WHAT WE ALREADY KNOW ABOUT SPATIALIZATION WITH COMPACT SPHERICAL ARRAYS AS VARIABLE-DIRECTIVITY LOUDSPEAKERS

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ABSTRACT

Our initial work with the icosahedral, variable-directivity loudspeakers (ICO) has revealed new possibilities of thinking spatial music and its aesthetics. In contrast to surrounding loudspeaker systems, the ICO technically offers control of the strengths of the wall reflections that could be excited from a single performer's location. The ICO has already been successfully employed in various compositions that were performed in concerts in different spaces and environments. Existing compositions yield sound objects that move away from the ICO into different shapes, distances, and locations in the room. This implies that the ICO orchestrates space with new composition elements in electroacoustic music, by influencing diffuse, early, and direct responses as artistic composition elements in a room. Our research project *Orchestrating Space by Icosahedral Loudspeaker* (OSIL) aims at understanding the inter-relation and control of these elements better, in terms of their sculptural-choreographic nature, and how they can be used to express motion, localization, extent, and depth. This contribution describes artistic and scientific research goals and approaches, and what our scientific research could already show.

1. INTRODUCTION

Spatialization. Interest in using space as a compositional parameter with different, partially movable sound sources did not begin with electronic music, however the use of loudspeaker systems enabled more accurate control thereof. In his definitive treatise of 1958, "Music in Space", Stockhausen states: "... we notice more and more that all musical ideas are becoming increasingly spatialised" [1, p. 155]. Since Chowning's publications [2] in the 1970s, various computer-based models were developed for the generation and positioning of virtual sound sources in space and for the generation of (half-) immersive sound environments [3], and this strand of development and research continues today. The Sounding Object project [4], though technically oriented, is a milestone in this process, Truax [5] addresses directly the question, and Smalley [6, 7] has very wisely built a refined system of concepts related to quality and space. The PEEK project Choreography of Sound 2013 by Eckel/Gonzalez-Arroyo has extended the discussion towards the plastic auditory object [8]. The common thread of these new approaches is the assumption that space is not only essential as a condition in concert situations for the reverberation of the music, but that it can also be created and shaped as a sound projection, understood as a formative factor and integrated into the composition. In this way one can arrive at forming auditory objects that permit a sculptural handling and composition of sound. It is however still an open question as to how these space-sound objects can be reliably produced and used for artistic purposes. "Even supposing that all of the scientific and technological difficulties are resolved, it remains unclear as to how we can organise space in its diverse meanings as a musical material [9]."

Common spatialization systems for computer music employ loudspeaker arrays that surround the listening area, such as the BEAST (University of Birmingham), the Espro (IRCAM), the Klangdom (ZKM), the CUBE and the MUMUTH (KUG). They either use the psychoacoustic phenomenon of a phantom source [10, 11] to create auditory objects between the loudspeakers, e.g. VBAP and Ambisonics [12, 13], or aim at recreating a physically accurate sound field, e.g. wave field synthesis [14, 15]. The quality assessment of such systems is a current research topic [16, 17, 18, 19, 20]. To a certain degree, these systems assume anechoic listening conditions and their accuracy suffers from reflections.

Compact spherical arrays. In contrast to common surrounding loudspeaker systems, the novelty in our project "Orchestrating Space by Icosahedral Loudspeaker" (OSIL) lies in controlling the strengths of the wall reflections that could be excited from a single performer's location. Namely an icosahedral loudspeaker (Fig. 1) is employed as an instrument of adjustable directivity at this location.

In electroacoustic music, the notion of adjustable-directivity loudspeakers was introduced in Paris in the late 1980s by researchers at IRCAM. For the renowned concept study "la timée" [21], a cube housing six separately controlled loudspeakers was built to achieve freely controllable directivity. Despite the ingenious idea and theory, loudness and focusing strength weren't convincing enough to be employed in concerts. In 2006, researchers at IEM (University of Music and Performing Arts Graz) reconsidered the theory aiming at an acoustically correct and powerful reproduction of musical instruments in their lower registers, including the entire 3D directivity pattern.

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The resulting icosahedral loudspeaker (ICO) is more powerful, of larger size, and larger number of loudspeakers. Moreover, a success in quality was achieved by reconsidering algorithms and acoustic calibration to control sound beams [22] that are three times narrower than beams of earlier systems. Except for the 120-channel array at CNMAT [23] that runs Zotter's algorithm (from 2007), none of the few comparable arrays is employed with similar goals or algorithms (12-channel system at ITA RWTH-Aachen [24], 6-channel and experimental systems Stanford/Princeton [25, 26]).

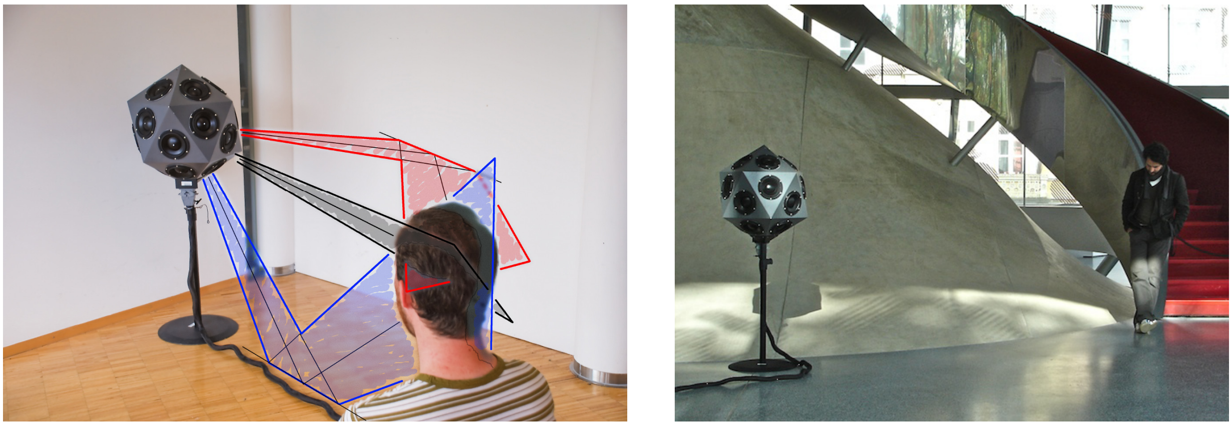

Figure 1: The IEM icosahedral loudspeaker is equipped with 20 transducers driven by spherical beamforming. Its artistic use exploits acoustic reflections to shape and orchestrate sound sculptures traversing space.

Our research focuses on creating sound primarily with one, really well-sounding icosahedral array, despite new theoretical work of Betlehem [27] *et al* shows thinkable benefits of surround arrays using spherical/circular loudspeaker units.

It first came as a lucky surprise that the ICO truly permits to form three-dimensional auditory objects in space. Its strongly focused sound beams can be projected onto floors, ceilings and walls, while direct sound from the ICO is often attenuated so that rather sounds from acoustic reflections become audible. Beams are freely adjustable in terms of direction. As alternative ways to spatialize, different beams can be blended, or their beam width manipulated. Spatial auditory objects created by the ICO can be moved around towards the reflecting surfaces or collapse onto the ICO. What is more, objects can be composed as to include useful gradation of depth, which was recognized by the audience, according to feedback statements.

Pierre Boulez' remark «Le haut-parleur anonymise la source réelle» inspired research in musical acoustics and electroacoustics [28] by stating that loudspeakers alienate natural sources by modifying how their sound is radiated into the room. There is plenty of evidence on how the radiation characteristics influence sound in rooms [29, 30, 31], and it is most plausible when motion of the musician is involved. Equipped with background knowledge about sound radiation [32], the powerful prototype of the IEM ICO [22], expertise in psychoacoustic evaluation and modeling of spatial sound [33], and pioneering experience in music written for the ICO as a new musical instrument [34, 35, 36], we postulate a slight variation of the above as the artistic research hypothesis of OSIL: Loudspeakers of adjustable radiation naturalize alien sounds by embedding them in the natural spatiality of the room, cf. also conclusion 2 in [37].

2. ARTISTIC AND SCIENTIFIC RESEARCH GOALS AND APPROACH

Our artistic research project OSIL aims at examining, analyzing, and elaborating on the initial experiences as described above. We have formulated the objectives that we wish to achieve in the course of the 3-year research period as follows:

1 A style of composition that integrates electroacoustic auditory objects of the ICO into the strategic, creative, and practical compositional process should be found, preferably by investigating composed material (miniatures, etudes, pieces).

2 In close cooperation between composers and engineers, listening experiments should be designed and conducted with a group of trained expert listeners to yield a suitable vocabulary of terms that describe these auditory objects, also in a quantitative way.

3 A perceptual model should be established that is capable of explaining psychoacoustical sound phenomena of the composed material based on their experimental evidence. The knowledge hereby obtained ensures targeted control when creating auditory objects with the ICO, which will be incorporated in software tools.

Bottom-up Composition: Miniatures, Etudes, Pieces. The methodology of OSIL revolves around the notion of the artistic case study, in a kind of bottom-up concept. OSIL will produce a number of such case studies (a set of musical miniatures, a set of etudes), each of which focusing on a few, clearly defined, separable, and researchable questions. This formalization gives us a strong tool to create from models a software environment with a well-distinguished set of tools, each of which capable of producing particular and pronounced ideas within entire compositions. The goal is to iterate the stages composition, listening experiments, verbalization, and psychoacoustic modeling.

2.1. Listening experiments for verbalization

A standardized verbal description would facilitate inter-subjective exchange, artistic discourse, and scientific understanding. In order to make this possible, a vocabulary must be available, or be created, that can describe certain phenomena and which necessarily has a generalizing function. For this purpose, we study, compare, and superimpose many kinds of descriptions and taxonomies for (electro-)acoustic music phenomena, [38, 39, 6, 7, 40, 41]. From the field of spatial audio, approaches can be adopted [19], and in [20], it was moreover found that despite typical spatial audio terms can be significant descriptors in terms of classical and popular music, they might, however, be irrelevant when it comes to contemporary music.

We suggest to explore a more exhaustive approach tailored to the particular perceptual space of the ICO. Auditory objects in *miniatures* can be initially tested by direct scaling in known or well-defined verbal terms (e.g. direction, width), using experiment designs, such as MUSHRA-like [42] or pointing methods [43]. Complementary, verbalization retrieves attributes by repertory grid technique or similar [44], possibly supported by multidimensional scaling [42]. Both direct scaling and verbalization are repeated until no additional expressions are found in verbalization.

Whether the hereby obtained vocabulary is exhaustive can be checked by applying it to new, more elaborated miniatures or those of the guest composer. If it is not, further refinement is necessary, and if it is, more elaborate *etudes* and *pieces* should be explored using the exhaustive vocabulary.

In parallel to listening experiments for verbalization, fundamental psychoacoustic studies should be done, so that, ideally, the resulting psychoacoustic models are able to explain what is heard and verbalized.

2.2. Fundamental psychoacoustical studies and models

Extending Bregman's fundamentals on auditory scene analysis [45], recent research on the formation of auditory objects has to be considered [46], especially concerning forward masking [47], influence of preceding sounds [48], and interaction of multiple components within an auditory scene [49]. The author's interest in the sound spatialization technique Ambisonics [50, 51, 52] brought forward new expertise on spatial perception of auditory objects created by multiple active surrounding loudspeakers. This is in contrast to former work that only uses two or three active loudspeakers per auditory object [10, 53, 54]. Previous investigations clearly indicate how to model such phantom sources in terms of direction, width, and coloration [16, 33, 55].

In terms of the auditory objects of OSIL, additional complications such as acoustic delays need to be considered, as the directivity of the ICO controls the amplification of each propagation path of sound (direct or reflected), of which each one is associated with a direction and an acoustic delay time at the location of the listener. So far, there is only one brief work about the topic [56]. A basic understanding of reflected sound is given in the work of Hartmann [37, 57] and Morimoto [58, 59], which underlines that directions, amplitudes, delays, and kind of sounds arriving at the listener determine what is perceived. Existing works on echo thresholds [60, 61, 62] can be also seen as a basis for models, however they do not incorporate multiple reflections with different levels.

2.3. Mobility and Spatialization Software

Previous experience shows that the ICO can be applied as an instrument to be used in small auditoria, in chamber music halls, and even large concert halls. But there is no restriction to this application scenario. In contrast to mounted loudspeaker facilities, the ICO, as a performance agent, does neither encircle the audience nor does it require big mounting rigs. Its compactness allows exploring other performance spaces that are otherwise not eligible. A new and diverse public audience will be invited and reached. It offers a more systematic way of spatialization compared to conventional, acousmatic sound art installations. In the case of absent surrounding surfaces, i.e. the performance in an open space, setting up compact reflection panels serves the purpose.

Since the early experiments working with the ICO, the authors tried several software approaches for implementing the beamforming algorithm and the spatial sound composition, such as Pure Data, SuperCollider, and MaxMSP. In the process of OSIL we will develop a VST-spatialization-plugin that is based on existing Ambisonics plugins [63]. All virtual sources (mono and multichannel files) controlled in their position, width, and diffuseness via MIDI or OSC. We are also planning a graphical interface that shows the position of the moving sources on the spherical surface of the ICO, the levels of the sources and channels used in the spatialization scene.

3. PRESENT SCIENTIFIC RESEARCH RESULTS OF OSIL

3.1. Orchestrating wall reflections in space by icosahedral loudspeaker: findings from first artistic research exploration [64]

A preliminary study about the perceived auditory objects created by the ICO has been presented at ICMC/SMC 2014 [64]. The study employed 8 excerpts from the pieces grrawe and firniss. Seven listeners were asked to quantify and characterize the auditory objects they perceive and describe their position in space or movements. The verbal answers were compared for parallels and significant discrepancies. The terms used by the listeners for characterizing the auditory objects of course varied but were surprisingly congruent for some stimuli. Exemplarily, we focus on a single excerpt which was a part of firniss, cf. left part of Fig. 2. Additionally to the listening experiments, all stimuli excerpts were recorded with a dummy head at the listening position. The recordings were fed into a binaural localization model after Lindemann [65]. The resulting inter-aural time-delay differences (ITDs) indicate the predicted direction, cf. right part of Fig. 2.

The study revealed that different listeners individually perceive these objects similarly, although using different verbal descriptions for characterizing the objects and their spatialization. The spatial character of the objects could partly be explained by geometrical and a binaural localization model. However, the model cannot explain all auditory aspects, e.g. three-dimensional localization, spatial extent, and shape.

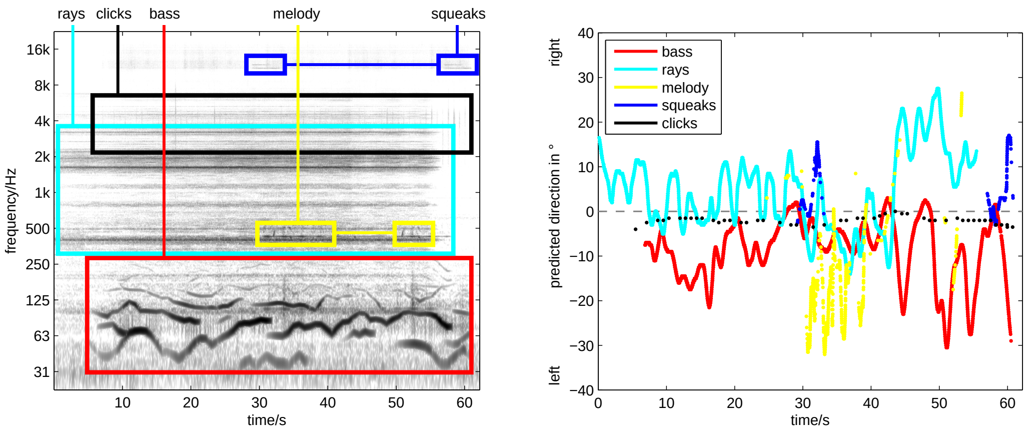

Figure 2: Spectrogram of the firniss excerpt and its sound objects (left) and composite ITD values for each object of firniss excerpt, calculated by binaural Lindemann model (right).

3.2. Preliminary study on the perception of orientation-changing directional sound sources in rooms [66]

Another study has been presented at Forum Acusticum 2014 [66]. It considers artificial-directivity sound sources with variable orientation. In the experiment with 9 listeners, direct sound and first-order reflections of a shoe-box room arriving at the listener were all simulated by surrounding full-range loudspeakers. The results confirm that the orientation of directional sound sources can be heard and that they can yield localization deviating from the direct path, cf. Fig. 3. Furthermore, a simple vector model was developed that considered a rough echo threshold of -0.25dB/ms [60].

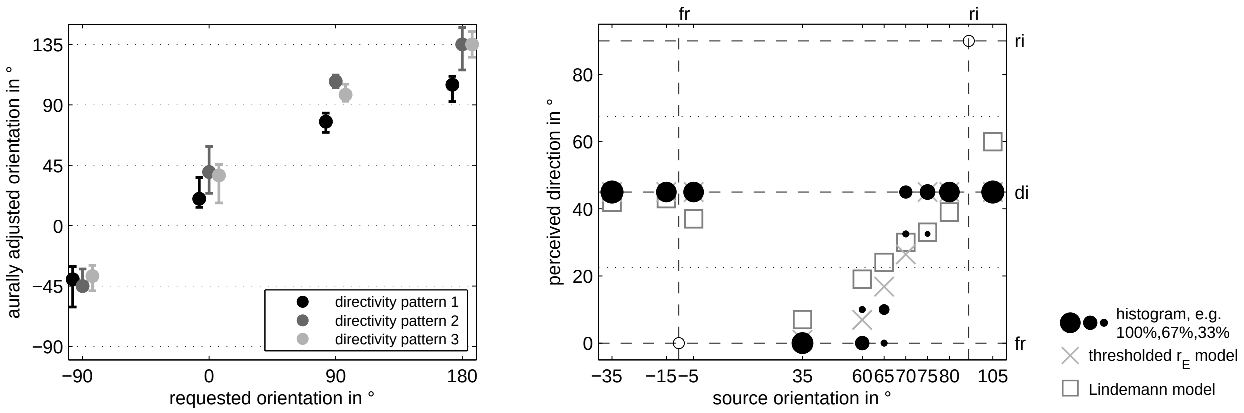

Figure 3: Left: In a listening experiment, orientation of a directional loudspeaker in a simulated shoe-box-shaped room could be controlled to look into primary directions with significant difference. However, there seems to be a systematic deviation that is remarkably consistent across all listeners. Right: The direction listeners perceived in such a setting, in response to a varied-orientation third-order source, led to localization that could be clearly directed away from the direct sound (di) to a reflection path (fr). The perceived direction was modeled by a binaural model (Lindemann) and a thresholded vector approach (r_{E}).

3.3. Investigation of auditory objects caused by directional sound sources in rooms [67]

The auditory impression of sound sources is strongly influenced by the room, which, e.g., determines the apparent source width. What is more, typical sources are not omnidirectional, which also makes their orientation a strong influence. This influence, however, has only been investigated a little, although it can even change the perceived location of the source. To provide more insight, we performed extensive listening experiments inside our anechoic laboratory that is equipped with a 24-channel loudspeaker playback to simulate both directional source and room. The directional source is described by two frequency-independent 3rd order directivity designs in 36 different orientations, and the room is simulated by the two-dimensional 1st and 2nd order image source method. Results of the experiment indicate that, in most cases, the auditory location can be determined by the loudest unmasked acoustic reflection path. This allows us to explain the primary direction perceived with an astonishingly simple model including precedence effects.

Fig. 4 shows results of this listening experiment, indicating the directions of the perceived auditory objects. In most cases, the primary auditory direction could be successfully modeled. There, localization is dominated by the acoustic reflection path that remains after applying to the ear-directivity-weighted time sequence of incoming reflections an exponentially-decaying mask that models precedence. The resulting model could be valuable in computer music and sound engineering practice to predict achievable spatial effects of not only compact spherical loudspeaker arrays, but also in surrounding loudspeaker systems when listeners are seated off-center. Other effects that are visible in the data were not modeled yet. In these special cases, either a onefold auditory localization is determined by stereophonic localization, or splitting occurs into twofold (or threefold) auditory directions. Stereophonic localization requires to be modeled using trading curves such as those in [28, 29]. Less is known under which delay and directional offset the localization splits. Predicting from listener statements about different localization at the end of the sound, the envelope of the sound [30] may play a significant role. Envelope may determine the sequence or strength, in which onefold, twofold, or a thinkable threefold localization is perceived.

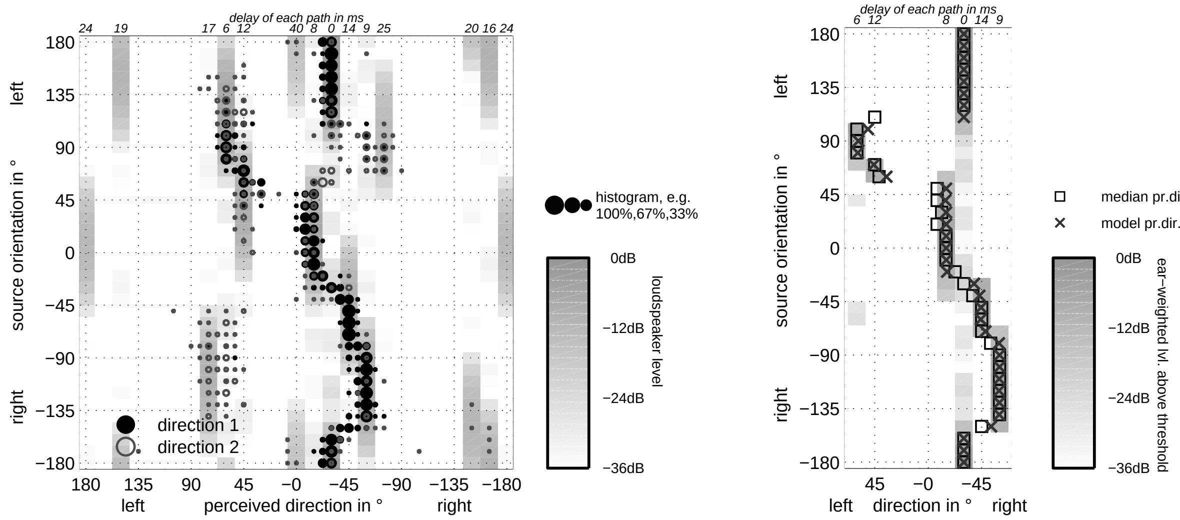

Figure 4: Listening experiment results (left) for 2nd order image source model; radii represent the number of answers for each direction; level of each propagation path is represented by the gray shading in the background. Medians of perceived primary directions (squares) and modeled directions (crosses) for 2nd order image source model; level of each propagation path after weighting with ear directivity and precedence masking is represented by the gray shading in the background (right).

3.4. Virtual ICO

The ICO, as a prototype, might not be reproducible in every detail, and the algorithms for spherical beamforming might evolve again. This leads to a crucial question of whether the artistic practice is always clearly related to simplified experimental setups, and whether other artists will be able to reconstruct the same effects investigated in OSIL. Moreover: How would a composer be able to have an impression of what the perceived objects of the ICO at a specific target venue, when this venue is not available during the composing phase of the musical piece, or how would one get an overview of how the ICO sounds where?

To overcome all these severe difficulties, a fully interactive virtualization of the ICO at different venues and for different listening perspectives can provide documentation, reproducibility of experiments, and a composing tool.

This *Virtual ICO* is achieved by measuring the room responses of the 20 loudspeakers of the ICO to the 32 channels of the Eigenmike EM32 in the hall and at the listening and ICO positions of interest. Such responses are used to achieve the following benefits due to modularization:

- The Eigenmike 32 is like a virtual dummy, whose orientation can be adapted interactively in real-time to the orientation of a listener with head-tracked headphone. Moreover, listener-individual HRIRs (head-related impulse responses) could be employed.
- The spherical beamforming of the ICO can be exchanged to allow improvement and development of the existing algorithms (which basically is a MIMO filter set), if, e.g., the filter set should contain other spherical harmonic weights, diffuse-field instead of free-field equalization, other dynamic limits, or other modifications.
- The rendering of the different audio tracks, their beam-layout, beam sizes, blending curves, etc, can be interactively changed, as the whole signal processing chain and the virtual ICO can be rendered in real time. Hereby it is possible to more easily master or preproduce musical pieces for different rooms.

The signal processing chain of the virtual ICO is shown in Fig. 5. The quality comparison between sonic objects created by the real and the virtual ICO needs to be evaluated in order to describe thinkable differences. Still if such differences should appear and are well-described, the virtual ICO is useful for artists all around the world to check how different effects and miniatures work with the ICO, and to pre-produce pieces for it.

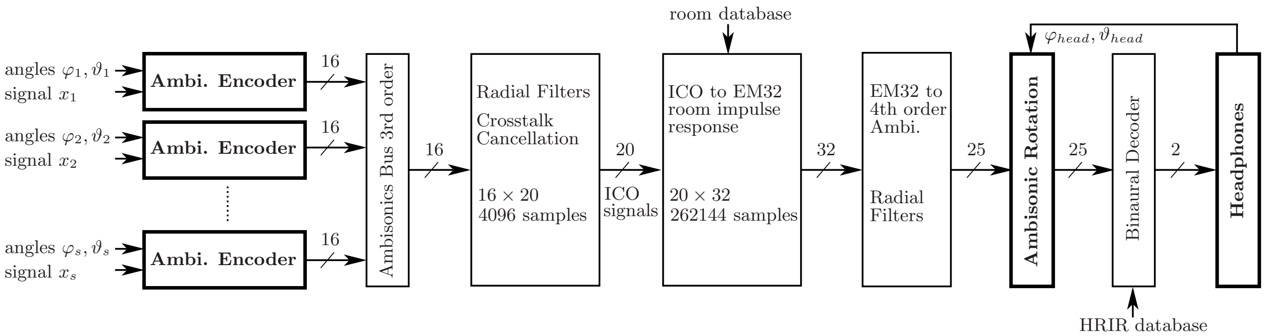

Figure 5: Block diagram of the *virtual ICO* contains units for real-time interactive encoding and head-tracked headphone playback (bold blocks). The encoding allows to spatially arrange the sound objects of a composition. The radial and crosstalk cancellation filters are used to drive the ICO. From there on, the virtual blocks takes over: The ICO to EM32 block contains a database of virtualized/measured room impulse responses (RIRs) of performance situations. The EM32 to 4th order Ambi pre-processes the RIRs to Ambisonics, which is followed by a dynamically head-tracked headphone playback whose real-time-rotated virtual dummy head is simulated by HRIRs that are customizable.

The documentation of the ICO in terms of the virtual ICO will allow to perform comparative studies revealing how safe auditory objects work under different acoustical settings in which a measurement has been done to virtualize the ICO. It will be interesting to see in how far modeled room impulse response functions of ICO and Eigenmike will resemble in terms of their perceived objects. So far, the ICO has been measured in the IEM CUBE and in two different concert locations in Zagreb (May 2015), cf. Figure 6. From now on it is planned within OSIL to measure a room response dataset in every performance venue the ICO is played in.

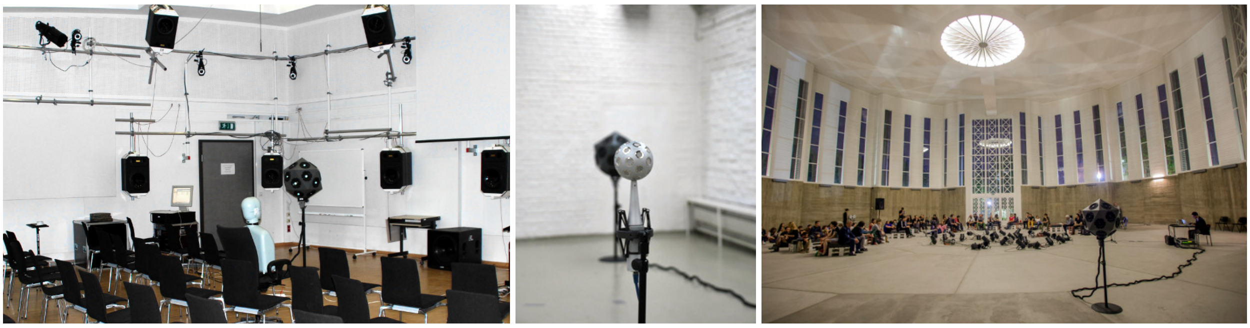

Figure 6: Venues at which a set of room impulse response have been measured from the 20-channel icosahedral loudspeaker (ICO) to the 32-channel spherical microphone array (Eigenmike EM32) in order to virtualize the performance situation to a *virtual ICO*.

4. CONCLUSION

In our project "Orchestrating Space by Icosahedral Loudspeaker" (OSIL), we have been starting artistic and scientific investigations, of which we could present some of the first findings in this paper. We accomplished to show by very simplistic psychoacoustic experiments that variable directivity can be perceived in terms of sound objects and their location. Models are able to predict main aspects of the perceived location (direction/lateralization), which even worked to model responses of an exploratory experiment using excerpts of complex spatial compositions for the icosahedral loudspeaker. Our simple model considers summing localization by an energy vector $\boldsymbol{r}_{\mathrm{E}}$ involving precedence. Its weakness right now is to only predict a single dominant direction, whereas, in some cases, experiments show that perception can yield multiple directions.

We clearly see that the localized direction depends on the level balance of the acoustic reflection paths and the direct sound in a room. This balance is directly influenced by the variable directivity of the icosahedral loudspeaker. If, e.g., the direct sound is suppressed and it is accomplished to exclusively excite one wall reflection then this reflection dominates the localized direction. It is clear that more complicated rooms and complex composition elements are always subject to physical limits of producing focused sound radiation.

On the one hand, we aim to extend our understanding by further fundamental psychoacoustic studies and models, for which reproducibility is paramount. On the other hand, we seek for extending the listening experiments for verbalization by miniaturistic composition elements. These miniatures are specifically composed for the ICO in order to focus on particular aspects of composition-relevant sound objects in space, to be evaluated in real performance spaces. How this verbalization could be obtained was sketched in the paper, and its result shall facilitate the artistic discussion and provide an inter-subjective, listener-based vocabulary.

By our new software device "virtual ICO", we will be able to offer the ICO as an instrument to a larger community of composers, and a database of virtualized performance venues will allow to investigate how well different composition elements work in different acoustic settings.

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