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DISCRIMINATION BETWEEN THE PRESENCE OF GLASS AND ETFE CUSHIONS IN ATRIUMS, LISTENING TEST RESULTS

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ABSTRACT

ETFE or ethylene tetrafluoro ethylene cushions are a popular design choice for covering large semi-public spaces due to their low weight and transparency to light. ETFE based constructions are increasingly used as an alternative to glass panes, due to their equally good admittance of light. Despite their presence in large-scale building projects, their acoustic absorption properties have not been thoroughly investigated yet [1] [2] [3] [4]. Single membranes have been characterized in literature [5] [6] [7] [8] [9], but the extrapolation from the behavior of membranes to the one of cushions is not straightforward. While the choice for ETFE over glass has a limited impact on light admittance in atria, the same cannot be said in terms of room acoustics. Compared to ETFE membranes, glass panes are more reflective (especially below 2000 Hz), leading to longer reverberation times inside the rooms. In this work, we reconstructed 4 real world rooms that are built with ETFE cushions as cladding. We created a new set of virtual rooms where the acoustic characteristics of these ETFE surfaces were changed to the ones of glass. We then performed an ABX listening test protocol using auralisations in these rooms as stimuli. The results show that the higher reflectivity of glass is perceptually significantly different in 4 real-world rooms where the choice between ETFE and glass for the translucent surfaces could made in the design phase.

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1. INTRODUCTION

ETFE or ethylene tetrafluoro ethylene is a fluoropolymer that can be extruded into thin films or membranes. Since the 1980's, these films have increasingly been applied as building skins (roofs or facades). Currently, designers and contractors of large to mid-size projects involving large spaces that benefit from day light protrusion (atria, stadia, shopping streets) increasingly opt for the application of these membranes, in the form of cushions, as cladding. There are several benefits to using these lightweight membranes (and especially ETFE cushions) as the cladding material of large spaces where daylight is vital. ETFE membranes let through almost all visible light as well as a large part of the UV-spectrum. The membranes are light, meaning that large structural spans are possible, reducing the weight on the primary structure and thus reducing the dimensions of it. For an overview of other benefits and drawbacks of the application of these membranes in architecture, we refer to Lamnatou et al [1].

In terms of acoustics, lightweight ETFE membranes exhibit high acoustic transparency due to their low surface weight. With a typical thickness of 0.1-0.25 mm, the critical frequency or coincidence frequency (0.3-0.4 MHz) is many times higher than the highest audible frequency for humans. Therefore, the acoustic behavior of the membranes in the 20 Hz – 20 kHz range is dictated by the mass law.

Theory learns that for low (63 Hz) frequencies, the mass (0.4 kg/m²) is so low that the membranes are practically fully acoustically transparent. With increasing frequency, the membranes are increasingly reflective (the flow resistivity is very high as this material is impermeable). At around 8 kHz, for a typical thickness of 0.15-0.25mm, the acoustic reflection coefficient of this material is around 1. This behavior has already been described for other types of impervious membranes, e.g. in the following references [5] [6] [7] [9]

If one or a combination of membranes is used as the cladding material in a room, then low frequency sound energy is allowed to pass right through the material while high frequency sound waves are reflected more back into the room. In room acoustics, sound energy that does not stay in the room can be considered as effectively absorbed. This is the apparent sound absorption.

Following the above, theoretically, the apparent sound absorption of ETFE membranes with typical thicknesses at low frequencies can be considered to be near 1 at low frequencies, and tends to 0 towards 8 kHz.

Glass panes, however, are much more acoustically reflective, even in the low frequency range (63 - 250 Hz) due to their high surface weight (20-40 kg/m²). If, design-wise, a choice between the two is to be made, it can be revealing to study the impact on the perceptual differences of the room acoustics to help designers opt for the correct material according to the function of the room. The difference between the absorption coefficient of glass panes and ETFE cushions is very large in the low frequency range but becomes smaller with increasing frequency. Given the complex nature of human sound perception, it is worth investigating the impact despite the large difference mentioned above.

2. METHOD

2.1 Measurement and extraction absorption coefficients

To the best of our knowledge, the absorption characteristics of real life ETFE membrane structures have not yet been reported in literature and neither are real measurements available. Using impulse response measurements measured according to ISO3382 in four rooms clad with ETFE cushions, we have attempted to extract the apparent sound absorption coefficient of the ETFE surfaces. Figure 1 and Figure 2 show pictures of the interiors of rooms measured in Berlin (MOA Mercure Hotel) and Rotterdam (Drijvend Paviljoen) respectively. The other two rooms were situated in Liège (Mediacité Liège) and London (Devonshire Square).

Figure 1. Interior of the room measured in Berlin, MOA Mercure Hotel Berlin

For each room, the following steps were taken to extract the acoustic absorption coefficients of ETFE cushions.

- Measurement of impulse response for a series of microphone and loudspeaker positions
- Measurement of the geometry of the rooms, including logging of all locations of materials and identifying the material and construction type
- Virtual reconstruction of the rooms in Odeon®, including the source and receiver positions of the measurements
- Entering in the Odeon® model the sound absorption coefficients and scattering coefficients for the various materials and surfaces in the rooms
- Extracting the sound absorption coefficient of the ETFE surfaces using a built-in genetic algorithm model in Odeon®

It should be noted that this method of extraction is not foolproof. There are a few sources of uncertainty, the main one being the absorption coefficients of the other materials in the room. The latter need to be reasonably accurate for the extraction to be accurate as well. In an upcoming publication, more information regarding this process is given. In Figure 3, the result of the optimisations is presented along with the absorption coefficient of double pane glass. The absorption coefficients of the ETFE

Figure 2. Interior of the room measured in Rotterdam, Drijvend Paviljoen Rotterdam

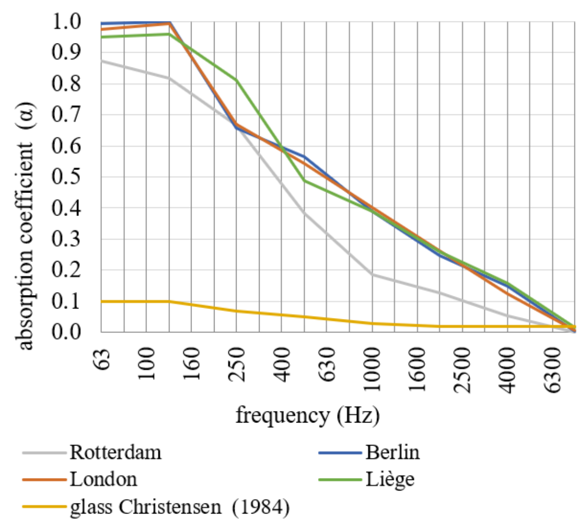

Figure 3. Plot of the absorption coefficients of the ETFE surfaces extracted with the genetic algorithm optimisations in Odeon®along with the absorption coefficient of double pane glass (in yellow)

surfaces are not equal in each room but there is some resemblance, and generally there is good agreement with an ad hoc chosen theoretical model (which assumed infinite boundaries) and with our previous measurements [10]. The largest deviation from theory and measurements occurs in the region above 2 kHz, where the obtained absorption coefficient is 0.1-0.15 higher than what the chosen model predicts and measurements show (except for the Rotterdam results, where the correspondence is significantly better).

After having determined the absorption coefficients of the individual materials in the room, four extra models were created, in which the ETFE surfaces were virtually replaced with glass surfaces. In Figure 4 the geometries of the four rooms are portrayed next to each other virtually. The relative amount of ETFE area can be observed at a glance. An overview of some characteristics of the four rooms is given in Table 1. Additionally, the absorption coefficients for ETFE cushions found in each room were applied in the other rooms (the absorption coefficient obtained in London was omitted because it was almost identical with the absorption coefficient obtained in Berlin), creating eight more models.

2.2 Auralisation

From these sixteen virtual models (ETFE models and glass models) several auralisations were made. For each room, a total of 6 auralisations were made. A virtual source with the directivity profile of a speaking person

Table 1. Summary of geometrical properties of the four rooms measured. The relative area that is represented by the ETFE cushions is also listed in the third column. Some rooms have a relatively higher percentage of ETFE cushion coverage than other rooms.

Name	area (m²)	%ETFE	V (m³)
Mediacité	7489	17	26177
Devonshire square	9800	13	31042
MOA Mercure	6376	21	17288
Drijvend Paviljoen	1847	46	3981

was placed roughly in the middle of each room. A virtual binaural microphone with HRTF was placed at 1.5m from the source. The source and receivers were oriented pointing towards each other. Three stimuli were auralised. Clear speech (middle aged male), pink noise (with a 0.5 s fade in and out to prevent transient effects), and a somewhat impulsive noise signal recorded in the anechoic chamber (a chair moving on the floor). No background

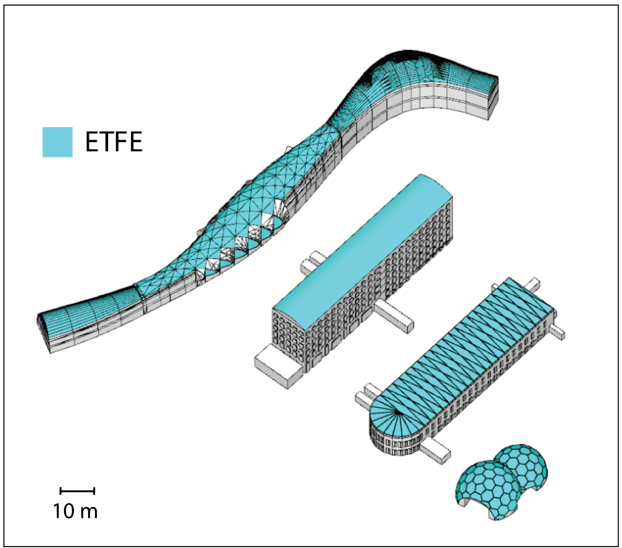

Figure 4. Overview of the four virtual models used in the optimisation problem. The blue surfaces correspond to the surfaces clad with ETFE cushions. These are the surfaces that were also "converted" to glass for the study. Left to right: Liège, London, Berlin, Rotterdam

noise was added. A total of 3x16 = 48 auralisations were generated. The reverberation times of a selection of cases is shown in Figure 5.

2.3 Listening test

The goal of the listening tests was to check the ability of people to discriminate between the auralisations. Our main interest was to check for the audibility of differences in absorption coefficients. Therefore, it was decided to only compare the same stimuli auralised in the same room but with different sound absorption coefficients. In other words, no auralisations with different stimuli or from different rooms/models were compared. Following this reasoning, from the 48 auralisations, 24 combinations were chosen.

The listening tests were performed according to the ABX protocol. Participants were asked to compare two sounds (A and B) and select two options: either A = X or B = X. There was no blank option, the trials were forced choice. There was no limit on the amount of plays per trial, there was no time limit either. Sounds behind buttons A and B were randomized per participant and per

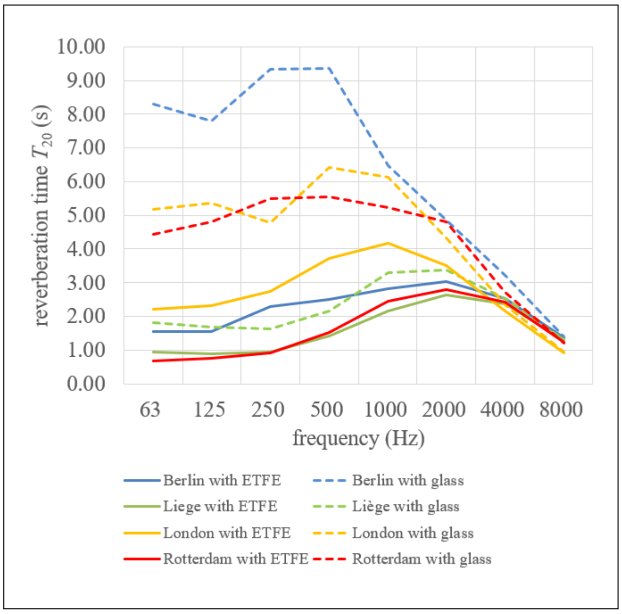

Figure 5. Reverberation times of a selection of cases. The absorption characteristics of the ETFE membranes was chosen according to the results of genetic optimisation in that location. The reverberation time is always higher in the case with glass applied instead of ETFE cushions (original design).

repetition. The reference sound (X) was fixed across all combinations, the reference sound was either A or B (randomly chosen). Each ABX trial corresponded to one of 24 combinations. Three stimuli were auralised, so the test was split in three sections (one per stimuli). Within one test (one stimulus) two repetitions were done. The total number of trials per test (1/3) was 3x24 = 72. The entire test (3x72) was repeated once 7-14 days after the first test. In Figure 6 a screenshot of the listening test protocol is shown.

2.4 Listening test conditions

Participants were asked to sit in the semi-anechoic room of the Laboratory of Acoustics of KU Leuven. This room has low background noise due to the box-in-box construction of the primary structure of the room. A high-fidelity sound card was used in conjunction with diffuse field calibrated open backed headphones. The sound pressure level of the presented stimuli was calibrated to be around 63 dB. This value fluctuated by around 2-3 dB between auralisa-

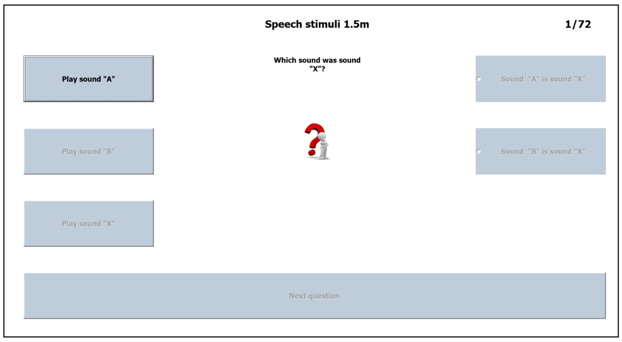

Figure 6. Screenshot of the listening test interface. ABX listening test protocol with forced choice.

tions, since the auralisations were not Loudness equalised. After all, not only reverberation varies in rooms with different sound absorption coefficients applied to the room boundaries but also the sound strength. In that sense, the level variations were representative of real-life conditions.

There was an allowed break between the three tests, which were performed on the same day. This break lasted approximately 2-5 minutes and allowed the participant to go to the toilet or drink water when thirsty. Each participant received the same basic instructions regarding the test, along with a warning that it is possible that they could sometimes not hear the differences between sound A and B and that they should try to not be discouraged by it.

2.5 Participants

Fourteen participants were invited to perform the tests. Before they were allowed to participate, a simple hearing test was performed (once, before the first test). Their ability to hear pure tone test signals of [125 250 500 1000 2000 4000 8000] Hz was tested with a simplified descending method. It was determined that the ability to detect these pure tone signals to a level of 20 dB was sufficient as a condition to participate in the test. Two people were rejected for having insufficient hearing performance, mainly for the 4 kHz and 8 kHz test tones. The participants who did complete the tests (n=12) were aged between 21 and 59. Half identified as male and half as female.

3. RESULTS

3.1 Ranking and comparisons

When a participant had correctly paired either A or B to the reference sound X, a score of 1 was given, and 0 otherwise. Every combination was tested a total of three times, meaning that either 0, $0.\overline{3}$, $0.\overline{6}$ or 1 were possible scores per person per combination.

Table 2. Combinations and combination number with the room and α combination. Scores are averaged across 12 subjects, three signals and two separate test moments (test and retest).

#	Room	α 1	α 2	score
1	Berlin	Berlin	Liège	0.58
2	Berlin	Berlin	glass	0.97
3	Berlin	glass	Liège	0.98
4	Berlin	Liège	Rotterdam	0.77
5	Berlin	Rotterdam	glass	0.98
6	Berlin	Rotterdam	Berlin	0.84
7	Liège	Berlin	Rotterdam	0.70
8	Liège	Berlin	glass	0.86
9	Liège	Berlin	Liège	0.63
10	Liège	Liège	glass	0.70
11	Liège	Liège	Rotterdam	0.53
12	Liège	Rotterdam	glass	0.75
13	London	glass	Rotterdam	0.75
14	London	glass	Berlin	0.89
15	London	Liège	glass	0.85
16	London	Liège	Berlin	0.54
17	London	Rotterdam	Liège	0.61
18	London	Rotterdam	Berlin	0.66
19	Rotterdam	Berlin	Rotterdam	0.94
20	Rotterdam	Berlin	glass	1.00
21	Rotterdam	glass	Liège	1.00
22	Rotterdam	Liège	Berlin	0.53
23	Rotterdam	Liège	Rotterdam	0.94
24	Rotterdam	Rotterdam	glass	0.98

In Table 2 the combinations and the average score across subjects are displayed. In Figure 7 the average scores per combination are plotted (across the two test moments and across the three stimuli types). There were 6 combinations per room (colours). Each combination included an absorption coefficient α 1 applied in room x combined with absorption coefficient α 2 applied in that same room x. The absorption coefficients are shown in Figure 3.

Looking at the average scores, one can clearly distinguish between cases with the glass absorption coefficient applied and the ones where there was no glass absorption coefficient applied. The scores of the former are

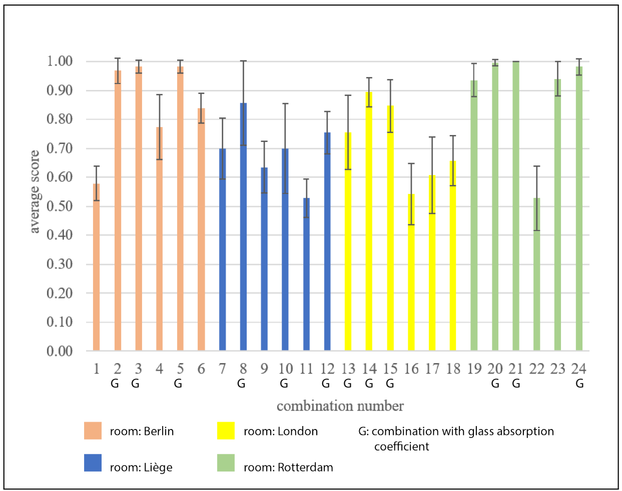

Figure 7. Average score per combination (averaged over 12 participants. The colours correspond to the rooms (geometries) in which the combinations were tested. The ”G” label below the columns indicates that one of the auralisations in the combination was simulated with the glass absorption coefficient. Given the big difference in the sound absorption coefficient (see Figure 3), it is reasonable to expect these combinations to have higher correctness scores since the reverberation was often more than 3 seconds higher with glass.

clearly higher in most cases except in the Rotterdam room. In the latter, 2 other combinations involving only various ETFE absorption coefficients received high average scores (>0.9). One combination (#22) involving α Liège and α Berlin scored lower (0.53) on average. This result could be expected, since the values of these two absorption coefficients are rather similar, compared to the two others.

In Figure 7, the standard deviations are also plotted as error bars. The standard deviation for glass variant combinations is lowest in rooms Berlin and Rotterdam. This is followed by room London and finally room Liège. Clearly, the scores are not only higher in rooms Berlin and Rotterdam but the standard deviations are also lower. We can conclude that it is simply easier to discriminate between absorption coefficients in rooms Berlin and Rotterdam. This is also an expected result: these rooms are smaller in volume and the surfaces that were changed were situated were closer to the listening position. In room Berlin and Rotterdam, the smallest distance to the changed surfaces in the model was approximately 8 m and 10 m while it was approximately 12 m for room Liège and 20 m for room London.

In Figure 8 the results from Figure 7 are split per stimulus type. The scores are generally highest for the third stimulus (chair noise) which was the shortest and most impulsive stimulus type, followed by speech and then pink noise as can be seen in Table 3.

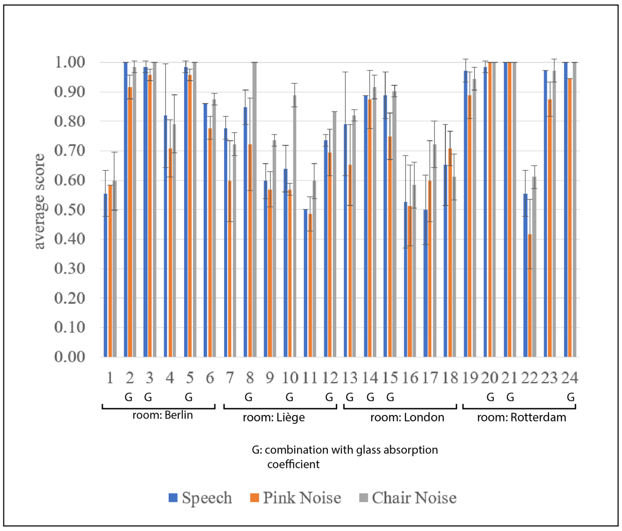

Figure 8. Column graph similar to Figure 7 but split in three stimulus-wise. The scores are averaged over subjects and two test moments. The scores are generally highest for the third stimulus (chair noise) which was the shortest and most impulsive stimulus type, followed by speech and then pink noise.

In Table 4 it is indicated that the score for room Rotterdam was the highest overall (averaged across α and stimulus). This is an expected result as the Rotterdam room originally contained 42% of surfaces covered by ETFE cushions (and thus subject to change), which is the highest percentage in the set.

Table 5 shows that clearly the scores for combinations containing α: glass were the highest on average (0.90). This is followed by α: Rotterdam (0.79). This result is an expected result, because in terms of absorption coefficient these values were more different from α: Liège and α: Berlin (see Figure 3).

Table 3. Combinations and combination number with the room and α combination. Scores are averaged across 12 subjects and two separate test moments (test and retest).

#	speech	pink	chair
1	0.56	0.58	0.60
2	1.00	0.92	0.99
3	0.99	0.96	1.00
4	0.82	0.71	0.79
5	0.99	0.96	1.00
6	0.86	0.78	0.88
7	0.78	0.60	0.72
8	0.85	0.72	1.00
9	0.60	0.57	0.74
10	0.64	0.57	0.89
11	0.50	0.49	0.60
12	0.74	0.69	0.83
13	0.79	0.65	0.82
14	0.89	0.88	0.92
15	0.89	0.75	0.90
16	0.53	0.51	0.58
17	0.50	0.60	0.72
18	0.65	0.71	0.61
19	0.97	0.89	0.94
20	0.99	1.00	1.00
21	1.00	1.00	1.00
22	0.56	0.42	0.61
23	0.97	0.88	0.97
24	1.00	0.94	1.00
AV	**0.79**	**0.74**	**0.84**

3.2 ANOVA results

An Analysis of Variances (ANOVA) was carried out on the results using the SPSS® software package. The data passed the Mauchly's test of sphericity (Sig >0.05 in all cases). The data was examined at different levels (within-subject effects). To account for the multiple comparisons within the study, the Bonferroni correction was applied. The levels are (top to bottom): test/retest (2), stimulus (3), room (4), α (2).

There were no significant differences (p=0.34) on the test level meaning that results between the first and second test moment (7-14 days apart) were generally consistent.

At the stimulus level, there were significant differences (1-2: p=0.001, 2-3: p=0.001, 1-3: p=0.004). This can be seen in Table 3 and Figure 8 where stimulus three comes out on top as the easiest stimulus to discriminate between αs with.

Table 4. Scores averaged across subjects, stimuli and αs to obtain a score per room.

room	**score**	**stdev**
Berlin	0.85	0.15
Liège	0.70	0.10
London	0.72	0.13
Rotterdam	0.90	0.17

Table 5. Scores averaged across subjects, stimuli and rooms, thus representing a score per α. Combinations that contained each α were simply averaged together leading to a single score. It is important to keep in mind that these are still averages of combination (comparison between two αs) scores. No single α is scored separately.

α	**score**	**stdev**
glass	0.90	0.11
Rotterdam	0.79	0.16
Liège	0.73	0.19
Berlin	0.75	0.17

At the room level there were significant differences (p<0.007) between all rooms except between London and Liège (p= 1.00). Rooms London and Liège are both larger in volume, but the amount of surfaces in those rooms that are covered in ETFE cushions (and thus subject to change in this parametric study) are different (see Table 1).

At the α level (absorption coefficient) there was a significant difference between combinations with glass and combinations with no glass (p=0.001).

Finally, when taking a look at the influence of the stimulus in the different rooms (stimulus*room analysis), we can observe a few phenomena:

- There was a significant difference between all stimuli in the Liège room. Figure 8 shows that indeed the scores between signals in the same combination differ substantially more than in the other rooms.
- There was no significant difference between stimuli in the Berlin room. Again, 3 shows that the

differences between scores for one combination is rather equal between stimuli.

- In the London room the results are more mixed. There was only a significant difference between pink noise and chair noise stimuli
- For the Rotterdam room the results are also mixed, there only the difference between speech and chair noise was significant as well as the difference between chair noise and pink noise.

From this analysis it can be concluded that the stimulus type indeed makes a difference in the scores of the participants, depending on the room. This is not surprising, since the stimuli are rather different and it is known that different sounds have different interactions with the acoustic fields of a room.

4. CONCLUSION

From this analysis it can be concluded that the application of glass in a room creates a significantly different acoustic field. This observation holds for three types of stimuli with no additional background noise. The discrimination performance was highest in the smaller rooms with the highest portion of changeable surfaces. Some significant audible differences could be revealed in the absorption coefficients for ETFE cushions in the different rooms, the cause of these differences is uncertain. The application of ETFE cushions in rooms results in a lower reverberation time when comparing the acoustic field in those same rooms with glass applied (same surface area and same location). This difference was found to be significantly audible in our tests, even as close as 1.5 m from the source (but without background noise). Whether or not the application of ETFE cushions also increases the perceived comfort in a room is outside the scope of this paper. Further listening tests will be needed to tackle this matter.

5. ACKNOWLEDGMENTS

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