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On the Effect of an Acoustic Diffuser in Comparison with an Absorber on the Subjectively Perceived Quality of Speech in a Meeting Room

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Summary

Acoustic diffusers and absorbers are important components in room acoustic design and treatments to control unwanted reflections or to increase sound diffuseness, both of which may enhance subjectively perceived sound quality. To date, little is known about whether the treatment with diffusers or absorbers is more favorable for the subjectively perceived qualities, e.g. of speech, in ordinary rooms. The aim of this study was therefore twofold. The first aim was to investigate the effect of an acoustic diffuser on the subjectively perceived quality of speech in a meeting room. The second aim was to determine if and to what extent there are perceptual differences if the diffuser is replaced by an acoustic absorber. Two separate listening tests were performed with stimuli obtained from the convolution of measured binaural impulse responses of a meeting room with excellent speech intelligibility and speech samples recorded in an anechoic chamber. The results of the listening tests confirm that despite the already excellent speech intelligibility and low values of early decay time, speech quality can be further improved by introducing diffusers or acoustic absorbers, with absorbers improving the subjectively perceived speech quality slightly more than the diffusers.

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1. Introduction

Since their invention in the 1970s, specially designed acoustic diffusers are used as one of the most important components in room acoustic design and treatments [1, 2]. Theoretically, the device evenly disperses the incident sound energy in all directions independently of the angle of incidence [3]. By doing so, the strength of the specular reflections is reduced in a controlled manner without introducing absorption, provided that the diffuser has a low sound power absorption coefficient. This property is used to control unwanted reflections, responsible for degrading sound quality, or to increase sound diffuseness in spaces such as auditoria or acoustic laboratories. In room acoustics, unwanted reflections are of two types.

The first type is early reflection(s) that due to the interference with the incident sound introduce sound colouration either in form of regular variation in the frequency response or colouration in form of temporal fluctuations. The former requires delays roughly less than 25 ms, equivalent to path length differences of approximately 8.5 m or less, and the latter requires delays roughly between 25 and 50 ms, equivalent to path length differences of approximately 8.5 and 17 m [4, p.169]. The frequency domain colouration (perceived in frequency domain as comb filtering effect) can happen due to a single strong reflection or by a periodic succession of reflections [5, p.203]. The temporal fluctuation colouration is referred to as flutter echoes and its perception (mainly related to the time domain) is described as an audible high frequency ringing heard when for example hands are clapped in stairwells with parallel walls [4, p.23] that supply the required delay. In case of delays greater than roughly 25 ms, the sound colouration gradually changes from being a frequency domain to a time domain phenomenon.

The second type is a late reflection arriving roughly after more than 50 ms with a level considerably higher than the general reverberation. This type of reflection will be perceived as a separate event referred to as echo when it is only one and again flutter echoes when there are rapidly spaced series of them [6, p.307]. Any form of flutter echoes occur when the sound bounces back and forth between parallel, smooth and flat surfaces. The late delayed flutter echoes are common in lecture theatres as well as any disproportionately stretched rooms whose distance of parallel walls provide the required delay.

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To control these unwanted reflections, diffusers are not the only solution. An alternative approach could be to use acoustic absorbers. By this method, part of the acoustic energy of incident sound is absorbed. Whether diffusers or absorbers are chosen as the method of treatment depends on whether the energy conserved by the application of diffusers improves or detracts other aspects of room acoustics including the subjective qualities. For smaller rooms, absorbers are a possible solution to control echoes. For much larger spaces such as concert halls where acoustic energy is scarce and precious, diffusers are favoured as they absorb less energy [4]. It must be remarked that the application of absorption accelerates the decay of sound and as a result, there is less time for sound to blend. For this reason, the use of absorbers reduces diffuseness [7].

In the early nineties, perceptual changes in early sound field due to the application of acoustic diffusers was investigated for an auditorium size room to test if the treatment of surfaces with diffusing elements affects the preference of listeners [8]. The results suggested that diffuse reflections in the early sound field were not perceived differently from specular reflections when participants were binaurally exposed to the full sound field.

With the growth of the computational power of PCs, computer simulation became commercially available.

Given the geometrical approach of such simulations, the audibility and corresponding perceptual nature of diffusion which was simulated by the mathematical models of sound scattering was unknown. This was until various studies [9, 10, 11, 12] showed that the change of scattering coefficient causes audible changes in perception of the sound field in a frequency dependent manner. It was also shown that the change in perception is input signal dependent and is less detectable for complex signals such as speech and music than it is for stationary signals such as random noise. It was proposed, that future work should involve the investigation focus on objective acoustic parameters and perceptual evaluation in a variety of other room dimensions.

Although these studies demonstrated that the application of diffusers changes the perception of the sound field, they did not investigate how it affects the perception of unwanted reflections. A more recent study investigated the subjective extent of echo suppression due to the application of periodic diffusers such as those with triangular profiles [13]. It was found that reflection response from such a diffuser can be up to 6 dB lower in amplitude relative to the direct sound, forcing the remaining energy to diffuse in space and smear in time. This holds true only when the size of the diffuser is kept below a maximum length of 9 m. When this condition is not met, the attenuation is overridden by the perception of colouration [10, 13]. Taking into account the amplitude attenuation and frequency dependency characteristics of diffusers led to investigate which of these and to what extent, if any, would affect the perception of an echo's threshold [14]. It was found that for speech signals the echo threshold is increased significantly with the use of diffusers. It was suggested that the echo suppression is not only a consequence of redirection and/or attenuation of a reflection but also because the diffused reflected wave is easier for the auditory system to suppress.

Parallel to be a treatment for controlling unwanted reflection, diffusers are also used to increase diffusion in spaces such as auditoria or reverberation chambers in laboratories. Along with that line, a high correlation between acoustic quality and surface diffusivity of concert halls was found [15]. In contrary, when the conditions crucial for singers' voice comfort in auditoria was investigated, several studies [16, 17, 18, 19] agreed that diffusion is less important than a strong support. Studies on preferences by talkers produced similar results and showed that the majority of talkers preferred high reflection levels and low temporal diffusion, despite the colouration which results from such condition [20, 21]. This is in spite of the fact that in auditoriums, singers rely more on cranial vibration due to their own voice than auditory feedback provided by the room acoustics [22]. All these studies [15, 16, 17, 18, 19, 20, 21, 22] concern spaces that can accommodate echoes. In smaller rooms where reflections between parallel walls cause colouration and/or flutter-echoes, combined diffusers and absorbers are recommended as a treatment. For the later type of rooms, it was found that regarding the quality of speech in small rooms the first order reflections are the prime source of colouration [23]. Further, a change in quantity of diffusive surfaces are also detectable in music stimuli for small performance spaces [24].

It is true that the role of diffusion in auditorium acoustics has been acknowledged [1, 2] and methods are proposed to evaluate its extent [25, 26, 27], but its influence on the subjective perception of sound field quality has remained open to discussion [4, 28].

With the exception of research [23] and [24], the above investigations are associated with rooms of auditorium size and acoustic evaluation through computer simulation. Although these spaces require a very high objective and subjective acoustic quality, they are not places where people spend most of their life communicating by speech. None of the above studies were concerned with the occurrence of flutter echo in real meeting and conference rooms. These are rooms for which the acoustic support by room acoustics is crucial in terms of both speaking ease and decision-making confidence. The impact of room acoustics on speech intelligibility may well have been established and investigated. The degrading effects of echoes are also rather well experimented and understood, however, the effect of flutter echo and colouration is not [29].

There are informal evidence and skeptical observations, that the presence of acoustic diffusers affects the perceived quality of speech in small rooms that suffer from flutter echoes [30, 31].

The aim of this study is two fold. The first aim is to investigate the effect of acoustic diffusers on the quality of perceived speech in ordinary rooms. The second aim is to determine if there are any perceptual differences and to what extent if the diffuser is replaced by an acoustic absorber. Two separate listening tests with stimuli are performed using the convolution of measured binaural impulse responses and speeches recorded in an anechoic chamber.

2. Materials and Methods

2.1. Scope of research

This study aims at answering the following research question: ”Does the presence of acoustic diffusers improve speech quality in ordinary rooms?” Thus, the focus is on ordinary rooms that are not used for performing arts, and are acoustically small or at the border of being small. Such rooms are more likely to have dimensions that accommodate problematic reflections. Examples of such rooms are courtrooms, classrooms, board rooms, meeting rooms, conference rooms and, to some extent, bedrooms and living rooms. As these rooms possess speech as the primary acoustic excitation, speech was selected instead of music for the research question.

To focus only on subjective qualities, the aim was oriented towards rooms with standard excellent Speech Transmission Index (*STI*) of highest categories ”A” or ”A+”($STI \geqq 0.72$) according to IEC 60268-16 Annex G [32], but with the high frequency ringing contamination of flutter echoes. The above question can therefore be concretized as: ”Does the presence of acoustic diffusers improve speech quality in ordinary rooms with $STI \geqq 0.72$?” A room with such *STI* leaves the objective measure of intelligibility as a controlled variable

Given the commercial implications of diffusers’ cost and also extensive quantity of total absorption demanded in such relatively small rooms, it is also reasonable to suggest that instead of diffusers, absorbers can be employed as another possible remedial. This leads to the a second research question: ”Does the presence of acoustic absorbers instead of diffusers (further) improve speech quality in ordinary rooms with standard $STI \geqq 0.72$?”

With these questions, two corresponding hypothesises and listening tests were developed as explained below.

2.2. Listening test concept

A meeting room was selected within authors’s institution Empa with standard *STI* in class ”A” and ”A+”. The room was observed to have flutter echoes - not very pronounced, but well perceptible. This one room served as three geometrically identical rooms in the experiment for the purpose of quality comparison when the room acoustics was altered by the application of acoustic diffusers or absorbers (see Figure 1). In order not to exceed the framework of this limited study the investigations were conducted only for *one* transmission path source-receiver. As shown later, it was aimed - and achieved - that the transmission path only differ little concerning common room acoustic parameters like EDT, STI and G of the investigated transmission path (see section 2.4).

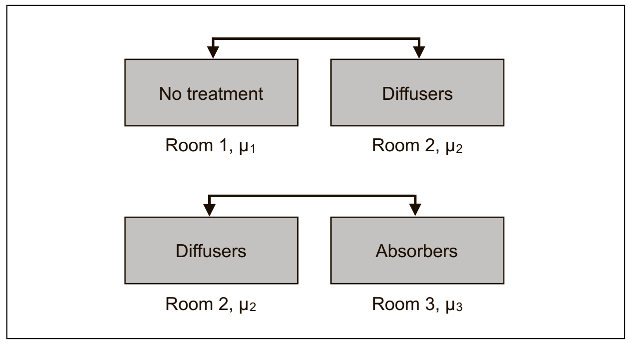

Figure 1. Schematic representation of hypothesis 1 (top) and hypothesis 2 (bottom).

Two null hypothesises were formed as:

1. On average, two ordinary rooms with identical geometries equipped with or without acoustic diffusers sound similar.
2. On average, two ordinary rooms with identical geometry equipped with acoustic diffusers or absorbers sound similar.

The two null hypothesises were tested following a slightly adapted procedure detailed in Recommendation P.800 of the International Telecommunication Union (ITU) [33] named as Comparison Category Rating (CCR). In P.800’s CCR, the Comparison Mean Opinion Score (*CMOS*) is computed directly as the mean value of individual Comparison Opinion Scores (COS). The current study, in contrast, accounts for the hierarchical structure of the data by accounting for the correlation of the data within subjects. To that aim, the Subject Comparison Mean Opinion Score (*SCMOS*) is first calculated for each participant as the mean value of individual Subject Comparison Opinion Score ($SCOS$) over different speech samples. The $SCOS$ are acquired by comparing the quality of one room with the another using several speech samples. The *CMOS* may finally be obtained as the mean value of all *SCMOS*. Except for this modification, the test procedure largely followed P.800.

If the application of acoustic diffusers or absorbers does not have any influence on perceived quality of speech, then the *SCMOS* will be equal to the rating of zero ($SCMOS = 0$) and the corresponding null hypothesis is true. Alternatively, if there is an influence, then the *SCMOS* will belong to a different rating population whose mean differences is not zero ($SCMOS \neq 0$) and the corresponding null hypothesis is rejected. This procedure is used to quantify the magnitude of preference difference when two quality categories are compared against each other with no anchor. This is particularly recommended when the two categories are already of high quality with a marginal difference between them [34, 35].

One potential way to implement the design was to invite real talkers and listeners in the room and rate the quality as the speech was spoken and listened to, in real time. This method was rejected for the following reasons:

1. The room acoustics could not be changed fast enough so the listeners could remember the difference between

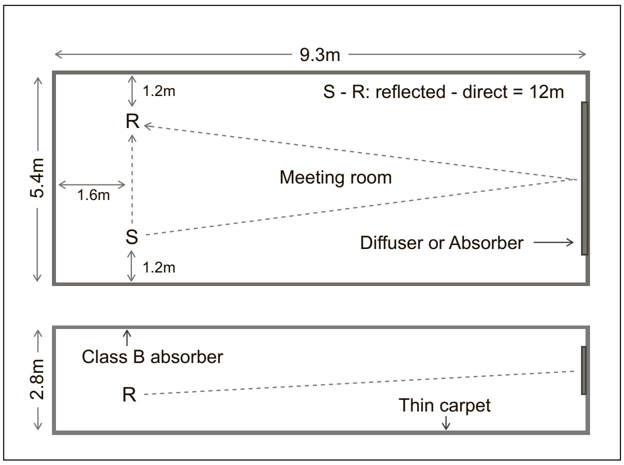

Figure 2. Room schematic plan (Top) and section (Bottom) showing dimension, position of source (S) and receiver (R), room treatment mounted on one short side wall. Drawing not to scale.

the two qualities and rate it. The idea of using an artificial source for a live listening panel was also rejected for the same reason.

2. The possible occurrence of random stationary or impulsive ambient noise due to the *in-situ* nature of the experiment.
3. Biasing due to visual impact of treatment.

An alternative cost effective and efficient approach was to auralise the speech exposed to different room acoustics and play it back to the listeners. Auralisation allows efficient enhancement of the signal to noise ratio (SNR) and also avoids justifying the cost of live speech in unsocial hours.

2.3. Room, diffuser and absorber setup

The room selected for the experiment was a typical cuboid meeting room with dimensions L=9.3 m, W=5.4 m and an effective height of H=2.8 m (Figure 2). The room ceiling and floor are covered with a class B absorber (rated in accordance with ISO 11654 [37]) and thin carpet respectively. Three side walls are hard and smooth surfaces and one side has glass windows on its upper 2/3 area. The room was furnished with a big conference table and 24 chairs.

As mentioned earlier, only one transmission path could be considered for the listing tests of this study. Thus for the measurements of impulse responses a source-receiver position with path length difference of approximately 12 m (Figure 2) was defined. As shown in the introduction this set-up is very well suited to develop flutter-echoes and can therefore be regarded as representative in term of the objective of the investigations.

One-quarter of one from the two side walls causing flutter echoes was symmetrically covered once with diffusers and once with absorbers, centred at the wall's diagonals intersection. The diffusers used in the experiment were 10 units of type RPG Hemiffusor™ (Figure 3 a). Each unit was a 2-dimensional quadratic residue diffuser (2D QRD®) which provide diffusion through reflection phase grating. Based on manufacturer specification, the system provides a normalised diffusion coefficient of greater 0.3 between 800–4000 Hz. The diffuser is made from expanded Polystyrene and is therefore lightweight and has a competitive price. Prime reasons for selecting this particular diffuser were diffusion performance specification, costs, ease of shipping, mounting and architectural aesthetics. The same surface area was also covered with the absorber. The acoustic absorber used in the experiment was 10 units of type CARUSO-ISO-BOND® (Figure 3 b) (CARUSO GmbH, Ebersdorf, Germany). This absorber was selected due to its efficient absorption over a broad frequency range, costs and mounting simplicity.

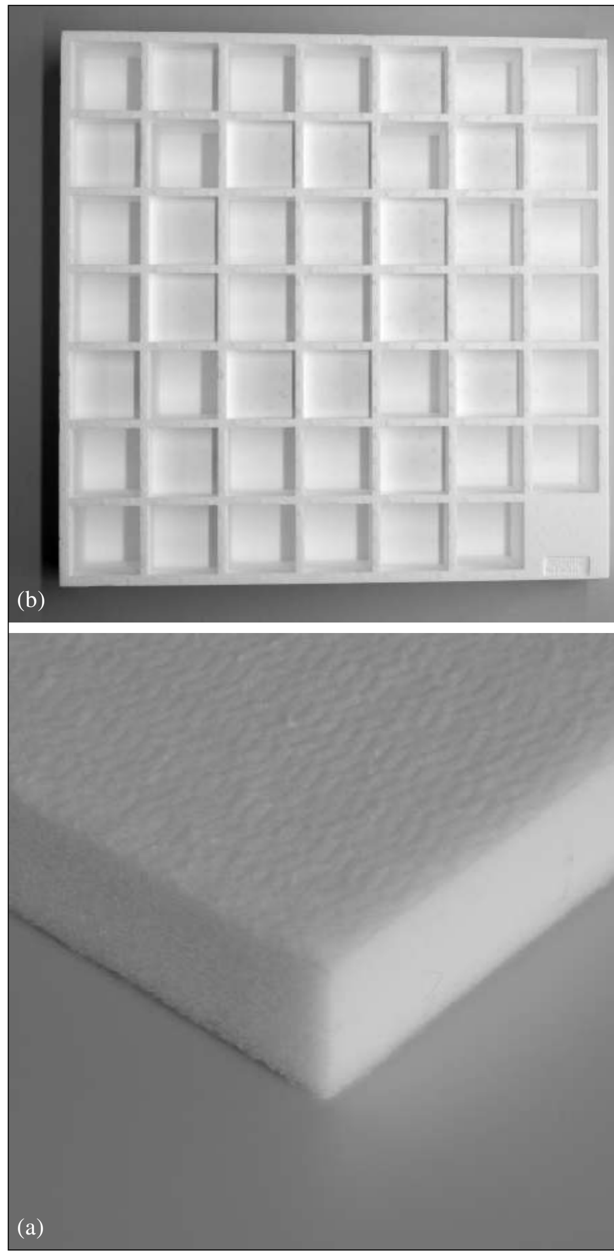

Figure 3. (a): RPG Hemiffusor (b): CARUSO-ISO-BOND.

The absorption coefficient of the absorber and diffuser was measured at Empa's reverberation chamber according to ISO 354 [36]. The normalised diffusion coefficient

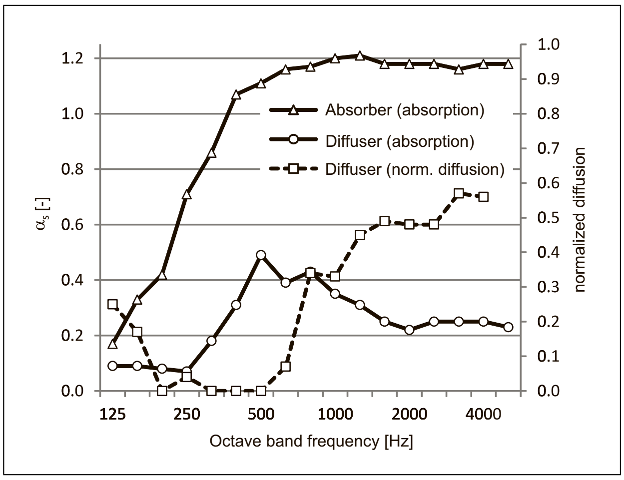

Figure 4. Absorption coefficient α_s of the absorber and diffuser, and normalised diffusion coefficient of the diffusor.

of the diffuser was calculated based on [4] using specifications reported by RPG Europe. The results are given in Figure 4. The absorber provides class A absorption according to ISO 11654 [37].

2.4. Room acoustical characterizations

2.4.1. Characterization of the room

Although in this study only one transmission path is investigated for the sake of completeness in this section an overall room acoustical characterisation of the meeting room is described. The room average reverberation time was measured following the procedure given in ISO 3382-2 [38] and is reported in Figure 5 for the three room acoustics. *STI* measured for different positions of sources and receivers in the meeting room for all three room acoustics were all higher than 0.74 (categories "A" or "A+" according to IEC 60268-16 Annex G [32]).

2.4.2. Characterization of the transmission path

The following measurements were carried out to characterise the three room acoustics specific to the Source (S) - Receiver (R) transmission path used in the test (see Figure 2) with the help of the most common room acoustical parameters. Early Decay Time (*EDT*) as an acoustic quantity for the perceived reverberance and relative sound pressure level (*SPL*) as an acoustic quantity for the subjective level of sound were measured in accordance with ISO 3382-1 [39]. The results are shown in Figures 6 and 7. Furthermore, the Speech Transmission Index (STI) as a acoustic quantity for speech intelligibility was also measured in accordance with IEC 60268-16 [32]. The results are shown in Table I.

The concept of Just Noticeable Difference (JND) was used to assess the differences between the three room acoustics observed in Figures 6 and 7 and Table I. According to [39], the JND for *EDT* is 5% and for *SPL* is 1 dB. The JND for the *STI* is given as the value of 0.03 in [40]. The differences between the three room acoustics thus are within the JND for the *STI* and the *SPL* and just

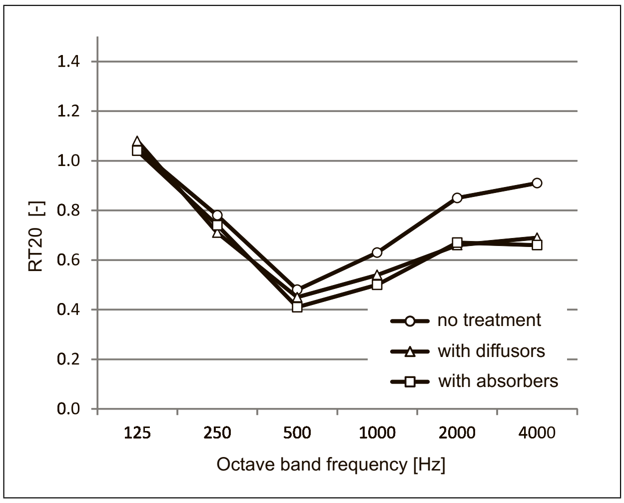

Figure 5. Measured mean Reverberation Time RT20 for the three room acoustics.

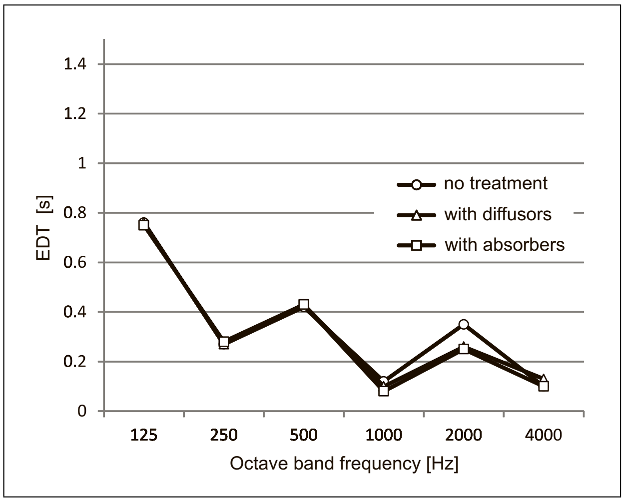

Figure 6. Measured Early Decay Time (*EDT*) for the three room acoustics for the transmission path S – R.

Table I. Speech Transmission Index *STI* for the transmission path S–R.

Treatment	*STI*
without treatment	0.83
with diffusors	0.85
with absorbers	0.85

exceeded for the *EDT*. Therefore, the differences are objectively measurable, but not or only barely subjectively perceptible.

2.5. Binaural room impulse responses

Once the required room acoustics were set up, binaural room impulse response (BRIR) measurement were carried out for the transmission path S - R (cf. Figure 2) for each room acoustics using the following apparatus: HEAD acoustics Measurement System HMS II.1 as BRIR receiver; RME Fireface 400 digital interface; Aurora plug-

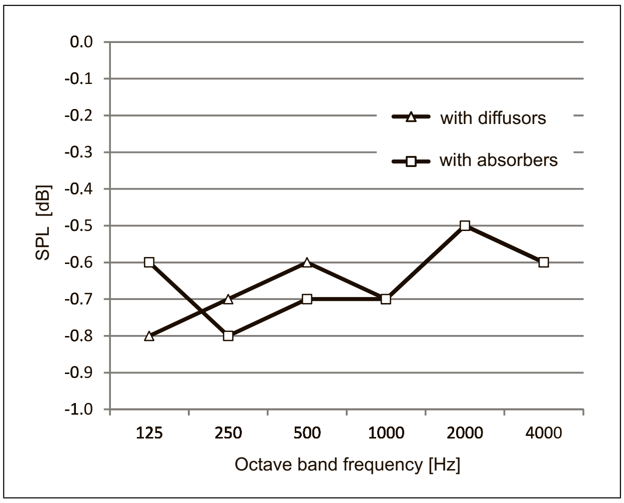

Figure 7. Difference of the sound pressure level (*SPL*) measured without treatment vs. treatment with diffusers and absorbers for the transmission path S – R.

ins [41] for Adobe Audition 3 (ISO 3382 compliant); Genelec 8030A Active Studio Monitor; Brüel & Kjaer OmniSource - Type 4295; Brüel & Kjaer omnidirectional studio microphone - Type 4006.

The studio monitor was used to reproduce the on-axis response of an artificial mouth. The monitor could also reproduce the off-axis directivity pattern of an artificial mouth to a good approximation [42]. The artificial head was used as the receiver. The system has several built-in filter, two of which were switched on. The first is HP1 which high-pass filters frequencies above 22.4 Hz and was engaged to remove ambient noise at barely audible frequencies. The second filter was ID (Independent of Direction) which compensated for the presence of semi auditory canal-shaped cavity at the artificial ear Concha so the degeneration of the ear canal resonance can be omitted during the audio playback when headphones are used.

A logarithmic sweep was used for the measurement for its exclusive robustness against source's harmonic distortion. The sweep was high-pass filtered above 80 Hz in conformance with the source's on-axis frequency response. The sweep was also Hanning windowed at start and ending to avoid time domain discontinuity and its associated frequency domain harmonics [43, 44].

The choice of sweep length is independent of the intended measuring reverberation time. Although a very short sweep put through a powerful source can be more than sufficient to measure a ten times long reverberation time in a very quiet church (provided that the sweep is followed by a silence long enough for collecting the whole reverberant tail), it may not be enough to provide adequate signal-to-noise (SNR) required for high quality auralisation. Taking into account the ambient noise level present during the measurements, the length of the sweep was elongated to 15 s at which, the maximum adequate SNR at low frequencies was reached. Four binaural impulse responses were taken for each of the three room acoustics. As a room is never a perfectly linear time invariant system, averaging within each set of impulse responses was shunned to avoid intrinsic cancellation in overall room impulse response. For each room acoustics, all four room impulse responses were carefully monitored and one was selected as the room's assigned impulse response for each of the room acoustics scenarios [43].

The temporal distortion of flutter echoes is caused by periodic succession of reflections. It is quite possible that these repeated reflections are buried under non-periodically distributed reflections. Autocorrelation function is a method to test the randomness of a signal, which in turn can reveal its periodic components, if any. Studies [45, 46] and their revision [47] have demonstrated that for short delay times below 20 ms, frequency domain colouration can be predicted by observing the spectrum or the weighted autocorrelation of an impulse response. For delays grater that 20 ms (that are related to current research) where frequency colouration gradually turns into repetitive temporal fluctuations, it is not possible to predict any distortion [48, p.82]. For this reason, the measured impulse responses were not processed further for signs of subjective distortions.

2.6. Anechoic speech

To produce results representative for the language and its statistics, 400 documented phonetically balanced sentences were acquired, courtesy of the Institute of Phonetics and Speech Processing, Munich, Germany. These sentences include specific wording order and words (sets of syllables) whose initial consonants, vowels and final consonants have variety of phonemes occurring at approximately the same rate as in ordinary conversation in that language. This means that for example if a particular phoneme occurs 80 percent of the time in the corresponding language, that phoneme also approximately appears at the same rate in a phonetically balanced sentence [5].

The sentences are in German. From the 400 sentences, 200 were selected that would last between 2 to 3 s when articulately spoken. The sentences were read and recorded in Empa's anechoic chamber by four hired professional talkers, two male and two female.

From these recorded 200 sentences, four sentences were selected for each talker making it 4 (talker) x 4 (sentences) = 16 different sentences in total. These sentences were then grouped to form two speech samples for each talker, each sample comprising two unique sentences resulting in a total of eight sentence pairs. This is schematically shown in Figure 8 for Talker 1 and in 9 for all talkers.

2.7. Auralisation

Stimulus generation was performed in MATLAB using discrete linear convolution of the recordings with the impulse responses to obtain the stimuli of the three different room acoustics for the listening test. The convolution was applied in the frequency domain to speed up the calculation process. Reproduction was effected through headphones. Using headphones has the advantage to make the experiment independent of the acoustics of the room in

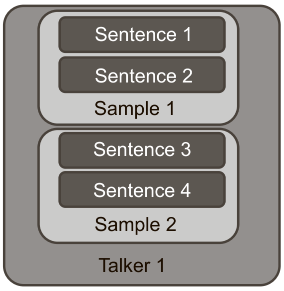

Figure 8. Speech grouping associated to one talker.

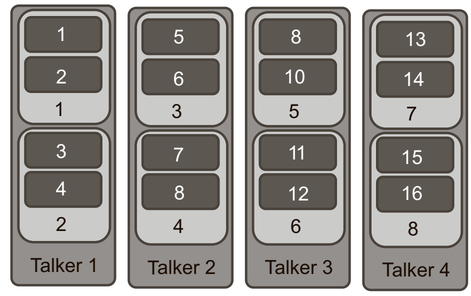

Figure 9. Speech grouping for all 4 talkers.

which the listening tests are performed, which could bias participants' judgements. Sennheiser HD800 were used as headphones, which are an open back construction principle and as a result provide a relatively flat frequency response. In spite of that, boost at low frequencies up to 5 dB was perceived and measured when compared to mid and high frequencies. The headphone frequency response was therefore compensated for by convolving the headphone's inverse response with the auralised audio signal before putting it trough to the headphones. Headphones' impulse response was measured using the same HEAD acoustics Head Measurement System as used in section 2.5. The response was then inverted according to the Nelson/Kirkeby frequency-domain regularisation [49] included in Aurora.

For the auralisation playback, the sound level was calibrated as follows. The play back level through the headphones was adjusted to a SLOW time weighted sound pressure 64 dB(A), 3 dB(A) higher than what was measured in the room at the receiver point with a talker reading the speech materials positioned at the source (see Figure 2). This increase in level was introduced to give the same intensity impression as from the live source, complying with the findings of Søndergaard M. (2001) as cited in [50]. Empa's semi-anechoic room was selected as the environment for auralisation playback over headphones to participants.

2.8. Objective evaluation of exemplary speech signals

The temporal fluctuation of flutter echoes is typically in order of few hundred Hertz or less. It is possible to trace and visualise flutter echoes and effect of a treatment in laboratory conditions where the number of reflections can be controlled and reduced to as low as one. Cox and D'Antonio [4] used the convolution of a music sample with different type of diffuser's -single- reflection response and investigated which one matches best the observed signal. This method can not be applied to the current study due to the presence of in-situ reverberation. Another approach to visualise the flutter echoes would be to plot the spectrogram for the three room acoustics auralisations and look for differences.

Figure 10 and Figure 11 correspond with the hypothesis 1 and 2 respectively. The former presents the spectrogram of the same speech sample for room with no treatment (top) and for room treated with the diffusers (middle) and the subtraction of the two (bottom). The latter shows the exact investigation for differences between using absorber

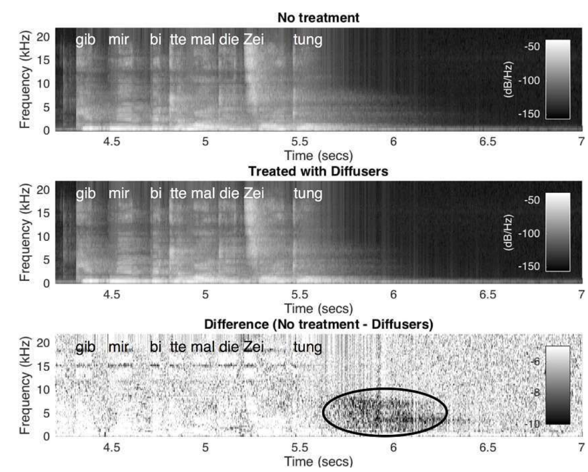

Figure 10. Speech in room with no treatment (top), in room treated with diffuser (middle), subtraction of top from middle (bottom) (Hypothesis 1).

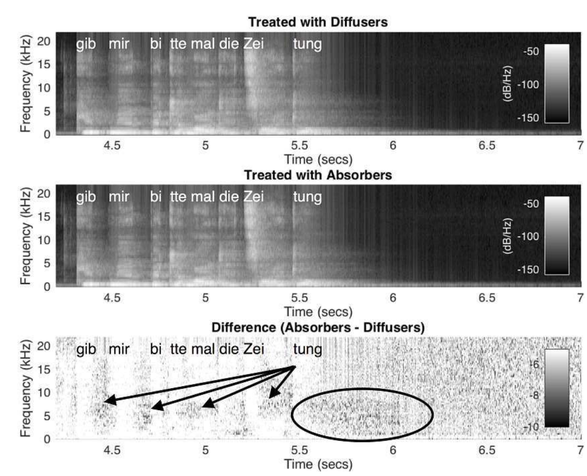

Figure 11. Speech in room treated with diffuser (top), in room treated with absorber (middle), subtraction of top from middle (bottom) (Hypothesis 2).

and diffusers. The subtraction figure reveals events that are present in top but are absent or attenuated in middle figure.

It can be seen that rapid repetition (around 20 Hz) of certain events has been attenuated up to 5dB across the signal, more explicitly between 5.5–6.5 s (darker region). This particular region is when a plosive consonant has stopped for a couple of 100 ms after which the receiver had captured the formation of flutter echoes and also the extent of attenuation when a treatment is used. It can also be seen that the attenuations are predominant for bandwidth between a couple of hundred Hertz and 8 kHz, occupied mainly by speech. Figure 11 shows the extra effect of absorbers over diffusers. Whether these fine differences are audibly detectable is what will be discussed in the next section.

Figure 12. Graphical user interface for the listening test interface produced with MATLAB.

2.9. Listening test implementation

2.9.1. Attributes for speech quality

Two separate listening tests were conducted to test the two hypothesises of section 2.1. For each hypothesis, four attributes of quality were tested. The dimensions were selected to possess no categorically unified scientific definition, no physical semantics and to not being measurable by an instrument such as warmth or height. Each participant may develop an individual perspective for the attribute and rate accordingly. These attributes (and the corresponding translation in English) are:

- *Klarheit* (Clarity): Clarity is the most important aspect of speech quality.
- *Behaglichkeit* (Comfort): Comfort was chosen to examine whether the reduction or absence of perceptually discomforting sources such as colouration and flutter echo can increase ease of listening experience.
- *Verfremdung* (Alienation): It is possible that the quality is considered clear and comfortable while still containing perceptual forms of contamination/alienation.
- *Qualität* (Overall quality): Overall quality intends to determine the final verdict on increased or decreased speech quality taking into account all possible dimensions of quality.

The number of attributes was limited to four. Given the number of hypothesises and participants, investigation of more attributes would have resulted in a test lasting considerably longer than the recommended duration [33], causing participants fatigue.

2.9.2. Participants

For the listening tests, participants were recruited via advertisement. A compensation of 20 Swiss Francs (approx. 18 Euro) was given for participation. In total, 32 persons participated, which is sufficient to obtain reliable results [50]. The participants (16 males, 16 females) were aged between 24 and 54. The majority worked at the authors' research institution, Empa. Only naïve listeners (non-experts) were included in the study to test whether the acoustic treatments were perceptible by untrained persons (non-acousticians). While this widens the generalizability of results, it may have induced some scatter to the results because ”speech quality” may not have been rated in an uniform way. Further, the large variation in age may induce an effect on the ratings, but this was checked in the statistical analysis (see below).

None of the participants included in the study wore a hearing aid, and all of them declared to have normal hearing and to feel well (without cold). No audiogram was done to test for normal hearing due to the following reasons. First, the effect of room acoustics treatments on ”normal” persons were to be investigated, so that ”perfect” hearing in all frequencies was no prerequisite for participation. Second, performing an audiogram prior to the listening tests would probably have led to fatigue of the participants during the listening tests, which were relatively long (see section 2.9.4).

2.9.3. Listening test software and user interface

A listening test software and associated graphical user interface was implemented in MATLAB for participants to control and perform the test individually. The graphical user interface is shown in Figure 12. The listening test procedure followed an adapted procedure CCR (see section 2.1.)

The listening test software embedded different simultaneously randomized stimuli as follows:

1. The order of talkers in each set of 8 comparison ratings per quality attribute (for 8 speech samples, cf. Section 2.6) was randomised for each attribute.
2. The order of presented room acoustics in each of those 8 comparisons was randomised.
3. The order of the four quality attributes in each listening test was randomised.

Finally, the order for which a participant took a particular listening test (diffuser vs. no treatment; absorber vs. diffuser) was balanced.

2.9.4. Test procedure

At the beginning of each listening test, the participants were given a brief overview of the experiment. After that, a consent form was signed to participate in the study. Consecutively data regarding the participant's self-reported physical hearing health, age and gender was collected anonymously with a questionnaire. The participant was then instructed on how to control the interface through a short trial session, after which the actual test was begun. Each listening test lasted 25–30 minutes, with a break between the two tests (∼1 h for both tests).

For the ratings, the participants were instructed to always compare the quality of the second sample with the first played sample, using a slide bar (cf. Figure 12) with the following features. It has a positive semantic description to its right, indicating superiority of the second compared with the first presented room acoustics, and a corresponding negative description to its left, with inverse meaning regarding the quality of the room acoustics. The middle of the slider is marked with zero, indicating zero perceived difference between the quality of the room acoustics. To the right of zero are ascending numbers up to a maximum +3 and to the left descending numbers up to a minimum −3, with a precision of 2 decimal places. The participants were encouraged not to choose the value of zero, but move the slider away from it, even if only little, if they have audible or psychological evidence that the two room acoustics are not exactly the same (i.e. a copy of each other). This is although no comparison between identical room acoustics was included and tested in the listening test.

The participants started each listening test by pressing the Play button (cf. Figure 12). This plays one speech sample of a particular talker and room acoustics. After a short break of 1 s, the same speech sample is played again but this time with different room acoustics. At this point, the participant was given an opportunity to form an opinion regarding the differences perceived between the room acoustics, if any. The participant was then directed to listen to the same scenario for a second time (*Wiederholen* (Repeat) button in Figure 12). It is only after this second time that the participant is allowed to declare a comparison rating by sliding the provided slider from the initial location of +3 to the desired location. For each rating the slider was originally placed at a less probable maximum comparison rating of +3 so the participants are encouraged to move the slider. It was considered probable that the slider would be left at zero if it originally appears at zero given the degree of similarity between the room acoustics (cf. Section 2.4).

Once the participant declares a comparison rating, the *Weiter* (Next) button can be pressed to proceed to the second comparison. The *Play* button must be pressed again to initiate the second comparison. 8 comparisons (for 8 speech samples, cf. Section 2.4) per participant are performed per quality attributes. Once the first set of 8 comparisons were finished, the *Merkmal* (Attribute) button (Figure 12) switches on to allow the change of the quality attribute. This change shows at either end of the rating slider. Once the attribute is changed, the participant is presented with a new set of 8 comparisons (same 8 speech samples in different order). The first listening test is completed once the comparisons for all 4 attributes are finished (total of 32 comparisons, see Figure 13). The participant

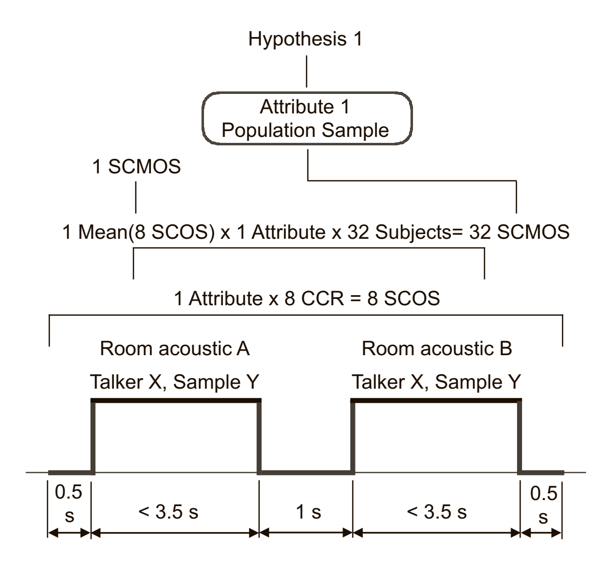

Figure 13. Timing diagram of test presentation to participants and development of Subject Mean Opinion Score (*SCMOS*).

is then offered a 10-15 min break before the second listing test starts (another total of 32 comparisons).

2.9.5. Statistical analysis

From the 8 individual SCOS ratings per participant, quality attribute and listening test, the *SCMOS* was calculated as the mean value (cf. section 2.2), averaging out the potential effects of speech sample or talker (including gender) on the individual ratings per speech sample. This resulted in a data set of 32 *SCMOS* values per quality attribute and test (Figure 13).

The participant's ratings were analysed on the basis of the averaged *SCMOS* ratings as well as on the SCOS ratings.

In the *SCMOS* analysis, two-sided one-sample t-tests were performed to test whether the *SCMOS* ratings are significantly different from zero or not. Further, effect size was estimated by Cohen's d [54], as $d = (\overline{x} - \mu)/s = CMOS/s$, where where $\overline{x}$ is the sample mean of all *SCMOS* corresponding to *CMOS* (cf. section 2.2), μ is the hypothesised true population mean = 0, and s is the standard deviation. Cohen's d gives an indication for the magnitude of the effect in practical terms. It can be classified as follows (based on the absolute values of d):

> 0.8	large (8/10 of a standard deviation unit)
0.5 - 0.8	moderate (1/2 of a standard deviation)
0.2 - 0.5	small (1/5 of a standard deviation)
< 0.2	trivial

By using the *SCMOS* data, not only potential effects on the ratings of the individual speakers (4 speakers), speakers' gender (male, female) and/or individual speech samples (8 pairs) are averaged and thus remain unaccounted for in the statistical analysis, but also the sequence of the presented stimuli in the listening tests, although the latter may not be negligible in some cases [51]. Finally, in the one-sample t-test, also the potential effects of gender and age of the study participants remains unexplored.

Therefore, in addition to the *SCMOS* analysis, the SCOS were analysed by means of linear mixed-effects models. These models allow combining fixed and random effects to predict the dependent variable (see e.g. [52] for a concise introduction). The analysis was carried out with IBM SPSS Version 22. In this study, the fixed effects may be the categorical variables Speakers (4 levels, i.e. speakers), Speakers' Gender (2 levels), Sentence Pairs (8 levels) and Participants' Gender (2 levels), and the continuous variables Sequence and Participants' Age, while the random effect is the participants (randomly chosen from a population with a large set of possible levels) . The variables Speakers, Speakers' Gender and Sentence Pairs are confounded in this study, i.e. their individual effects on the SCOS values cannot be distinguished from each other. Therefore, three different initial models containing the variables Participants' Age, Participants' Gender and Sequence, as well as one of the three confounded variables were established. From these models, the model containing the confounded variable with the largest effect (smallest p-value) was chosen. This model was subsequently simplified by stepwise removal of non-significant variables ($p > 0.05$) until only variables with significant effects were retained. In any case, also the simplest model, containing only the intercept and random effect, was established. The different established models were compared using the Bayesian Information Criterion (BIC) [53], where the model with the lowest BIC is preferred. Based on these insights, the final model was chosen. Separate final models were established for the four attributes ratings, and for both listening tests (8 models in total).

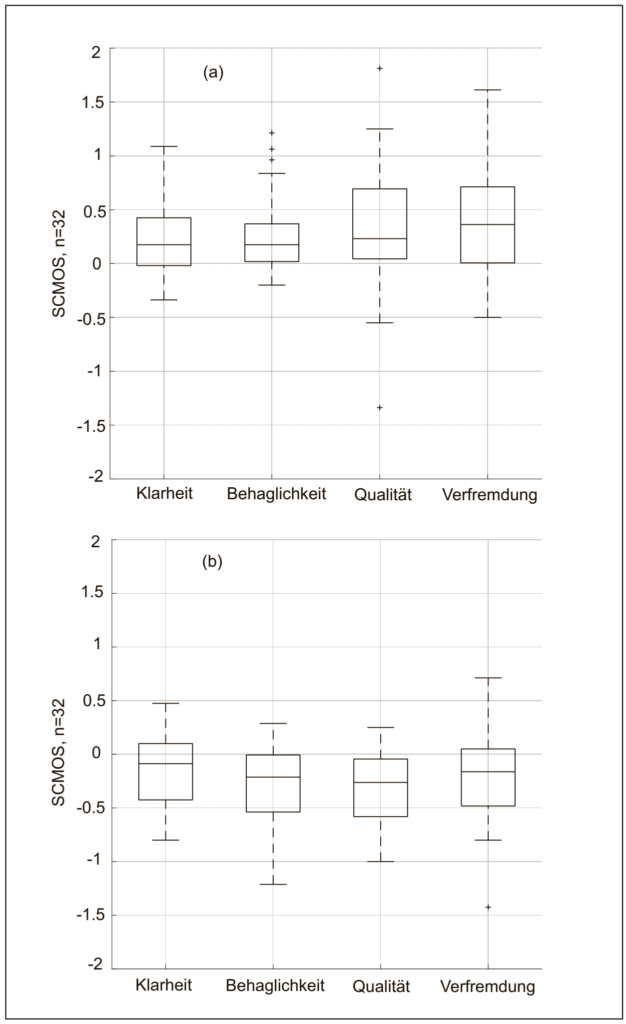

Figure 14. Box plots of *SCMOS* for the four attributes Klarheit (Clarity), Behaglichkeit (Comfort), Qualität (Overall Quality) and Verfremdung (Alienation). Boxes represent the interquartile range with the median (horizontal line), the whiskers show values inside ±1.5× box length, and plus signs are outliers outside 1.5× box length. Top: listening test 1 (room acoustics with diffusers compared to no with treatment); The positive *CMOS* values indicate higher quality ratings with diffusers compared to no treatment. Bottom: listening test 2 (room acoustics with diffusers compared to with absorbers); The negative *CMOS* values indicate lower quality rating with diffusers compared to absorbers.

3. Results

Boxplots of the *SCMOS* data are shown in Figure 14. They reveal upwards (Figure 14, top) and downwards (Figure 14, bottom) skews in the vicinity of $SCMOS = 0$. Note that while the individual ratings per quality attribute scattered strongly, with individual SCOS values covering the major part of the ordinate from −3 to +3, the same trend as in Figure 14 can still be observed.

Table II present the *CMOS* (mean *SCMOS*) and the p-values resulting from t-test. The *CMOS* of all quality attributes significantly differ from zero for both listening tests, indicating that both null hypotheses (Section 2.1) can be rejected. This means that both, diffusors and absorbers, significantly improve the subjectively perceived speech quality and that the room with absorber sounds significantly different to the room with diffusers.

Concerning listening test 1 the positive mean *CMOS* scores of Table II (Top) disclose that on average, the speech quality of the transmission path in the room with acoustic diffusers as a treatment is significantly favoured over the quality of speech in the untreated room. The negative mean *CMOS* scores of Table II (Bootom), in contrast, reveal that on average the speech quality of the transmission path in the room with acoustic absorbers is significantly favoured over the quality of speech in the room with acoustic diffusers. Further, Cohen's d of both listing tests, suggest that with values of mostly 0.5 or higher, the assessed differences have a considerable practical magnitude and hence are worth to be investigated further (although the absolute values of the *SCMOS* are quite small). This is in spite that the effect of small effect size in long term is not clear.

The analysis of the linear mixed effects models allow for analogous conclusions regarding the effects of diffusers and absorbers on the subjectively perceived speech quality as the above analysis. For both listening tests, Participants'

Table II. *CMOS* (= mean *SCMOS*), *p*-values (two sided *t*-test), and Cohen's *d* for the four attributes Klarheit (Clarity), Behaglichkeit (Comfort), Qualität (Overall Quality) and Verfremdung (Alienation). Top: listening tests 1 (room acoustics with no treatment compared to with diffusers). Bottom: listening test 2 (room acoustics with diffusers compared to with absorbers).

Listening test 1			
Attribute	*CMOS*	*p*-value	Cohen's *d*
Klarheit	0.239	0.00	0.6
Behaglichkeit	0.254	0.00	0.7
Qualität	0.316	0.00	0.6
Verfremdung	0.358	0.00	0.8

Listening test 2			
Attribute	*CMOS*	*p*-value	Cohen's *d*
Klarheit	−0.146	0.03	−0.4
Behaglichkeit	−0.265	0.00	−0.7
Qualität	−0.308	0.00	−0.9
Verfremdung	−0.216	0.01	−0.5

Gender and Participants' Age had no significant effects on the ratings. Further, for the first listening test (diffuser vs. no treatment), the model with the smallest BIC was always the simplest one (intercept only). Only the variable Sentence Pairs had a significant effect ($p < 0.02$) on the individual COS of the attribute Qualität, and the variables Speakers or Sentence Pairs slightly (non-significantly) affected the COS of the attribute Klarheit ($p < 0.06$), but the BIC in these cases was larger than the BIC of the simplest model. Thus, the same model (intercept only) was chosen as the final model for all four attributes. For the second listening test (diffuser vs. absorber), the model with the smallest BIC was always the simplest, except for the COS of the attribute Verfremdung. Here the model including the variable Speakers' Gender had a slightly smaller BIC than the simplest model, and the latter variable had a significant effect on the COS ($p < 0.02$). Also the variable Sentence Pairs had a significant effect on the COS of the attribute Verfremdung ($p < 0.05$), but the respective model had a substantially larger BIC than the simplest model. Besides, for the attribute Klarheit, Speakers ($p < 0.02$) and Sentence Pairs ($p < 0.01$) significantly affected the COS, but the respective models had larger BICs than the simplest model. Thus, the confounded variables only in some cases had a significant effect, and showed no clear pattern as to which variables had the strongest effect. Therefore, again the same model (intercept only) was chosen for all attributes, as in the first listening test.

The model variable intercept of the final models corresponds to the mean difference of the *SCMOS* discussed above, takes its value (cf. Table II), and thus confirms the effects revealed by the one-sample *t*-test. In addition, however, the linear mixed-effects models show that the phonetically balanced sentences and professional speakers chosen in this study helped excluding potential effects of sentences and speakers to a large extent, reducing to the effect of room acoustics as the one important remaining predictor variable.

4. Discussion and Conclusion

In this study, the effect of acoustic diffusers and absorbers on subjectively perceived speech quality for one tranmission path in a meeting room was investigated in a laboratory study. As far as the authors are aware, this is for the first time that this topic was investigated experimentally.

The first listening test revealed that with respect to the subjectively perceived speech quality the room selected for the experiment equipped with diffusers outperforms the original room without diffusers. This result is in line with expectations and recommendations and confirms that diffusers are a remedial measure to control flutter echoes, while uniformly dispersing the energy to improve the quality of spoken speech. Further, the results show that the attenuation of flutter echoes and additive smearing into the general reverberation with diffusers is subjectively detectable, even if differences between room acoustics are small (cf. Section 2.4) and despite the fact that the problematic nature of reflections with delays longer than 20ms cannot be objectively predicted (cf. in section 2.5).

Whether the use of diffusers is the ultimate solution to control unwanted reflections is answered further with the results of the second listening test. The latter revealed that the subjective perception of speech quality of the investigated transmission path of the room equipped with absorbers is better than of the same room equipped with the specified diffusers.

It thus appears that acoustic diffusers convert the perception of flutter echoes into a new form of perception that is flutter echoes free and not problematic in that sense. However, given the results of the second listening test, this does not seem to be sufficient when further improvement of quality is desired. By using acoustic absorbers, the unwanted reflections are substantially suppressed and do no longer contribute, positively or negatively. This seems to enhance the rating of quality when it is compared with the quality provided by diffusers. The diffuser type used in this study was selected with small depth of 0.10 m for aesthetic reasons and to replicate a real life likely architectural demand. It can be assumed that by optimising the diffuser depth, an approximation to the effect of absorber could be achieved when diffusion frequency response of the diffuser is extended to low frequencies.

It is obvious that this preliminary study hast limitations. Only one transmission path in a meeting room could be taken into account. It would be desirable to investigate additional transmission paths, other meeting rooms with different geometrical and acoustical characteristics and also further types of rooms. Also the study is limited to speech. Nevertheless, it can be assumed that the results are of great relevance for the acoustics of all ordinary rooms.

Experience shows that the fundamental requirements for speech intelligibility and noise are often not met for everyday rooms such as classrooms, meeting rooms or restaurants, and considerable progress has yet to be made within this regard. However, such progress should not focus only on the basic requirements such as reverberation time and speech intelligibility, but also on subjective qualities. The results of both listening tests confirm that despite the excellent speech intelligibility and low values of the early decay time the subjectively perceived speech quality can be further improved simply either by introducing absorbers or diffusers.

Future studies can include investigations to find the optimal diffuser (scattering and absorption) or absorber specifications for enhanced quality of speech, when cost and aesthetics are constrained.

Speech signals contain frequent occurrence of impulsive sound due to the presence of consonants. This form of excitation may lead to a more pronounced observation of flutter echoes and hence treatments for rooms with speech function may appear more evident. Whether the same subjective outcome holds for rooms used for music production remains untested and may be checked in further investigation.

Further work could investigate a presumed effect of absorbers and diffusers on psychoacoustic parameters and the spatial listening.

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