Composing spatial soundscapes using acoustic metasurfaces

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ABSTRACT

In this work, we explore the use of acoustic metamaterials in delivering spatially significant acoustic experiences. In particular, we discuss a user study run in a space where a dedicated composition is played through a metamaterial "prism". Results show users perceive sound to be louder in the direction determined by the metamaterial, depending on its frequency. 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, even with a single speaker. We underpin our conclusions with user observations and heuristic considerations on possible application scenarios.

CCS CONCEPTS

• **Human-centered computing** → **Sound-based input / output**; • **Hardware** → *Sound-based input / output*; *Emerging interfaces*; • **Applied computing** → Physics.

KEYWORDS

metamaterials, immersivity, digital composer, sound interface, soundscape

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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 multiple speakers and complex signal processing (i.e. speaker arrays), typically used in immersive cinemas to elicit in the audience the feeling of spatial audio[1], 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 a more immersive and optimal experience than in other locations.

The increasing demand on delivering directional cues in the audio industry has led to the development of parametric speakers[2]. These devices exploit the directional emission of an ultrasonic array and the non-linearity of sound propagation in air to produce audible sounds in a narrow beam. The emission of these speakers is typically contained within $\pm 10^{\circ}$ from the speaker axis [7, 8], with the sound outside up to 16 dB lower. They are often used to elicit surprise in listeners or for personal messaging, in advertising and educational contexts [7], but they are not widespread due to the associated costs and to the low quality of the reproduced sound.

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 [9, 10]. A low-cost 3D printer can therefore be used to

[1] "Spatial Audio" exploits delays and intensity variations between speakers to create for the audience the experience of localised sources [1, 2].
[2] "Parametric speakers" use highly directional sources [3, 4], often used to deliver different sounds to parts of the audience [5, 6].

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 plate for sound [11–17]. Effects like anomalous refraction [18], self-bending [19] and super-lensing [20] have also been observed. Until recently, however, metamaterial solutions at audio frequencies were bulky or very limited in their frequency range.

Recently, Memoli et al. [21] have shown how to design metasurfaces of practical size for audio applications, with a bandwidth close to 1 octave: two crucial requirements for space-hungry applications in the audio range. These authors also demonstrated that simple design laws used in optics, like the thin lens equation, are also valid in acoustics when metamaterials are involved. Building on this finding, these authors managed to transform a commercial, low-cost speaker into a directional one [21] and to realise a low-cost personalised sound delivery system [22]. This has opened new opportunities, one of which is discussed here.

In this paper, we design an acoustic prism - i.e. a metasurface designed to emphasise or attenuate qualities of the sound in different places - and use it to deliver a soundscape composition into an indoor area. Through a user study (16 participants), we investigate whether a composer can give a spatial component to the perceived loudness, using just a single speaker and a metasurface in front of it. We find that the prism successfully allows the performer to transform the temporal dynamic of a composition into a spatial message, thus creating a unique audience experience.

2 STATE OF THE ART

Acoustic metasurfaces

Acoustic metamaterials are "common" materials - e.g. wood, metal or 3D-printer plastic - which, engineered at the subwavelength scale, have properties not otherwise available in nature [9, 10]. Of particular practical interest are acoustic metasurfaces [23] i.e. acoustic metamaterials whose thickness in the direction of propagation is smaller than one wavelength (i.e. less than 1 m for a 350 Hz tone in air).

Memoli et al. [17] 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 preconfigured, LEGO-like bricks, appropriately selected from a set of 16 designs. Each of these bricks has a labyrinthine meander [11], to delay the sound passing through. 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. Bricks assembled into a structure, mounted in front of the acoustic source, allow tailored applications like the manipulation of directional audio [24] and human-computer interaction [19, 21].

For the audio-expert, the procedure to pass from a desired sound shape to an assembly of bricks is similar to WaveField Synthesis (WFS) [1]: each of the bricks approximates one of the secondary spherical sources in the Huygens-Fresnel principle and the metasurface is a hologram of the desired shape [15]. The main difference with WFS 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: a single metasurface in front of a speaker may achieve what was previously possible only using multiple sources.

Spatial sound experiences

While designing a theatre or a cinema, architects strive to ensure everyone in the audience will get the same experience. While seats may have a different price according to the quality of the visual, in fact, this is unacceptable for sound: even in the case of 3D spatial audio, there is either the same sound for everyone or none.

Parallel to this binary approach to sound, the idea of using multiple sources to create spatially-dependent experiences has been practiced in music since the the mid 16th [25], when choirs were positioned in different areas of churches and chapels to create a surround-sound-like experience. More recently, artists like La Monte Young (*Dream House* [26]), Bernhard Leitner (*Sound-Space* [27]) or Iannis Xenakis (*Philips Pavilion* [28]), have investigated the relationships between sound, space, and body, creating different acoustic experiences in a single space. Added to parametric speakers, these approaches lead to the theoretical concept of "sound zones" [29]: areas which are very close in the physical world (e.g. two adjacent seats in a theatre), but extremely far in terms of experience (e.g. two different sounds, without headphones).

These technologies, however, rely on multiple speakers: they easily increase in cost and energy consumption as the acoustic experience gets more complex or the area to cover gets larger. In this study, we propose a different approach: using one or more acoustic metamaterials to enrich a sound space. Metamaterial-based devices, like the prism used here, are in our vision a novel set of tools: used in parallel or as an alternative to multiple speakers, they enable to play with new compositional ideas, hitherto impossible.

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 meta-surface 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. Here, we describe the two synergistic components underpinning the final experience: the prism itself and the composition designed to exploit it.

Prism design

A prism in optics is a device that splits white light in its components, sending different colors is different directions, depending on their wavelength i.e. creating a rainbow. In this study, we use a metasurface to achieve a similar effect i.e. to redirect sound within a range of audible frequencies over a range of angles.

While most studies use numerical methods to design metasurfaces (see e.g. [15, 30, 31]), 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 [12]. 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 [32]:

$$\sin\theta = \frac{c}{2\pi f}\frac{d\Phi}{dx} \tag{1}$$

where c is the speed of sound and θ 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 ϕ is the associated phase of the bricks along the x direction. According to equation (1), when the gradient is constant the angle of deviation only depends on the frequency: lower frequency notes would get a larger deviation than higher ones.

For this study, we used the designs reported in the supplementary information of [17], but scaled each brick to be 3 cm wide and 6 cm thick, thus expecting their output intensity to be maximised at $\sim$ 5.6 kHz. As shown in Figure 1, this gives a total dimension of the device of $24 \times 24 \times 6$ cm. We exploit equation (1) and design our acoustic prism using a repeated pattern of 4 different bricks (with phase delays 23.3°, 115.6°, 226.2° and 335.3° at 5.6 kHz). The final device was fabricated using three-dimensional additive manufacturing, making it relatively inexpensive, compared to hardware based methods of redirecting sound. Furthermore, as metasurfaces are built separately from sound sources, our prism can be used with any standard audio speaker.

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 that our arrangement of bricks gives a constant gradient $\frac{d\phi}{dx} = C(\lambda)$ in some regions of the audible spectrum, where C is a constant that depends on the wavelength. These regions are followed by others where the gradient varies significantly for a small variation of the frequency.

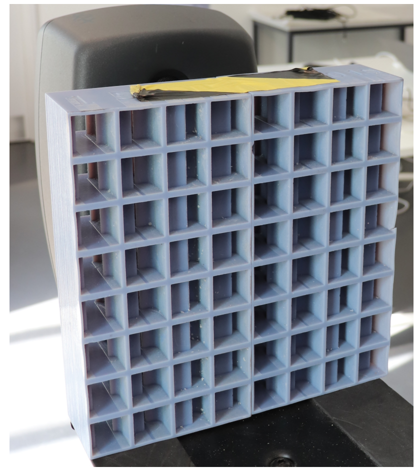

Figure 1: The 3D printed prism used in this study.

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 (D_7) to 3,300 Hz (G_7) should go at a different angle from the ones between 4,300 Hz and 5,300 Hz (corresponding to the following octave, between D_8 and G_8). Within the regions of constant gradient, according to equation (1), the different notes should be sent at angles determined by their frequency.

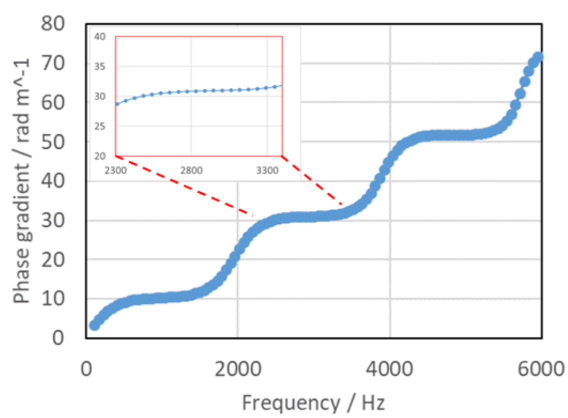

Figure 2: Simulated behaviour of the acoustic prism, as predicted by 2D COMSOL Multiphysics simulations. The plot shows that, as frequency changes, the value of the gradient $\frac{d\phi}{dx}$ (in rad m^{-1}) passes from areas of very small variation (e.g. between 2,300 Hz and 3,300 Hz in the inset) to regions of abrupt change.

Composition design

The music in this experimental setting was composed with the *Threnoscope* [33]: a musical interface designed for live performances, where real-time coding (live coding [34]) is projected on a display on stage and becomes a key part of the audience experience. The Threnoscope is built in SuperCollider [35] and its graphical interface (Figure 3) highlights the spatial and micro-tonal component of the composition. In the piece made for this study, the idea was to explore timbral "movement" in sound, for example through slight detuning of oscillators and resonant filtered white noise.

We distributed this effect over a number of "drones" (the shaded areas in Figure 3), each in charge of a different frequency range or aspect of the composition. The temporal evolution of the different drones is represented by changes in the corresponding colored region, as it rotates around the central axis in Figure 3 (see supplementary video). Normally, Threnoscope pieces work by sending drones to 8 different loudspeakers (represented by the 8 highlighted radii in Figure 3), relaying on the distribution of the speakers in the room to create a spatial effect. In this experiment, however, we only use one of the 8 loudspeakers and rely on the prism to create a spatial effect.

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 acoustic 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 acoustic prism, which articulates and transforms the temporal features of the sound into a spatial, dynamical message.

What makes the use of the prism interesting in this compositional context is that through one speaker only, the spectrum of the sound is diffused across the space. This adds a novel experience for the listener, who can now navigate the space to experience nuanced qualities of the sound. Further work would be to add the prism in front of all the 8 speakers to create "zones of intensity".

4 USER TESTS

A user study was conducted using 16 participants (8 male and 8 female), all with normal hearing and 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 4). In order to minimise the effects of the room, the experiment was run in two different rooms, one smaller (reverberation time:

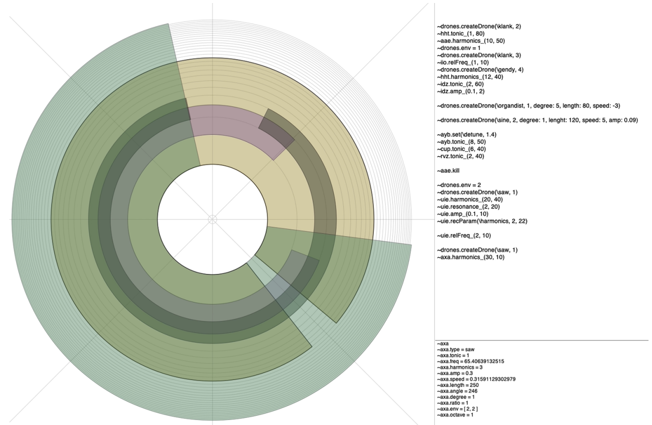

Figure 3: The Threnoscope in action, during the user experience. The visualisation highlights the different drones operating in the composition (colored regions on the left) and the code used to control them in real life (text on the right).

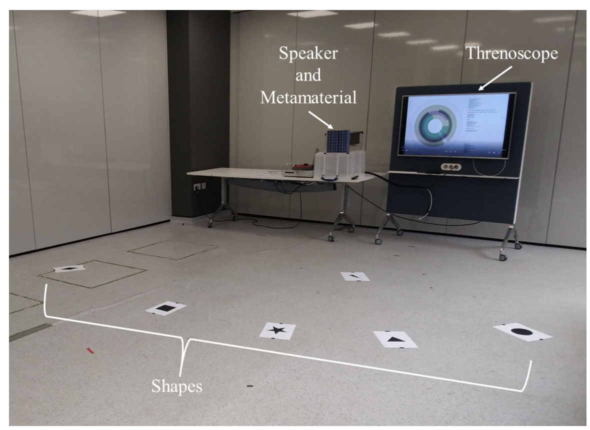

Figure 4: A wide shot of the area in front of the prism, highlighting the different shapes used during the user studies.

$T_{20} \sim 3s$ at 5 kHz) than the other ($T_{20} \sim 5s$) and with 8 participants in each. As shown in Figure 4, the floor of the room was marked with 8 different shapes, positioned at a range of angles between $-40°$ ("Diamond") and $+40°$ ("Circle")[3] and at distances from the prism between 1.5 m and 6 m.

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 (using the chart in supplementary Figure 9a). Perceived loudness [36] was evaluated using a 5-point numerical Likaert scale, as recommended for interview-based assessments [37]. After the "exploration" stage was over, users were then asked to fill a

[3] The emission of the speaker without the prism was perceived to be constant within this range of angles, changing by a maximum of 3 dB at 1.5 m.

questionnaire (see supplementary Figure 9b) 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 [37]. Questions were left open-ended, as suggested by soundscape research [38], to capture the experience in the user's words. A list of key-words, previously used to assess user perception in auditoria [39], was also added at the end of the questionnaire.

5 RESULTS AND DISCUSSION

As mentioned earlier, in the first part of their experience, users were asked to explore the space and to report their perceived loudness in different locations, distributed on the floor like in Figure 5. This was done using a hand-held map of the space, where a scale of 1 (very quiet) to 5 (very loud) was reported near each of the marker (see supplementary Figure 9a). Figure 5 shows the results of this in-situ survey, plotted as the arithmetic mean (over the 16 participants) of the reported loudness at the different positions (error bars report the standard deviation). Some key results:

- The "Bolt" marker is a reference point and, being the closest, had the highest level of perceived loudness with a score of 3.75 ± 0.35.
- The markers "Bolt" (1.5 m from the prism), "Star" (3 m) and "Cross" (6 m) are on the same line, at +20° from the axis in Figure 5. In absence of the prism, a reduction of 6 dB is expected with each doubling of the distance.
- The quietest perceived space in the room was at the "Diamond", which is 3 m and $-40°$ from the prism, where the mean perceived loudness has a value of 2.88 ± 0.18. This result confirms that most of the intensity goes towards one side of the prism.
- The first two markers on the +20° line have a very similar perceived loudness, significantly different from the other locations. This confirms that most of the intensity goes in one specific direction and that, along that direction, perceived loudness does not change much in the initial 3 m.
- Another interesting comparison is between the "Triangle" (at 3 m and +40°), the "Star" (also at 3 m and +20°) and the "Cross" (at 6 m and +20°). While the "Star" has almost the same score as the "Bolt", the "Triangle" has almost the same perceived loudness as the "Cross" (where we would expect a reduced loudness, due to the distance). This suggests that, for the same loudness, a listener can therefore move at twice the distance or just step 20° to the side, while remaining at 3m.
- A similar effect can be noticed between the "Circle" (3 m, +60° and the "Crescent" (6 m, 0°). Further studies will include microphone measurements.

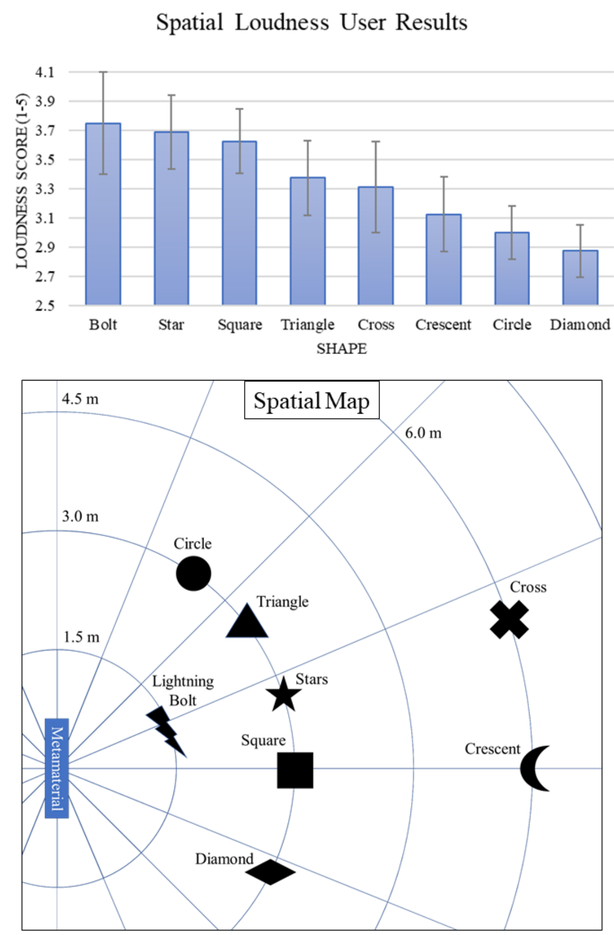

Figure 5: Top: a ranked bar chart of the mean perceived loudness at each marker, averaged over the results of 16 users sampled in two different rooms. The maximum perceived loudness was perceived at the "bolt" (1.5 m and 20° from the device) and the quietest perceived shape was the diamond (3 m and -40° from the device). Bottom: a to-scale plot of the spatial distribution of the shapes, relative to the metamaterial acoustic prism, positioned 102 cm above the floor.

An initial analysis of the responses to the question *"Overall, how would you describe your experience?"* (see supplementary Figure 9b) is visually summarised in Figure 6 through a word cloud, where the relative size of the words is proportional to their frequency of appearance in the feedback.

The most frequent words show that the users remember the experience as "interesting" and "different". Some examples of users' feedback in this direction include *"I felt the sound different at various locations in the room"* and *"There were different volumes at unexpected locations"* or *"It was interesting to hear the different variations of sound in the room"*. All the users noted the complexity of the soundscape, but in a non-uniform way (as shown by many different words of similar weight in Figure 6). Future studies will investigate some of these statements in terms of classical psycho-acoustic indicators like sharpness or roughness [36] or more modern ones, related to the dynamics of the sound and bench-marked in environments enriched by adding artificial soundscapes [38].

Figure 6: A word cloud, summarising feedback of the 16 users to the first question of the questionnaire shown in Figure 9b.

A word cloud is also used - see Figure 7 - to represent the preliminary analysis on the second question *"Did you find any difference between the sound at one marker and the sound at another? If you did, please describe the difference"*. The most frequent words ("sound", "felt", "different", "Triangle", "Star", "marker") in the feedback show that the users remembered a difference between the different positions, and in particular between the "Star" and the "Triangle" (see Figure 5) even after the end of the experience. Notably, one of the users reported "Yes [there was a difference between markers], in particular between the Star, Triangle and Circle". As shown by the relative size of other words, like "changing" and "similar", this conclusion was controversial. Users were in fact unclear whether the difference they experienced was due to the position or to the changing music. This is well summarised by one of the users, who wrote: "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. Finally, users were asked to mark the words that best described the sound during the experience, taking them from a list of acoustic descriptors, borrowed from evaluations of auditorium acoustics [39]. The results are plotted as

Figure 7: A word cloud, summarising feedback of the 16 users to the second question of the questionnaire shown in Figure 9b.

a pie chart in Figure 8. The overall experience was decided to be "reverberant", "enveloping" and "focused" by at least half of the users. Future studies will consider the use of a more systematic vocabulary, specific to the qualification of sound experiences [40].

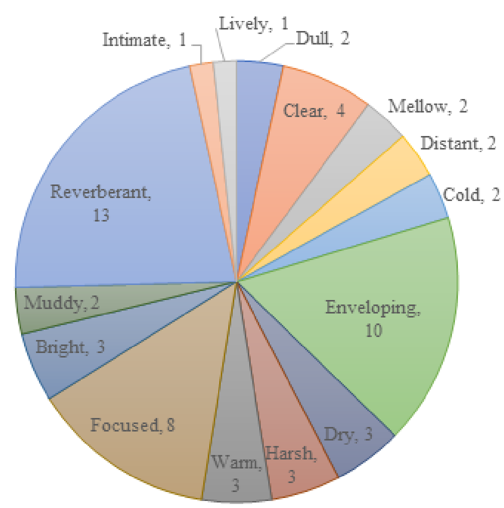

Figure 8: A pie chart, showing the total count of selected feedback of the 16 different users describing the acoustics of the experience in Figure.

6 CONCLUSIONS

In this work we have explored how an acoustic metamaterial prism may be used to redirect sound, and in particular a multi-frequency musical piece, to certain areas of a room.

We run a user study, where most of the participants perceived sound to be louder at some locations relative to the others. This was particularly true on one side and across a small range of angles. We also showed that, even if the transmission of our metasurface was optimised for a narrow band of frequency, the device could be successfully used to influence sound over a much larger range.

Most of our users described their experience as "different" and, when asked to highlight words from a pre-defined list, chose the words "reverberant" and "enveloping", thus suggesting that the musical experience was changed (as well as redirected). Further studies are suggested to investigate the perceived aspects of the device, in particular using multiple speakers or repeated musical pieces.

This work has significant implications on the use of metasurfaces in musical performances or as a novel creative tool, giving composers an easy way to add a spatial dimension to their pieces. Applications are anticipated in cinemas, in concert venues or even in home theatres.

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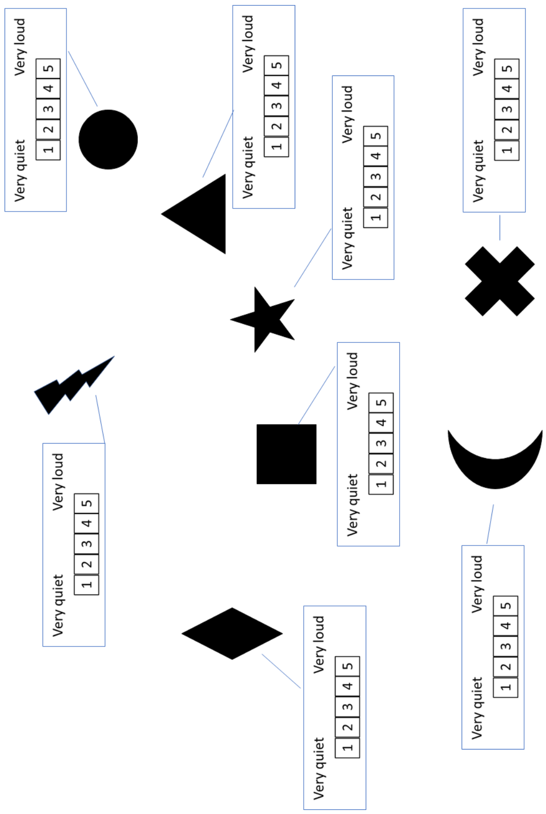

(a)

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?									
Dull		Clear		Mellow		Distant		Cold	
Enveloping		Dry		Harsh		Warm		Focused	
Bright		Muddy		Reverberant		Intimate		Lively	

(b)

Figure 9: Running the user tests: (a) the perceived loudness map using during the "exploration" phase; (b) the questionnaire handed to the participants to the user study.

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A RESEARCH METHODS

Figure 9 reports the map used to assess loudness during the "exploration 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.