HEARING THROUGH DARKNESS: A STUDY OF PERCEPTUAL AUDITORY INFORMATION IN REAL ROOMS AND ITS EFFECT ON SPACE PERCEPTION.

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1 INTRODUCTION

Hearing in enclosed spaces is a complex process, as any sound emitted within is superimposed by a multitude of delayed and attenuated copies of it, known as *reflections*. In small rooms the first arriving reflections normally occur within the 'fusion' interval of the *precedence effect*, whereby the disruptive spatial information (i.e. *reflections*) is suppressed[1,2], whilst the human brain attends to the sound-emitting source; a process known as *echo suppression.* This process helps our auditory system to segregate source information from a perceived cacophonous mixture enabling *angular localisation,* and *distance discrimination* between the listener and the emitting sound source. However, if this 'suppression' theory was to be followed uncritically, it would be impossible to perceive acoustical differences between spaces in real-life. More importantly if the auditory system only processed the sound source signal, ignoring all other information, no cues would be available about the space, the source's distance, its location, and its properties.

Following this notion, numerous studies support that while (early) reflections are perceptually suppressed and 'unheard'[3] they normally affect the global percept; by subjectively altering the *spatial impression* of the source[4,5], the *timbre*[6], and *speech intelligibility*[7]. Does this provide evidence that 'echo suppression' operates at early stages of processing aiding sound localisation, while the 'suppressed' and perceptually 'unheard' reflections are passed to higher levels? Are these reflections cognitively processed, enabling auditory system to extract information from reverberation if required?

This paper investigates the effect of *room reflections* on higher cognitive processes, such as the spatial and auditory space perception; whereby humans are able to create a virtual representation of an unknown space from auditory stimuli, and self-locate within it. An experiment was conducted where participants (N=30) identified their position in an unknown virtual space, by listening to sound simulations whilst being standing, and blindfolded. Furthermore, performance is contrasted between a group of Professional Musicians and a group of Non-Musicians, investigating the role of the alleged superior auditory processing in musicians, in the context of space perception.

2 THEORETICAL BACKGROUND

2.1 Space Perception

Space perception could be described as the process of defining the geometrical structure of the environment and our location within that space[8]. It is suggested that the visual system creates a cognitive representation of the environment by comparing sensory information from retinal images; normally perceived as a three-dimensional image[9]. It is assumed that this representation provides 90% of the information needed[10] for space perception. Still, the integration of information from other modalities (i.e. hearing and touch) is central to create a complete representation of space[8].

However, sensory modalities have different spatial ranges in different functional regions of space. Figure 1 depicts the spatial range of sensory modalities combined with Hall's definition of extra-personal space[11]. It shows that the auditory system provides information about a much larger spatial field than vision and touch, as it extends behind the head and the body, in both personal, near, and far spaces. Thus, it can be argued that space perception[8] can be aided by other senses depending on the functional area of space involved. Further, it has been shown that in dark conditions, or when visual information is limited, the role of auditory information in space perception gains significantly in importance[12].

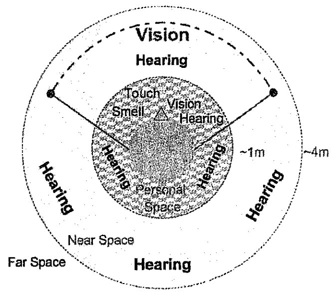

Figure 1: Hall's extra-personal space definition, and the spatial range of the visual auditory and somatosensory modalities aiding space-perception[8]. The visual field is illustrated in red.

2.1.1 Auditory Spatial Perception

Hearing in real-life environments (i.e. rooms) is not straightforward. The interaction between the sound source and the room reflections introduces spatial distortions leading to a biased auditory representation of the physical space. In addition, reflections from the room boundaries are normally clustered together at a very narrow time interval. Combining this evidence, with the argument that hearing has restricted ability to resolve simultaneous acoustical events[13,14], it has been hypothesised that reflections are simply masked by the louder and first arrived sound, resulting in a *perceptual/sensory limitation*. Yet, this 'masking' approach is highly challenged as a body of multidisciplinary scientific research suggests that the human auditory system maintains robustness to reflections. This echo suppression mechanism has often been linked to the highly adaptive *precedence effect*; involving the case where the first wavefront is isolated and later signals are suppressed[2,15].

The ability to isolate the original sound and its reflections is most clearly demonstrated in the case of some visually deprived individuals who use self-produced sounds to navigate through space (echo locating). A common notion is that visually deprived individuals hear 'better'; however no definition of what 'better' involves[16] is given.

The question arising from these observations is whether the ability to use reverberant information is related to enhanced low-level perceptual sensitivity, or to highly improved cognitive processing. Even if this ability is mostly observed in situations where the observer needs to rely on the auditory information because the visual information is absent or reduced, it must be the case that these information is available to the auditory system regardless of availability of visual information. The ability to make use of the information contained within reverberation could however depend on extensive auditory training, whereby participants' ability to attend and process reverberation is improved. For example one form of training maybe implicate superior auditory processing as found in professional musicians[17], which might extend to higher detectability of room reflections[18].

2.2 Perceptibility of Reflections

Although reflections are by definition replicates of the original sound, they are not identical to the source, as they are modified through the interactions of the reflective surface[14], geometry, size, and shape of space[14,18]. Thus, each reflection has a unique delay, intensity, spectrum, and direction of incidence based on the reflection point of the surface. These reflection points effectively become 'virtual' sound sources, creating a situation similar to a "cocktail party" (see [19]) whereby each 'virtual' source is emitting slightly different information to the listener from a different angle and distance.

Due to the complexity of these acoustical sceneries, initial psychoacoustic research has mainly focussed on the effects of single-reflections. Summarising the literature[2,4,20,21] it could be argued that detecting reflections follows three major principles. At relatively low levels, reflections are generally not detected; though it has been argued that they subjectively affect the sense of 'spaciousness'. At higher levels, reflections may not be consciously perceived yet, but it is argued that they affect the global auditory percept (i.e. by shifting the auditory image in the direction of the delayed signal). When the sound pressure level is high enough, the reflection is perceived as a second auditory image. In addition to sound pressure, the detectability of reflections depends on the relative delay between the original sound of the reflection, and its direction; the relationship between these is also not linear (see [18]). These findings were based on single-reflection detectability under anechoic conditions and it could be argued that they lack ecological validity. Nevertheless, they formed the baseline for further scientific research looking into the precedence effect *per se,* where it was shown that detectability of reflections follows three principles including: (1) summing localisation[17] (2) localisation dominance/precedence[22] (3) Second Image or Echo perception.

2.2.1 The Precedence Effect. Cognitive or Not?

The adaptive nature of the precedence effect was demonstrated by Clifton[23], suggesting that the echo suppression mechanism can be altered from one moment to next. Along with other studies, Clifton *et al.*[24] argued that the precedence effect is an active perceptual process that depends on the listener's expectations and recent experience. This was also supported by room adaptation studies, suggesting that precedence phenomena are products of more central brain mechanisms based on dynamic models of the acoustic environment[25].

Animal single brain cell studies have linked the precedence effect with the inferior colliculus, and auditory cortex[26,27], showing that the neural activity in these areas was highly correlated with general spatial suppression[28-31]. Following this evidence, it has been argued that 'suppression' is automatic and immediate, affecting low-level sensory processing. However, a recent electrophysiological study[32] has found effects of echo suppression on neural markers associated with higher-level processing, including the auditory N1 (70-100ms) and a space specific correlate (150-250ms). There is also strong evidence that the precedence effect is directly affected by other modalities such as vision[33], as both elicit similar brain responses[34]. Based on this evidence it is suggested that precedence effect is cognitive[22,35] and requires high-level processing.

The highly complex mechanism that the auditory system undertakes while listening to reverberated signals has been also identified by blind source separation studies. These studies acknowledged reflections as a major factor in the ability to segregate and localise sources by algorithms. Similar findings have been also identified in cochlear implant listeners[36]. It is however clear, that humans can demonstrate good localisation and source segregation in echoic environments in everyday life. This suggests that the human auditory system possesses cognitive mechanisms that recognize spatial distortions and further process the information contained within such signals.

This study aims to investigate the ability to use this information. In other words, whether the information contained within reverberation, could be cognitively processed in the context of space perception, despite the assumed suppression of the early reflections in small rooms. A further aim was to investigate whether this ability was affected by extensive auditory training (i.e. formal musical training). These questions were addressed by measuring the ability to self-locate within a room in a group of professional Musicians and a group of Non Musicians.

3 EXPERIMENTAL DESIGN

A group of thirty individuals took part in the experiment, including equal number of Professional Musicians, and Non Musicians. All participants completed the task under two listening conditions.

In the first condition (Condition A) the subjects listened to different types of sounds presented from an external source and they were asked to identify their location as listeners in a virtual room.

Based on findings from studies looking into distance discrimination and sound localisation, it is suggested that acoustic cues such as binaural differences, spectrum, Direct-to-Reverb Ratio (D/R), and source intensity are dominant in such *egocentric* representation of space[35].

In the second condition (Condition B) the participants were asked to listen to sounds emitted from the listening location, simulating the scenario of 'self-produced' sound (i.e. listening to ourselves speaking). Consequently, in this condition the acoustic cues of D/R, source intensity variation, and binaural differences originating from the source were removed. In the absence of these cues it was expected that listeners would perform the task based on the perceived differences in early reflections at the different room locations. Consequently, this condition intended to force the participants to create an *allocentric* representation of the environment based on object-to-object spatial relation to the environment, rather than a self-centred approach of attending to an external fixed source as in Condition A.

The participants listen to sound simulations of a real room and performed the task blindfolded and standing. The task was performed in an unknown semi-anechoic booth in order to minimize visual biases or sensory discordance effects; found to be at a play in previous studies[38,39].

4 EXPERIMENTAL METHODOLOGY

The participants' ability to self-locate was determined by recording their perceived location in a space perception task. Participants listened to 84 room simulations, representing listening to a set of 6 sound sources, at seven room locations, under two listening scenarios: (a) Listening to a fixed sound source and (b) Listening to 'self'-produced sounds. The presentation of the stimuli was based on MUSHRA recommendation[40], providing self-paced and self-controlled capability to participants over the response device. A hidden reference was also embedded within each block, representing the centre of the room.

A group of thirty individuals (N=30) participated in this experiment. The 'Musicians' group included fifteen active professional instrumentalists with at least ten years of musical training. The 'Non-Musicians' group consisted of fifteen individuals who had no more than two years of training or active engagement with performing for at least twelve years. The musical training level of Musicians was assessed using the psychometric tool GoldMSI[39].

An empty 'typical' room (2.94Wx2.94Hx4.67L) was used for the room measurements. The room was selected based on its small size, its physical structure incorporates a full glass-wall, and its availability. This box-shaped room consisted of carpeted floor, acoustically treated suspended ceiling, and identical sidewalls. A summary of the setup is shown in Figure 2; also see Appendix.

The in-situ BRIRs were captured using a Cortex Instruments MKII Head And Torso Simulator (HATS), simulating the listener's location in the room, and two Genelec 8020A active loudspeakers simulating the sound-emitting source; one for each condition respectively.

The Impulse responses were then convolved in MATLAB with six short anechoic recordings; male speech, percussion, trumpet, cello, handclaps, and pink-noise bursts. These anechoic stimuli were level-matched using a BS1770-2 recommendation[41], before convolution to avoid digital clipping. After convolution they were also level-matched to the 'loudest' convolved stimulus. Using this two-step approach, the Direct-to-Reverb ratio was maintained while the 'source' Intensity and the overall stimulus Loudness was controlled. The stimuli were presented from MAX/MSP through a Digidesign Mbox 2, driving AKG 702 headphones. At the start of each session, the listeners set a confortable listening level. The experiment was performed in a dark audiometry booth (IAC1200), and the participants were standing, blindfolded.

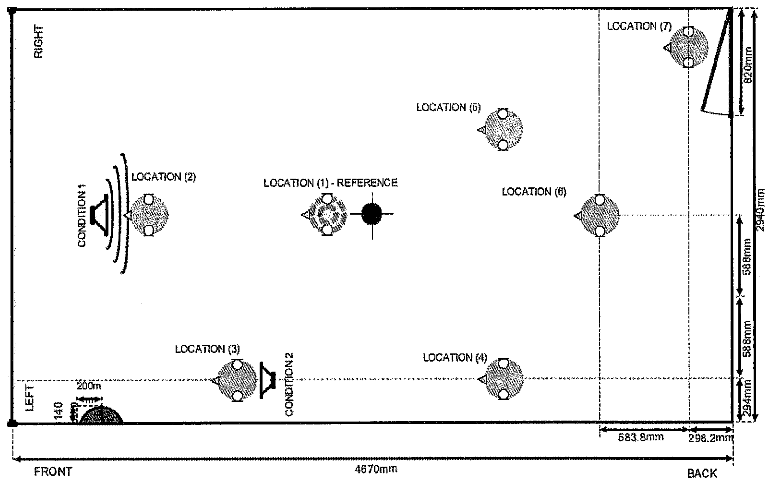

Figure 2: Schematic of the room indicating the loudspeaker placement and the 7 recording locations used in the study. The physical centre of the room is illustrated by the cross. Head Height: 1.65m. Speaker (1) 1.68m. Speaker (2) 1.72m

On each trial the participants listened to a short stimulus and they were asked to determine their position in the virtual room. They responded by clicking one of the forty available buttons on the response device (modified Novation Launchpad), which corresponded to the locations of the room. The experimental setup is show in Figure 3.

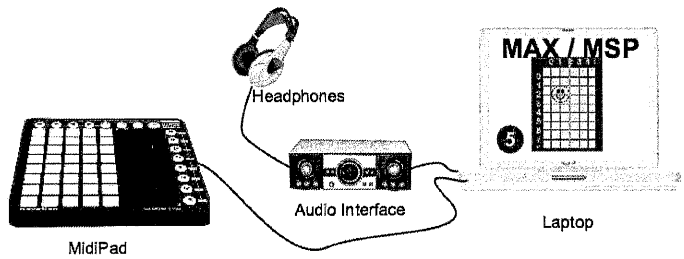

Figure 3: Experimental setup.

The participants could perform the test in any order and repeat each stimulus as often as they liked; the playback control and trial selection was accessible from the response device. After completing all 7 trials within a block (7 locations including the hidden reference) the participants were able to continue to the next block. Each block consisted a randomised set of the seven listening locations in the room, while the type of the stimulus was different in each block. Thus, six blocks of seven trials were completed for each listening scenario. Each listening scenario was treated as a different Condition and listeners were briefed beforehand. At the start of each condition they were asked to perform a training block of three trials to familiarise with the setup and the experimental procedure; feedback was provided at this point.

5 RESULTS

The ability of participants to place themselves in the virtual room was quantified as the absolute difference between the button representing the actual recording point (R), and the button that was pressed by the participants (B). Using the Cartesian coordinates collected from the response pad, the Euclidian distance between the two was calculated for X and Y separately; a summing vector was calculated for each trial as a non-directional error term. This was subsequently converted in meters, based on the original dimensions of the room. This measure will be referred to as *Error* and its magnitude represents the *accuracy* in the task. In order to evaluate the participants' performance

(%) on the task, a new variable was computed. This variable coded responses as 'correct' when the correct button was pressed; consequently the *Error* vector was equal to 0. This will be referred to as *Score*.

5.1 Performance

Figure 4 shows the score of correct button presses in each listening scenario. It can be seen that all participants performed the task above the estimated chance level. Across both Conditions Musicians correctly identified the room Location in 424 trials out of a total of 1260 (33.65%), whereas Non-Musicians correctly identified the room Location in 210 trials (16.67%). The score difference between the two groups was found to be significant (p<0.001), showing that musically trained individuals performed better at this space perception task.

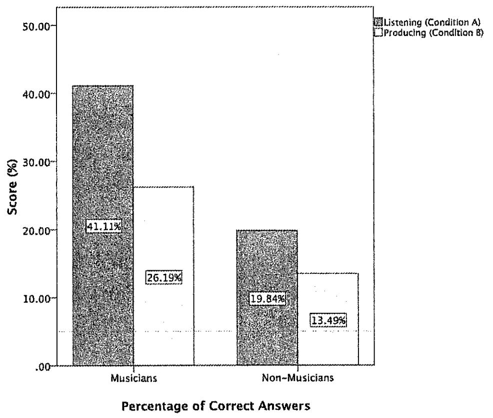

Figure 4: Score percentage illustrating the correct answers achieved in both conditions, between the two groups. Grey-Line shows the estimated chance level.

While listening to an external source (Condition A), Musicians identified the correct Location in 259 trials (41.11%) out of the 630, whereas Non-Musicians in 125 Trials (19.84%). In the Condition B, Musicians identified the correct Location in 165 trials (26.19%), while Non-Musicians did in 85 trials (13.49%) (see Figure 4). The difference in scores between the two Conditions was significantly different overall (p<.001). In addition, analysis within each group shows an effect of Condition in Musicians (p<.001) and Non-Musicians (p<.002). The observed enhanced performance by all subjects in Condition A suggests that whilst listening to an external source, more information for space perception is available and used, as compared to listening to 'self'-produced sounds. Still, Musicians show better performance than Non-Musicians in both listening conditions, providing evidence for more efficient use of spatial information contained within reverberation.

5.2 Accuracy

Figure 5 shows the accuracy of the participants in the task, expressed by *Error*; the distance between the actual recorded point (RP) and the response given (RG). Across both conditions Musicians performed the task more accurately as their responses were closer to the actual location (M=.85m, *SD=.91*) than Non-Musicians (M=1.42m, *SD=1.04*).
A mixed design ANOVA was used for the analysis with factors: the Type of Stimulus (6 Levels), the room Location (7 Levels), and the Condition (2 levels - External source Vs self-produced). The initial analysis revealed no effect of the Type of stimuli on the participants' accuracy ($F(5,28)=3.772$, $p=.554$). This may be related to adaptation with the room, enabling appreciation of qualities intrinsic to the sound source[42]. In addition all sounds selected included rich transient content that may explain the results. For subsequent analyses the data were averaged across type of stimulus to increase power. Thus, for each participant a single *Error* term for each Location and Condition was calculated.

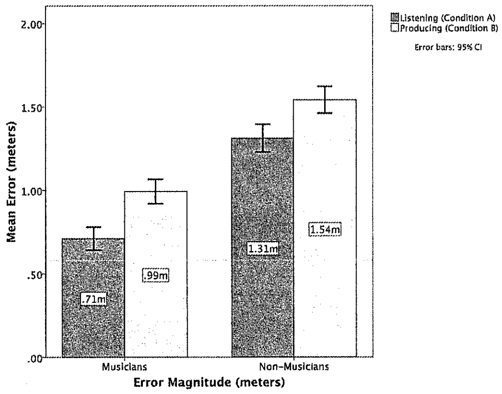

Figure 5: Accuracy of participants expressed in *Error* magnitude in meters. Grey-line shows the real distance between two locations / Pad-buttons.

After pooling across sound types, a similar mixed-design ANOVA was conducted, as described above, omitting the factor Type. Overall the analysis showed that Musicians were more accurate than Non-Musicians, as reflected by the main effect of Group ($F(1,28)=243.520$, $p<.001$), indicating that the Musicians' *Error* ($M=.85$, $SD=.91$) was significantly smaller than Non-Musicians ($M=1.42$, $SD=1.04$).

In addition, a main effect of Condition was observed ($F(1,28)=22.785$, $p<0.001$) indicating that participants were more accurate when listening to an external source ($M=1.01$, $SD=.90$) than listening to 'self'-produced sounds ($M=1.26$, $SD=.97$) (see Figure 5). However no interaction was found between Group and Condition ($F(1,28)=.416$, $p<.524$), suggesting similar behaviour within listening scenario by both groups.
The analysis also revealed that room Location had a significant effect on the participants' accuracy ($F(6,168)=59.213$, $p<.001$). No interaction was observed between Location and Group, showing that both groups show similar accuracy patterns for the locations tested.

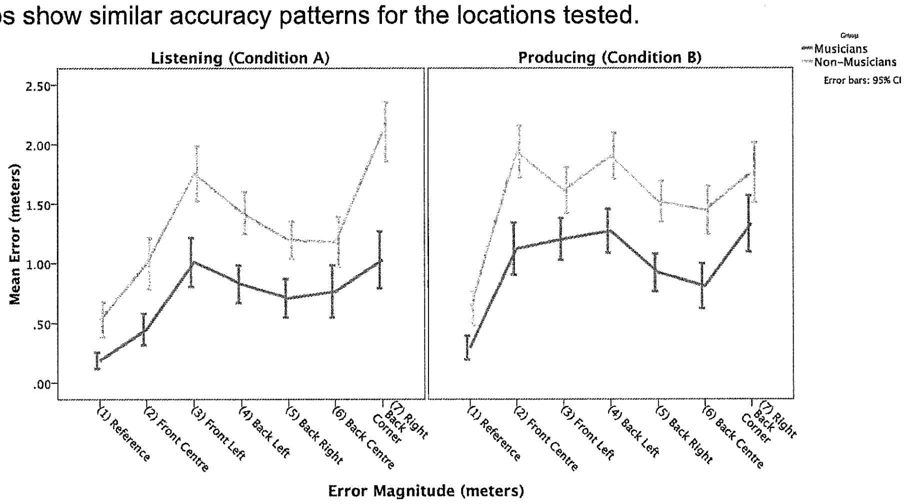

Figure 6: Error Magnitude between locations, in both conditions, showing the similar trends between the two groups.

A significant interaction was found between room Location and Condition ($F(6,168)=8.53$ $p<.001$) regardless of group, showing that the patterns of accuracy for the locations tested differed between the two listening conditions, possibly due to the different cues provided to the participants.

Figure 6 further illustrates the accuracy findings for the two groups. These graphs show similar trends as were observed for the performance analysis (*Score*). It can be seen that overall the

Musicians show better accuracy whilst both groups show very similar patterns of accuracy across the locations tested.

5.3 Location Biases / Further Analysis

In order to investigate any systematic biases in the interpretation of the stimuli, Data Density plots were created in Matlab for each location, and condition.

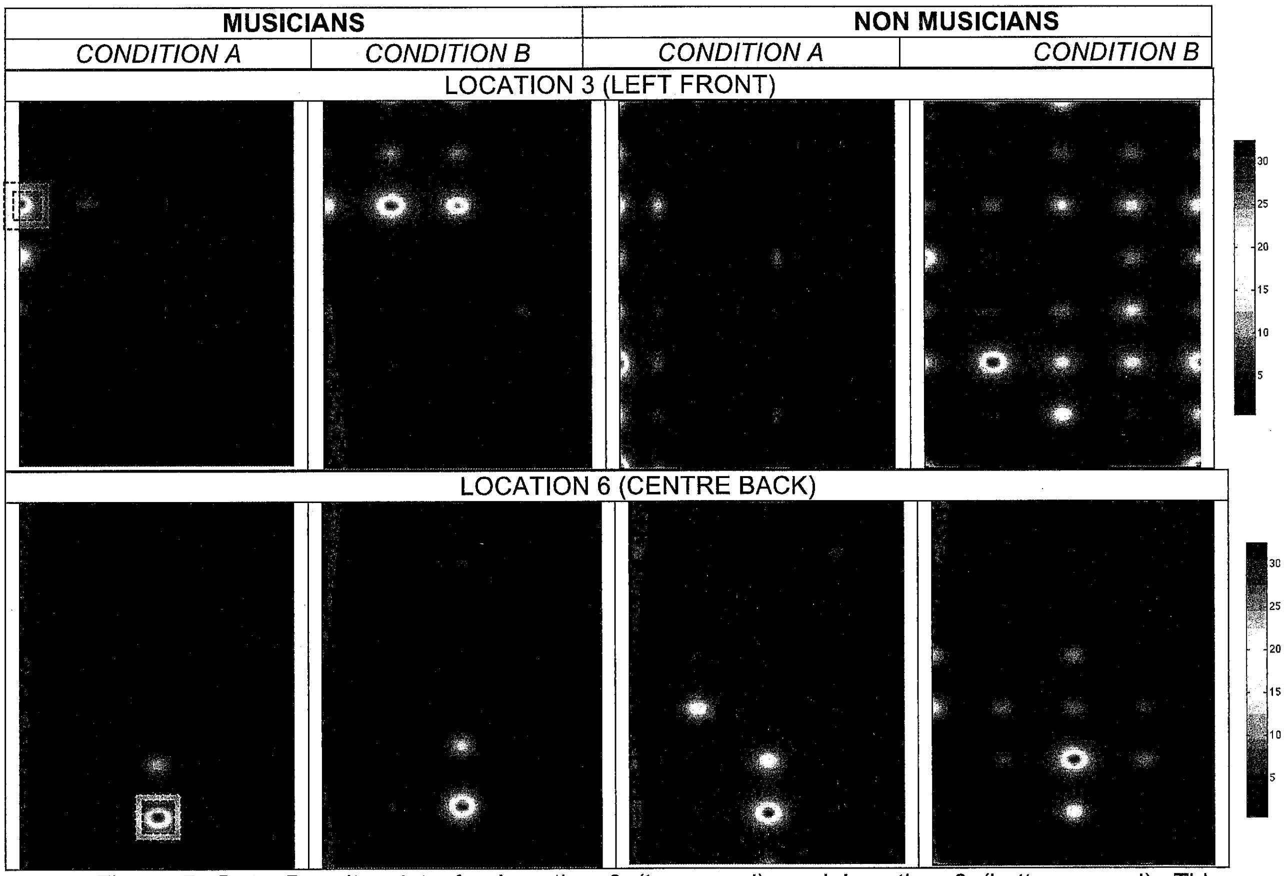

Figure 7: Data Density plots for Location 3 (top panel), and Location 6 (bottom panel). This represents a graphical representation of the responses distribution within the available responses on the midi pad. Rectangle = Real Location. The rectangle in the left panel indicates the actual recording point.

The data density plots provide information about the frequency distribution of responses for each available response button. Different frequencies are represented as different shades of colours,; locations corresponding to buttons that were never pressed are illustrated in dark blue, while red shows the mode of the distribution of response locations.
Figure 7 shows the responses of each group for Location 3, and Location 6. The density plots support the above finding that Musicians performed better in the task than Non-Musicians. The plots also reveal multiple modes within the distribution for condition B for both groups indicating that the task was more difficult for both Musicians and Non-Musicians.

In addition it was observed that non-musicians overestimated the distance of the source for location 3 in condition A, and also produced highly variable, responses. However, there were no responses supporting that the participants identified their location on the opposite side. In contrast, when subjects performed condition B, the same location was not appropriately identified and the variability in their responses was very high. In some cases non-musicians responses included the opposite side of the room.

In summary, the distribution of responses shows superior performance in identification and interpretation of the correct location by Musicians in both listening conditions. It also suggests that the ability to localise the lateral (horizontal) position in the room was poorer in the absence of an external sound source (condition B) while the front-back (vertical) orientation was not affected significantly.

6 CONCLUSION

The aim of this study was to examine the ability of human listeners to use auditory reverberation cues for spatial and space perception, in the absence of vision. In two listening conditions, participants determined their position within a Virtual Acoustic Space based on real recordings (BRIRs) obtained in a small room. A second aim of the study was to investigate the role of musical training on auditory processing and the ability to use reflections contained in reverberated signals. To study this, the performance and the accuracy in the task were compared between a group of professional Musicians and a group of Non-Musicians.

Overall, the findings suggest that reverberation contains critical information about the surrounding environment and the human auditory system is capable of processing this information. Musicians show superior space perception in both tasks, in particular, in radial distance discrimination, behaviour reported before[16] in blind individuals. This suggests that extensive auditory training greatly benefits the ability to make use of the spatial cues provided by reverberant information in space perception. The similar patterns across locations found in both musicians and non-musicians however, suggests that this mechanism is also evident in the normal population.

This study provides evidence that information within reverberation could provide enough information to create an accurate auditory representation of the space, and self-locate within that. Further, the results of listening to 'self-produced' sounds suggest that the precedence effect is not reflecting a perceptual limitation, or 'masking' of reverberant information. Although removing spatial distortions from the source of interest is important to provide accurate angular localization and distance estimation of the source, this information might not be lost. Our data suggests that the reverberant information is perceived and passed on to brain areas involved in higher-order auditory and spatial processing, aiding cognitive processes such as space perception and spatial mapping. These processes may in turn affect the global subjective characteristics of the stimulus, as was previously claimed[4-6,18].

7 ACKNOWLEDGMENTS

The authors would like to thank Dr. Russell Mason from the Institute of Sound Recording, University of Surrey, for his support and helpful input in this study.

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9 APPENDIX A

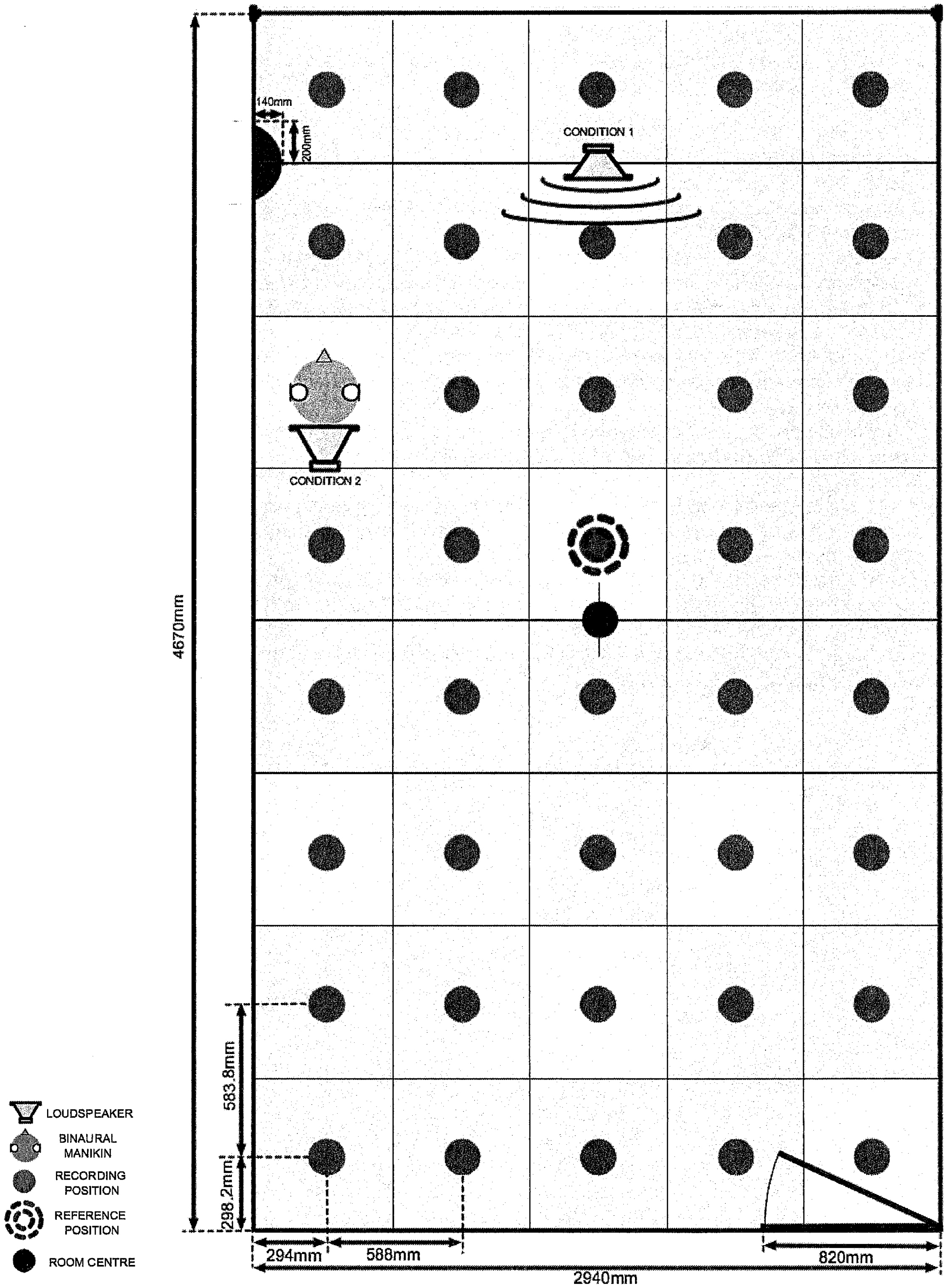

Figure: Detailed, on scale schematic of the recorded room. Each rectangle represents a button on the response device. Grey rectangles indicate the selected locations for this study.