response than the dummy head. In **Pörschmann et al. [11]** we investigated the influence of face masks on the directivity of the human voice based on high-resolution spherical measurements of a HEAD HMS II.3 dummy head. The results show a significant frequency-dependent transmission loss, which for the two respirator masks significantly affects the directivity index, deviating by up to 7 dB above 3 kHz compared to the unmasked condition. For all other masks, the deviations are less than 2 dB in all one-third octave frequency bands.

3. DATABASE

The database contains datasets from 19 studies from the literature, where the results are either presented in tables and polar plots, or the data are provided in a separate electronic repository published with the study. For most studies, the datasets are given in frequency bands, typically either in octave or one-third octave bands and for some studies only a few selected frequency bins are shown. However, some recent studies [11, 14, 15, 42] provide full impulse responses or transfer functions, which allow extended analysis, e.g. to include phase information or to study directivity patterns in arbitrary frequency bands. The last column in Table 1 marks each study that is included in the database. While a [○] means that the dataset is well-suited for further analyses, an [x] indicates that the dataset is sparse regarding the frequency resolution only showing a single frequency, regarding the sampling grid or there are other reasons why the dataset can only be employed for specific comparisons. The datasets from the plots or tables in each publication were transferred to an Excel document. The data from each study is stored in a separate sheet, allowing the datasets to be easily expanded with data from new studies. Datasets available in other forms, for example, stored as transfer functions and made accessible in other repositories, are not included in the Excel document. Instead, the Supplementary Material [40] provides the DOI or permalink where the data can be accessed. Because the datasets originate from different measurement setups and procedures, the sampling grid and frequency resolution vary. The routines include spatial upsampling to an arbitrary target grid. This is done using functions from the SUpDEq toolbox that can be applied to both the frequency-band and transfer-function-based datasets. Finally, routines are added, that can also be modified and extended by the user, to visualize each of the datasets. The supplementary material [40] is available at `https://doi.org/10.5281/zenodo.7834210`.

4. DATASET COMPARISON

We present exemplary visualizations of datasets from three studies included in the database [6, 13, 40] that provide data on a spherical grid and at least in one-third octave bands. Figure 1 shows the polar plots in the horizontal and vertical planes. In general, the directivity increases with frequency which is very similar across the studies. However, our dataset [40] has a narrower directivity than the other studies in the higher frequency bands, especially around 8 kHz. This is probably due to a higher signal to noise ratio, but needs further analysis. Figure 2 depicts the directivity patterns of the same three measurements on a continuous frequency axis. Two of the datasets [6, 13] were interpolated from the values given in one-third octave bands to a continuous frequency scale. In the horizontal plane, similar for all studies, there is a broadening of directivity at about 1 kHz. In the vertical plane, the main radiation direction is for most frequencies downward, with a peak at about 800 Hz. However, as shown in our recent study [41], between 1 kHz and 1.5 kHz, all measurements show an upward main radiation direction.

5. CONCLUSION

This paper gives an overview of studies that have measured human voice directivity patterns and briefly discussed the different measurement methods and setups. Furthermore, a database has been presented that can be employed to visualize and compare various measured directivity patterns and thus can help compare different measurement techniques and setups.

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