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Tunable sonic crystals as an extension of acoustical musical instruments

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Abstract

Sonic crystals are made by the periodic arrangement of hard scatterers in a host medium, such as air, and are efficient devices for controlling the propagation of sound. There is a vast literature that shows many of their extraordinary capacities like forbidden frequency bands, hyperfocusing, self-collimation or negative refraction, and potential applications such as sound barriers, acoustic switches or acoustic diodes. In this work we describe the first application of a sonic crystal to the domain of musical acoustics. We constructed a tunable sonic crystal that when placed between the sound source and the audience, it is able to greatly modify the timbre and directivity pattern of the source during the performance, acting as an acoustical extension of the musical instrument. The sonic crystal can be dynamically tuned by changing its internal geometrical configuration. Different configurations of the sonic crystal and their possible effect on the localization of two instruments from the woodwind family were evaluated by analyzing a transverse section of the sound field and binaural recordings.

Keywords: Sonic crystal, Musical performance, Binaural intensity, Interaural Level Difference.

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1 Introduction

Musical performance is a complex practice comprising perceptual, motor and cognitive processes, interacting with acoustical phenomena occurring in the room and the musical instrument [1]. During the last century, this practice has been radically transformed by the advent of electronics and, more recently, by the development of new digital musical instruments and interfaces. However, the acoustical basis of the performance remained basically the same. Ultimately, sound coming from loudspeakers and acoustical sources has to travel through air as a wave before it can be perceived by the audience.

In a traditional performance, the musician acts on the source and/or resonator of the musical instrument, generating sound that propagates through the air and is further modified by the acoustical characteristics of the room. The audience perceives the sound only after these modifications, and this is the main concern for studying the acoustics of concert halls. Recent works also have studied systematically how the musician's perception of the sound, transformed by the room acoustical environment, influences the way he/she plays [2]. Ideally, the acoustics of the room should fit the musical performance, and vice versa. Many composers through history have taken this into account in their compositions [3], composing for specific buildings or even designing buildings for their own music [4]. Furthermore, following this approach the room can be considered as an extension of the resonator of the musical instrument, altering its spectral and spatial attributes. However, unlike the instrument's resonator, the characteristic of the room cannot be articulated during performance. Several examples of concert halls with variable acoustics exist [5], yet the design concept for these buildings is that they can be adapted for different types of performances. Still, in ordinary music performance, the acoustical source and the room are conceived as separate entities[2].

In this work we present a new kind of musical instrument that is conceived as an intermediate stage between the acoustical source and the room, which basically consists of a tunable sonic crystal of large dimensions (in some cases comparable with the size of the room). A sonic crystal is an artificial structure made by a periodic arrangement of rigid scatterers which exhibits many singular acoustical properties, like blocking or deviating the propagation of waves for certain frequencies, acting as an acoustic lens or as a waveguide [7,8]. Also, sonic crystals are able to induce spatial auditory illusions, as it was previously shown in a work from our group [9]. But the particularity of this kind of structure that makes it

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[2] A different approach where the room can be played literally as a musical instrument (or as an extension of an acoustic instrument) has been employed in some sound art works [6].

interesting for designing acoustical devices is that its properties can be varied by only changing its geometrical configuration.

In this work we present a sonic crystal whose geometrical configuration can be changed dynamically, or tuned, in order to reinforce, attenuate or deviate the propagation of certain harmonics of an acoustical source. Figure 1 depicts such a tunable sonic crystal, that is made by 60 wooden columns with a U-shape profile (a more detailed explanation will be given in the next section). The structure dimensions are 3.6 X 1.5 X 2.6 m (wide X depth X height) is located between the performer and the audience. Thus, the listener receives the sound emitted by the acoustical instrument after being modified by the transmission through the arrangement of columns. The configuration (and therefore the acoustical properties of the crystal) can be changed simply by rotating independently the columns around their vertical axes.

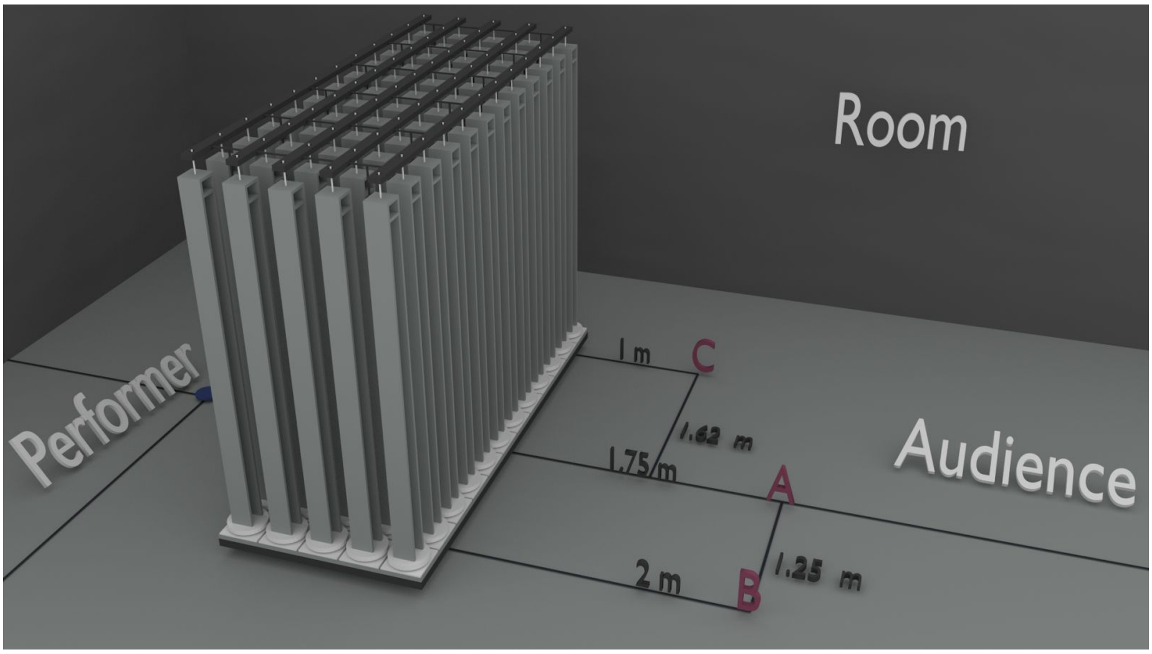

Figure 1: Schematic view of the tunable sonic crystal slab, placed between the source (performer, blue dot) and the audience. Sound waves radiating from the source are scattered by the columns of the sonic crystal and then further modified by the room. The acoustical properties of this device can be modified by changing its geometrical configuration, namely rotating the U-shaped columns around their vertical axes. The red letters denote the recording positions (see Section 3).

We can consider this new device a musical instrument since it can create new sonorities based on an existing acoustical instrument, or from an inherent source, articulating them during the performance. We also postulate that it represents a change in the usual interactions between the performer, the musical instrument, the audience and the room, as we illustrate in the two diagrams of Figure 2. The acoustical and haptic flow of information for a traditional musical performance is depicted in panel a), as a reference. In this case, the performer plays the musical instrument either by acting on the source, the resonator, or both, and also receives acoustical and haptic feedback from it. The listener receives acoustical input from the musical instrument (direct sound) and from the room (reverberant sound). The performer also receives acoustical feedback from the room. The alternative sonic-crystal-based performance proposed in this work is represented in Figure 2.b). In this case, the performer can also act upon the sonic crystal (through electronic controls) and change its configuration. The sound waves coming from the resonator of the instrument are modified while traveling through the air and before they can reach the audience. Then, the direct sound is replaced by a modified version of it. The reverberant sound is also altered since most of the acoustical waves arriving at the walls were previously scattered by the sonic crystal's columns. Finally, the performer also receives the sound reflected back from the sonic crystal and the reverberation of the room. In this way, the sonic crystal can be conceived as a new musical instrument modifying the direct and reverberant sound of a sound source purely by acoustical means. The source could be a separate musical instrument, or be incorporated in the sonic crystal as a loudspeaker or any other acoustical source (in this work we will explore the first option).

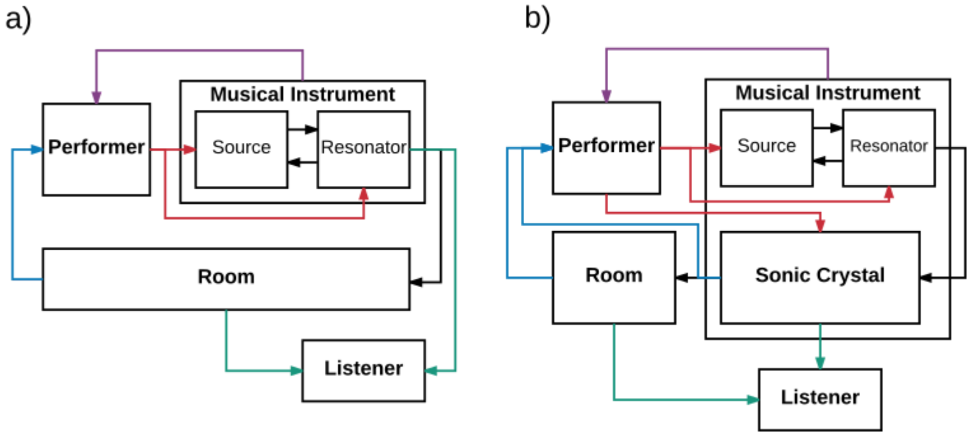

Figure 2: Acoustical and haptic flow of information for (a) a traditional musical performance and (b) the sonic-crystal-based performance proposed in this work. Colored arrows represent the flow of information for different stages of the performance.

2 Tunable Sonic Crystal and Theoretical Model

The tunable sonic crystal slab presented in this work is composed of 60 wooden columns of U-shaped section, arranged in a 12x5 square lattice of spatial period a=0.3 m (see Figure 1). The columns are 2.6 m high and each side of the U-shape measures 150x15 mm. The columns can rotate around a vertical axis passing through the center of mass, by virtue of an axial bearing assembly mounted on square wooden bases of 0.3 m side. The rotation of the columns is controlled independently by 60 servo motors driven by six arduino nano boards (each board controls two rows of columns). At a higher level, the arduino boards are controlled via the I2C protocol by a Raspberry Pi computer running a web server attached to the platform. All the programs and libraries were developed using open source software.

For the sake of clarity, it is worthwhile to define some new terminology related to this new musical instrument. A **sonic crystal configuration** is a static attribute of the instrument which is completely determined by the angular position of its columns. For example, in Figure 2 all the columns of the sonic crystal slab are oriented with the concave part of the U-shape pointing to the audience. This angular position is defined as 0 degrees. In this work we will analyze three differents configurations: “all-45”, “divergent” and “zigzag” (displayed in the top row of Figure 3). A **sonic crystal gesture** is a dynamical attribute defined by the transition between two configurations, including all the delays and rates of change for each individual column. For example, a simple gesture could be going from “all-zero” to “all-45” in three seconds with no delay. However, more complex gestures could include columns rotating at different speeds or with variable delays.

As a preliminary study we developed an interactive tool for designing sonic crystal configurations and evaluating their effect on the sound field generated by a sound source in a room. Since the number of possible sonic crystal configurations is huge and we wanted to perform a quick exploration, we adopted a 2D finite element scheme based on the COMSOL API. A graphical interface developed in Matlab allowed us to control the frequency and the location of the source, and each individual column’s angular position interactively. We also incorporated a partially absorbing boundary condition that matches the coefficients of the sound absorbing walls of the room that we used for the recordings (melamine pyramid foam). Upon selecting a configuration for the columns of the sonic crystal, a frequency and position for the source and a boundary condition, the computation of the sound field was completed in a few seconds. In this way, the frequency response of the whole room, for different configurations and source positions, could be explored in a reasonable time.

From this exploratory study, we identified three distinctive spatial patterns of the sound pressure field that could lead to changes in the timbral and spatial attributes of the source: (a) inhibition of transmission (due to the band-gap of the sonic crystal, see reference [8]), (b) focalization on the central line, and (c) focalization on two diagonal beams. We then selected three simple configurations that display these behaviors for some frequency range and which can be transformed from one to another by minimal gestures. The configurations are displayed in Figure 3 (top row), along with the computed sound pressure levels for three selected frequencies (f= 700, 800 and 1350 Hz), as an illustration of the spatial patterns mentioned above. The dimensions of the rectangle in the simulations are 8 X 4.4 m, and the source is the small white circle located at the right. In the first configuration (left) all the columns are rotated 45 degrees clockwise from the direction perpendicular to the sonic crystal slab (“all-45” configuration). In this case, there is a band-gap around 700 Hz, a focalization on the central line around 800 Hz and a focalization on two diagonal beams forming a distinctive V-pattern around 1350 Hz (bottom row). The second configuration ("zigzag") corresponds to columns rotated by 45 degrees, clockwise and counterclockwise in alternating rows. For the same frequencies, we observe slight changes in the spatial patterns. There is a greater transmission for 700 Hz with a subtle V pattern, the maximum of the central focalization at 800 Hz is displaced away from the sonic crystal slab and the V pattern at 1350 Hz is less definite. In the third and last configuration ("divergent") the left half (as seen from the source) of the sonic crystal is rotated by 45 degrees counterclockwise and the right half is rotated by the same amount in the opposite direction. Now, for 700 Hz there is a central focalization close to the sonic crystal, and the V pattern is recovered for 1350 Hz.

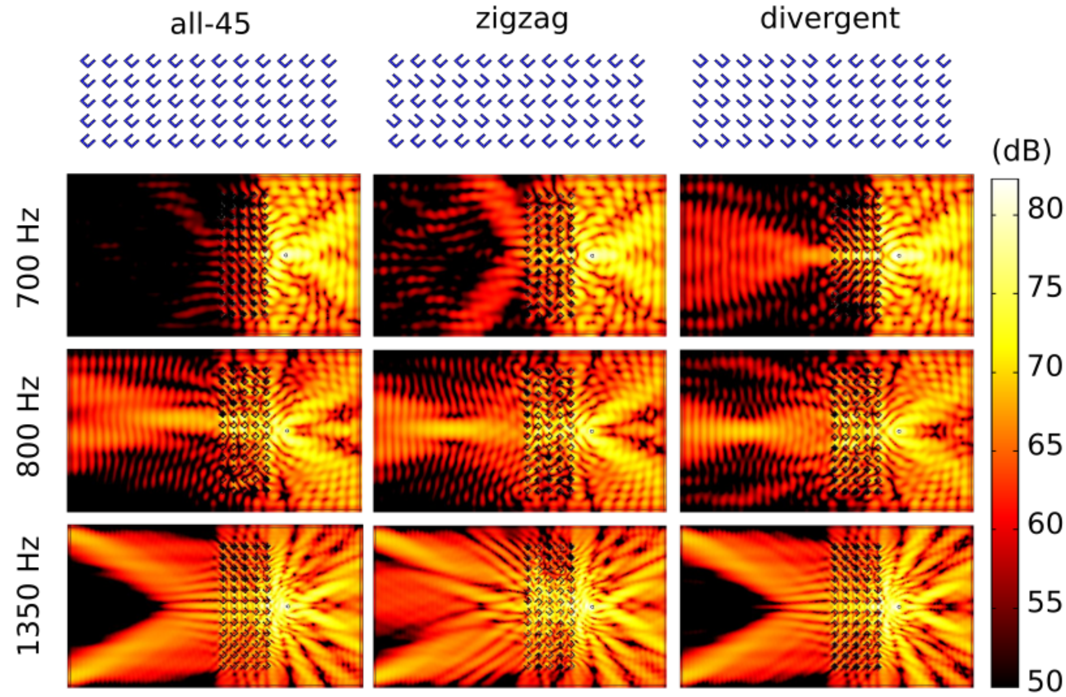

Figure 3: Schematic representation of the three studied configurations (top row) and sound pressure level maps for three fixed frequencies obtained via a FEM model.

For each frequency range, the sonic crystal configurations reorganize the spatial distribution of acoustical energy in the room. From a musical point of view, we can consider that these configurations operate as spatial filters for the harmonics of a note, creating different timbres at different places, but also probably affecting the spatial perception and segregating partials. We also hypothesize that gestures could induce dynamical changes in the spatial and timbral qualities of the note. In order to test these hypothesis, we carried out binaural recordings of two musical instruments behind the sonic crystal, and evaluated two magnitudes derived from these recordings that are related to the timbre and localization of sound sources: the binaural intensity (BI) and the interaural level difference (ILD), as described in the next section.

3 Experimental Setup and Recordings

Two different instruments of the saxophone family (alto saxophone and baritone saxophone) were used for the acoustical recordings. The instruments were played by two highly trained saxophone players. During the recordings, the musician was at one side of the sonic crystal slab (Performer on Figure 1) positioning the bore of the instrument on the central line and 0.5 m away from the sonic crystal edge, while a dummy head, equipped with DPA 4060 Miniature Omnidirectional microphones was located on the other side. The average (A-weighted) reverberation time of the room is 0.4 seconds. For each instrument, and for each of the configurations displayed in Figure 3, recordings were carried out at the three different positions (A,B,C) displayed in Figure 1. Seven notes were chosen from the useful pitch range on each instrument in order that the frequencies of the third and fifth harmonics fall within the frequency range affected by at least one of the three configurations. The notes chosen are displayed on the top row of Figure 4. We also recorded a sequence of gestures (transitions between the configurations) while the musician played a long note in the same place as before. Finally, we asked the musicians to play the same notes, with the same dynamics, in the same room, and at the symmetrical position with respect to the dummy-head but without the sonic crystal in between. These recordings were taken as a reference for the intensity of different partials of the notes.

From the binaural recordings we computed the BI and the ILD separately for each harmonic after bandpass filtering the recordings. For each harmonic the binaural magnitudes were obtained as follows:

$$BI = 10\, log_{10}\left(s_l s_r\right) - 10\, log_{10}\left(r_l r_r\right)$$

$$ILD = 20\, log_{10}\left(s_l / s_r\right)$$

where s_l and s_r are the RMS values of the left and right channels of the binaural recordings (after the filtering) with the sonic crystal, and r_l and r_r are the same magnitudes from the reference recordings.

A value of BI significantly different from zero indicates that some harmonic was attenuated or reinforced (hence producing an alteration of the timbre) with respect to the original sound, while an ILD value different from the theoretical value determined from the azimuth angle (see [10] as a reference) indicates that some harmonic could be, in principle, be spatially segregated. The values of ILD for the individual partials must be taken with care, due to the fact that for low frequencies the ILD is not useful as a cue for localization [10] (also the modes of the room can introduce large variabilities in this magnitude). Therefore we restrict our analysis to the harmonics above 1 kHz.

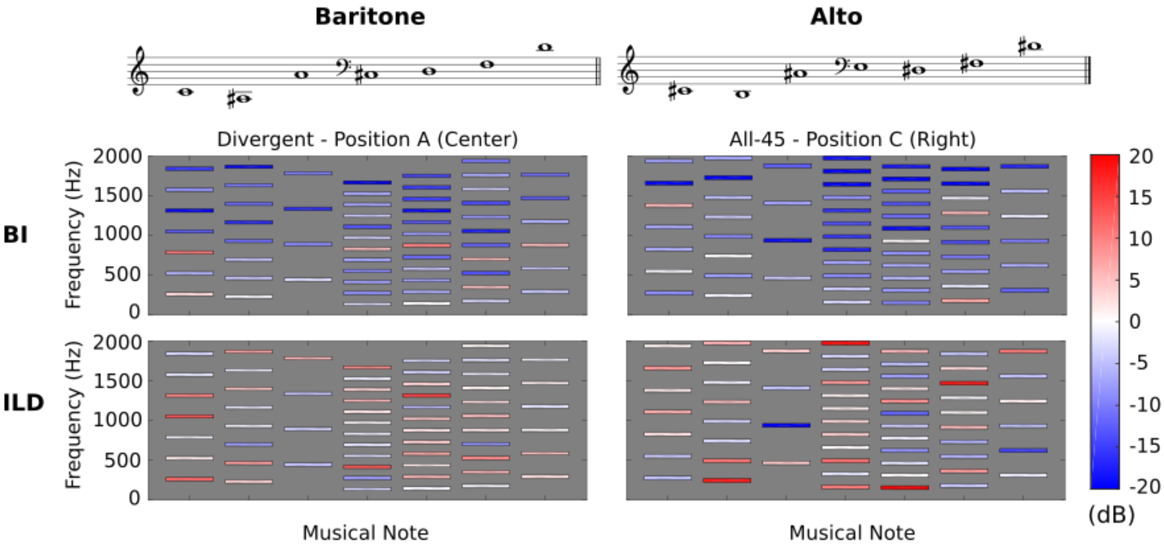

Figure 4: Spatial and timbral analysis of the notes played by the performers. On the top row the musical scores corresponding to the baritone and alto saxophone are displayed. Binaural intensity (BI) and Interaural level difference (ILD) for each harmonic of the vertically aligned musical note (until 2000 Hz) are shown as a color code on the two lower rows.

4 Results and discussion

In Figure 4 we display the two sequences of notes played by the musicians. We also display the BI and ILD for the individual harmonics, up to 2000 Hz for a particular position and configuration as an example of the results obtained, in color scale (the same for the two magnitudes). A positive ILD value correspond to a higher sound level in the left channel. For the baritone saxophone we selected the “divergent” configuration and the recording in the position A (center) in order to show the effect of the central focalization around 800 Hz (see Figure 3, right column). Some of the harmonics near this frequency are reinforced, as it can be seen from the BI diagram. Noticeable effects (BI greater than 5 dB) are observed in the third harmonic of the first and last notes, and in the sixth harmonic of the fourth and fifth notes. The ILD of the notes (including all partials) was close to zero in average, as expected. For the alto saxophone we display an example of the “all-45” configuration recorded at position C (right), which lies approximately on one of the diagonal beams of the V-pattern at 1350 Hz (see Figure 3, bottom row). A noticeable BI reinforcement near that frequency is observed only in the first (5th harmonic) and sixth note (7th harmonic). For these harmonics the ILD is close to zero, which deviates from the overall positive ILD values of the notes (the source is located to the left of the dummy-head). However, for some notes the reinforcement is more subtle or even they do not display reinforcement at all. This was probably due to the instrument’s inherent variability in sound production. For the remaining configurations and positions we observed a similar behavior. For each sequence of seven notes, recorded at a particular position and for a given configuration, an average of four notes displayed a significant reinforcement or displacement in the harmonics, as predicted. This make the tunable sonic crystal, even when not completely effective, a valuable instrument that can modify the spatial and timbral characteristics of an acoustic source by enhancing or deviating the propagation of its harmonics. Yet, the more compelling expression of this device is obtained by varying its configuration during the execution of a note, performing what we called a sonic crystal gesture.

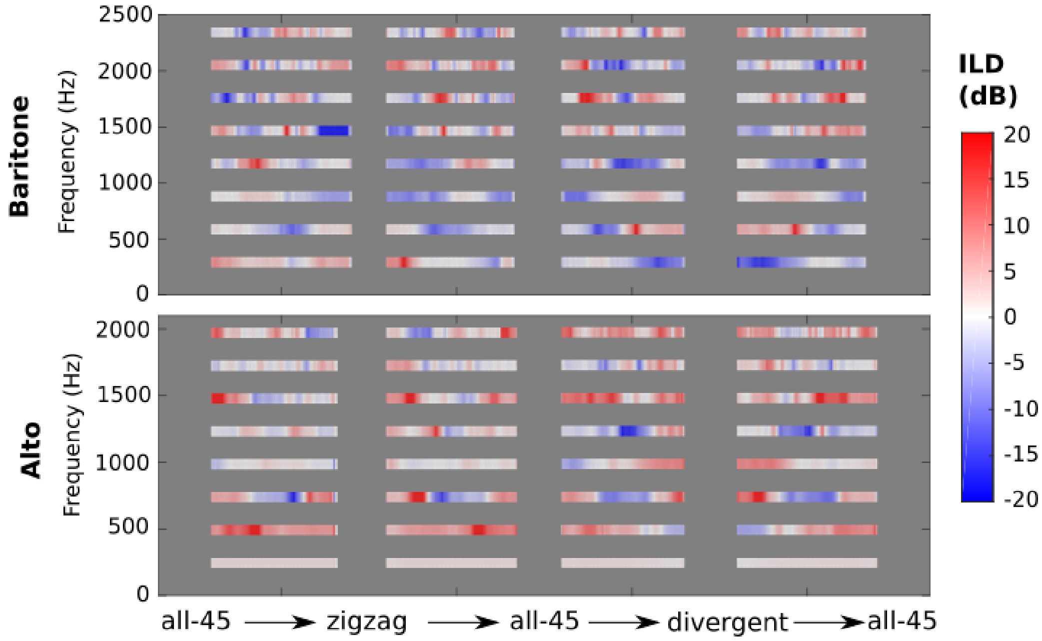

Figure 5: ILD for a D4 and a B3 played by a baritone and alto saxophone, respectively. The ILD was calculated from a recording of the note played while performing a six-seconds long sonic crystal gesture. The intermediate configurations of the gestures are indicated at the bottom of the figure.

Figure 5 illustrates the changes observed in the ILD of the first 8 harmonics for a repeated note (D4 for baritone and B3 for alto saxophone) played during four sonic crystal gestures: starting from the all-45 configuration and switching back and forth to zigzag and divergent configurations. The duration of all notes was approximately equal to the duration of the gestures (six seconds). It can be clearly seen now that the ILD of the harmonics (and consequently the angular localization for the higher ones) changes during the execution of the note. For example, the fourth and fifth harmonics of the note played by the baritone for the first two gestures and the third harmonic of the alto saxophone for the four gestures display variations of the ILD by more than 30 dB during the playing. It is highly plausible that these dynamical changes in ILD would contribute to the spatial segregation of the corresponding harmonics, both from a lower-level lateralization and from a higher-level assumption of a ‘common-fate’ rule acting on them [11]. Higher harmonics also show ILD variations, however the effect on localization and segregation is probably smaller due to the celerity of these changes and the lower level of the harmonics. Also, note that the second and fourth gestures are expected to be time-reversed versions of the first and third gestures, respectively. An approximate temporal symmetry is observed in all harmonics up to the sixth, but is less preserved in the last two harmonics.

In summary, we presented a new musical instrument that is able to change some spatial and timbral characteristics of an acoustic source dynamically during performance. We made a first succinct analysis of the changes in the BI and ILD of the harmonics of seven notes played by two musical instruments. Further research should be undertaken to study the perceptual effects of these changes.

Acknowledgments

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