

Museum Acoustics

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ABSTRACT

In this project acoustics at museum are to be examined and the objective is to find out what optimal museum acoustics are.

Research was done on three different museums in Denmark and their acoustical conditions were analysed in detail. Employees at *The Danish National Gallery*, *Aros* and *Arken* were interviewed and acoustic consultancy company *Jordan Akustik* was also collaborated with.

The National Museum of Iceland was collaborated with for further research. Reverberation time measurements were carried out at the museum and they showed some problematic acoustical locations. One particular location at *The National Museum of Iceland*, *The Arc Hall* was chosen for further acoustical examination. It was modelled in the room acoustic software *Odeon* in four different acoustical versions.

In order to assess subjectively the listening conditions at *The Arc Hall*, two independent listening tests were prepared. They were designed so they would imitate the two most important situations present at a museum. In the former test the subjective parameters *intelligibility*, *listening efforts* and *noise distraction* were assessed in different source combination in varying acoustical settings. The latter listening test was aimed for privacy and the subjective parameter *speech privacy* was evaluated in three source combinations in four varying acoustical settings. A rating scale method was used in the listening tests with a five point evaluation scale. Both the listening tests gave good results in terms of correlation and the trend was clear. In some cases *central tendency error* was though seen.

1. INTRODUCTION

With respect to museum architectural design the visual perception has been put into priority. Often this leads to rather uncomfortable environment concerning the acoustics. Whether the museum building itself is a new or old it often features large openings, concave ceilings and walls made of rather reflective materials like stone, glass, marble or tile. The main emphasize has been put on the museum's visual features and first when the museum opens up the acoustical problems become apparent.

The ultimate acoustical challenge in museum is probably met, that is, to fulfil differing acoustical demands. Often a private moment, where the guests can read in a quiet and relaxing environment is desired but at the same time being able to enjoy guided tours where the speech intelligibility is good enough. Whether one of this situation, is preferred, it is probably most important to realize where the sound is wanted and where it is not.

The main objective of the project is to get an evaluation of optimal museum acoustics. More precisely what acoustical parameters are most important? How can the sound field in museums be described and what can be done to optimize possible surroundings for a successful museum design in terms of acoustics?

2. Collaboration Museums

A relatively few studies have been carried out handling acoustics in museums. On the other hand different areas within acoustics are well-known and relevant issues since a museum may often include a café, cinema, lecture hall and even small concert halls.

A research was conducted at three museums in Denmark in order to gain knowledge concerning museum acoustics and background for further studies. The museums are: The Danish National Gallery (Statens Museum for Kunst) where an extension of a former building led to acoustic considerations. Museum for Modern Art in Ishøj (Arken), recently opened museum where acoustic design played an important role in the overall architectural design. Aros a modern museum in Århus that opened in 2004 and acoustical design was an important factor in the overall design of the building.

2.1. The Danish National Gallery

The Danish National Gallery has a historical importance within the cultural and museum society in Denmark. The original building is from 1896 [1]. In 1966 the museum went through major renovation due to lack of space and it reopened in 1970 with twice as much exhibition space. About twenty years later the space problems were still present and a competition was held, where an expansion of the museum as well as more effective utilization of the space in the old building were among the demands. The museum was reopened in 1991 after reconstruction. Shortly after the reopening it became apparent that the acoustical conditions were not satisfactory, particularly in the new halls Panoptikon and the multi-purpose hall. Panoptikon is a hall connecting the old and the new building and they are both made of reflective surfaces (glass and marble). One of the museums' requirements was that the multi-purpose hall could accommodate diverse activities including music performances and lectures with acceptable acoustics.

2.1.1. Acoustic Design

The architect's idea in the Panopticon and the Multi-purpose Hall was that the guests would sense that they were outside in the nature, "sounds coming from all directions". With respect to this idea a term "Street-acoustics" was applied, where it was desirable to imitate acoustics in an open street. After the opening the acoustical problems became apparent where a measurement showed a reverberation time of 10 s at the middle frequencies. In a way it is somehow unrealistic to compare acoustics in an open street to a hall made of very reflective surfaces with a high ceiling since the sound is reflected by the ceiling while it is absorbed out in the sky in the street. The goal of the acoustic improvements was to shorten the long reverberation of 10 sec down

to approximately 2-3 sec. In order to achieve the target, a great amount of absorbing materials had to be installed in both halls. The acoustic improvements lead to a general acceptance of both the personnel and museum guests. The number of various cultural activities in the halls was at a minimum but with improved acoustic surroundings they increased.

2.2. Aros

Aros is a modern art museum in Århus and it was opened in 2004. The building itself is a cube of an area 52 x 52 m² and it has a height of 43 m. Along the cube a curved path is laid and here the museum-street can be found.

2.2.1. Acoustic design

The main emphasis was put on the museum-street in the acoustical design. The museum-street is a large open space with a high ceiling. It was acknowledged beforehand that there might exist acoustical problems, the Hall being too reverberant. One of the objectives in the acoustical design was that the museum guests would be aware that they are in a large hall, therefore a long reverberation was deemed satisfactory. In this acoustical design the museum-street was divided into two parts the space below terrain and above terrain. The Hall under terrain consists of three stories and it accommodated various arrangements such as meetings, lectures and different exhibitions. The hall is open to the museum-street from above and therefore an acoustical connection exists between the two halls. Since the hall should provide good environment for lectures the most important acoustic parameter in the acoustical design is the Speech Transmission Index. In order to optimize the listening conditions various absorption techniques were utilized. In the simulation a reverberation time of 2,3 sec was achieved without audience but 1,4 sec with 200 persons present [2]. Additionally, absorptive curtains were also recommended in order to optimize the intelligibility. The hall above terrain consists of a large open space with many levels. The intention with the Hall was to function as a large foyer for the museum guests but should not be used for any arrangements. It was desired to damp the room such that activities would not disturb the guests in adjacent galleries. A reverberation time of 2.4 sec was achieved by use absorption materials in the street.

2.3. Arken

The museum opened in 1996 with an exhibition space of 9200 m². One of the requirements made by the architect was that the museum building would provide flexibility for different cultural activities and exhibitions.

2.3.1. Acoustic design

The museum building consists of large open galleries, small exhibition rooms, square rooms and odd angle and tilted pathways. The most dominating part of the building is the Art Axis, which is a 150 m long exhibition room. It has varying ceiling height from 3,5 m in one end and 12 m at the other end. The surfaces in the Art Axis are reflective which results in a rather reverberant room, but with appropriate absorptive installations in the room a reverberation time of 2,5 sec is attained. With respect to guided tours the conditions in the Art Axis can lead to acoustic problems, especially with large number of people. The tours should be aimed for small groups, where the guest can be near to the guide. It has also given some problem to use multi-media in the hall, where it has turned out to be rather difficult to find a satisfactory strength level of the source. When school children are visiting the museum the noise levels often become very high. In the museum there is a music and lecture hall for about 320 guests. A general satisfaction is among the visitors and personnel with the acoustics of the hall.

3. The National Museum of Iceland

The National Museum of Iceland was established in 1863. The original building is from 1946 and the architect of the building is Sigurður Guðmundsson. The building has 3 storeys, each with an exhibition space of 1270 m². The museum was opened again after extensive renovation in September 2004. Hornsteinar Architects were the designers of the museum renovation. The objective was to create excellent museum environment that would provide good exhibition surroundings offering multi-media and other types of information that would fulfil today's and future demands.

3.1. Acoustic Conditions

A short description of the most important locations at the museum is given. The intention is to offer a conventional introduction of the sites in the museum.

3.1.1. Acoustical Improvements and Location of Interest

Some acoustical improvements were attained by the renovation. These included in particular placement of acoustic panels in the ceiling of the largest exhibition halls. A general satisfaction is met both among the museum guests and the staff with the acoustic improvements in the large exhibition halls. In this project other placements within the museum were analyzed. Six measuring locations were agreed upon for room-acoustical investigation. The locations were considered to feature problematic acoustic environments and therefore they were investigated especially. These placements are: The Arc Hall, The National Gallery of Photography, The New Foyer, The Old Foyer, The Café and The lecture hall. The five first locations were reported to have too long reverberation time which results in a uncomfortable acoustics for a museum. The locations feature rather acoustically-hard and reflective surfaces, marble floors (Old and New Foyer, National Gallery of Photography and Café) and concrete or gypsum walls. Since in this experiment a theoretical exploration of the museum acoustics is of main concern one specific location is to be analyzed further. The analyses consist of simulations in room-acoustic software and later an assessment of the objective parameters in subjective listening tests are carried out. The Arc Hall was chosen for this purpose, firstly because of interesting location in terms of acoustics and potential in acoustical improvements.

3.2. Measurements

Impulse response measurement was conducted at six locations within the museum. They were carried out according to the international standard ISO 3382-2 using the Dirac measurement software [3]. It was acknowledged beforehand that the acoustical environment was not acceptable at some of the locations, especially in the Café, the Arc Hall and in the Foyers.

The reverberation time results in the Arc Hall have values from 1,6 sec up to 2,2 sec see figure 1.

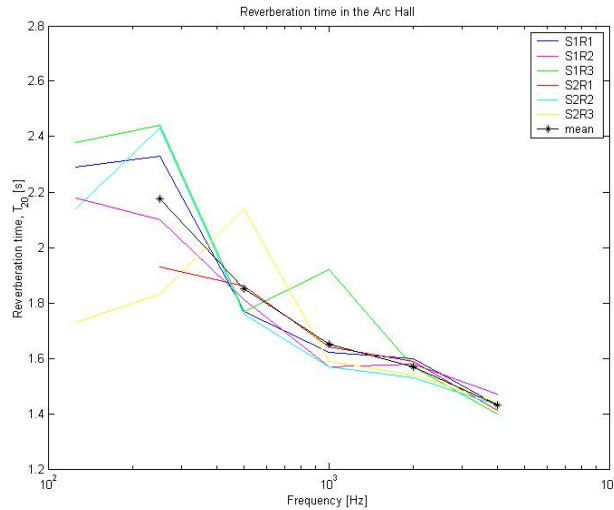


Figure 1. *The results of impulse response measurement at The Arc Hall, T20.*

At the time the measurement took place the back wall in the Hall was covered with carpet and the Hall was also furnished. This certainly has a great impact on the measurement, where without these installations a much longer reverberation would have been seen. Considering its size, a volume of approximately 514 m^3 and such a long reverberation in a furnished state certainly gives an indication of acoustical problems.

4. The modelling Procedure in Odeon

In order to verify the model simulation to the measurement results, it was necessary to perform a calibration on the model simulation done in Odeon.

4.1. Model Calibration

In the model calibration G-RT diagram methodology was utilized [4]. After several iterations by selecting materials in Odeon a satisfactory match was obtained between calculated mean-absorption from Sabine and mean absorption according to Odeon. Appropriate diffusion and transparency coefficients were also assigned to every surface [5]. A satisfactory match was attained between the measured and the simulated values.

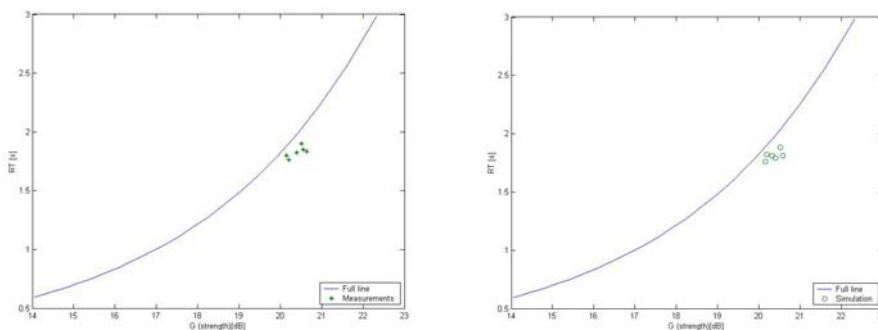


Figure 2. *G-RT diagrams for the measurement (left) and simulation (right).*

The graphs above show the measured values and the simulated data respectively. The curved line on the graphs is the expected relation in a diffusive field as a function of varying absorption coefficients. The dots indicate the six different source-receiver locations.

Table 1. *G and RT values for the measurement and simulation.*

Positions	Source-Receiver distance [m]	Measurement values			Simulated values		
		RT[s]	Alpha-measured	G [dB]	RT[s]	Alpha-simulated	G [dB]
1	3,64	1,83	0,10	20,64	1,81	0,10	20,58
2	4,66	1,83	0,10	20,39	1,88	0,10	20,52
3	4,10	1,85	0,10	20,56	1,79	0,10	20,41
4	5,16	1,90	0,09	20,51	1,76	0,10	20,16
5	6,59	1,80	0,10	20,14	1,82	0,10	20,19
6	4,83	1,76	0,10	20,21	1,81	0,10	20,33
Mean			0,10			0,10	

The average of the alpha-mean values for the measurement and the simulation are identical with 2-digit precision. A slight deviation can be seen in the G-values where the maximum difference becomes 0.35 dB at the fourth position. Similarly a maximum deviation is attained in the reverberation values for this same position of 0.14 sec. The difference for G and RT is considered in an acceptable range since the match in the two graphs is satisfactory.

4.2. Model Simulations

A precise model of the Arc Hall is simulated in Odeon and the aim is to make a model that would provide realistic listening conditions for listening tests. In order to get an extensive range of listening experience with regards to speech intelligibility, noise distraction, listening effort and speech privacy four different models of the Arc Hall were prepared.

Table 2. Reverberation time and STI for each model, values calculated at receiver position at 500 Hz.

Model	Description	RT [s]	STI
1	Unfurnished	3,11	0,39
2	Furnished	2,08	0,43
3	Furnished and absorptive ceiling	0,71	0,55
4	Furnished and absorptive ceiling and screens	0,62	0,56

The values in the table above are taken from the interaction between the target source and the receiver in the four different acoustical settings. The STI is given at the receiver position for 500 Hz. It is clear that the STI improves as the reverberation time decreases, as expected.

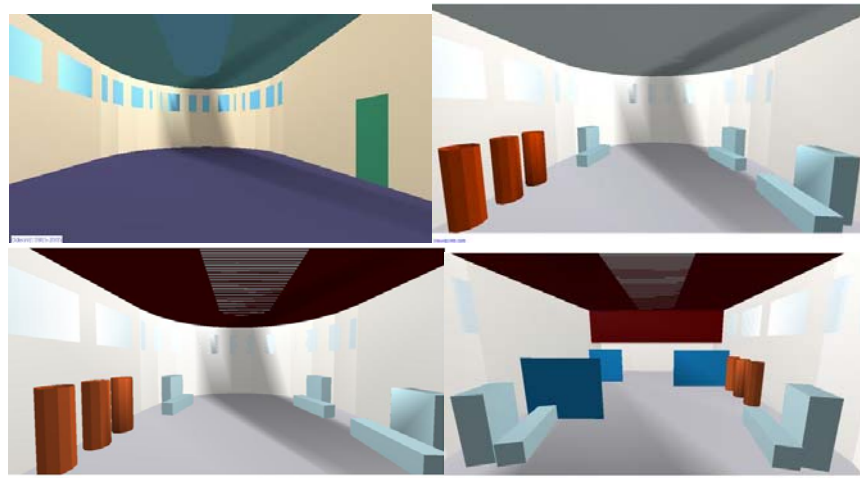


Figure 3. Interiors of the four models in Odeon

Table 3. Absorption data for each model

Alpha-mean	Frequency bands					
Model	125	250	500	1000	2000	4000
1	0,072	0,061	0,058	0,055	0,055	0,056
2	0,087	0,075	0,076	0,07	0,074	0,074
3	0,196	0,216	0,282	0,281	0,289	0,269
4	0,218	0,231	0,289	0,283	0,288	0,255

In the table it can be seen how the mean absorption at 500 Hz is increased with every model. The absorption change is most significant between models 2 and 3. It is clear that the absorptive ceiling has the most considerable influence on the overall results among the models. The effect of the screens in the simulation for

model 4 is not seen to have significant impact on the overall results, except at 125 and 250 Hz, where their contribution to the total reverberation time becomes apparent.

Table 4. *STI values for all session in listening test A (left) and listening test B (right).*

Session	Version of the model				Session	Version of the model			
	1	2	3	4		1	2	3	4
TS	0,39	0,43	0,55	0,56	Male	0,39	0,43	0,55	0,56
TS+MS	0,22	0,32	0,42	0,44	Music	0,32	0,35	0,44	0,44
TS+FS1	0,31	0,35	0,49	0,51	Male+Music	0,28	0,32	0,42	0,44
TS+MS+FS1	0,19	0,27	0,4	0,42					
TS+FS1+FS2	0,26	0,29	0,44	0,49					

The resulting STI values can be seen in the tables. In listening test A each version of the model is simulated with five different source scenarios where TS is the target source, MS is the music source, FS1 and FS2 are the female speaker sources. The impact of the absorptive ceiling is apparent as the STI increased for every source-session from model 2 to model 3. Since the target source and the noise sources are simulated to have the same sound power the STI is seen to decrease when the noise sources are present. This can be explained by the fact that the signal-to-noise ratio has a relative low STI value at the receiver position. The effect of the screens can be seen as the STI values increase from model 3 to 4. This improvement is at most in the last session where the STI increases from 0.44 to 0.49. The two separate screens block direct sound from the noise sources (FS1 and FS2) from reaching the receiver. Only first order reflections from the two noise sources reach the receiver with paths of 7.56 m and 6.44 m in each case and the STI is improved due to higher signal-to-noise ratio.

The same STI values are attained in listening test B as in the first session in test A, as expected. An improvement of STI values can be seen in every model due to lower reverberation time and the STI values in the last two sessions are decreased due to higher sound pressure level and lower signal-to-noise ratio.

5. Listening Tests

The main objective of the listening test was to get a subjective evaluation on the acoustical quality at the National Museum of Iceland. The objective acoustical parameters; The Speech Transmission Index (STI) and the reverberation time (RT) have an essential impact on the acoustic outcome. Loudness and type of noise, placement of absorbing materials have a major impact on speech intelligibility, noise distraction and listening effort. In order to get a reliable estimate a subjective assessment is performed in two different listening tests. A public place like a museum must be viewed as a multi-source environment. Several noise generators can be present, HVAC-systems, noise from other museum guests, multi-media producing either music or dictations and sounds from guided tours. When all these possibilities are considered the situation becomes rather complex and several options are relevant.

Simultaneous conversations are one of the most important activities at a museum; they can be desired at one incident but transform into a noise generator at another occurrence. Conversations are therefore thought to be on of the main aspects when a listening test simulation for a museum is created. When the listening tests were designed three main situations were focused on;

- Firstly, when a private moment is desired and speech privacy should be optimized.
- Secondly, when guided tours are given and speech intelligibility, noise distraction and listening effort are important factors.
- The third possibility is when the two former situations are gathered together. This last option can become quite complex, since opposite optimizations in terms of intelligibility and privacy are desired.

Two listening tests were prepared where four different objective parameters are subjectively assessed. The test-subjects listen to a target source while various noise generators are activated. This is done in each acoustical settings of the Arc Hall. The test-subjects estimate their listening experience on a five-point scale for three acoustical parameters; Speech intelligibility, noise distraction and listening effort.

The latter listening test estimate speech privacy where the test-subjects are exposed to various noise-generators but at the same time they are focused on reading a text. In this test the subjects are presented to 12 audio files created in Odeon and the speech privacy is evaluated on a five-point scale.

5.1. Listening Test Structure

5.1.1. Listening Test A

Four different acoustical settings of the Arc Hall and five varying source-noise combinations are utilized in the test. It starts with a single-source auralizations, where the target source is defined. The remaining source auralizations are a multi-source where the target source is always present but different noise sources are used, either as a single noise generator or at its most where two noise sources are added to the target signal. The target source is a male speaker in all sessions and the two noise sources are female speakers.

Table 5. Organization of listening test A.

Session	Target source	Noise source
1	Male speaker	-
2	Male speaker	Music source
3	Male speaker	Female speaker
4	Male speaker	Music and female speaker
5	Male speaker	Two female speakers

Table 6. Rating scales for listening test A.

Intelligibility		Listening effort		Noise distraction	
Excellent	1	Complete relaxation	1	No distraction	1
Good	2	Attention necessary	2	Slight distraction	2
Fair	3	Moderate effort required	3	Distracting	3
Poor	4	Considerable effort required	4	Much distracting	4
Bad	5	No meaning understood with any feasible effort	5	Very much distracting	5

In this test the main parameters of concern are intelligibility, listening effort and noise distraction. In order to assess the auralization files five point rating scale was used for each parameter, [6]. The first two parameters are closely related and can be described by the Speech Intelligibility Index (SII). The intelligibility represents if all of the sentence and all words in the sentence are understood by the test subjects. The SII is defined by two variables; intelligibility of the words in the sentence and listening effort. The listening effort becomes very important especially in a multi-source environment [6]. The third parameter is an evaluation of the noise source. The word intelligibility decreases when STI decreased below 0.3 and listening difficulty begins for STI values lower than 0.7 [7].

5.1.2. Listening Test B

In the latter test where the speech privacy is to be analyzed 12 auralizations are prepared in Odeon. The test-subjects read a text meanwhile they are exposed to differing noise sources modeled in Odeon. In this test three different noise sources are used in four different acoustical settings.

Table 7. Organization and rating scale for listening test B.

Session	Noise source	Speech Privacy	
		None	1
1	Male speaker	A little	2
2	Music	Acceptable	3
		Moderately good	4
3	Male speaker and music	Confidential	5

The structure of the speech privacy test can be seen in the former table and in the latter a rating scale and designations are shown [8].

In acoustical research where the main goal has been to relate objective measures to perceived speech privacy it has been shown that the SP is dependent on the speech-to-noise ratio rather than the absolute levels of either the speech or the noise [8]. Some studies imply that value of 0.15 for Articulation Index or less refers to normal or acceptable speech privacy [7]. In the speech privacy test, which can be described to be a task-oriented listening test, the selection of the test-subject's task has to be chosen carefully, since the rating is strongly influenced by their activity. The subject's activity in the listening test was text-reading. Since a museum is considered a multi-source environment with many possible noise generators the noise sources in this test were chosen to be firstly a speaking person (male speaker) and secondly a music source. Twelve different text pieces were chosen for the test as it was not thought to be advantageous that the test-subjects could learn the text by heart and thereby judging the speech privacy possibly better because they were familiar with the text piece. The speech privacy was evaluated on a five point scale.

5.2. Listening Test Results

In Figure 4 the evaluated parameters are shown for four acoustical settings. A music source is activated as a noise source.

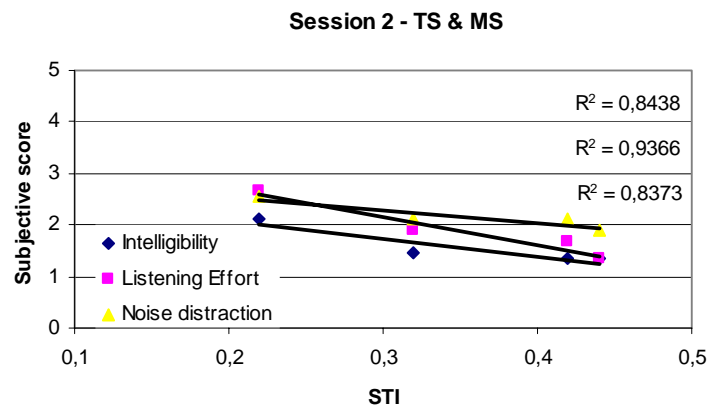


Figure 4. Mean ratings for session 2 in listening test A

The listening effort has a strong correlation of $R^2=0,9366$ but where the other two have a little less correlation of $R^2=0.84$. It can be argued that since the noise source in this session is a music source some of the test-subjects might have found it not so distracting. Contrarily, pleasing experience with the music source activated, some test-subjects claimed. The hypothesis can be accounted for when data for noise distraction is analyzed especially. The mean of the subjective rating vary from 2.6 to 1.9 for the first acoustical setting to the last one. Using the designations, the test-subjects find the music source slightly distracting on average in last three settings but distracting in the first. One could have expected a broader range of the subjective ratings since the acoustical settings extend from a reverberation time of 3.11 sec in the first model to 0.62 in the last version.

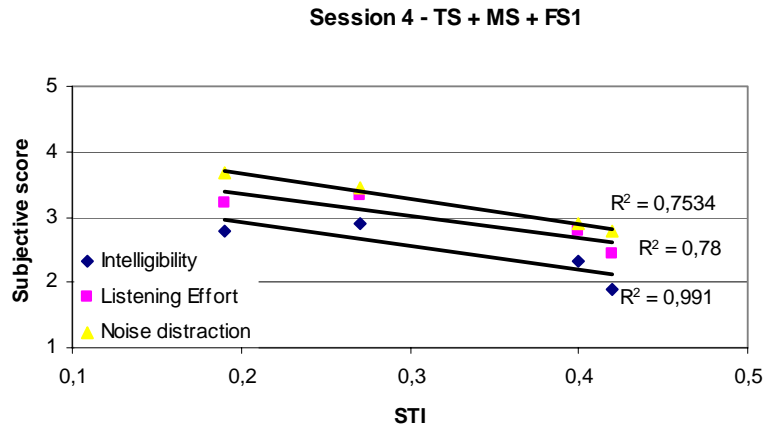


Figure 5. Mean ratings for session 4 in listening test A

In Figure 5 the mean scores for the acoustical settings can be seen when two noise sources are active, a music source and a female speaker. The noise distraction has a nearly perfect correlation, while the other parameters show not as good results, with correlation of $R^2=0.7543$ and $R^2=0.78$ respectively.

The subjective parameter speech privacy is plotted for each session in the same four different acoustical settings as in listening test A.

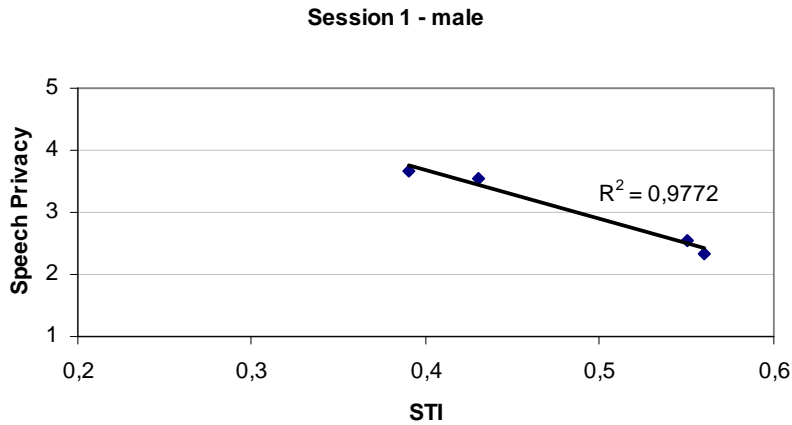


Figure 6. Mean ratings for session 1 in listening test B.

In Figure 6 the subjective scores where a male speaker is active can be seen. The speech privacy is in good correlation with the STI, where $R^2=0.9772$.

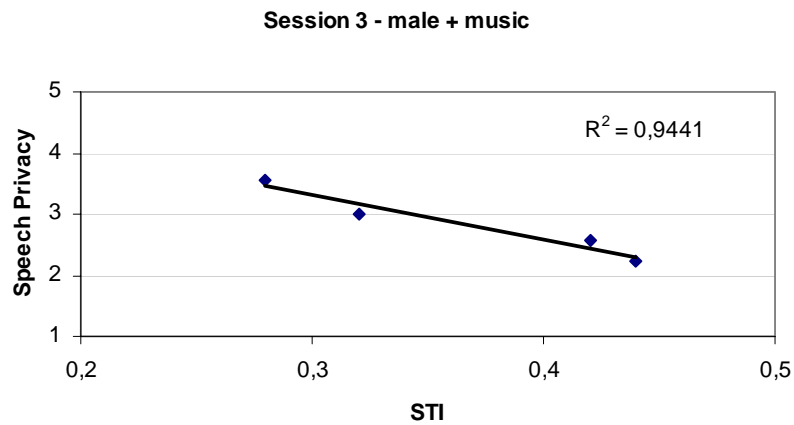


Figure 7. Mean ratings for session 3 in listening test B.

Mean scores for speech privacy can be seen when the noise source are simulated as music and a male speaker in figure 7. The mean score is in a good agreement with the speech transmission index with a correlation coefficient of $R^2=0.9441$.

6. Discussion and Conclusion

In the investigation at the museums in Denmark several interesting aspect concerning acoustical quality at a museum arose. The research gave an indication of very different approaches towards acoustic improvements and design. The museums have one particular aspect in common. With respect to museum design it can be stated that a magnificent architecture with open areas and high ceilings are often desired. This applies for both old and historical museum buildings and newly designed museums. The museums are therefore faced with halls and rooms which are often too reverberant which can lead to undesirable acoustic conditions.

The cooperation with the National Museum of Iceland lead to an investigation of its acoustic environment. Acoustical problems at several locations at the museum entailed an extensive experiment and research. One particular placement was chosen for subjective assessment in two separate listening tests.

The subjective scores for intelligibility in listening test A gave the best correlation when the noise source was simulated as a female speaker (session 3). The lowest correlation in terms of intelligibility was attained in session 1. Listening effort resulted in best and least correlation in sessions 2 and 3 respectively where the noise sources were music and female speaker. Noise distraction was least correlated in session 3 and best correlated in session 4. Best correlation with respect to speech privacy is obtained in session 1 when the noise source is modeled as a male speaker.

In listening test A the mean ratings show a rather limited usage of the rating scale. In listening test B session 1 according to the subjective scores acceptable speech privacy is attained with a STI of approximately 0.47. The mean of the subjective ratings do not extend over other ratings possibly due to fairly narrow range of STI values. From this observation it can be seen argued that a stronger requirement is put on the speech privacy in a multi-source environment than when a singular noise source is present. Listening tests A and B gave satisfactory results, more precisely, in both tests the objective parameters STI and SPL(A) are well correlated to the subjective measures intelligibility, listening effort, noise distraction and speech privacy. Even though a good correlation is obtained and the trend in the ratings can easily be seen the subjective ratings are concentrated in the middle of the rating scale and the results suffer from a central tendency error.

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