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A Pilot Study on Tone-Dependent Directivity Patterns of Musical Instruments

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ABSTRACT

Musical instruments are complex sources that radiate sound with directivity patterns that are not only frequency dependent, but can also change as a function of the tone played. Using a publicly available musical instrument directivity database, this paper analyzes the tone-specific directivity patterns of three instruments and compares them to their averaged directivities. A further listening test is conducted to determine whether differences between auralizations using averaged directivities and tone-specific directivities are audible under anechoic conditions. The results show that the differences are audible for woodwind and string instruments, and less noticeable for brass instruments.

1 Introduction

Accurate representation of the directivity characteristics of sound sources is fundamental to achieving authentic simulations of virtual acoustic environments [1]. Variations in the directivity characteristics of a source can potentially influence the perceived localization [2] and auditory distance [3]. Sound sources, like human voice, loudspeakers or musical instruments have each a distinctive directivity pattern that vary significantly across the frequency range and can also change depending on other aspects.

Several researchers have measured the directivity of musical instruments, dating back to the 1970s with the pioneering work of Meyer [4], who conducted an extensive investigation on the radiation of musical instruments. Further studies have measured the directivity of musical instruments, generally using repeated capturing methods with artificial excitation that allow the directivity of the instrument to be obtained at high resolution [5, 6], or with spherical microphone arrays that allow measurements to be made in a natural situation with a musician [7, 8].

Studies on the influence of source directivity on the perception of acoustic simulations have demonstrated that listeners are able to perceive differences caused by different directivity representations. Wang and Vigeant [9] demonstrated that subjects can distinguish between omnidirectional and extremely directional sources, and Otondo and Rindel [10] that varying the directional characteristics of sound sources affects room acoustic parameters and can lead to audible differences in terms of loudness, reverberance and clarity.

Musical instruments, as well as the voice, are dynamic sources whose directivity varies according to the movement, the played tone in the case of musical instruments [11], or to the phonemes in the case of voice [12].

One of the first investigations on the perceptual implications of such dynamic characteristics of musical instruments on auralizations was carried out by Otondo and Rindel [10]. They showed that listeners can perceive changes caused by different directivity representations (averaged or tone-dependent directivity patterns) in static auralizations. However, to evaluate the audibility of different directivity representations, the authors only tested one tone-dependent directivity pattern with melodies that did not always include the tone that corresponded to the directivity pattern studied.

More recently, Ackermann et al. [13] demonstrated that the fluctuations created by the movement of the musicians during solo musical performances are audible both under anechoic and reverberant conditions. Similarly, Ehret et al. [14] performed a perceptual evaluation involving static and dynamic phoneme-dependent voice directivities. They showed that participants were not able to distinguish phoneme-dependent directivities from averaged directivities and that their subjective preference might not be dependent on the realism of the directional rendering.

To better understand the perceptual requirements of musical instrument directivities in virtual acoustic environments, this paper analyzes the differences between tone-dependent directivities and the directivity averaged over all tones. Using multichannel single-note recordings from the Technical University of Berlin (TU Berlin) database, the directivity patterns of several musical instruments were derived. To validate the classification of the instruments into three categories, the patterns were analyzed based on their maximum directivity index and direction of maximum directivity. After selecting a single instrument representative of each group, the spectral differences of each tone were calculated from their spherical harmonic representations of 4th order. Subsequently, a listening test was performed to investigate whether listeners can hear differences between auralizations using averaged directivities and auralizations using tone-specific directivities of the three selected instruments under anechoic conditions.

2 Sorting of musical instruments based on TU Berlin database

2.1 Instrument database

The analysis of directivity patterns in this study is based on the measurements from the open-access TU Berlin database [15]. This database contains scales and single-tone recordings of 41 symphonic orchestral instruments at two dynamic levels (*pianissimo* and *fortissimo*), along with their calculated directivities and audio features.

The instruments were recorded at the anechoic chamber of the TU Berlin using a spherical array of radius 2.1 m, consisting of 32 microphones placed on the faces of a truncated icosahedron [8]. By using a microphone array, the instruments could be measured in a performance situation, which allowed the acoustic effect of the musician and the natural excitation of the source to be included in the measurements. The resolution of the measurements is limited by spatial aliasing, which is apparent over large parts of the frequency range of the instruments. However, to the best of our knowledge, databases of single-tone recordings of musical instruments with higher spatial resolution are not publicly available.

2.2 Overall analysis of musical instruments

In order to investigate the differences between time-varying (tone-specific) and static (averaged) directivities, and to reach general conclusions about symphonic instruments, a set of instruments was selected from groups with similar radiation characteristics. The conventional classification divides the symphonic musical instruments into four groups or families: strings, woodwind, brass, and percussion instruments. However, this and other traditional classifications are not based on the radiation of the instruments but on other criteria, such as the morphology of the instruments or the way the sound is generated [16, 17]. Shabtai et al. [15] made a preliminary sorting into three groups depending on how the instruments radiate sound (see Table 1). To validate this classification, this section presents a general analysis of the musical instruments according to their maximum directivity index and direction of maximum directivity.

From the TU Berlin dataset, 38 musical instruments were selected for analysis; all but the timpani, which did not contain single-note recordings, and the singer, which was excluded in order to focus on musical instruments. The recordings of single notes in *ff* were used for the analysis to guarantee a good signal-to-noise ratio. Different methods can be used to calculate the directivity patterns from the multichannel recordings [18, 19].

Category	ID	Instruments
I	1	Alto trombone historical
	2	Bass trombone historical
	3	Bass trombone modern
	4	Basset horn
	5	English horn
	6	French horn
	7	Natural horn
	8	Trumpet historical
	9	Tenor trombone historical
	10	Tenor trombone modern
	11	Trumpet modern
	12	Tuba
II	13	Alto saxophone modern
	14	Baroque bassoon
	15	Baroque transverse flute
	16	Bass clarinet
	17	Modern bassoon
	18	Clarinet historical
	19	Modern clarinet
	20	Classic bassoon
	21	Classic oboe
	22	Contrabassoon
	23	Dulcian
	24	Historical transverse flute
	25	Modern oboe
	26	Romantic oboe
	27	Tenor saxophone
	28	Modern transverse flute
III	29	Acoustic guitar
	30	Historical cello
	31	Modern cello
	32	Harp
	33	Historical double bass
	34	Modern double bass
	35	Historical viola
	36	Modern viola
	37	Historical violin
	38	Modern violin

Table 1: List of musical instruments belonging to a specific category (suggested by [15])

For the overall analysis of the instruments, this study follows the procedure proposed in [15, 19], but without source centering and without transforming the data into spherical harmonics. To identify the fundamental and overtone frequencies, the stationary parts of each single-tone recording, provided by the authors of the database in sample indices, were windowed using a Hamming window and transformed to the frequency domain. Then, the magnitudes of the first ten partials (fundamental and nine overtones) were extracted and averaged over one-third octave bands. To obtain a compact overview of the directivity characteristics of each instrument, this study focuses on their averaged directivity representations, obtained by averaging the directivity of all available tones. In order to examine their general similarities and differences, their maximum directivity index and direction of maximum directivity were calculated from the representation in third octave bands.

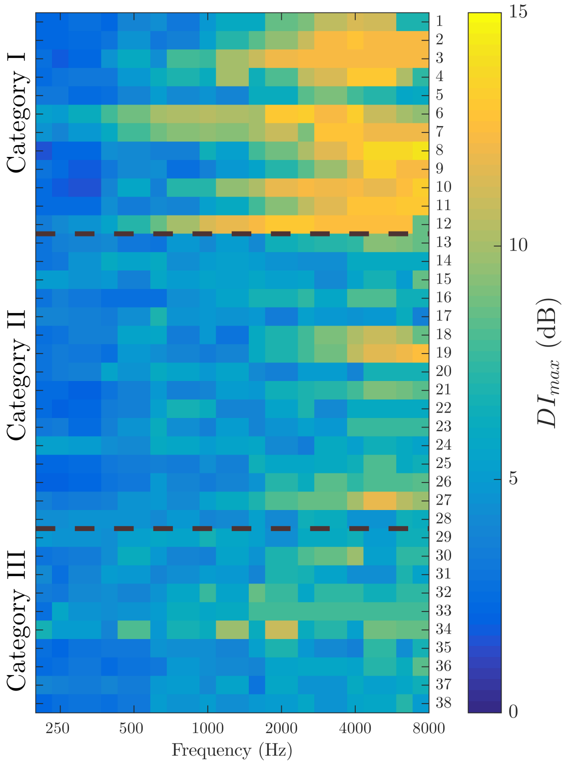


Fig. 1: Maximum directivity index (DI_{max}) of the TU Berlin database, grouped in three categories suggested by Shabtai et al. in [15]. The names of the instruments associated to the ID number can be found in Table 1.

In this study, the directivity index (*DI*) is defined as the ratio between the sound power at a certain direction and the average power over all measured directions [20]. The *DI* of a source indicates the extent to which the source's radiation is biased towards a certain direction,

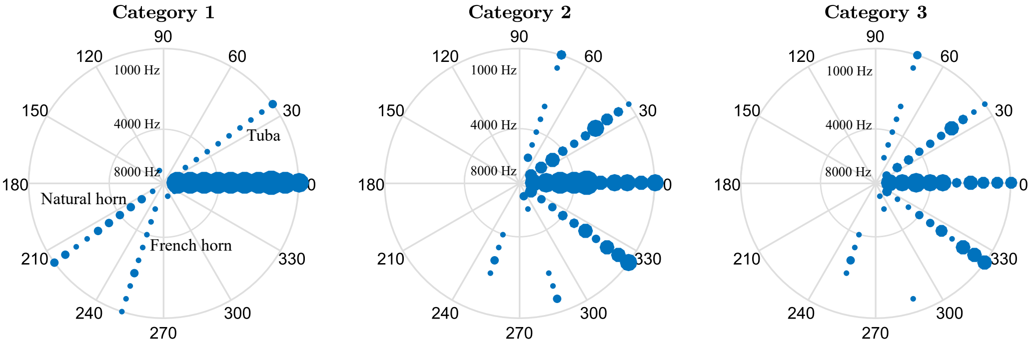


Fig. 2: Direction of DI_{max} in degrees of instruments of the TU Berlin database, divided in three groups (suggested by [15]). Concentric circles in the polar plot indicate the frequency band, with the lowest band (1000 Hz) being the outermost one, and the highest (8000 Hz) the innermost. A larger dot indicates that more instruments have identical results, increasing each time an instrument has the same direction of DI_{max}.

as a function of angle and frequency. It is defined in dB as

$$DI_{\theta,\phi}(f) = 10log_{10}\left(\frac{\left|p_{\theta,\phi}(f)\right|^2}{\tilde{p}(f)}\right) \qquad (1)$$

with $\left|p_{\theta,\phi}(f)\right|^2$ being the power at azimuth and elevation angles θ and ϕ, and $\tilde{p}(f)$ the average power over all L directions $\frac{1}{L}\sum_{\theta,\phi}\left|p_{\theta,\phi}(f)\right|^2$. The DI was calculated for each instrument, frequency band, and measurement position. Then the DI_{max} values were obtained for each frequency band by selecting the highest DI value from all directions ($DI_{max} = max(DI_{\theta,\phi})$). As the name implies, the direction of DI_{max} is the direction with the highest DI. For this study, only the azimuth values are considered.

Figure 1 shows the DI_{max} of all selected instruments, grouped into the three categories proposed by Shabtai et al. Each row in the figure corresponds to an instrument, shown in the order and with the ID specified in Table 1. In general, brass and many woodwind instruments present low DI_{max} at low frequencies and higher DI_{max} as the frequency increases. Musical instruments in the Category I (all bras instruments, English horn and basset horn) show the highest DI_{max}, which increases considerably with frequency. However, the English horn, with a constant DI_{max} value over the entire frequency range, does not show the same behavior as the rest of the instruments in this category. It is therefore surprising that this instrument falls into the same category as all brass instruments.

Some woodwinds (tenor saxophone, the modern and classical clarinets) also exhibit high DI_{max} at frequency bands above 3000 Hz, but to a lesser extent than brass instruments. In contrast, strings and some woodwinds, such as the flute, tend to exhibit low DI_{max} values over the entire frequency range, suggesting that they are less unidirectional (they radiate less in a single direction, like brass instruments). It should also be noted that, although measurements were carefully done with the instruments pointing in a specific direction (for example, brass often pointing at one specific microphone), the DI_{max} of some instruments may vary slightly, as the measurement point may not coincide to the maximum point of radiation of the instrument.

The DI_{max} direction of the instruments is depicted in Figure 2, divided into the three categories mentioned above and for the frequency bands between 1000 Hz and 8000 Hz, showing the trends followed by the instruments in each category. Frequency bands below 1000 Hz are not shown, as most instruments exhibit a less directional behavior at low frequencies (see Figure 1).

Brass instruments exhibit a very clear direction of DI_{max} to the direction of the bell: to the front in most cases, or to the back, in the case of the Natural horn and French horn, as seen in Figure 2. While the direction of DI_{max} for most woodwinds varies with increasing frequency, the direction of DI_{max} of the English horn is kept constant to the front throughout the studied frequency range, showing a radiation behavior closer to the brass instruments. Similarly, the basset horn also shows a direction of DI_{max} towards the direction of the bell, which corresponds to the same azimuthal direction as the natural horn. Nonetheless, since the study only focuses on azimuth values, it should be noted that elevation angle may still vary despite the instrument showing a maximum direction to the front. String and woodwind instruments show a greater variation compared to the brass instruments, as their direction of DI_{max} changes throughout the whole frequency range.

Based on the values of the DI_{max} and direction of DI_{max}, the preliminary sorting proposed by Shabtai et al. seems to be adequate in almost all cases, except in the case of the English horn. This instrument, with a lower and steady DI_{max} at all frequencies, has a behavior more similar to instruments in the Category II. Nevertheless, other metrics [21] can be used to analyze the directivity of the musical instruments that may affect the evaluation of this classification.

3 Tone-dependent directivity analysis

The listening test and note-dependent objective analysis were conducted using the open-access database of spherical harmonic (SH) representations of sound sources provided by Ahrens [22]. This database contains impulse responses of various notes of several instruments, based on the TU Berlin measurements [15] and representing the directivity of the sound source in various given discrete directions [23].

To obtain the directivity pattern at a particular direction around the instrument in the horizontal plane, the spherical harmonic representation of 4th order of the directivities was first obtained from the data using the toolbox provided by Ahrens in [22]. Then, the magnitude directivity was computed from the SH representation in various directions. One musical instrument representative of each of the three aforementioned categories was used for the tone-dependent analysis and listening test: a trumpet, an oboe, and a violin.

3.1 Spectral analysis

To identify test directions that would be of interest in the subsequent perceptual analysis, spectral differences between tone-specific directivity and averaged directivity were obtained. The calculated spectral differences allow estimating the perceived differences between the tone-specific directivity and the averaged directivity. The spectral differences per direction were calculated in dB as

$$\Delta D_{ton}(\theta, f) = 20log\left(\frac{|D_{ton}(\theta, f)|}{|D_{avg}(\theta, f)|}\right) \qquad (2)$$

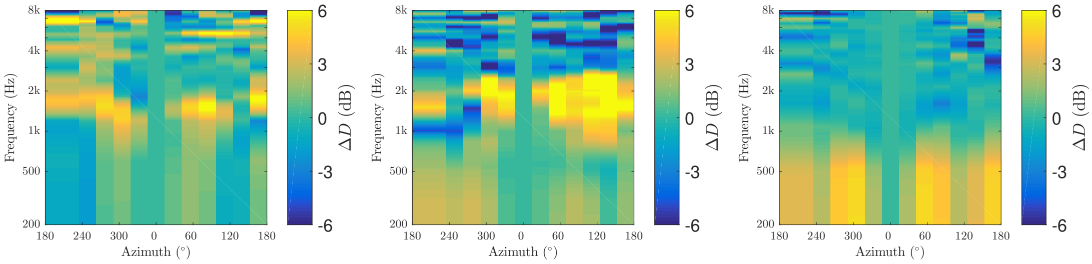
where D_{ton} is the directivity pattern per tone and D_{avg} is the directivity pattern averaged over all tones. For each tone, ΔD_{ton} was determined from the directivities normalized to the front in 30-degree increments in the horizontal plane, as given in [22]. Figure 3 shows ΔD_{ton} in the horizontal plane for different tones that were included in the listening test. The directivity of each particular tone results in different spectral differences. Figures 3a, 3d and 3b and 3e indicate that, for those tones, the oboe and violin have an increasing or decreasing sound radiation in all directions in the horizontal plane, while the trumpet presents variations mainly on the sides and at the back (see figures 3c and 3f).

3.2 Generating stimuli for the listening test

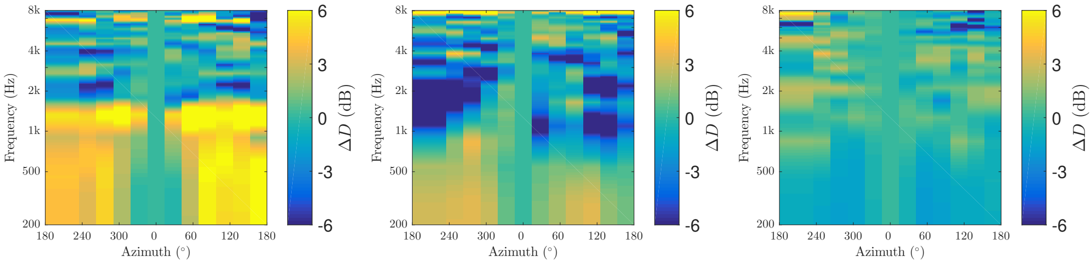
Following [24], stereo signals were approximated by using the directivity at two directions separated 5 degrees in the horizontal plane (ear-to-ear distance of 18 cm, calculated for a distance of 2.1 meters to the source), centered at 60 degrees. This direction was chosen based on the results of the spectral analysis, which suggested that differences would be audible at this angle. It should be noted that since this pilot study evaluates a simplified situation with only direct sound under anechoic conditions, binaural signals are not used in the listening test. However, future investigations should include binaural signals to study tone-dependent directivities in room simulations.

The anechoic recordings used for the listening test were obtained from the denoised versions of anechoic orchestral recordings [25] provided in [26]. To avoid colorizing the spectrum, the directivities were normalized by the directivity in the direction of the microphone used in the dry recordings (azimuth = 0° and elevation = 11°) [25], obtained from SH interpolation.

Static directivity auralizations were obtained by convolving excerpts of anechoic recordings of the three



(a) Oboe D5 **(b)** Violin B4 **(c)** Trumpet C5



(d) Oboe A4 **(e)** Violin C5 **(f)** Trumpet G#4

Fig. 3: Spectral differences $\Delta D_{ton}(\theta, f)$ between the directivity patterns of selected tones and the averaged directivities for an oboe, a violin and a trumpet.

instruments with the averaged directivities. The averaged directivities were calculated for each instrument by averaging the magnitude across all available tones before performing the normalization by the recording microphone. Following [23], minimum-phase filters were computed from the magnitude spectra.

Time-varying auralizations using tone-dependent directivities require knowing the tone being played at every moment in order to use their corresponding directivity patterns. Therefore, in this study the monophonic pitch tracker CREPE [27] was used to estimate the pitch of the chosen sound excerpts, with a time step of 10 milliseconds. The output of the pitch tracker contains the timestamps, the predicted fundamental frequency in Hz, and the confidence (value from 0 to 1). Before using this information to generate the stimuli, the predicted fundamental frequencies with a confidence lower than 0.5 were set to the previous predicted frequency with a higher confidence level. Predicted pitch with frequencies higher than the expected highest frequency per instrument were considered outliers and were replaced by a lower neighboring value. In order to avoid misleading results derived from the use of vibrato in the recordings, the estimated pitch of the anechoic excerpts was smoothed by applying a median filter. The predicted pitch of the excerpts was then manually revised and fixed if needed, and linked to their corresponding tones and directivity patterns. Finally, the tone-specific stimuli were generated by block-wise and time-variant convolution of the anechoic recordings with the directivity filter of each corresponding tone.

3.3 Listening test

An ABX listening test was conducted to determine whether differences between tone-specific directivities and averaged directivities of instruments of different kind are audible. This type of test allows the listeners to detect very small differences between the samples. On a user interface developed in Matlab, listeners were presented with stimulus A, B and X and two forced answers: X equals A or X equals B. For each trial, the simulation with the tone-specific and averaged directivities were randomly assigned to the A and B buttons and one of them was randomly repeated on button X.

The participants could listen to the sound samples as many times as desired before giving an answer. To ensure that a variety of notes was included in the test, participants listened to three melodies of 2-5 seconds each. The sounds were presented through headphones

(Beyerdynamic DT990), with the same playback level for all listeners.

To familiarize themselves with the test procedure and stimuli, participants underwent a training session with 3 conditions (one per instrument) prior to the listening test. After the test, the participants completed a short questionnaire about their musical background (years of experience) their experience with listening tests, and whether they had any hearing impairments. They also answered in their own words what auditory cues they had used to differentiate the sounds.

A total of 10 listeners, 4 men and 6 women, aged 20-33 years (mean 24.9 years) participated in the listening test, which lasted about 30 minutes on average. Written informed consent was received from all participants at the beginning of the session. All of them reported normal hearing and had at least 12 years of musical experience (mean 17.2 years) or experience with listening tests, therefore they were considered trained listeners. Every participant was presented with a total of 45 test trials (3 instruments $\times$ 3 melodies $\times$ 5 repetitions). While during the test the order of the instruments was randomized for each participant, in the training, the conditions were presented in the same order to all participants.

4 Results

This study compares the tone-specific directivities and the averaged directivities of an oboe, a violin and a trumpet. Overall, differences are most noticeable on the oboe, while the trumpet is the instrument on which differences were most difficult to discern. Figure 4 shows the pooled results for all tested conditions for 9 participants. One participant was discarded from the analysis, as both the number of correct answers and the time spent on the test were detected as outliers.

For each test condition, there were a total of 135 answers (9 participants, 15 repetitions). Applying the binomial distribution for the analysis of the results [28] allows the calculation of the probability that a number of correct answers occur by chance. If the number of correct answers is above the critical value, the differences between tone-specific and averaged directivities are considered to be significant. For a 5% significance level with Bonferroni correction ($p < 0.05/3 = 0.0167$), the critical number of correct answers in order to reject the null hypothesis is 81 (detection rate 60%). For a 1% significance level ($p < 0.01/3 = 0.0033$), the number of correct answers must be equal or higher than 84 (detection rate 62.2%).

As seen in Figure 4, the pooled detection rates for both the violin and oboe stimuli are significantly above the critical values, indicating that differences between tone-specific and averaged directivity representations are audible. For the trumpet, this difference was barely significant only for a significance level of 5% but was not significant for a significance level of 1%.

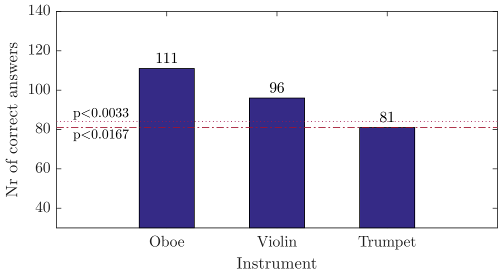


Fig. 4: Results of the ABX listening test of tone-specific and averaged directivity patterns for all participants and conditions. The height of the bars indicates the number of correct answers. Null hypothesis (listeners cannot hear any difference) is rejected for scores on or above the dotted lines (significance levels at 5% and 1%).

After completing the listening test, participants wrote in their own words which auditory cues influenced their decisions. All listeners identified timbre or color as their main cue for distinguishing sounds (also reported as brightness, harmonic content, and how muffled the sounds were). Furthermore, a couple of participants also mentioned audible changes in the onset of the tones.

5 Discussion

Inspired by previous studies that demonstrated the differences between the individual directivities of the tones [11, 19] and their perceptual significance [10], a pilot listening test was conducted to compare simulations using tone-specific and averaged directivities. Results of the listening test showed a tendency for the differences –which under anechoic conditions translates into variations in the timbre– to be most audible for the oboe, followed by the violin and trumpet. These results are in line with the literature demonstrating the strong similarity of the tone-specific directivity patterns of brass instruments. [11, 19].

According to the results of the listening test with 9 participants, tone-specific directivities differ significantly from the averaged directivities for the oboe and violin, and slightly for the trumpet. Differences for the trumpet were detected in 60% of the times, which coincide with the bare minimum value for the binomial distribution to be significant at $p < 0.05$. Given the small number of participants, these results should be interpreted with caution. Increasing the sample size should lead to more accurate results and a more clear trend depending on the type of instrument.

It should be noted that the current study was based on measurements with low spatial resolution that may result in smoothed or inaccurate patterns, especially at high frequencies. Nevertheless, the results of this pilot study provide general insight into the perception of tone-specific directivity patterns, showing that differences are perceived when using different directivity representations and motivate the extension of this work to analyze the perceptual influence of tone-specific directivity patterns in reverberant conditions. It would be useful to perform single-tone measurements of musical instruments with higher resolutions that would allow for more accurate studies of tone-specific directivities. High resolution tone-specific directivity patterns would lead to more accurate simulations that could result in clearer conclusions about the impact of using averaged directivity representations of the instruments.

6 Summary

This paper assessed the audibility of differences between auralizations using tone-dependent directivity patterns and averaged directivity patterns under anechoic conditions. To this end, three instruments (an oboe, a violin and a trumpet) representative of groups of instruments with similar directivity characteristics were investigated. The spectral differences between the two directivity representations were determined. A subsequent listening test showed that listeners can perceive timbral differences between tone-specific directivities and averaged directivities. Significant differences were found for the oboe and the violin, and marginally significant for the trumpet.

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