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The Influence of the Directivity of Musical Instruments in a Room

Felipe Otondo, Jens Holger Rindel
Ørsted-DTU, Acoustic Technology, Technical University of Denmark, building 352, Ørsteds Plads, DK-2800, Kgs.Lyngby, Denmark

Summary
Measurements of the directivity of musical instruments are presented as part of the study of the influence of their representation in room acoustic simulations and auralizations. Pairs of measured and averaged directivities have been used both for room simulation comparisons and as a basis for listening experiments with auralizations. Room simulation results show a clear influence of the changes in the representation directivity on the distribution of acoustical parameters in the room. The results of the listening experiments with auralizations show that some changes produced by directivity variations can be perceived by the listener. Among these changes, loudness was perceived in the highest degree, followed by reverberance and clarity.

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1. Introduction

The directivity of musical instruments has been studied by several authors [1, 2, 3, 4], Jürgen Meyer being the one who has contributed with most specific information about the radiation characteristics of musical instruments in a real performance situation [5]. However, Meyer's directivity data mostly provide directivity averages over the whole performing frequency range of the instruments. Very little information about the directivity of instruments for particular tones is included, even though it is shown that the directivity can change dramatically over the performing range [5]. Most of the data available nowadays on the directivity of musical instruments used for room acoustic simulations and auralizations use the averaged directivities from Meyer's studies. A few attempts have been made to study and use a different directional representation, a representation that would include the directivity changes of the musical instruments within the performing range [6, 7, 8, 9]. At the same time, experiments using room acoustics auralizations have shown that the directional representation of sources in room acoustic simulations is important, and that changes in their directivity can significantly affect the perceived sound in a room [10].

Therefore, the first goal of this investigation has been to measure the directivity of different musical instruments in a performance situation and compare it to the averaged directivity used traditionally for room simulation and auralization purposes. The second goal has been to use these two types of directivity representation in room simulations in order to investigate how important the changes in the radiation representation can be in the spatial distribution of acoustical parameters in a room. The third goal has been to use the two types of directivities to build auralizations in order to evaluate the perceptual importance of the changes in the radiation in a room by means of listening experiments.

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2. Directivity of Musical Instruments

2.1. Directivity measurements

Three different classical musical instruments with distinctive directional behaviours were used for the directivity measurements: a Bb clarinet, a Bb trumpet and a French horn. The measurements were carried out as a post-processing of simultaneous recordings done with thirteen flat response electret microphones in an anechoic chamber at 45° intervals in the horizontal and vertical planes, using a 24-bit quantization and 44.1 kHz sampling rate at a distance of 1.5 meters from the source. Figure 1 shows one of the performers playing a trumpet in the anechoic chamber and Figure 2 shows the recording/measuring setup with the thirteen microphones in the horizontal and vertical planes. As it is shown in Figure 2 the setup chosen for the directivity measurements was conceived in such a way as to measure the variations of directivity of the instruments in the horizontal and vertical planes according to the traditional representation of the directivity of sound sources in the room acoustic software available nowadays. The goal with this setup was not to obtain a detailed description of the whole radiation sphere of the instrument, but to obtain a sample of the variations of the radiation in both planes to be used afterwards in the room simulations soft-

Figure 1. Trumpet player during the directivity measurements in the anechoic chamber.

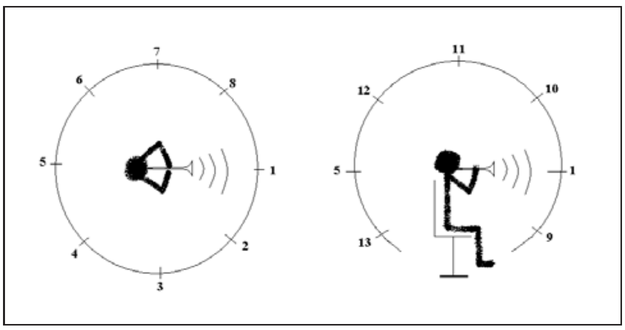

Figure 2. Setup for the simultaneous directivity measurements with 13 microphones. The left part of the figure shows the setup in the horizontal plane and the right part shows it in the vertical plane. Microphones 1 and 5 appear in both planes.

ware. The method consisted of simultaneous recordings of short isolated tones played on the instruments with a similar musical intensity of mezzo forte over the whole performing pitch range. These recordings were repeated once. Performers were asked to maintain their usual performing positions while playing, holding the instrument without moving it as much as possible.

2.2. Results

Short samples of 700 ms of the recordings of each of the tones played by the performers by each of the microphones were used to create the directivities in octave bands. Each of the recorded tones was post- processed and filtered in octave bands from 125 to 8000 Hz in order to build the directivities of the specific tones. The representation in octaves was chosen to fulfil the traditional representation of the directivity in room acoustic softwares in order to be able to make the comparisons of simulated parameters in a room as well as the listening tests with auralizations.

The directivities created for the specific tones were then averaged using a logarithmic average of all the tones of each instruments in the pitch range for each octave as done in previous studies [5, 11]. The directivities were then calculated for each octave band considering the samples of the 13 microphones. Once all the directivities of the tones were calculated, the averaged directivities were computed for each octave making a logarithmic average of all the specific directivities of the instruments. Figures 3 and 4 shows an example of the measured directivity for three specific tones and the averaged directivities over the whole performing pitch at 1000 Hz. All the results shown in the figures have been normalised to the level at the frontal microphone (mic.1) for the three instruments in the horizontal and vertical planes.

As shown in the examples of the figures, the directivities of the instruments show variations from one played tone to another in the same octave band. Comparing different particular directivities for tones one could observe that variations of the directivity in the same octave band were greater for the clarinet and the French horn than for the trumpet. The averaged directivities for the three instruments over the whole performing pitch range proved to be less directional than the ones of the specific tones compared in most of the cases compared.

3. The directivity in a room

3.1. Room acoustic simulations

In order to investigate how the changes of the directivity of the above-mentioned musical instruments affect the sound in a room, computer room simulations were carried out with measured and averaged directivities. The simulations were done assuming the same sound power for the sources in a model of the concert hall ELMIA in Jönköping, Sweden, using the software ODEON [11]. This software was chosen due to the fact that it offers the possibility to make both room acoustic simulations and auralizations with a high level of accuracy of the calculations method [12]. The calculations are carried out using the ray- tracing method considering a source with a defined directivity in octave bands in a room with a particular geometry and absorption characteristics. The acoustical parameters considered for the simulations in the room were the sound pressure level (SPL), the clarity factor (C80, ratio of the energy in the first 80 ms arriving to the listener's position divided by the energy after 80 ms), the lateral energy fraction (LF80, ratio of the weighted energy in the sound that does not come from the direction of the source to that which comes from all directions), and the early decay time (EDT, the reverberation time calculated from the first 10 dB of decay of sound in the room). These parameters were selected in order to have a basis for the later comparison with the results of the listening tests, which are the next stage of the investigation. Two different directivity representations per instrument were used for the simulations, the specific directivity of a tone and the averaged directivity over the whole pitch range of the instruments. The specific tones selected were: C4 for the trumpet, B3 for the French horn and C#4 for the Bb clarinet. These tones were chosen because their directivities were considerably different from the averaged directivity for the different octave bands.

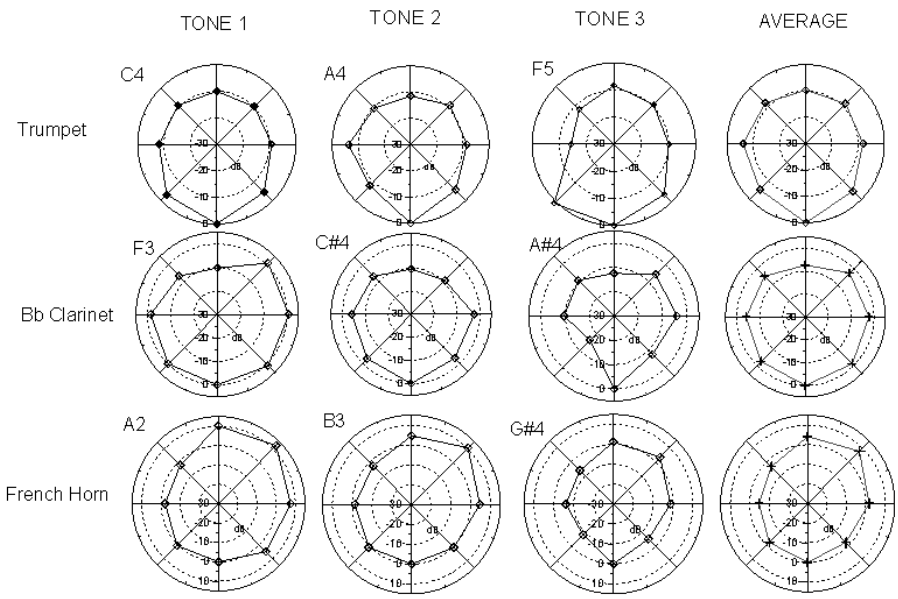

Figure 3. Specific and averaged directivities for the trumpet, the clarinet and the French horn in the 1 kHz octave band in the horizontal axis. The front of the instruments is facing downwards and in the case of the French horn the bell is facing left, as seen from the position of the performer. The averaged directivity corresponds to the average over the whole pitch performing range of the instruments.

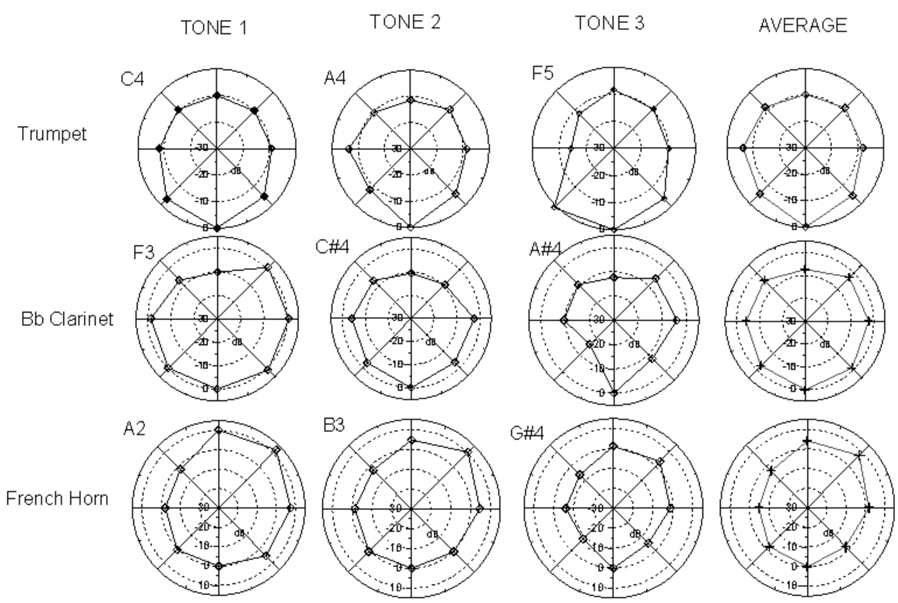

Figure 4. Specific and averaged directivities of the trumpet, the clarinet and the French horn in the 1 kHz octave band in the vertical axis. The right side of the figures corresponds to the front of the instruments. The averaged directivity corresponds to the average over the whole pitch performing range of the instruments.

3.2. Results

The simulations were carried out per instrument with the pairs of directivities, keeping the rest of the parameters constant as a way to test only the influence of the radiation representation. The results of the simulation of the mentioned acoustical parameters indicate a very distinctive sound distribution in the room for each of the compared directivities for the different frequency bands that can be linked with the original directivities measured in the anechoic chamber. As an example, Figure 5 illustrates the grid-response of the SPL in the 1000 Hz octave band simulated in the hall for the three instruments. As it can be noted from comparing the distribution in this figure with the horizontal anechoic averaged specific directivities of Figure 3 and 4, the original directivity shapes are clearly present in the distribution of the SPL in the room at 1000 Hz. In the cases where the two directivities are similar in shape the distribution is similar, and in those cases where the directivities are different in shape the distribution in the room is different. In most of the cases the simulations with the averaged directivity exhibited a more homogeneous and symmetrical distribution than the ones of the tones. The symmetry of the directivity of the sources also proved to be relevant in the distribution of the acoustical parameters.

In order to compare the magnitude of the variations of the simulated acoustical parameters with both directivities

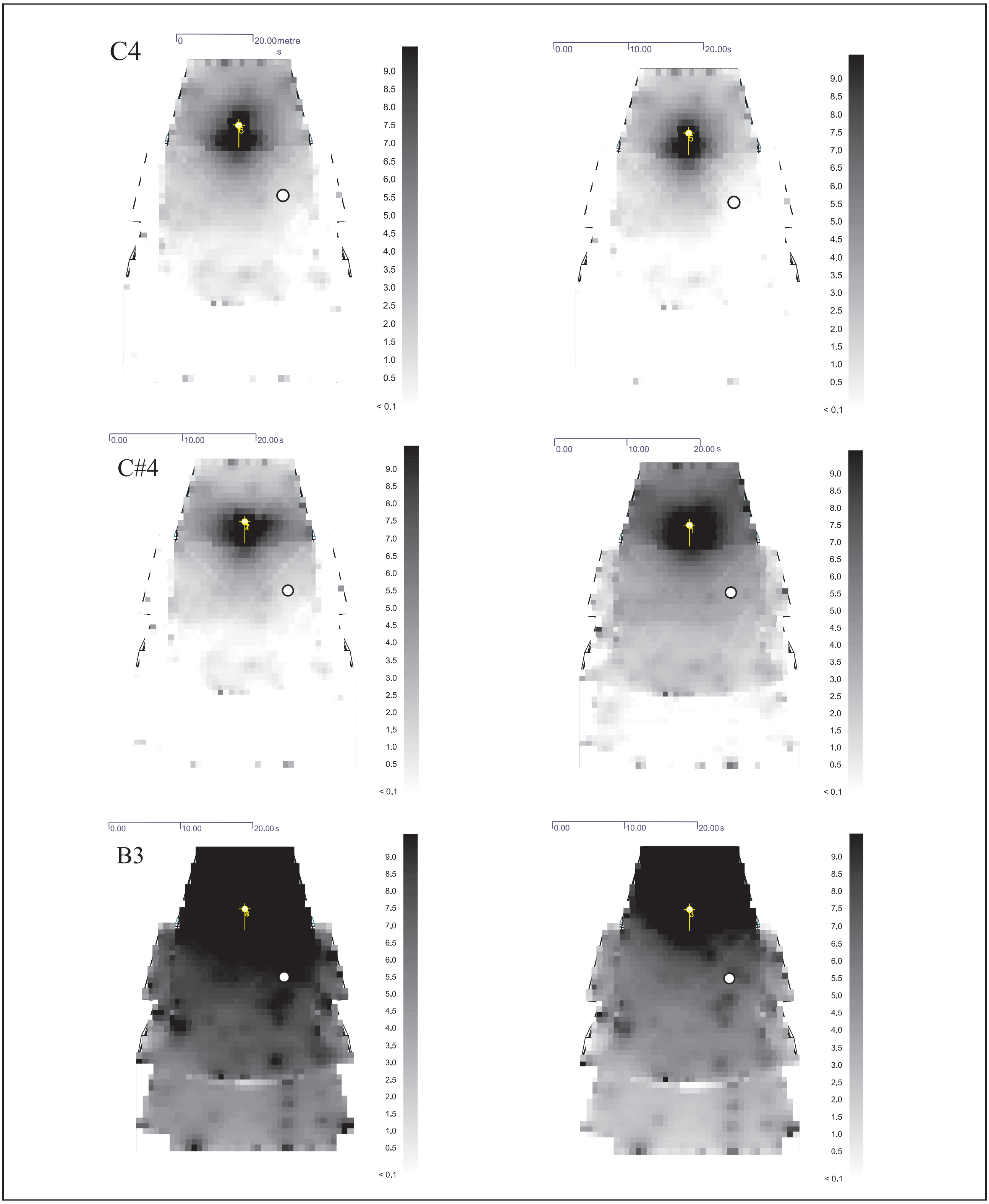

Figure 5. Grid-response of the sound pressure level (SPL) of the three musical instruments (from top to bottom: Trumpet, Clarinet, French Horn) in the 1 kHz octave band, simulated at the ELMIA concert hall with the directivity of a tone (left) and the averaged directivity (right). The scale is relative and shown from 0 to10 dB with white and black as the minimum and maximum values, respectively. The white dot is the position chosen for the evaluation of the acoustical parameters in the room and for the auralizations described later.

at a certain position in the room, a location in the audience was chosen at 8.93 m from the source, 3 m to the right side of the central axis of the hall. This position was chosen as representative of a good listening location within the audience in the room and can be seen in Figure 5 as a white dot. Table I shows the acoustical parameters simulated at

Table I. Different simulated acoustical parameters for the three musical instruments in the position of the listener in the room acoustic simulations.

Trumpet						
Frequency (Hz)	500		1000		2000	
Directivity Representation	C4	Average	C4	Average	C4	Average
SPL (dB)	13.7	6.7	8.6	6.8	7.2	6.6
C80 (dB)	0.1	0	1	2.1	2.8	2.0
LF80	0.28	0.20	0.14	0.2	0.16	0.18
EDT (s)	1.78	1.79	1.60	1.52	1.36	1.41
Bb Clarinet						
Frequency (Hz)	500		1000		2000	
Directivity Representation	C#4	Average	C#4	Average	C#4	Average
SPL (dB)	1.3	7.1	2.8	5	7.4	7.4
C80 (dB)	3.6	0.3	1.9	1.6	0.2	2.1
LF80	0.10	0.21	0.10	0.19	0.16	0.17
EDT (s)	1.29	1.82	1.49	1.58	1.54	1.4
French Horn						
Frequency (Hz)	500		1000		2000	
Representation	B3	Average	B3	Average	B3	Average
SPL (dB)	4.2	4.4	9.7	7.3	15	4.3
C80 (dB)	0.8	0.8	-0.3	-0.1	-0.5	1.2
LF80	0.16	0.17	0.22	0.21	0.32	0.17
EDT (s)	1.79	1.79	1.97	1.92	1.77	1.61

the selected position in the room for the three instruments with two different directivity representations in the three octave bands. In most of the cases the results of the comparisons showed considerable differences in the acoustical parameters for the different directivity representations. As it can be observed for a single musical instrument in the three compared octave bands, the tendency is far from being predictable: in some cases the simulated acoustical parameters with the two directivities are similar and in some others they show great differences. As to the spatial distribution of the acoustical parameters in the whole room, the differences are also greater in this particular position for the SPL and the C80, less noticeable for the LF80, and minor for the EDT, with the exception of the comparison at 500 Hz for the clarinet where the difference is surprisingly very big. The reason for this difference cannot be given a clear explanation.

4. Listening Experiments

4.1. Method

Listening tests were designed with two goals. The first and main goal was to test the audibility of different sound qualities in the case of the two types of directivity representations: the averaged directivity and the directivity of a particular tone. This was done in order to see to what degree the perceived sound in auralizations is affected by different directivity representations and what are the changes in the perceived sound that could be lost when using a fixed directivity representation. The second goal of the tests was to try to find possible connections between the results of the listening tests and the simulated acoustical parameters of the previous section. Pairs of room acoustic auralizations were created with the same directivity representations as in the case of the simulations using the software ODEON [12]. The first room auralization was created using the directivity of a measured tone and the second one using the averaged directivity of all the measured tones of the instrument. Short melodies of approximately 15 s played on the three musical instruments were recorded anechoically and used as sound input for the auralization with the two directivity representations. The melodies recorded did not necessarily include the tones corresponding to the directivities chosen for the representation and considered different long and short tones as a way to test the influence of the changes in the directivity in a normal performance situation. The software ODEON filters the input sound to the auralizations per octave, reproducing the components of the sound in each octave according to the directivity in that octave band. Over the 8 kHz octave there is gradual low pass filtering process.

A forced choice paired comparison method was used for the listening tests considering eleven subjects. The subjects were presented with pairs of auralizations created for each of the instruments through Sennheiser Hd 250 headphones. After a training session the listeners were asked to make a qualitative comparison between the two auralizations and select one according to five perceived acoustical features. These features were: loudness, perceived reverberance, clarity, localization of sound, and difference in timbre. The test subjects were given graphically through a computer screen the possibility of listening separately, and

Table II. Statistically significant results, according to the McNemar test, of the listening tests. The directivity pattern that was found to be favoured for each parameter is shown as averaged directivity or the directivity of a tone. In the cases where no conclusions could be made from the analysis "N.p. (No preference)" is stated.

	Trumpet	Bb clarinet	French Horn
Loudness	C4	Average	B3
Reverberance	N.p.	Average	B3
Clarity	N.p.	N.p.	B3
Localization	N.p.	N.p.	N.p.
Timbre	N.p.	N.p.	N.p.

as many times as they desired, to the two auralizations that they should evaluate for each instrument. After they had listened to the pair of sounds the subjects had to assess the quality of the sound of each auralization according to the five acoustical features mentioned above.

4.2. Results

The results of the experiments were first analysed using the McNemar test in order to determine the level of randomness of the data [13]. This method was used to separate the data provided by test subjects who were consistent from those provided by subjects who were inconsistent in their answers. The test was also used to determine the level of significance of the consistent results. A level of significance of 0.95 was chosen in this case [14, 15].

The results were then analysed for each of the five parameters for the three instruments. Table II shows the significant results according to the McNemar test.

As shown in Table II, the results of the listening experiments show that in some cases the test subjects were able to hear differences for the evaluated parameters, while in some other cases they were no able to do so. These perceived differences proved to be different for the five acoustical parameters evaluated and also different for the three instruments. More specifically, the results show that all test subjects were able to hear a difference in loudness between the two auralizations that were compared. The audibility of the changes in reverberance proved to be significant for two of the three instruments and the audibility of the clarity was significant only for the French horn. The audibility of timbre and the localization of the source did not prove to be significant.

4.3. Discussion

The results of the listening tests have shown that there are changes in the sound produced with the different directivity representations, changes that were perceived by the listener. This means that with the traditional fixed representation of the directivity used by the room acoustic softwares nowadays all these changes would be neglected. This would remove liveliness from the source representation and could result in a lack of realism in the reproduced sound. Further investigations could consider alternative ways of radiation representation of the sonic sources avoiding the use of a single fixed source directivity representation but using multiple sources as has already been done [8]. Comparing the results from Table I and Table II, one can see that the only parameters that proved to have the same tendency in the simulations and the listening tests were the sound pressure level and the loudness. The comparison between the results for the perceived reverberance and the simulated EDT shows that there is some correspondence between them. The perceived reverberance could be related with the sound pressure level. This means that the level of the sound could have helped the listeners to hear better the decay of the sound of the instruments in the auralizations. The discrimination of the clarity of the listening tests for the French horn did not prove to be strongly correlated with the simulations of the C80 in the room, especially in the octave band of 2000 Hz. Not much more information can be obtained from the results of the other simulated acoustical parameters that could be related to the results of the listening tests. It seems that much research needs to be done in order to have a more direct perceptual relation with the room acoustic parameters and in order to know what can really be heard in an auralization.

As to the high number of acoustical parameters that were evaluated inconsistently by the listeners for the three instruments, there are two possible main reasons. The first and main reason was that was quite difficult for the subjects to discriminate the audible differences in the compared pairs of auralizations for most of the parameters. In most of the cases these differences proved to be very subtle or non-audible. The second reason was, as shown from the analysis of the disregarded inconsistent information and also from interviews with the test subjects after the experiments, that many subjects were not familiar with the evaluated room acoustical parameters.

5. Conclusions

The directivity measurements of musical instruments in a performance situation have proved that significant changes occur in the directivity in the horizontal and vertical planes. Room simulations using averaged and specific directivities of tones have shown that the directivity of the musical instruments has a direct influence on the distribution of acoustical parameters in a room. Listening tests with the same directivity representations as in simulations have shown that the directivity changes are mostly audible in the perceived loudness in the room and that only some of the results of the listening experiments can be linked with the simulated acoustical parameters. Further investigations could study alternative types of directivity representations for room simulations and auralizations, where the changes of the directivity of the source would be considered.

Acknowledgements

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