Composing spatial soundscapes using acoustic metasurfaces

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Figure 1: We use 3D-printed metamaterial bricks to create an acoustic prism (a), designed to send different notes in different spatial positions. We use this device, in conjunction with a digital composer (b) to create an acoustic experience, reporting the result of a preliminary user study (c).

ABSTRACT
In this work, we explore the use of acoustic metamaterials in delivering spatial-significant acoustic experiences. In particular, we conduct a user study of the acoustic perception of music played through the metamaterial. Results show users perceive sound to be louder in the direction determined by the metamaterial. This demonstrates how an acoustic metamaterial prism, in combination with an electronic composer, may be used to deliver different sound messages to different parts of an audience. We underpin our conclusions with measurements, user observations and heuristic considerations on possible application scenarios.

KEYWORDS
Acoustics, perception, musical experience, metamaterials

ACM Reference Format:

1 INTRODUCTION
Any theatre director or sound artist experiences that there is a net difference between the way light and sound are managed. While it is possible to deliver light cues almost matching the director's wishes, including moving spotlights, diffused illumination and alternated areas of light and shadows, similar solutions are not easily available for audio. Delivering personalised sound experiences to different members of the audience - while keeping costs at bay - requires them to wear headphones.

Even solutions including multiples speakers and complex signal processing (i.e. speaker arrays), typically used in immersive cinemas to elicit in the audience the feeling of spatial audio, are designed for the whole audience to have the same experience. That, however, is often difficult as there will be "sweet spots" in the room that give more immersive and optimal experience than in other locations.

The increasing demand on delivering directional sound in the audio industry has led to the development of parametric speakers [25]. These devices exploit the directional emission of an ultrasonic...
Acoustic metamaterials may offer a cheaper alternative. These are standard materials (i.e. 3D-printer plastic, wood, metal, paper), engineered at the sub-wavelength scale to control, direct, and manipulate acoustic waves in uncommon ways [5, 13]. A low-cost 3D printer can therefore be used to fabricate a 'metasurface': a metamaterial designed to be thinner in the direction of propagation of the impinging sound which, once placed in front of a standard loudspeaker, can act as a lens, a diffraction grating, a holographic plates for sound [11, 12, 17, 18, 21, 24, 27]. Effects like anomalous refraction, self-bending [20] and super-lensing have also been observed.

Only recently, however, it has been possible to design metasurfaces thinner than one wavelength and with a bandwidth close to 1 octave [19]: two crucial requirements for practical, space-hungry applications in the audio range. Memoli et al. [19] showed that simple design laws used in optics, like the thin lens equation, are also valid in acoustics when metamaterials are involved. These authors built on this finding to transform a commercial, low-cost speaker into a directional one.

In this paper, we use an acoustic prism - i.e. a metasurface designed to emphasise or attenuate qualities of the sound in different places - to deliver a soundscape composition into an outdoors space.

2 ACOUSTIC METASURFACES

Acoustic metamaterials are 'common' materials - e.g. wood, metal or 3D-printer plastic - which, engineered at the sub-wavelength scale, have properties not otherwise available in nature [5, 13]. Of particular practical interest are acoustic metasurfaces [1] i.e. acoustic metamaterials whose thickness in the direction of propagation is smaller than one wavelength (i.e. less than 1 m for a metasurface operating at 350 Hz in air).

Memoli et al. [18] showed how to give any desired diffraction-limited shape to an acoustic field (including focusing sound or making it go round a corner) using an array of pre-configured, LEGO-like bricks, appropriately selected from a set of 16 designs. Each of these bricks has a labyrinthine meander [12], to delay the sound passing through. Therefore, used in transmission at a specific wavelength, each of the bricks encodes a corresponding phase shift on the passing sound, which depends on the wavelength. When assembled in a structure and mounted in front of an acoustic source, each of the bricks then becomes a secondary source. These authors propose a number of tailored applications for this approach, making it relevant to directional audio [10, 19] and human-computer interaction [20].

For the audio-expert, the procedure to pass from a desired sound shape to an assembly of bricks is therefore similar to Wavefield synthesis (WFS) [2], where each of the bricks approximates one of the spherical sources in the Huyghens-Fresnel principle and the metasurface is a hologram of the desired shape [17]. The main difference is that shaping sound through metamaterials is a passive and static process. The main advantage is that the sources can be as small as practically achievable and therefore a single metasurface in front of a speaker may achieve what was previously possible only using multiple sources.

3 EXPERIENCE DESIGN

In this work, we mimic the improvisation-based dialogue between a performer on stage and his/her audience. The presence of a metasurface offers in fact an additional degree of freedom to the performer, who can play to different regions of the audience in a directional manner - splitting the harmonics of chords or projecting single tones. The practice of using space to create a new experience has been practiced in music since the the mid 16th [9], where choirs were positioned in different areas of churches and chapels in order to create a surround-sound-like experience. Here, we suggest using one or more acoustic metamaterials to enrich a sound space and create a unique audience experience.

3.1 Prism design

A prism in optics is a device that splits white light in its components, sending different colors in different directions, depending on their wavelength i.e. creating a rainbow. A similar effect has been achieved in acoustics, using leaky waveguides [6]. In this study, we use a metasurface to achieve the same effect and to redirect sound over a range of audible frequencies of sound.

While most studies use numerical methods to design metasurfaces (see e.g. [3, 17, 23]), there are some cases where the desired shape of the sound can be connected to the phase map given by the bricks through analytical solutions [11]. A linear phase distribution across the metasurface, for instance, leads to "anomalous refraction" i.e. to a deflection of the impinging sound even at normal incidence. This effect is dictated by the generalized Snell’s law [26]:

$$\sin \theta = \frac{c}{2 \pi f} \frac{d\phi}{dx}$$

Where $c$ is the speed of sound and $\theta$ is the desired angle at which we want to send that sound of frequency $f$. $\frac{d\phi}{dx}$ is the phase change profile of the device, where $\phi$ is the associated phase of the bricks along in the x direction.

In this work, we used a repeated pattern of 4 different bricks (with phase delays 23.3°, 115.6°, 226.2° and 335.3°, as shown in Figure 1a) to create a value of the gradient $\frac{d\phi}{dx} = C(\lambda)$, where $C$ is a constant that depends on the wavelength. Fabrication of these devices is completed using three-dimensional additive manufacturing. These 3D devices are polymer based and relatively inexpensive, compared to hardware based equivalents. Furthermore as these devices are built separately to the sound sources they are designed for, we suggest they can be used with any standard audio speaker. These bricks are 3 cm wide and 6 cm long and in total the device is 24 by 24 cm wide, remaining 6 cm thick.

As shown in Figure 2, we used computer simulations (COMSOL Multiphysics) to predict the value of the gradient as a function of frequency of the impinging sound, assuming normal incidence. Preliminary results, obtained with 2D simulations and neglecting
absorption effects in air, show regions where the gradient is almost constant followed by others where the gradient varies significantly for a small variation of the frequency. When used in front of a loudspeaker, our prism should therefore send the notes contained in the areas of small variation to very precise angles - e.g. the notes from 2,300 Hz (D7) to 3,300 Hz (G7) should go at a different angle from the ones between 4,300 Hz and 5,300 Hz (corresponding to the following octave, between D8 and G8). Within the regions of constant gradient, according to equation (1), the different notes should be sent at an angle that only depends on the wavelength.

3.2 Composition design

The music in this experimental setting was composed with the Threnoscope [15]: a musical interface designed for live performances, where real-time coding (live coding [14]) is projected on a display on stage and becomes a key part of the audience experience. The Threnoscope is built in SuperCollider [16] and its graphical interface (Figures 1b and 3) highlights the spatial and microtonal component of the composition.

In the piece made for this test, the idea was to explore timbral “movement” in sound, for example through slight detuning of oscillators and resonant filtered white noise being spatially distributed over eight channels. The musical progression of the piece is slow and gives the listener the possibility of walking around the space in order to “tune into” and explore the spectral diffusion of the sonic prism. In a sense this piece transgresses the distinction between a composition and a sound installation in that, when run as software, it can evolve in a generative manner forever. A crude distinction between music and sound art would be that music is about time and sound art about space, and with this piece we are playing with both, thanks to the multi-channel system and the sonic prism technology which articulates and transforms the spatial features of the sound.

4 USER TESTS

A user study was conducted using 16 participants (8 male and 8 female), all with normal hearing. Participants were equally distributed between males and females, with an age between 23 and 40. The test was run in an empty room, with a speaker and the prism on one side, together with a screen displaying the Threnoscope in action (see Figure 1b). In order to minimise the effects of the room, the experiment was run in two different rooms, one smaller (and therefore more reverberant) than the other and with 8 participants in each. As shown in Figure 7a, the floor of the room was marked with 8 different shapes: some positioned approximately at the angles from Figure 2 and others randomly.

During the 10 minutes user experience, participants were asked to explore freely the space, but also to report the perceived loudness over the different shapes. Perceived loudness [28] was assessed using a 5-point numerical Likert scale, as shown in the sheet handed to the participants (Figure 7b).

After the “exploration” stage was over, users were then asked to fill a questionnaire (see supplementary Figure 7c) with the purpose of assessing: the acoustic quality of their experience, whether their perceived a notable difference in intensity at different positions, their self-assessed sensitivity to noise [7]. Questions were left open-ended, as suggested by soundscape research, to capture the experience in the user’s words. A list of key-words, previously used to assess user perception in auditoriums [4], was also added at the end of the questionnaire.

5 RESULTS AND DISCUSSION

An initial analysis of the responses to the first question in Figure 7c is visually summarised by a word cloud in Figure 4c, showing that the users felt the experience was “interesting” and “different”. Notably, one of the users reported ’I felt the different sound at various locations in room’ and ‘There were different volumes at unexpected locations’ while others noted the complexity of the soundscape saying “It was interesting to hear the different variations of sound in the room”. Future studies will investigate some of these claims.
to test the perceived levels and sharpness. A similar analysis, run on the second question in Figure 7c, plotted as a word cloud in Figure 1c. The feedback shows that the users perceived a difference between the different positions, but that they were unclear whether this was due to the position or to the changing music. Notably, one of the users reported “Yes [there was a difference between markers], in particular between the star, triangle and circle” while another “Yes, there was difference in tone and depth of sound, although it was confusing because the sound kept changing”. Future studies will consider using the same musical piece, repeated in different positions.

Users were also asked to fill in a checklist of acoustic descriptors. They were asked to mark the words that best described the sound during the experience. The results are plotted in a pie chart in Figure 5. The overall experience was decided to be “reverberant”, “enveloping” and “focused” by at least half the users. During the experience, users were asked to fill in a map of the space with the different shaped markers on it. There they marked on a scale of 1 (very quiet) to 5 (very loud) of the sound they hear at the markers. Figure 6 shows the results of the in-situ survey plotted as perceived loudness and standard error bars. Clearly, the “bolt” marker 1.5 m and 20° from the device had the highest level of perceived sound of 3.75 ± 0.35. The quietest perceived space in the room was at the “diamond”, which is 3 m from the −40° from the device and has a value of 2.88 ± 0.18. In comparison the “triangle” marker, at 3 m and 40°, has a perceived loudness of 3.38 ± 0.26.

6 CONCLUSIONS

In this work we have demonstrated that the acoustic metamaterial prism is perceived to redirect sound to certain areas of a reverberant room, as users perceived the sound to be louder on one side of the room in comparison to the other. Furthermore, most users described the sound coming from the device as different. Although notably users mentioned it was hard to discern the difference between volume changes due to spatial movement and the progression of the musical piece. Further studies are suggested to investigate the perceived aspects of the device and to repeat the experiment using repeated musical pieces.

This work has significant implications on the use of these devices that have previously been thought to be used at single or very narrow ranges of frequencies. Using a piece of music users were able to discern that the device was projecting in a direction, suggesting that this device can be used for music with possible applications in cinemas, concert venues or even in the home.

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REFERENCES


Figure 4: A word cloud, summarising the feedback of the 16 different users to the first question of the questionnaire in Figure 7.

Figure 5: A pie chart, showing the total count of the selected feedback of the 16 different users describing the acoustics of the experience in Figure.
16 users sampled in two different rooms. The maximum perceived loudness was perceived at the "bolt" (1.5 m and 20° from the device). Top is a to-scale map used in the user tests. Bottom is a ranked bar chart of the average perceived loudness at each shape, averaged over the results of 16 users sampled in two different rooms. The maximum perceived loudness was perceived at the "bolt" (1.5 m and 20° from the device) and the quietest perceived shape was the diamond (3 m and ~40° from the device). Top is a to-scale plot of the floor positions of the shapes in comparison to metatlas positioned 102 cm above the floor.

\[\text{Spatial Loudness User Results}\]

\[\text{Spatial Map}\]

**Figure 6:** Bottom is a ranked bar chart of the average perceived loudness at each shape, averaged over the results of 16 users sampled in two different rooms. The maximum perceived loudness was perceived at the "bolt" (1.5 m and 20° from the device) and the quietest perceived shape was the diamond (3 m and ~40° from the device). Top is a to-scale plot of the floor positions of the shapes in comparison to metamaterial positioned 102 cm above the floor.


**A RESEARCH METHODS**

Figure 7 reports the map used to assess loudness during the "exploitation phase" and the questionnaire used for the final phase of the user study.

**B ONLINE RESOURCES**

Supplementary resources include a video with the music composed for this study. Only the last 10 minutes of this composition were used in the user tests.
Questions to be answered after the musical experience is complete:

**Overall, how would you describe your experience?**

Did you find a difference between the sound at one marker and the sound at another? If you did, please describe the difference

**Overall, how loud was the music?**
1- Very quiet  2- Quiet  3- Neither  4- Loud  5- Very loud

How sensitive are you to noise?
1 - Not at all  2  3  4  5 - Extremely

Do you have anything else that you want to say about the device?

Please indicate which words best describe the acoustics of the experience?

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<th>Clear</th>
<th>Mellow</th>
<th>Distant</th>
<th>Cold</th>
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