Evaluation of reverberation
time differences: an fMRI study

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Abstract: Acoustics, since its foundation, aims to make correlations between the subjective opinions of listeners and objective, measurable criterias. Reverberation, is the most important and the most referenced acoustical property since it’s all about reflected sound and it’s behaviour in an enclosed space. It has direct effect on the pleasantness, intelligibility and the tonal character of the sound. Therefore, it is one of the most important acoustical properties which shapes the listener’s subjective opinions. The aim of this study is to determine the changes that reverberation time differences cause in human brain, focusing on the auditory cortex.

Keywords: Reverberation, Reverberation Time, Acoustics perception, Brain

1. Introduction

Music studies supported by neuroimaging, include a range of subjects such as musical & timbral perception, musical taste, tonal preference, timbral analysis of instrument sounds, motor musicianship activities, acoustics etc. Hence, there’s a growing interest for interdisiplinary studies between researchers from musicology, music technology, psychology, radiology, arts and humanities and so on. The irrelevant studies will not be mentioned, for this paper is based on the neurological correlates of an acoustical concept.
Neuroscience and acoustics have formed their collaboration in the recent times so the diversity and the number of studies are limited. The leading research about the neurological correlates of acoustics and spatial perception are Ando’s studies. Ando proposed a concert hall design theory which is based on a model of auditory-brain system. He constructs this model over listener’s subjective preferences which he successfully observed the correspondences in the human brain using electroencephalography (EEG) and magnetoencephalography (MEG) scanning methods. Ando defines subjective preference judgment as the primitive response of a living creature in any subjective attribute and says that these preferences entail judgments that steer an organism in the direction of maintaining and/or animating life. He then states that these preferences may as well relate to aesthetic issues. From this point of view, he derives his theory of subjective preference from the results of subjective preference studies in relation to the temporal and spatial factor of the sound field. (Rossing, 2007: 353) He takes different concert hall designs into consideration and defines listening “sweetspots” according to four criteria, which are the listening level, initial time delay gap, subsequent reverberation time and interaural cross correlation. In another study, Ando, Chen and Nishio state that parameters known as listening level (LL), initial time delay gap ($\Delta t_1$), subsequent reverberation time ($T_{sub}$) and interaural cross correlation (IACC) are important aspects of the sound field in an enclosure which effects the subjective preferences thus the seating positions of the listeners in a concert hall. They classify these parameters as temporal and spatial aspects of a soundfield. (Soeka, Nakagawa, Tonoike, 2002) Ando conducted an EEG study and observed the activations in the participant’s brains to find out how these parameters are perceived. He found out that temporal aspects, ITD (initial time delay gap), the time difference between the direct sound and first reflection, and $T_{sub}$ (subsequent reverberation time), created activations in the left hemisphere of the brain. On the other hand, spatial aspects, IACC (interaural cross correlation), measurement of the difference in sound reaching each ear, and LL (listening level), created activations in the right hemisphere. (Ando, 2003) Zatorre and Belin also attempted to classify the perceptive differences in both hemispheres. Their results are similar to Ando’s. (Ando, 2003) He used the data from the EEG and MEG scans to see if there was any correlation between the subjective preferences and neural activities. He observed
that when a preferred soundfield is experienced, brain activity area in both hemispheres is larger than the area of activity in a less preferred one. This is the basis of the correlation between subjective preference theory and the auditory brain system. With this method he proposes a whole new approach in concert hall design which has successfully been applied to various concert halls.

Ando’s leading studies helped us see what could be revealed if we could go any further in the subject. To begin with, we took one acoustical concept, reverberation time, and we used a different and more advanced scanning method, functional magnetic resonance imaging (fMRI). But first of all, it would be good to begin with a brief summary of the concept, reverberation.

2. Sound in Enclosed Spaces and Reverberation:
To understand the concept of reverberation we must first understand how sound waves behave in an enclosed space. Sound reaches the listener in two ways. These are direct sound and sound reflecting from the room’s surfaces.

Direct sound is the sound which radiates away from the source, directly to the receiver. Since it does not get affected by the acoustics of the room, it carries important cues about the source. For example, a high direct sound level is required for a clear and intelligible sound. (Howard, Angus 2006: 263) Direct sound also has an important effect on localization of the sound source. Adequate direct sound perception provides the listener with important data about where the sound is coming from. (Ozis, Vergili 2008:9)

Reflected sounds, on the other hand, reflect from room surfaces and reach the listener’s ears after the direct sound. These reflections are directly related with the acoustical properties of the room surfaces, so they are important indicators about the acoustical quality of the room. Reflections can be classified as early and late reflections.

Early reflections are first reflections following the direct sound. They reach the listener, after a time period called the initial time delay gap, ITD. The amplitude of these first reflections are directly correlated to factors such as the absorption properties of the reflective surface and the distance to the listener point. Too much early reflections cause decrease intelligibility and undesirable timbral changes on the perceived sound. (Howard, Angus 2006: 264) Direct sound, ITD gap and early reflections can all be seen in figure 1.
As seen in figure 1, the temporal distributions of the reflections in a room can be shown graphically with impulse diagrams. The vertical axis shows the amplitude of the signal, while the horizontal axis gives us the arrival time of the impulses. Each impulse arrives with a lower amplitude than the preceding one while the following signals follow the same pattern. The impulses are so many in number and so close in time, that the hearing mechanism cannot detect them as separate impulses. What the hearing mechanism perceives is like a continuation of the direct sound, in other words, reverberation. Accordingly, in practice, the decay curve of the sound pressure level in a room is not shown as separate bars but as a line. The slope of this line gives the decay rate, meaning that if the slope of the line gets higher the decay of the sound will be faster. (Mehta, Johnson, Rocaford 1999) The dense lines following the early reflections, which have constantly decreasing amplitudes, are called late reflections. This part of the graph can be named as “reverberant soundfield” because late reflections are the cause of our perception of reverberation. For the late reflections to be perceived, sound has to travel in the room in many directions, reflect countless times from different room surfaces and reach the listener from many different angles. Since there are countless reflection paths and the time difference between each of these late reflections are very small the ear cannot discriminate the reflections and the listener hears a dense body of reflections. These dense late reflections are a desirable acoustical property which enriches the direct sound within certain limits. Direct sound and the following reverberant field is illustrated in figure 2. (Howard, Angus 2006: 268)
Reverberation, as an acoustical concept, emerged from the empirical experiments of W.C. Sabine in the late 19th century. With these experiments Sabine aimed to measure the effect of absorption on reverberation time. He used a stopwatch to measure the time until the sound could no longer be heard, in other words faded away, while he made changes to the amount of absorption. After gathering all the data he proposed the following well known equation. (Everest, 2000:159)

\[ RT_{60} = \frac{0.161V}{Sa} \]

In the equation;

- \( RT_{60} \) = Reverberation time, the time needed for a 60dB fall in amplitude,
- \( V \) = Room volume,
- \( S \) = The area of room surfaces,
- \( \alpha \) = The average absorption coefficient of the room,
- \( Sa \) = Total absorption of the room in “Sabines”.

Thus, reverberation time or \( RT \), can be identified as the time it takes for a 60dB fall in amplitude. There’s another concept called the early decay time or \( EDT \), which is known as the first 10 dB decay, and this concept is sometimes used interchangeably with \( RT \).

Reverberation gives us the sensation of being in an enclose space and it helps us to perceive the distance from the sound source. Accordingly, it has been used as the only parameter in characterising room acoustics quality for a long time. However, further research in existing concert halls have revealed that, halls with equal reverberation times could be different in acoustics. Therefore, the need
for new and supplemental acoustical criterias has risen. Nowadays, acousticians take RT as a rough estimate in measuring the acoustical qualities of enclosed spaces, especially in spaces with longer reverberation times. Nevertheless, RT is still considered a useful acoustical parameter, since it can easily be calculated when the acoustician knows the room geometry and the absorptive properties of the room surfaces. It also provides an appropriate estimation about the general acoustical tendencies or characters of the rooms. (Abdou, 1994)

The main parameters affecting the RT of enclosed spaces are volume and the amount of absorption. (Ozis, Vergili 2008: 9) In a smaller room, time delays between early and late reflections are short so the sound decays faster. Accordingly, a larger room with the same amount of absorption will have a longer RT giving us the parallel relationship between volume and RT. But if we increase the amount of absorptive materials in a large room, we can have RT’s similar to those of small rooms. Sound travels in all direction inside the enclosure and it reflects from the surfaces. With each reflection, it loses energy in connection with the absorptive properties of the surfaces and finally fades away. Figure 3 shows direct sound and some of it’s many reflections.

![Figure 3. Reflections and their energy changes (Maden, 1999)](image)

Since the sound arriving at the listener’s ears is the sum of all reflections with the direct sound, too much absorption will also reduce the loudness in the room. Therefore, room volume and the amount of absorption on the surfaces should be considered carefully for an adequate reverberation time in the design stage. (Ozis, Vergili 2008: 9)
3. Method

Two rooms with different reverberation times have been modeled for the fMRI experiment. Both rooms have 35 m² floor area and 3 m ceiling height. The absorbers have been placed equally on all room surfaces to achieve uniform absorptive properties in both rooms. The room surfaces are angled 5 degrees to prevent possible flutter echoes. There’s 1 meter distance between source and receiver locations in both rooms. Source and receiver height is 1,2 meters. The number of rays used for ray tracing method is 1000. An anechoic clarinet sample from the ODEON sound library has been used as the source. The directivity of the clarinet sound has also been taken from the directivity library of ODEON.

After the source and receiver placement, the surfaces of the first room has been covered with materials which have 10% absorption. After the calculations a reverberation time of 0,8 seconds has been achieved. The absorption rate used in the second room is 5% which provided a reverberation time of 1,8 seconds. The scattering values in the rooms are default values of the ODEON software.

After the modelling of the rooms, the room convolutions were applied to the anechoic clarinet sample and the new samples have been normalized. At the end of the convolution process two samples with different room impulse responses were gathered.

The two samples and the anechoic sample were equalised because the tubular structure of the fMRI headphones cause a change in the frequency response. This change happens especially in the lower frequencies, preventing the samples to be heard correctly. The equalised frequencies can be seen in figure 4.

![Fig. 4. Equalizing process of the samples](image)
The frequency responses of all samples after the convolutions and the additional equalizings are shown in figures 5, 6 and 7.

Fig. 5. The frequency response of the equalised anechoic sample

Fig. 6. The frequency response of the clarinet in the first room with 0.8 sec RT
10 male participants were chosen for the fMRI experiment. All of the participants were graduates or senior year students of Dokuz Eylul University, Fine Arts Faculty, Department of Music Technology. The participants were 100% right handed according to the Edinburgh Handedness Inventory results. The participants were asked to focus on the acoustical effects in each stimuli.

The fMRI experiment was carried out using a Siemens Magnetom Symphony Class 1.5T scanner. The scanning parameters are as follows: Paradigm Size: 16, Threshold: 4.00, Measurements: 64, Delay in TR: 500, 1 Ignore, 7 Baseline, 1 Ignore, 7 Active.

During the scan, each stimulus was given a period of 4 minutes. The sample was played for 30 seconds and this was followed by a 30 second rest. Thus each stimuli was played 4 times followed by 4 rests. The stimulus order was the anechoic stimulus, the stimulus with 0.8 sec RT and finally the stimulus with 1.8 sec RT. After the experiment the participants were asked if they had any difficulty hearing the stimulus. All of the participants stated that they have heard the stimuli and the acoustical effects clearly.

The fMRI results were then analysed using the SPM2 (Statistical Parametric Mapping) software, which is an add-on of MATLAB. The analysis method is the “one sample T test group analysis” method.

The results of the group analysis in auditory cortices, more specifically in superior temporal gyruses which show the maximum activations, in both hemispheres is given in the following table. The term “voxel count” represents the
activation area. The term “T score”, on the other hand, represents the activation amplitude.

Table 1. Results of the “One Sample t test” Analysis

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Activation Point</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anechoic</td>
<td>Left Superior Temporal Gyrus</td>
<td>Voxel Count: 669 (Width) T score: 19.47 (Amplitude)</td>
</tr>
<tr>
<td></td>
<td>Right Superior Temporal Gyrus</td>
<td>Voxel Count: 773 (Width) T score: 17.05 (Amplitude)</td>
</tr>
<tr>
<td>1st Room 0.8 sec RT</td>
<td>Left Superior Temporal Gyrus</td>
<td>Voxel Count: 1889 (Width) T score: 18.1 (Amplitude)</td>
</tr>
<tr>
<td></td>
<td>Right Superior Temporal Gyrus</td>
<td>Voxel Count: 1310 (Width) T score: 15.95 (Amplitude)</td>
</tr>
<tr>
<td>2nd Room 1.8 sec RT</td>
<td>Left Superior Temporal Gyrus</td>
<td>Voxel Count: 1561 (Width) T score: 13.47 (Amplitude)</td>
</tr>
<tr>
<td></td>
<td>Right Superior Temporal Gyrus</td>
<td>Voxel Count: 1484 (Width) T score: 11.18 (Amplitude)</td>
</tr>
</tbody>
</table>

Fig. 8. The color-coded representations of the activation areas

The color-coded representations of the activation areas are given in figure 8. The anechoic signal is represented by the red, the 1st room (0.8 sec RT) is
represented by the green and the 2nd room (1.8 sec RT) is represented by the blue colors. Figure 9 shows the same representations over a 3D Picture. The color codes are the same with the addition of white, which shows the intersection areas of the stimuli.

![Fig. 9. 3D representations of the activation areas](image)

4. **Conclusion:**

Our aim in this study was to examine the differences in human brain activity while experiencing different acoustical conditions, taking reverberation time as the main acoustical criteria. The lack in the number of studies in this field is a problem for this study.

After the statistical analysis, there is evidence that the activation areas in superior temporal gyruses located in auditory cortex in both hemispheres change. The activation area rises as the reverberation time rises, and this can be visually confirmed in colored brainscan images seen in figures 8 & 9. An inconsistent activation area in the left hemispheric superior temporal gyrus has been observed with the last sample and this requires further attention. The activation area of the first sample (0.8 RT) was larger than the anechoic sample as expected, but the activation area of the second sample (1.8 RT) was less than the first sample. The right hemiphereic superior temporal gyrus showed no such inconsistency. The activation area got larger with each sample as expected.
Another conclusion obtained from the statistical analysis is about the activation amplitudes of the three samples. It’s been observed that the activation amplitude decreases as the reverberation time increases in both hemispheres. The highest signal level is observed with the anechoic sample. On the other hand, the activation amplitude of the sample with 1,8 second RT was the lowest. This may be due to the fact that the reverberant sound lowers the intelligibility of the direct sound.

The obtained results and brain images help us see which brain regions show activation differences. These activation differences in different brain regions may be further evaluated to see which acoustical conditions are more desirable. This way, we can gather more objective clues about the subjective preferences of the listeners. This will definitively aid researchers and acousticians in designing better sounding acoustical environments.

References