The 'Virtualmonium': an instrument for classical sound diffusion over a virtual loudspeaker orchestra

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ABSTRACT
Despite increasingly accessible and user-friendly multi-channel compositional tools, many composers still choose stereo formats for their work, where the compositional process is allied to diffusion performance over a 'classical' loudspeaker orchestra. Although such orchestras remain common within UK institutions as well as in France, they are in decline in the rest of the world. In contrast, permanent, high-density loudspeaker arrays are on the rise, as is the practical application of 3-D audio technologies. Looking to the future, we need to reconcile the performance of historical and new stereo works, side-by-side native 3-D compositions. In anticipation of this growing need, we have designed and tested a prototype 'Virtualmonium'. The Virtualmonium is an instrument for classical diffusion performance over an acousmonium emulated in higher-order Ambisonics. It allows composers to custom-design loudspeaker orchestra emulations for the performance of their works, rehearse and refine performances off-site, and perform classical repertoire alongside native 3-D formats in the same concert. This paper describes the technical design of the Virtualmonium, assesses the success of the prototype in some preliminary listening tests and concerts, and speculates how the instrument can further composition and performance practice.

Author Keywords
Sound diffusion, performance practice, Ambisonics, acousmatic, electroacoustic music, loudspeaker orchestra, acousmonium

ACM Classification
H.5.5 [Information Interfaces and Presentation] Sound and Music Computing

1. INTRODUCTION
By combining speakers placed at different distances and angles from the audience, loudspeaker orchestras furnish performers with complex possibilities to project and enhance spatial contrast, movement and musical articulations. The performer draws on spectral and spatial changes in the music, loudspeakers of diverse frequency response and power, room acoustics, and how changes in the precedent effect and directional volume influence our perception of the spatial scene. From the 1960's, through to the present-day, loudspeaker orchestras remain alive in Europe, where the GRM Acousmonium[1] and BEAST[2] are at the forefront of this continuing movement.

Harrison [1] emphasises that diffusion is motivated by more than performance practice: it is also inextricably linked to the acousmatic compositional process where spatial diffusion 'completes' a work. Yet few composers fully understand, or are proficient in, the art of diffusion upon which the performance of their work relies. Furthermore, in 3-D sound, the trend moves towards permanent, high-density loudspeaker arrays (P-HDLAs), constructed from similar speakers, evenly distributed around the space. Examples include ZKM's (Center for Art and Media in Karlsruhe, Germany) 43-speaker Klangdom and IRCAM's 75-speaker 3-D array in the Espace de Projection. Such systems maximize audience area, eliminate laborious and time-consuming setup time, and the density of speaker distribution renders the installation compatible with all commercial and non-commercial multi-channel formats, *except* that of stereo sound diffusion.

Although each P-HDLA is accompanied by unique solutions for sound control (such as in the ZKM's Zirkonium [2]), recent developments in the flexibility and accuracy of higher-order Ambisonics (HOA) decoding e.g. [3], and hybrid combinations of this technology [4], renders HOA a cross-platform spatial format compatible with any P-HDLA. Although some composers have chosen pre-spatialised multi-channel formats, which demand pre-defined loudspeaker layouts, the inherent inflexibility of these formats in the face of a real-world concert scene have lead to ad-hoc channel to speaker remapping. In contrast, stereo or hybrid solutions such as multiple-stereo that can be performed in diffusion remain popular [5].

The Virtualmonium emulates a classical acousmonium in HOA. The software is built in MaxMSP using IRCAM's Spat package [6], which draws on established ambisonics equations and includes convenient room models and acoustic emulation. In the interim between collecting 'impulse responses' (IRs) from real acousmoniums, the loudspeaker emulation draws on IRs from the online database at the 3-D Audio and Applied Acoustics Lab at Princeton [7]. Leveraging existing tools allowed the design of the Virtualmonium to focus on its goals, which are: to provide the infrastructure to perform new stereo works and classical repertoire alongside native 3-D ambisonics in the same concert, to design new acousmonium orchestral colours and configurations, and to allow diffusion performances to be rehearsed off-site.

In this paper we present details of the technical infrastructure and rational behind the chosen approaches to space and sound, results from preliminary user tests and a discussion that has grown out of tests and concerts.

[1] http://www.inagrm.com/accueil/concerts/lacousmonium
[2] http://www.beast.bham.ac.uk

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2. THE VIRTUALMONIUM OVERVIEW

Figure 1 illustrates an overview of the Virtualmonium's architecture. A stereo composition is split into the same number of channels as there are virtual loudspeakers, normally in a standard left-right panning. The performer controls the volume of each of these channels, as would be the case in classical diffusion. The signals are then passed through the appropriate speaker emulation modules that consist of fixed attenuation, filtering or IR convolution. The output from each emulated speaker is then spatialised in HOA and a room model added. The signal is then decoded with the correct parameters for the given ambisonics loudspeaker array.

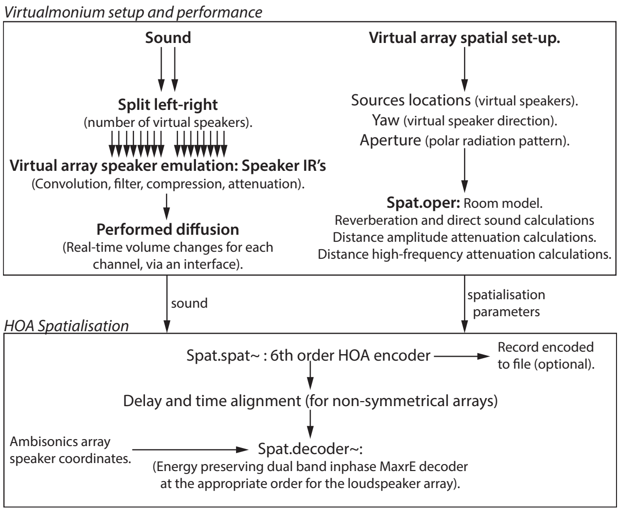

Figure 1: The Virtualmonium overview

3. EMULATING THE ORCHESTRA

Loudspeaker orchestra layouts can be generalised into two categories: in one approach, loudspeakers form a frontal stage with fewer speakers surrounding the listeners, such as in the Gmebaphone [8]; while the other approach more evenly distributes loudspeakers throughout the space, such as in the BEAST system [5]. Both layout conventions combine loudspeakers of different power and frequency response, where in performance, speakers are blended. The resulting complexity is controlled during the act of performing-listening.

In the emulation, the properties of the loudspeaker orchestra can be grouped into four categories: (1) loudspeaker locations as azimuth and distance from the listener; (2) loudspeaker rotation and the effect on directional volume, frequency and room stimulation; (3) a room model to aid the impression of distance and for angled speakers to create diffuse wall reflections; and (4) loudspeaker colour, power and radiation pattern. These four categories can then be grouped into matters concerning loudspeakers and matters concerning space.

3.1 Loudspeaker emulation

The Ambisonics array will itself colour the sound, but at this stage we will assume that these loudspeakers are broadband, matched, and of a relatively flat frequency response. Gathering information about the loudspeakers (and their driving amplifiers) that we want to emulate is not trivial. Toole [9] lists 11 criteria, amongst which we find frequency-amplitude responses, as well as harmonic and transient distortion.

To simplify the pilot project, a generalised approach has been taken that only considers spectral impulse responses (IR) and frequency plots, dynamic performance and polar radiation patterns. In practical application, IRs can be used for real-time convolution, frequency plots in filter design and polar radiation patterns used to control angle dependent frequency distribution and virtual room stimulation. There are however few available databases, and being in the development phase, we have not begun our own loudspeaker measurements. In the long-term, we hope to collaborate with real loudspeaker orchestras to obtain interesting spatial-IRs. For the time being, IRs from the online database at the 3-D Audio and Applied Acoustics Lab at Princeton, were used [7]. In the database, measurements were made for every 5-degree speaker rotation. In the first stages of the emulation it was necessary to reduce the spatial complexity of speaker responses to more clearly understand how the orientation of each virtual speaker interacted with the total spatial model described in the next section. For the test study, single IR's were used as well as cascaded biquad filters. Rather than adding compressors to mimic dynamic response characteristics, linear attenuation was applied to a selection of virtual speaker responses. This latter simplification was also applied with the intention of simplifying the test subjects' first encounter with the system. The second Virtualmonium revision will use directional IRs from each 60-degree rotation, where each virtual speaker will be represented by six directional virtual sources. Dynamic compression and other non-linear modifications will also be implemented.

3.2 The Virtualmonium and HOA

Ambisonics is a spatialisation system that captures (records or encodes) 3-D sound in spherical harmonics describing the sound field [10]. HOA is an extension of the format to include more directional components than the original B-format (1st order Ambisonics), achieving a more accurate representation of the spatial scene and an increased sized of sweet spot suitable for public audiences. The original HOA decoding strategies relied upon loudspeaker layouts of specific geometries. Developments, such as the energy-preserving decoder [3], allow loudspeaker layouts to depart from these conventions, and serve as practical decoders for a HDLA. Near-Field Compensated HOA (NFC-HOA) is an extension of HOA, controlling wavefront curvature correlated to proximity, resulting in focused sounds in front of the loudspeakers and improve image stability for sounds outside of the array [11].

The Virtualmonium spatial emulation requires accurate control over the perceived angle and distance of each virtual source. For our auditory perception, the discrimination of direction depends on the angle and elevation of the sound in relation to our ears. Localisation blur (the minimum audible angle of discrimination) is at its lowest for sounds in the frontal horizontal plane, and can vary between 0.75–3.2 degrees depending on the sound's frequency content. Blur increases to as much as 10 degrees as the sound moves away from the front [12]. In Ambisonics, few studies have tested subjective evaluations. Localisation in the frontal plane for a 5th order system has been shown to be comparable to that of real-world sound fields [13]. For listeners located in an area spanning from the centre to the perimeter of the loudspeaker array, a far greater diversity was shown by [15]. With these results in mind, the Virtualmonium will require at least a 5th order loudspeaker array.

In terms of distance differences, implementing the mathematical solution for NFC-HOA presents practical challenges. Spat implements the technique proposed by [11]. Improvements are however possible, for example those described in [14], and developments in NFC-HOA technologies continue to advance.

Wave Field Synthesis has been shown to more clearly stabilise the image than HOA [15], yet there are practical considerations concerning spectral bandwidth, lack of verticality and restrictions on the listening position in relation to focused sources inside the loudspeaker array.

3.3 Spatial emulation

The Virtualmonium spatial emulation is carried out in NFC-HOA where Spat's sources are used to spatially represent the virtual loudspeaker locations. To synthesise in HOA the location and rotation of speakers as virtual sources in a virtual space, the Spat objects `spat.spat~` and `spat.oper` were used. Besides the author's familiarity with Spat, it offers a number of useful features making it a natural choice: all HOA encoding and decoding variables are easily accessible, there is no limit on the Ambisonics order or decoding convention, and it is straight forward to design an interface where virtual loudspeaker orchestras can be graphically defined by other users.

The virtual loudspeakers are defined by a position in space, a direction of face and an aperture of radiation. These parameters are passed on to `spat.oper` that automatically calculates distance related amplitude and air absorption attenuation for each 'source', and a delay derived from the virtual loudspeaker's distance. A room model embedded in `spat.spat~` is controlled by `spat.oper`, which further calculates the appropriate direct and reverberant signal levels based on the location of the source in space and its radiation aperture. Although IRCAM's reverberation model is based on their own perceptual studies combining convolution and panned early reflections [16], a true Ambisonics room model is currently beyond the scope of real-time calculations.

The audio sources and defining parameters are passed on to `spat.spat~` that calculates the encoding. So far, the Ambisonics loudspeaker array has not been defined. This happens in the `spat.decoder~` where various decoding options are parameterized and the loudspeaker coordinates of the real Ambisonics array are given. As the encoding and decoding stages are independent, the encoded performance can also be recorded to a sound-file and decoded in a different space.

3.4 Interfaces

In diffusion performance a mixer is the traditional instrument, where the stereo source is split over many individual channels, and where one fader controls the volume of one speaker. The mixer is organised ergonomically: eight centrally located faders, falling comfortably under the hands, control the main eight speakers. These speakers are also most sensitive to smaller changes in gain. Further channels spread left and right from this central fader area, approximately in keeping with back, front and elevated speaker locations. Exceptions are found with performer preference and for 'special' speakers with strongly alternative colouration or dynamic qualities. Harrison [1] provides one of the few published texts in English about this intuitive approach. The faders: their length, resistance and spacing are important. They should be long, and with a resistance for the performer to feel gesture from the body, through the hands and to the sounding space, and for tiny movements to not result in enormous jumps in gain. For this reason, the major diffusion orchestras commonly construct their own mixers from selected fader modules.

As with any performance technique, the art of diffusion is mastered with regular practice. Yet few are fortunate to have access to suitable facilities. This is one reason why we believe the mixer as a performance instrument has been criticised, by for example Johnson and Kapur, as a 'disembodiment' and contrary to an 'intuitive and sophisticated command of the spatial field'. Johnson and Kapur then argue for alternatives such as tactile.space [17]. In tactile.space, by interacting with a 2-D visual interface approximating to a birds-eye view of the room, the user is able to position mono sources. The spatialisation engine then uses a panning algorithm to calculate the gains of a circular loudspeaker array. Although the user may spread a point-sound over a defined azimuth, this is far from offering the possibilities of spatialisation necessary for stereo diffusion. Although it would be possible to change the signal processing part of tactile.space to Ambisonics and a Virtualmonium style emulation, the problem lies inherently in the interface. A 2-D visual overview is in danger of conveying a false impression of the perceptual spatial scene, or encourages the performer to consider sounds as points in space rather than the reality of complex musical images. In contrast, the mixer as a layer of abstraction plays an important performative role.

For these reasons, the Virtualmonium is performed using a set of MIDI faders, emulating the function of a traditional mixer. An expansion of the possibilities of the one fader controlling one speaker principle have been described in the Resound project [18] and in BeastMulch [5], and these can be easily layered into the Virtualmonium interface.

4. TESTING THE VIRTUALMONIUM

In order to evaluate the first version of the Virtualmonium, both performer and listener studies were undertaken. Tests were carried out in the 3-D lab at the Department for Musicology at the University of Oslo: a room 8m x 5m x 3m, housing a 47-speaker Genelec 8020 array (Figure 2). Besides heavy drapes, the room is untreated for reflections, where floor-ceiling and back wall reflections are most prominent. However, with a small audience, these reflections are significantly reduced. Despite the suboptimal room geometry, a 6th order 3-D decoding functions well.

The goal of the pilot project was to emulate the possibilities offered by the acousmonium as a spatialisation orchestra rather than recreate the illusion of a single speaker in space. However, as it was not possible to setup a real acousmonium as well as the 3-D HOA array (not only a lack of equipment but also the space being too small) a direct comparison between real and virtual could not be made. Instead, the tests addressed how successfully a group of performers executed some standard sound diffusion techniques, and how a group of listeners perceived the results. The tests were aligned with diffusion performance tradition based on the author's lengthy experience.

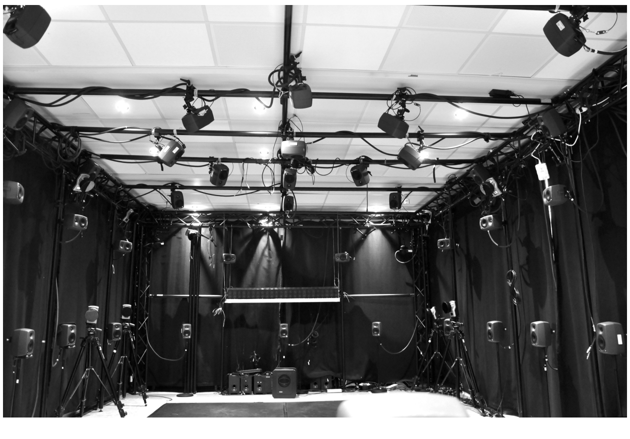

Figure 2: The 3-D Ambisonics array at the Department of Musicology, University of Oslo

4.1 Setup and conditions

A small Virtualmonium, consisting of 15 virtual speakers was defined, shown in Figure 3 (displayed using `spat.viewer`) where the inner rectangle is the boundary of the real Ambisonics array and the outer rectangle is the size of the room model. The speakers are numbered as they appeared on the faders and their radiation pattern shown by the white shading. Speakers 13 and 14 are elevated, emulating tweeter grids. One fader on a Peavey PC 1600x controlled each virtual speaker feed. Performers were tested on their ability to execute a number of spatialisation techniques idiomatic of classical diffusion practice. Appropriate custom-made sounds were allocated to each test. Table 1 provides an overview.[3]

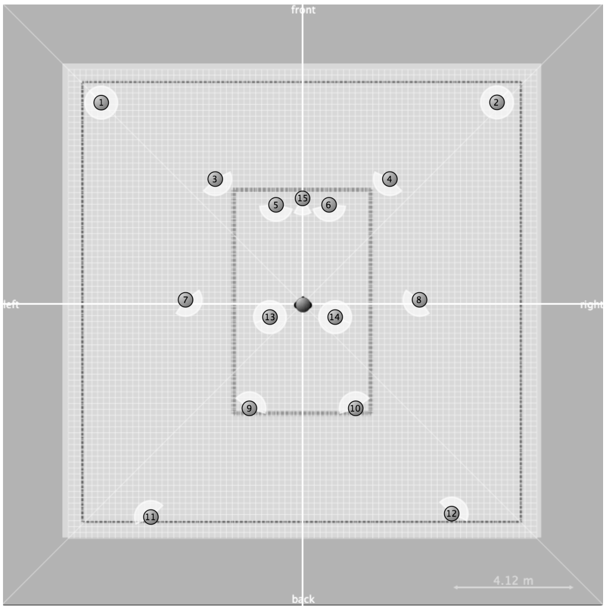

Figure 3: The virtual loudspeaker array for user tests

Unlike the UK or France, in Norway we lack a diffusion performance tradition. Rather than invite volunteers without any performance experience we settled on six subjects: two with proficient and four with passing sound diffusion experience. Performers were centrally located and allowed to practice each task and then indicate when they were ready for evaluation.

Listeners were seated, spanning a diameter of 2/5 the width of the loudspeaker array, with their back to the performer so as not to be influenced when it was their turn to perform. Before each evaluation, an omnidirectional version of each sound was played as a reference. To be consistent with diffusion practice, performers were allowed to interpret the specified spatial action. For example, an interpretation of 'front narrow then widening' may widen with a front, side, rear or surround bias. However, performers were not allowed to interpret the speed of the action, which was determined by the duration of each test sound. For example, by performing 'Gesture, medium speed' too slowly, would result in the sound having ended before it had moved very much in space, resulting in a low evaluation.

Two types of evaluation were made: by the listeners and by the performers (as self-evaluation). Each indicated their evaluation on a scale from 0 to 4, where 0 reflected no difference to the reference and 4 reflected a performance matching the specified action. As both the performance and evaluation involved subjective components of interpretation and quality, subjects were advised that a score of 2 would indicate similarities to the action, but that the results were vague.

[3] Sounds can be downloaded from http://users.notam02.no/~natashab/NIME_experiment_test.zip.

Table 1: Spatial performance tests and sound types

Spatial performance action	Sound type
Front close	Short impulse with repetition v1
Sides close	Short impulse with repetition v1
Front narrow then widening	Short impulse with repetition v2
Rear narrow then widening	Short impulse with repetition v2
Wide space	Short impulse with repetition v3
Move mid to distant space	Gesture move mid to distant
Gesture, medium speed	Gestural archetype, medium
Gesture, fast speed	Gestural archetype, fast
Gesture, curved (circular)	Gestural archetype, long
Spatial perspective shift	Perspective shift
Immersion wash	Full bodied wash
Immersion detailed	Detailed textural flow
Intimate sensation	Whisper close
Erratic motion	Erratic texture
Layered space, simple	Two-part complex environment
Layered space, complex	Multi-part complex environment

4.2 Results

Figure 4 shows the mean and standard deviation for all evaluations of the 16 tests. Although only six performers were involved, the results are promising. From these basic observations we can see that all performance actions were relatively clearly articulated, that performers generally scored themselves harder than listeners, and that moving gestures scored slightly lower than static sounds. The lowest listener score was for intimate sounds. Layered spaces, which can be tricky to project over a real loudspeaker array, scored well.

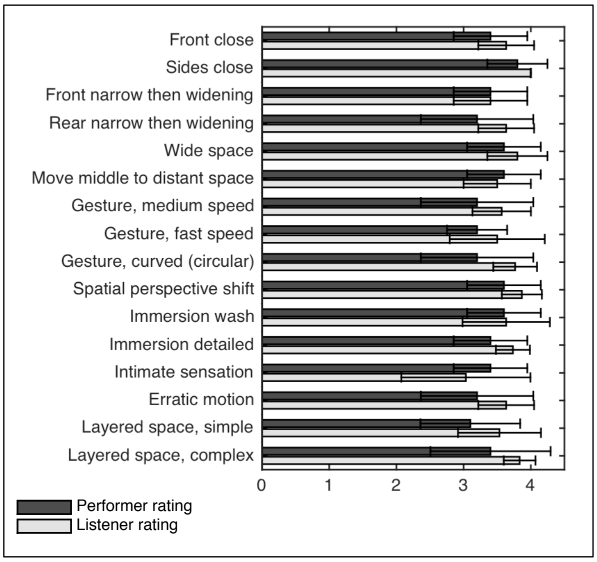

Figure 4: Test results for performers and listeners

Although all performers where also composers who had at some stage used 2-D screen-based interfaces to control spatial information in a compositional context, none questioned the use of faders in the performance. The direct 'one to one' mapping, of one fader to one virtual loudspeaker, appeared intuitive and allowed performers to easily investigate the more complex spatial results of virtual speaker combinations. Furthermore, there appeared no hinder to spatial control, fast or slow movements. We were already aware that the spacing of the faders could be improved (widened), for the fader caps to be larger and the fader lengths to be longer. These improvements will be addressed as the system develops.

5. CREATIVE PRACTICE

5.1 Preliminary concert experiments

Concerts present a more complex set of challenges for both performer and listener. Beyond expressing musical spatial gestures, performers may become acquainted with the colour and diversity of the loudspeakers as an orchestral ensemble, as was the case with the early GRM Acousmonium and performances. As an on-going project the first author runs a small concert series performing classical stereo diffusion using a 32-speaker Virtualmonium. In these concerts we also play native 3-D Ambisonics compositions. So far we have performed stereo works by François Bayle, Bernard Parmegiani, Manuella Blackburn, Beatriz Ferreyra, alongside native 3-D works by David Monacchi, Ludger Brümmer and myself. This practical context has raised some interesting considerations:

- The stereo diffusion performance is perfected in advance with the performer centrally located, and the results encoded by recording to a sound file. In the concert, the performance position is removed for the audience to occupy the optimal listening area, and the encoded version decoded to recreate the work.
- Although 32 virtual speakers are used, it is unclear where diminishing returns lie. Earlier we drew attention to the inconsistencies in the objective and subjective assessments of angular blur for each order of Ambisonics. Differentiation between virtual sources based on distance (both NFC-HOA as well as acoustic emulation) and colouration also needs consideration.
- The room model is an important component in projecting distance and in emulating rotational and directional characteristics of loudspeaker constellations. Our test space is small and the room acoustics, although suboptimal, don't conflict with the room model. In larger spaces, the room model would need to be addressed so as not to conflict with the listening space, whereby it may be interesting to calibrate a room model that is appears as an 'extension' to the real room acoustics.

5.2 Composition, rehearsal and portability

Performers can set up their Virtualmonium inside a small HOA system (given the restrictions discussed in section 3.2), and practice the art of sound diffusion. This is directly portable from one space to the next. The performance can also be encoded in HOA and decoded in other spaces without the performer present. Tests listening binaurally, where the ambisonics signal was transcoded via HRTF's, proved unsuccessful as listeners experienced a front-back spatial confusion. Headphones furthermore removed the spatial cues normally obtained by small, natural head movements.

In composition, ambisonics and stereo sound diffusion each offer creative and technical spatial fortunes. Although outside the scope of this paper to address these features in detail, incorporating the Virtualmonium in the compositional workflow combines advantages of each discipline, either in a hybrid live performance or in the final HOA encoding.

If rehearsing over the Virtualmonium is aimed towards performance over an acousmonium, the translation between the two systems is indirect. Aside from the number of differences discussed in the next section, large acousmoniums will support a greater number of channels than the Virtualmonium. In these situations, the correlation between the number of perceptually relevant virtual loudspeakers and the degree of HOA will add an inevitable restriction. On the other hand, we can likewise question whether a listener is able to differentiate between individual real speakers when numbering the extent of the BEAST system (on the order of 100). Instead it is more interesting to understand the orchestra as a combination of colour and spatial possibilities. With this view, the challenge for the performer is directed towards the control interface, where one fader may control a number of acousmonium loudspeakers. This interface can instead serve as a front end for the Virtualmonium, controlling similar zones of spatial sound, and allowing the performer to rehearse off-site.

6. DISCUSSION AND FUTURE WORK

Although only at a pilot stage, it is clear that the Virtualmonium is achieving many of the possibilities inherent to a real acousmonium. It is however far from sounding the same. Besides the need for more varied and precise loudspeaker emulation, it is unclear how close we can emulate the spatial presence of near-field sources, which is partly confirmed by the lower score for intimate effects. However, some performers quickly developed a technique blending the tweeter emulations (channels 13 and 14) with the closest virtual speakers (channels 5, 6 and 15), whereby improving the sensation of intimacy. This technique is common practice in acousmonium performance when tweeter grids or tweeter trees are suspended above or within the audience. A future test could also incorporate direct feeds to some of the real speakers, as well as new developments in the NFC-HOA practical implementation.

A second problem concerns distance emulation. To model the real loudspeaker orchestra it is necessary to delay the signal from virtual sources further away (maintaining the ratio between distance, sound pressure level of the direct sound, and the reverberant sound). However, for virtual sources of only a few meters difference in distance, a clear phasing was heard. This is likely due to there being fewer acoustic complexities in the model than in reality, both in terms of the room model and in the speaker emulation. This phenomenon may be addressed through improved emulation and dither.

Thirdly, although traditional acousmatic concerts may be held in near darkness, loudspeakers play a visual role in both performance and listening. The loudspeakers shapes are apparent, and lighting is often used as a scenographic effect. It is commonly understood how such visual information influences our auditory perception and can take precedence over our hearing [19]. Yet the Virtualmonium creates invisible virtual loudspeakers within an Ambisonics sound field, where the listener paradoxically sees the Ambisonics loudspeakers while the sound appears from a zone of 'empty space'.

For stereo diffusion performance, the Virtualmonium presents an interesting alternative when a P-HDLA is the standard installation. Through further development and greater use we will be able to explore subjective performance experiences other than those of direct comparison to a real acousmonium.

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