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Increase of voice level and speaker comfort in lecture rooms

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ABSTRACT

Teachers often suffer from health problems related to their voice. These problems are related to their working environment, including the acoustics of the lecture rooms. However, there is a lack of studies linking the room acoustic parameters to the voice produced by the speaker. In this pilot study, the main goals are to investigate whether objectively measurable parameters of the rooms can be related to a increase of the voice sound power produced by speakers and to the speakers subjective judgments about the rooms. In six different rooms with different size, reverberation time and other physical attributes, the sound power level produced by six speakers was measured. Objective room acoustic parameters were measured in the same rooms, including reverberation time and room gain, and questionnaires were handed out to persons who had experience talking in the rooms. It is found that in different rooms significant changes in the sound power produced by the speaker can be found. It is also found that these changes mainly have to do with the size of the room and to the gain produced by the room. To describe this quality, a new room acoustic quantity called 'room gain' is proposed.

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I. INTRODUCTION

The primary means of communication in most educational settings are speech and listening. The acoustics of the lecture room can restrict or support the speaker and improve the sound of the voice and the intelligibility of speech. The room acoustics in lecture rooms is therefore an important issue when considering the productivity and working environment in schools and other teaching situations. Thus, a large amount of work has been carried out within this field. However, the large body of published articles focuses on the point of view of the listener. It is therefore easy to find works on speech intelligibility in the room and advisable reverberation times and background noise levels in order to achieve good learning condition, et cetera, see e.g. Bistafa and Bradley.[1] There are also standards and recomendations,[2–4] indicating how well established this field is.

However, it is known that teachers often suffer from health problems or tension related to their voice. Recent works made it evident that teacher's labour is one of the professions with high vocal demands.[5] Examples of other professions with high vocal demands are actors, singers, journalists, telephone operators and military personal. Studies show that a majority of teachers have experienced vocal problems, about one tenth have severe problems, and 5% have experienced such severe, numerous and frequent voice problems that their working ability is challenged.[5] For the teacher, in the long run, this voice load due to speaking in the classroom can result in voice disorders such as hoarseness, voice fatigue and can even force teachers to retire early from their profession. Lubman[6] discloses that this is an important economic problem for governments and private schools.

Most teachers have probably experienced that different rooms vary in comfort when one speaks in them. However, even though the vocal problem is so important, just a few studies about the speaker and his behavior in and impression of the lecture room have been accomplished. One example is Kleiner and Berntson,[7] where the early reflections of the sound produced by the speaker were studied in a synthetic experimental setup. A system of loudspeakers in an anechoic chamber were used to simulate different rooms. All settings simulated rooms with different shape but the same volume. The interest was in the effect of lateral and vertical early reflections on the speakers' comfort. Different combinations of delayed simulated reflections were tested. A paired comparison test was used in order to find the setting preferred by the speakers. It was concluded that symmetrical settings were preferred over asymmetrical. There were however no significant difference between the different symmetrical settings, and perfectly symmetrical settings are not realistic in real rooms with a movable speaker. It can be noted that this was an entirely subjective study – no objective values were calculated from the simulated impulse responses. Kob et al.[8] has presented results from a study where the voice status of 25 teachers were investigated using standard methods as applied by audimetrisists, phoniatricians and speech therapists, in addition to an acoustic analysis of speech and voice samples. The acoustics of some rooms was also investigated, and the result of speaking in different rooms was analysed in dependence of the voice status. The results indicate an influence of both the room acoustics and the voice status on the voice quality of the teachers. But the study used reverberation time and speech transmission index as the parameters describing the room acoustic environment. Thus, no clear distinction was made between the problem perceived by the listener and the speaker.

Several studies in which different voice parameters were measured in real classrooms have been reported, e.g. Rantala et al.[9,10] or Jonsdottir et al..[11] However, in these studies the influence of the room were not included. Instead, the focus here was to study different subgroups of speakers, e.g. with and without voice problems. The voice parameters were primarily the voice level (defined as the sound pressure level (SPL) a distance of 1 m from the speaker) and pitch (more specific the fundamental frequency F_0 of the voice signal), and fluctuations in these parameters.

Thus, the literature relating the room with the speaker and the voice signal produced is rather thin; not much information is available on how to design or improve the room in order to make a better environment for the speaker. However, such information is available in the field of acoustics of rooms for music performance. Also here, the majority of works deal with the conditions for the audience, but there have also been studies concerning how musicians experience and react on the room acoustics. Important examples is Gade,[12] who in a laboratory experiment in an anechoic chamber equipped with a loudspeaker system similar to Kleiner and Berntson[7] let musicians play in and react to simulated sound fields. Gade[13] also carried out corresponding subjective and objective studies in real concert halls. In both cases the subjective response answered by the musicians were correlated with different objective measures. Gade found that the 'support' provided by the room – the sensation that the room responds to his instrumental effort – is important for the musicians. Gade defines an objective measure, called ST, that correlates well with the sensation of 'support'. ST is determined as

$$ST = 10 \log \frac{E_{20-x}}{E_{dir}} \tag{1}$$

where E_{20-x} is the energy in the impulse response from 20 ms to x ms (x being either 100 ms, 200 ms, or even infinity), see equation (2), and E_{dir} is the energy in the direct path, defined as $E_{dir} = E_{0-10}$, that is the energy within the first 10 ms. The impulse response is to be measured with a source-receiver distance of 1 m. Obviously, 1 m distance is larger than the typical distance between the musicians ear and his instrument, but this distance was still chosen to obtain a measure with sensible variation and dynamic range. ST is thus the fraction of energy coming later than 20 ms relative the direct sound. In absence of reflected sound ST equals $-\infty$ dB, and a zero support, $ST = 0$ dB, means that the total contribution from the reflections equals the direct sound. This definition works well in large rooms where the direct part of the impulse response is clearly separated from the reflexions, but measurements of ST is problematic for smaller rooms. Another problem with the definition equation (1) is that it does not clearly reflect what happens close to the source, which at the same time is the position to be studied. In the real situation, e.g. in case of singing or speaking, the source is the mouth and the receiver position is the ear, just a few centimetres away. The direct path is thus described by the transfer function (or impulse response) from the mouth, around the head, to the ear in absence of reflections. How to deal with this is not obvious in case of the definition in equation (1). A third problem is that an anechoic chamber is included in the present study, and ST is undefined in such a room. Thus, in the present study we have made use of another definition, using the measured impulse response of a setup with an artificial dummy head torso, and taking as reference the measured value in an anechoic room. The new quantity is called room gain, abbreviation RG and variable G_{RG}, see section II C.

It seems likely that the vocal problems of teachers are due to the voice level being increased in different situations when teachers feel uncomfortable with the environment. The environment here not only includes the physical environment of the lecture room, but also the students and the overall working conditions. There are two hypotheses here, one being that vocal health problems are related to an environment where the speaker feels that he must increase his voice, the other being that the physical environment it self can cause the speaker to increase his voice. Only the latter will be tested in the present paper. The aim of this project was thus to find some of the parameters that cause the speaker to force their voice, and situations when it is uncomfortable to speak.

Aspects not taken into account in this study are: the influence of the audience, including the background noise produced by them; the change in voice during the day; the influence of voice problems of the subjects and other aspects related to the subjects (e.g. mood or attitude toward teaching); and the speech intelligibility in the rooms, subjectively or objectively. Moreover, the study only deals with non-amplified voices.

One question is then which objectively measurable parameters to include in the study? Real rooms are to be used and the focus is on the speaker, not the listener.

Thus, the parameters should be related to what the speaker experiences at the position where he speaks. Parameters related to speech recognition and intelligibly are therefore left out. The impulse response contains all information of the transfer path from source to receiver, and most measures can be calculated from it. It is however important that the source and receiver positions are as correct as possible. Parameters that are extracted from the impulse response are the reverberation time, and the room gain. Parameters not included in the impulse response are those not directly related to the acoustic transfer path – that is background noise and the size of the room. Thus, four basic parameters are chosen to characterise each room – *reverberation time*, *room gain*, *background noise level* and *volume*. However, different variants of these parameters were tested as well.

In the subjective study, most of the questions were related to the objective parameters. Thus, the subjects were asked about the impression of reverberation and support, as well as background level in the rooms studied. They were also asked about the general impression of speaking in the room, and if they raised the their voice when speaking. A question about echo phenomena was also included in order to be able to say if this parameter influences the general impression of the room.

The main findings in this paper is that the different rooms significantly change the sound power produced by the speaker. It is found that these changes mainly have to do with the size and the room gain of the room.

II. Method

A. Method overview

Both subjective responses and objective measures of the room and of the voice level are collected. A selection of different natural acoustic environments are used – opposite of using a synthetic sound field. In simulated sound fields the variables can be changed rapidly and with precision in wide ranges. However, the sound quality is still limited due to the need of real time processing of the signals produced by the speaker. Moreover, the visual impression of the room can not easily be included –

this might be a positive aspect in many cases, but here it is important to get the visual size of the room and the distance to the audience right. Therefore, real rooms were chosen to be used – six in total. The range in the physical parameters of the rooms used were wide, including small meeting and listening rooms; a medium size lecture room; two lager auditoria's, one with high reverberation time and one with low; and a large anechoic room.

In the six rooms the sound power level produced by six speakers were measured. Each of the speakers held a short lecture (about 5 minutes). Objective room acoustic parameters where measured in the rooms as well, and a subjective questionnaire was handed out to about 20 persons who had experience in speaking in the rooms. A statistical analysis was then used to find relationships between the subjective responses and the objective measures.

B. The Subjects

In the objective study 6 speakers were used. 3 of these where teachers at Acoustic Technology, Ørsted*DTU, the other 3 were students in acoustics. In one of the rooms (meeting room 112, build. 352) only 5 speakers were present. The speakers had no known voice pathology. Each speaker was instructed to give the same lecture in all rooms. However, as the speakers did not have a written text to read, the lectures were not identical. Most speakers used a laptop computer with a power point presentation as the basis of the speech. In order to get the background level identical, a laptop and a video projector (if available in the room) were present also for those not using it. All speakers where male, age about 20 to 55. There is a possibility that the speakers are are not fully representing all relevant speakers, as it consisted of those finding it interesting to participate. Actually, the teachers participating are known to have weak voices (low voice power). However, most of the analysis are made on a relative VPL, see section II C, which decreases the variance in the data. Another subset problem might be that all subjects were acousticians, a fact that might influence the result – we choose to believe that this has a minor influence only.

In the subjective study 21 subjects participated (between 14 and 21 responses were collected for each room, see Tabel I). The subjects were teachers and students in acoustics – the participants in the objective part were also present in the subjective part. Both male and female subjects aged between about 20 and 60 participated.

C. Objective measurements and equipment

1. Impulse response measurements

The impulse response $h(t)$ of the rooms is measured to calculate reverberation time and room gain. The equipment used for the measurements were: Power amplifier LAB 300 from LAB Gruppen. Microphone unit Type 4192-L-001 Brüel & Kjær (B&K). Conditioning preamplifier Nexus Type 2690 B&K. Sound Level Calibrator Type 4231 B&K. In case of the reverberation measurements, an omni directional dodecahedron loudspeaker was used and in case of the room gain measurements a dummy head torso was used, as described below. The Dirac software[14] was used with e-sweep excitation signal. The sweep length was 21.8 seconds.

2. Reverberation time

Generally, the most important room acoustic parameter is the *reverberation time* RT (variable T_{30}), see ISO 3382.[15] The *early decay time* EDT (variable T_{EDT}), is the reverberation time determined from the first 10 dB range of the decay curve. The EDT is known to be more closely related to the subjective impression of reverberation than RT. In the analysis mainly EDT was used. (A reference of these basic room acoustic parameters is Kutruff.[16])

The reverberation time is calculated from the impulse response using the Schroeder method.[16] The reverbation times were calculated in octave bands. In order to describe the reverberation time as a single number, the arithmetic mean of the reverberation time in the octave bands centred in 500 and 1000 Hz are used.

3. Room gain

The transmission path from the mouth to the ear has three parts: bone conduction, a direct airborne part and a room reflections part; it is the latter path that is of interest here. The perceived beneficial increase in the loudness caused by the room is assumed to be due to the early reflections as compared to the direct response without reflections, perceived as ones ability to hear oneself properly in the room. This is here denoted as a gain, or support, caused by the room. The parameter used in the present study is called *room gain* RG (variable G_{RG}). It is defined as the energy (in decibels) of the impulse response measured between the mouth and the ear of a dummy head torso, taking as reference the corresponding measurement in the anechoic chamber where only the direct sound is present. As explained earlier, the reason for not using the support measure ST is that small rooms are also to be included in the present study, and then the definition of the ST is not appropriate, as the direct part of the impulse can not be separated from the rest of the impulse response. Moreover, an anechoic chamber is included in the study, and here $ST = -\infty$.

The energy of a impulse response in a time interval t_1 to t_2 can be calculated as

$$E_{t_1-t_2} = \int_{t_1}^{t_2} h^2(t)\mathrm{dt}, \tag{2}$$

where $h(t)$ is the impulse responce. The energy in the entire impuls responce is in the same way

$$E = \int_{0}^{\infty} h^2(t)\mathrm{dt}. \tag{3}$$

The corresponding impulse energy level is $L_E = 10 \log E/E_{ref}$, where E_{ref} is the reference value. The room gain is then defined as the energy in dB in the signal relative to the direct energy as measured in the anechoic chamber,

$$G_{RG} = L_E - L_{E,ach} = 10 \log E/E_{ach}, \tag{4}$$

where $L_{E,ach}$ and E_{ach} is the impulse energy level and energy in the anechoic chamber respectively.

The room gain is related to the support ST, as defined in equation (1). If it is assumed that $E_{dir} \approx E_{0-20} \approx E_{ach}$ and $E_{20-x} \approx E_{20-\infty}$, then

$$ST \approx 10 \log \frac{E - E_{0-20}}{E_{ach}} \approx 10 \log \left(10^{G_{RG}/10} - 1\right) \quad (5)$$

A support value of $ST = 0$ thus corresponds to $G_{RG} = 3$ dB, meaning that the reflections contributes with the same energy as the direct sound. It should however be noticed that the source/receiver distance is different in the definition of ST as compared to G_{RG}.

The equipment used was the same as described under the impulse response above, with the following changes: Dummy head, Head & Torso Simulator Type 4128 with Right Ear Simulator Type 4158 and Left Ear Simulator Type 4159 B&K. Power amplifier for the sound source (the dummy mouth).

The dummy head was placed in the area where the speaker normally stands during the lecture (next to the blackboard or similar). The average of six different positions of the dummy head was used. Moreover, the average RG of the left and right channel was calculated and used in the data analysis.

The RG was calculated from the impulse response by means of post processing in Matlab. All signals have been normalised with a maximum amplitude of the signal to 1 (amplitude of the first peak of the impulse response). Some problems with the signals were found during the analysis. Noise was found in all the signals. In order to reduce the effect of this problem, all the impulse response signals were truncated (cutted) so as to avoid the last part of the signal which mainly contained noise. Thus, the noise effect was minimized, and it is judged that its influence can be disregarded.

The RG was calculated per octave band. In order to define the RG of the room with one characteristic value, the arithmetic mean of the RG in the octave bands between 125 Hz and 4 kHz are used.

4. Background noise level

In a speech situation the *background noise level* BNL (variable $L_{BN,A}$) is important. BNL can be defined as the sound pressure level of the noise measured in the absence of the sound under investigation – in this case the speech. The background noise can originate from the ventilation systems, the outdoor environment and traffic, equipment as computers and projectors, and from the students/audience. As the BNL increases, the speaker may increase his voice to compensate and overcome the noise in order to be heard. The voice will be affected by the mental pressure due to the failure of being heard. The frequency content in the voice signal will then be changed – there will be more high frequency content due to an increased fundamental frequency. These changes are known as the Lombard effect; an early reference is Lane and Tranel.[17] The effect is included in ANSI-S3.5.[2] (Sometimes is the term 'Lombard effect' restricted to just the increase.) This is also closely related to the fact that in a situation with several people talking to each other, they increase their voice to overcome the background noise level that is produced by all the persons speaking, producing a non-linear feedback loop, see e.g. Hodgson.[18] Naturally, the number of students and their behavior during the lecture also may play an important role here – the students will contribute to the background level and probably react in relation to the Lombard effect. However, this aspect is not part of the present work (due to schedule reasons and time limits); the present project is focused on the characteristics of the room only, leaving this important aspect to further research. The number of listeners present in the room was just a few (3-5) and adult, so there contribution to the BNL is assumed to be low. The BNL naturally present in the rooms (from the ventilation system, video projector, computers etc.) were however registered.

The equipment used to measure L_{BN} is the same as for the impulse response measurements for the reverbation. The measurement duration is 21.8 seconds. The mean value of six microphone positionsin have been used in all rooms. The positions were in the area the teacher was using. To get a single value, the A-weighted level $L_{BN,A}$ is used. The equipment used by the speakers (laptop computer and projector) was present in the room during the measurement.

5. Room volume

Of the objective parameters describing the rooms, finally the size or *volume* (variable V) has also been used. The hypothesis here is that the speakers unconsciously adjusts the level of the voice depending on the room size and the distance to the audience, so that everyone is likely to hear. However, it is not clear if it is the volume by itself of typical length scale in the room that is the primary variable here. Thus, V, $\log V$ and $\sqrt[3]{V}$ were all tested.

6. Voice power level

With the rooms defined, the last step is to define the behaviour of the speaker in the room. In this project, this is described by the strength of the speaker's voice. The quantity used here is the *voice power level* VPL (variable L_W), that is the source power in dB. Thus, the sound power level produced during speech by the different test speakers was measured in the different rooms.

The measurement of the voice power level is a central issue of this paper. The measurements are made with a computer phone conversation headset, placed on the speaking subjects. The experimenter made sure that the position of the headset was fixed to the same position in all measurements, about 3 cm from the mouth. The equipment consisted of Headset Creative HS-390 and sound analyser Dirac. The signals were measured while the speaker was lecturing for about 5 minutes. And an average of 15 signal segments of 21.8 s were used for each subject.

A calibration procedure was needed to transfer the measured signals to sound power level L_W. The dummy head torso equipped with a loudspeaker in the mouth where placed in a reverberation chamber with the headset attached in the same position as described above. A broad band noise signal was fed to the loudspeaker and measured simultaneously by the headset and with microphones in the reverberant field of the room according to SWL standard measurements (ISO 3743-2). The measurements and calibrations were preformed in octave bands. The relation between the sound power of a source and the sound pressure level in one position determined by a microphone can generally be expressed as $L_W = L_p + G$, where G is a gain constant for the setup (depending on the source receiver distance and source directivity) and L_p is the sound pressure level as measured by the headset. It is now assumed that the microphone is so close to the source that only the direct field is present (i.e. the signal to noise ratio is assumed to be so good that the room response can be neglected). Moreover, it is also assumed that all speakers had the same directivity, equal to that of the dummy head. It is thus assumed that G is constant during all measurements in all rooms. (Note that this quantity obviously is different from G_R.) Finally, having determined both L_W and L_p at the same time in the reverberation chamber, the gain constant G is determined.

The voice power level is determined in octave bands from 125 Hz to 4 kHz. In order to have a single value three different methods are tested: linear ($L_{W,l}$) and A-weighted ($L_{W,A}$) absolute VPL, and linear voice power level relative to the voice power level in the anechoic chamber ACH, ΔL_W. Note that the subtraction is made for each speaker, so that ΔL_W is made relative to the VPL for that speaker in the ACH. In this way the variance is reduced. The ACH room was chosen as it was the room with the highest average voice power level. (The room with the lowest VPL, the meeting room MR, was also considered to be used as reference, but this idea was dropped as not all speakers spoke in this room.)

D. The rooms

To get good statistic results, it is important to apply a wide range and even distribution of the different physical variables defining the room. The rooms and the values of the objective measures is given in Table I. The rooms were: a small meeting room (MR) and a IEC listening rooms (IEC); a medium size lecture room

(LR); two larger auditoria's, one with high reverberation time (A21) and one with low (A81); and a large anechoic room (ACH). Including the anechoic room means that the subjects have a very clear reference for reverberation time and room gain – which both are zero in this room. Besides, ACH is relevant as it represents out door surroundings. The range covered by the volume, the reverberation time and the room gain can be considered as large in comparison to what can be found in real life situations. For the background noise, only the naturally present background noise was included. Thus, this variation is small as compared to what can be found in real life situations.

E. Questionnaire and subjective response

In an attempt to relate the objective parameters of the room and the voice power level to with the subjective experience of the rooms a questionnaire was designed. The questions where formulated after a first interview with a few teachers. The parameters considered are described below.

The questions were answered for each of the rooms in which the subject had experience talking in. Thus, the subjects were not necessarily in the room when the questions were answered – in an attempt to increase the number of answered questionnaires. 21 subjects answered the questions, the number of answer for each room varied between 14 and 21, see Table I. The questions were answered on a scale form 1 to 7. Only the natural numbers where used. Taking the arithmetic average of these answers, a subjective response variable S_i was formed, where the index i is the abbreviation of the question, see below.

The questions are the following (the questions are given in italic fonts) – it should however be noted that the these are not exactly the questions used (due to bad English).

Do you consider this room to be good to speak in? This question is referred to the degree of comfort and how easy it is to speak in the room. The rank is between low, if the room is not good to speak in and high if it is good to speak in. This parameter is labelled GSI, variable S_{GSI}.

Do you think the reverberation time is to long in the room? This question clearly refers to the objective parameter of reverberation time. The rank in this case goes from 'no' if the reverberation is not too long or 'yes' if it is to long. This parameter is labelled TR, variable S_{TR}.

Have you noticed echo phenomenas in the room? The sensation of echo might influence the general impression of the room, so this response is introduced even though it is not represented in the objective parameters. The answers should be covered between low, if no echo is noticed, and high if there is too much echo. This parameter is labelled ECHO, variable S_{ECHO}. A low score is considered good.

Is the background noise to high in the room? The subjects response might be from 'yes', if they think there is a lot of background noise in the studied room, to 'no', if they think that there is no noise in the room. This parameter is labelled BN, variable S_{BN}. A low score is considered good.

Do you have to increase your voice in this room to be heard? This question is interrelated with the sound power level. The answer is between 'no', if the subjects think they did not increase the voice, to 'yes', if they did have to increase the voice. This parameter is labelled IV, variable S_{IV}. A low score is considered good.

Is there enough support in this room? This has to do with if the room helps the speaker to hear himself. The rank is between bad support, if they believe that the room does not yeild support at all and good support if the support is sufficient. This parameter is labelled ES, variable S_{ES}. A high score is considered good.

F. Data analysis

The statistical analysis of the data was carried out in Matlab. This analysis incorporates ANOVA, correlation coefficients and linear regressions.

In order to find relationships between the subjective responses and the objective parameters – a psychometric function – some post processing has been done. The psychometric function, relating a subjective parameter S, with upper limit S_{max} and lower limit S_{min}, and an objective parameter d (or a linear combinations between such parameters) should be an S-shaped function. The reason for this is that the objective parameter is not bounded, $d \in [-\infty \, \infty]$, but the subjective parameter is bounded, $S \in [S_{min} \, S_{max}]$. One choice of such a function is,

$$S = \frac{S_{max} - S_{min}}{1 + e^{-d}} + S_{min}. \tag{6}$$

(this choice of psychometric function is taken from paired-comparison theory[19,20]). The point of using such a relation is that S has a finite domain $S \in [S_{min} \cdots S_{max}]$ whereas d might have an infinite domain $d \in [-\infty \cdots \infty]$. In the present case $S_{max} = 7$ and $S_{min} = 1$. Solving for d in (6), a suitable transformation from the finite S-domain to the infinite d-domain of the objective measures is found,

$$d_S \equiv -\ln \frac{S_{max} - S}{S - S_{min}}. \tag{7}$$

The parameter d_S can be used as the dependent variable in regressions connecting objective measures to subjective response.

However, in some cases the objective parameter is non-negative, $d > 0$. That is the case for the reverberation time and the room gain. Moreover, in the present study the extreme situation of zero reverberation time and room gain is included in the study due to the use of the anechoic chamber. In these cases the equations (6–7) have to be modified. The following equations then applies,

$$S = \frac{2(S_{max} - S_{min})}{1 + e^{-d}} + 2S_{min} - S_{max} \tag{8}$$

and

$$d_S \equiv -\ln \frac{S_{max} - S}{S - 2S_{min} + S_{max}}. \tag{9}$$

However, in many cases is the range of the objective parameter so small that the error of using a linear regression directly between d and S is small. That is actually the case in the pressent study, and in the result section below, the regressions are often preformed both using the psychometric function and directly between S and d.

III. Results

A. Validity and quality of the data

An analysis of variance (ANOVA) is used to examine if the variations in the data are sigificant. The left part of Table II presents these results concerning the subjective parameters. The variations are significant except for background noise BN, where no significant variations are found at the 5% level or better (p-value 0.16), and for detection of echo ECHO, where the variations are significant at the lower level of 5% (p-value 0.046), but not higher. It should here be noted that the variation in the background level of the rooms were small, and that there are no known problems with echo or flutter echo in the rooms used. In the same way, the right part of Table II presents the significance test of different versions of the voice power level. Here the significance of the variations in the data is less, probably due to the lower number of subjects participating. However, taking VPL relative to the result in the anechoic chamber, ΔL_W, yields significant variations at the 5% level (p-value 0.036).

In the further analysis, only $L_{W,l}$ and ΔL_W will be used describing the VPL. $L_{W,A}$ is disregarded as it does not increase the significance much, and because it is not as straight forward as $L_{W,l}$. Moreover, results depending on the subjective responses BN and absolute VPL, $L_{W,l}$, should be considered only as trends.

B. Relationships among objective parameters

The objective parameters used to describe the rooms were presented in Table I. The objective changes of the voice power level is presented in Table III. The correlation matrix between these parameters is given in Table IV. It should be noted that the VPL measures correlate well with the volume, especially $\log V$, and the room gain G_{RG}. There is no significant correlation between the VPL measures and reverberation time and background noise. It should also be noted that the reverberation time measures and the background noise measure do not correlate significantly with any other measure.

Note that the correlation between support ST as calculated in equation (1) and the other parameters is not included here as the support is undefined in the anechoic chamber due to the lack of reflexions (the value would be $-\infty$).

The results of single variable linear regression are found in Table V. Only results with $p < 0.1$ are shown. It is shown once again that $\log V$ and G_{RG} correlates well with VPL. A multiple linear regression model using these two variables is

$$\Delta L_W = -5.68 + 1.81 \log V - 2.28 G_{RG}, \tag{10}$$

with $R^2 = 0.86$ and $p = 0.05$. The improvement of using two parameters is described by the fact that R^2 increases from 0.78 to 0.86 and at the same time the model being at the limit of significance. The model is shown in Figure 1.

C. Relationships among subjective parameters

The subjective responce parameters are presented in Table VI. The correlation matrix for these parameters is given in Table VII. Using the objective domain transformation according to equations (7) and (9) yielded similar results.

The results of single variable linear regressions are found in the right part of Table V. Only results with $p < 0.1$ are shown. It can be seen that S_{IV} and S_{ES} correlates well with S_{GSI}; these regressions are also shown in Figure 2 and 3. A multiple linear regression model using these two variables is

$$S_{GSI} = 6.82 - 0.715 S_{IV} - 0.189 S_{ES}, \tag{11}$$

with $R^2 = 0.74$ and $p = 0.13$. Thus, the improvment of the two parameter model was not large, and the model is not significant. This is probably due to a high linear dependency between S_{IV} and S_{ES}.

D. Relationships between subjective and objective parameters

Table VIII shows the correlation between the objective parameters and the subjective responses (the number of objective parameters has been reduced as T_{30} and

$\sqrt[3]{V}$ have been ignored). Using the objective domain transformation according to equations (7) and (9) again yields similar results (a slightly better correlation on average).

The results from single variable linear regressions are found in Table IX. Only the regressions with $p < 0.1$ are shown. The regression between IV and ΔL_W is shown in Figure 4, and between TR and T_{EDT} is shown in Figure 5. A multiple linear regression model for IV using two variables is

$$S_{IV} = -0.198 + 1.73 \log V - 1.11 G_{RG}, \quad (12)$$

with $R^2 = 0.90$ and $p = 0.03$. The improvment of using two parameters is described by the fact that R^2 increases from 0.86 to 0.90 while the model is still significant.

IV. Analysis and Discussion

The ANOVA test in Table II indicates that in general the statistical quality of the subjective data is better than in the VPL data. One reason for this is probably the higher number of participants in the subjective questionair (about 20) as compared to the VPL measurements (about 6). However, it is known that it is difficult to get statistically consistent data for the voice strength, see e.g. Rantala.[9] Anyway, in the present study significant variations in the VPL data are found in case of the relative VPL, ΔL_W, using just 6 subjects. One reasons for this is the normalisation procedure of the data by taking the value relative to the anechoic chamber. In this way the natural variation in VPL among the subjects is reduced, and only the increments for different rooms are studied. Moreover, using a wide range of different rooms – including the anechoic chamber, large auditoriums and small meeting rooms – is likely to increase the variation in VPL.

Considering Table IV, room volume and room gain show high correlation with the voice power level. An increase in volume increases the VPL and an increase in room gain decreases the VPL. These results are significant if considering ΔL_W related to $\log V$ and G_{RG}. Of the size measures, the logarithm of the volume, $\log V$, has the highest correlation. One can regard $V^{1/3}$ to be a typical length scale of the room and $\log V$ to be related to the average sound pressure level in the room for a given source power level. Thus, the fact that the increase in VPL is better correlated to $\log V$ than $V^{1/3}$ suggests that the aural cues might be more important than the visual cues. The VPL relative to the value in the anechoic chamber, ΔL_W, correlates in general better than the absolute linear VPL, $L_{W,l}$. This is probably linked to the fact that ΔL_W has higher significance than $L_{W,l}$ in the ANOVA test in Table II. Equation (10) express the relationship between ΔL_W, $\log V$ and G_{RG}, also shown in Figure 1. In Table VIII there is a trend that ΔL_W is correlated with ES, the question related to support in the room. Moreover, $\log V$ and G_{RG} are correlated to IV, the question if the subject had to increase the voice to be heard. There is also a trend that $\log V$ and G_{RG} are correlated to ES. These results confirm the results above.

Considering again Table IV, reverberation time and background noise level did not show any correlation with the VPL. Both of these results can seem surprising; reverberation time is the generally most frequently used room acoustic measure and background noise is known to increase the speech level in other circumstances, e.g. in connection with the Lombard effect.[18] However, there is an important difference between these parameters in the present study. The variation in the reverberation time data is rather large, T_{EDT} from 0.01 s in the anechoic room to 1.53 s in auditorium 21, but the variation in background level is small, from 41.8 dB(A) in auditorium 21 to 53.5 dB(A) in auditorium 21, see Table I. 'Large' and 'small' should be understood as relative to what is normally found in lecture rooms. Moreover, the BNL in the room used were too low to influence speech. It is thus quite likely that a dependency in background noise could be found if more extreme values had been included. The same conclusion does not apply for the reverberation time. Moreover, in Table VIII it can be noted that ΔL_W is not correlated with the corresponding subjective responses TR or BN, which confirms the discussion above.

Considering the correlation among the subjective responses, Table VII, it can be noted that the question if the room is good to speak in, GSI, is correlated with the question about increase in voice level to be heard, IV. Thus, the ability to make oneself heard is judged to be important in the general judgement of the room. This is confirmed in Table VIII where GSI is correlated with ΔL_W. There is also a trend that GSI is correlated to ES, the question if there is enough support in the room. The other questions (TR, ECHO and BN) do not show any correlation. It can thus be concluded that a room is good to speak in if it has support and it is not necessary to increase the voice to much.

In Table VII it can also be seen that the question if the reverberation time is too long, TR, is correlated to the question if there is to much background noise, BN (with negative sign due to the orientations of the subjective scales). Moreover, in Table VIII it is found that also T_{EDT} is correlated to BN but L_{BN} is not. This might seem strange. However, it should be remembered here that the questionnaire was not answered at the same time as the measurements, and that the subjects had the option to answer it while being elsewhere. Thus, BN is rather the experience of the background noise as they could remember it. The most severe source of background noise is probably the students present during the lecture. In the light of the Lombard effect it is likely that this noise increases with increasing reverberation time. It is thus not so surprising that T_{EDT} turns out to correlate well with BN. Thus, the subjective response BN does not refer to and is not related to the measured background noise.

In Table VII it is also found that there is a trend that the question if echo is noticed, ECHO, is correlated to the question if there is enough support in the room, ES. This can be interpreted as that the reflections that contribute to the room gain and support also might be imagined to cause echo phenomena, e.g. flutter echo. However, ECHO does not show big influence on any other parameter, and is not correlated with GSI or IV, so it is judged that echo phenomena have not influenced the results. None of the rooms are known to have problems with flutter echo.

In Table VII the question if there is enough support in the room, ES, is correlated to the question about if the subject had to increase the voice to be heard, IV. This seems natural, and it is also reflected in the correlation between ΔL_W and G_{RG} among the objective measurements, Table IV.

The strong correlation between the subjective response of increasing the voice, S_{IV}, and the objectively measured VPL should be noticed in Table VIII. This can be interpreted as the subjects being aware that they have to increase the voice in the room.

In Table VIII T_{EDT} is strongly correlated to TR. Thus, the subjects are aware of the reverberation time. It should then be remembered that all subjects were teachers or students in acoustics, and therefore familiar with the concept of reverberation time.

Concerning the frequency rang of RT and RG: the frequency rang used (the octave bands from 125 Hz to 4 kHz for the RG and 500 Hz and 1 kHz octave bands for the RT) have in this study been assumed to be most responsible for the impression of the two measures. Different versions of the parameters have been tested, but not reported, and the chosen definitions and frequency range give good correlation. However, there probably is a need for more research in order to fine tune the measures.

Using the regression between ΔL_W and IV, Table IX and Figure 4, some preliminary design guidelines can be proposed. If a subjective response of $S_{IV} \leq 3$ is regarded as a good room, the model yields that this corresponds to $\Delta L_W \leq -3.1$ dB. Now, using the model in equation (10), see Figure 1, this corresponds to $G_{RG} \geq 0.80 \log V - 1.1$ dB. Thus, for a room with volume 100 m^3 the room gain should be $G_{RG} \geq 0.5$ dB, and a room with volume 1000 m^3 the room gain should be $G_{RG} \geq 1.3$ dB. It should however be noted that such guidelines are preliminary, and should not be used before further evidence has been obtaind. Also note that the recommended values might be difficult to realize in reality for large auditoriums. Thus, these guidelines are limited to smaller rooms and rooms without voice amplification systems.

V. Conclusions

- The voice power relative to the value in the anechoic chamber varies significantly between room.
- The increase in the voice power produced by a speaker lecturing in a room is correlated with the size of the room (especially $\log V$) and the gain produced by the reflections in the room, G_{RG}. These relations are significant.
- No significant correlation is found between the increase in the voice power and the reverberation time or background level of the room in this study. The latter is probably due to the too small variations in the background levels in the rooms studied.
- The general impression of whether a room is good to speak in is linked to the impression of whether it is necessary to increase the voice in the room, and if the room provides support to the speaker. The former relation is significant, the latter only a trend.
- There is a significant correlation between the question if the subject had to increase the voice and the actual increase of voice power. There is also a significant correlation between the question about the reverberation in the room and the measured reverberation time. This means that the subjects participating were aware of these parameters.

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FIGURE CAPTIONS

1. Regression model (10) versus to real data of increase in voice power level ΔL_W. Room abbrevation according to Table I.

2. Regression model between subjective variables, S_{GSI} (good to speak in) against S_{IV} (increase voice), according to right part of Table V. Room abbrevation according to Table I.

3. Regression model between subjective variables, S_{GSI} (good to speak in) against S_{ES} (enough support), according to right part of Table V. Room abbrevation according to Table I.

4. Regression model between subjective variable S_{IV} (increase voice) against increase in voice power level ΔL_W according to Table IX. Room abbrevation according to Table I. Solid line: Using objective domain transformation equation (7). Dashed line: Linear regession.

5. Regression model between subjective variable S_{TR} (reverberation) against early reverberation time T_{EDT} according to Table IX. Room abbrevation according to Table I. Solid line: Using objective domain transformation equation (9). Dashed line: Linear regession.

TABLE I. The rooms used in the experiments and their objective values. All rooms are located at DTU, Lyngby, Denmark. ◇ number of questionnaire answers for each room.

Name	abbrev.	V m^3	T_{30} s	T_{EDT} s	G_{RG} dB	$L_{BN,A}$ dB	nr.◇
Auditorium 81	A81	1900	1.06	1.12	0.28	41.8	14
Auditorium 21	A21	1220	1.53	1.72	0.29	53.5	19
Lecture r. 019	LR	190	0.46	0.40	0.42	47.5	21
Meeting r. 112	MR	94	0.42	0.33	0.58	47.5	17
Large anechoic ch.	ACH	1000	0.06	0.01	0	45.9	17
IEC listening r.	IEC	100	0.34	0.32	1.12	46.7	16

TABLE II. Significance test of the subjective response parameters, and VPL parameters (different versions), using ANOVA. The following symbols are used: * means significant at the 5% level, *** means significant at the 0.1 % level, and – means no significans at the standard levels.

Question	GSI	TR	ECHO	BN	IV	ES	$L_{W,l}$	$L_{W,A}$	ΔL_W
p-value	$< 10^{-6}$	$< 10^{-6}$	0.046	0.16	$< 10^{-6}$	$< 10^{-6}$	0.13	0.11	0.036
significance	***	***	*	–	***	***	–	–	*

TABLE III. The rooms used in the experiments and their objective values.

Abbrev.	$L_{W,l}$ dB	$L_{W,A}$ dB	ΔL_W dB
A81	62.9	60.0	-1.30
A21	63.9	60.9	-0.08
LR	62.9	60.1	-1.93
MR	58.7	55.2	-4.33
ACH	65.0	62.1	0
IEC	59.8	57.0	-4.32

TABLE IV. Correlation matrix for the objective measures, including the voice power level. Only correlations with p-values lower than 0.2 are shown. In parenthesis: $0.2 > p > 0.1$; roman upright: $0.1 > p > 0.05$; italic: $0.05 > p > 0.01$; bold face: $p < 0.01$.

Objec.	$L_{W,l}$	ΔL_W	T_{30}	T_{EDT}	V	$\log V$	$\sqrt[3]{V}$	L_{BN}	G_{RG}
$L_{W,l}$	**1**	**0.97**	–	–	(0.63)	*0.82*	0.76	–	-0.81
ΔL_W	**0.97**	**1**	–	–	(0.72)	*0.88*	*0.84*	–	*-0.86*
T_{30}	–	–	**1**	**1.00**	–	–	–	–	–
T_{EDT}	–	–	**1.00**	**1**	–	–	–	–	–
V	(0.63)	(0.72)	–	–	**1**	**0.96**	**0.98**	–	(-0.63)
$\log V$	*0.82*	*0.88*	–	–	**0.96**	**1**	**1.00**	–	-0.76
$\sqrt[3]{V}$	0.76	*0.84*	–	–	**0.98**	**1.00**	**1**	–	(-0.72)
L_{BN}	–	–	–	–	–	–	–	**1**	–
G_{RG}	-0.81	*-0.86*	–	–	(-0.63)	-0.76	(-0.72)	–	**1**

TABLE V. Single variable linear regression. Only regessions with $p < 0.1$ are shown. Left: between VPL ΔL_W and the objective parameters. Right: between S_{GSI} and the subjective parameters. The variables b_0 and b_1 are the regression constants, the constant term and the linear term, respectively.

Dependent variable	ΔL_W		S_{GSI}	
Independent variables	$\log V$	G_{RG}	S_{IV}	S_{ES}
R^2	0.78	0.74	0.73	0.61
p	0.02	0.03	0.03	0.07
b_1	2.94	-4.40	-0.90	0.72
b_0	-9.64	-0.021	8.30	1.91

TABLE VI. The rooms used in the experiments and their subjective response values. The scale is between 1 and 7. The notation is $\bar{S}/s$, where $\bar{S}$ is the average value and s is the standard deviation. In the further analysis the average value is used, then denoted S.

Abbrev.	S_{GSI}	S_{TR}	S_{ECHO}	S_{BN}	S_{IV}	S_{ES}
A81	5.64/0.74	2.64/1.34	1.93/1.64	4.00/1.52	4.50/1.34	3.29/0.83
A21	3.37/1.54	5.16/1.50	3.42/2.11	3.74/1.59	5.16/1.26	4.16/0.96
LR	5.71/0.78	1.76/0.54	2.95/2.01	4.33/1.43	3.29/1.27	5.05/0.86
MR	6.12/1.27	2.00/1.00	2.53/2.03	4.59/1.80	2.12/1.05	5.53/0.94
ACH	2.59/2.03	1.00/0	1.41/1.46	5.29/2.73	5.41/2.12	1.29/0.99
IEC	5.88/1.54	1.63/1.08	2.38/2.31	5.06/2.38	2.31/1.01	5.50/0.97

TABLE VII. Correlation matrix for the subjective measures, using the subjective scale S. Only correlations with p-values lower than 0.2 are shown. In parenthesis: $0.2 > p > 0.1$; roman upright: $0.1 > p > 0.05$; italic: $0.05 > p > 0.01$; bold face: $p < 0.01$.

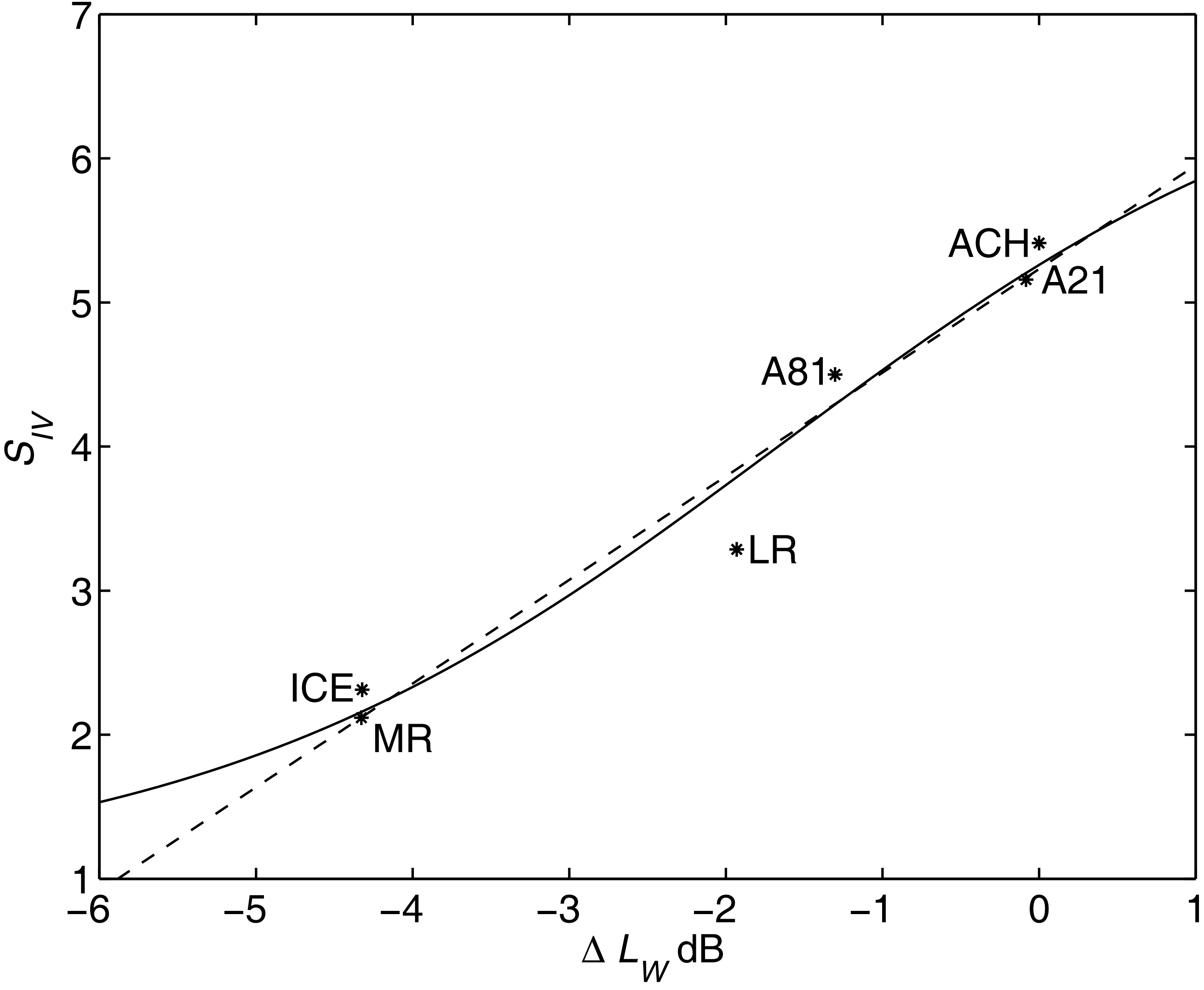
Subj.	GSI	TR	ECHO	BN	IV	ES
GSI	**1**	–	–	–	*-0.85*	0.78
TR	–	**1**	(0.71)	*-0.84*	–	–
ECHO	–	(0.71)	**1**	(-0.66)	–	0.66
BN	–	*-0.84*	(-0.66)	**1**	–	–
IV	*-0.85*	–	–	–	**1**	*-0.85*
ES	0.78	–	0.66	–	*-0.85*	**1**

TABLE VIII. Correlation matrix for the objective and the subjective measures, using the subjectiv scale S. Only correlations with p-values lower than 0.2 are shown. In parenthesis: $0.2 > p > 0.1$; roman upright: $0.1 > p > 0.05$; italic: $0.05 > p > 0.01$; bold face: $p < 0.01$.

Obj. & subj.	S_{GSI}	S_{TR}	S_{ECHO}	S_{BN}	S_{IV}	S_{ES}
$L_{W,l}$	-0.80	–	–	–	**0.94**	-0.80
ΔL_W	*-0.82*	–	–	–	**0.98**	-0.79
T_{EDT}	–	**0.96**	–	*-0.90*	–	–
V	–	–	–	–	0.79	(-0.65)
$\log V$	(-0.63)	–	–	–	**0.93**	-0.77
L_{BN}	–	(0.65)	0.78	–	–	–
G_{RG}	0.68	–	–	–	*-0.83*	0.80

TABLE IX. Single variable linear regression between subjective and objective variables. Only regressions with $p < 0.1$ are shown. The upper part is using the subjective domain S and the lower part is using the objective domain d_S according to equations (7) and (9).

Dependent variable	S_{GSI}	S_{TR}	S_{IV}		
Independent variables	ΔL_W	T_{EDT}	ΔL_W	$\log V$	G_{RG}
R^2	0.68	0.92	0.96	0.86	0.69
p	0.04	0.003	0.0006	0.007	0.04
b_1	-0.64	2.20	0.72	2.27	-3.13
b_0	3.61	0.94	5.23	-2.12	5.20
R^2	0.71	0.89	0.97	0.86	0.69
p	0.03	0.005	0.0004	0.008	0.04
b_1	-0.50	0.903	0.538	1.68	-2.32
b_0	-0.27	-0.075	0.895	-4.55	0.863



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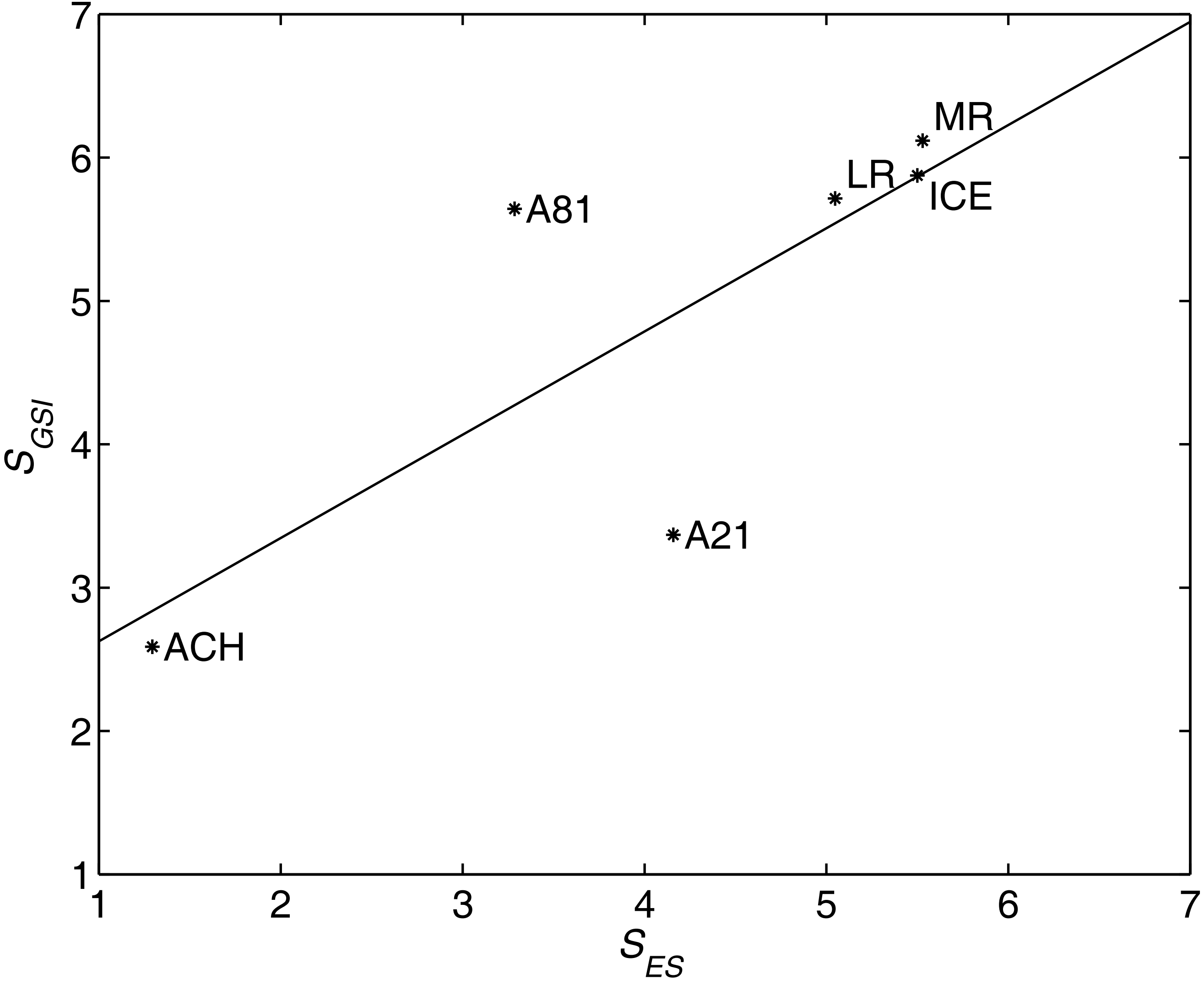

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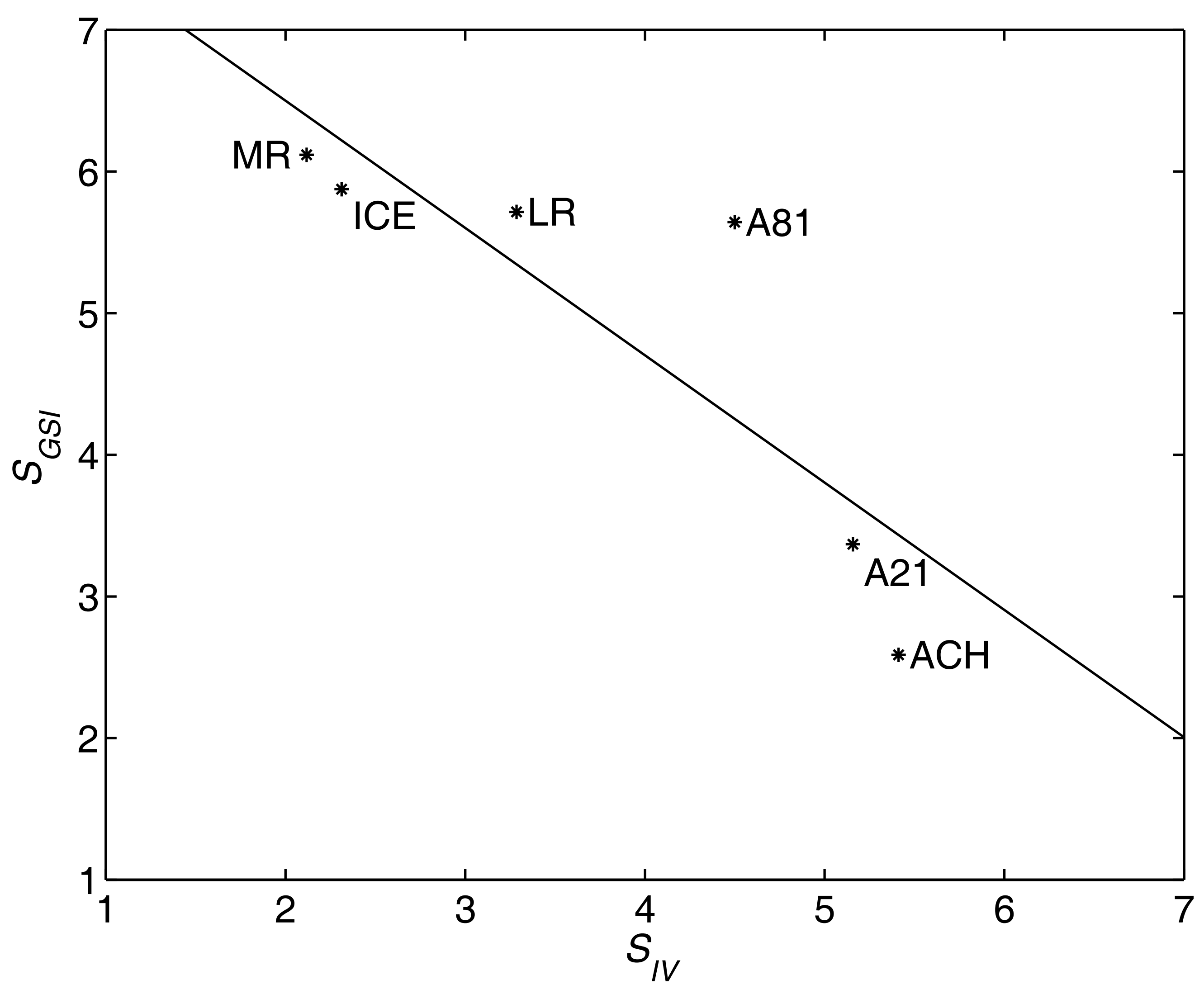

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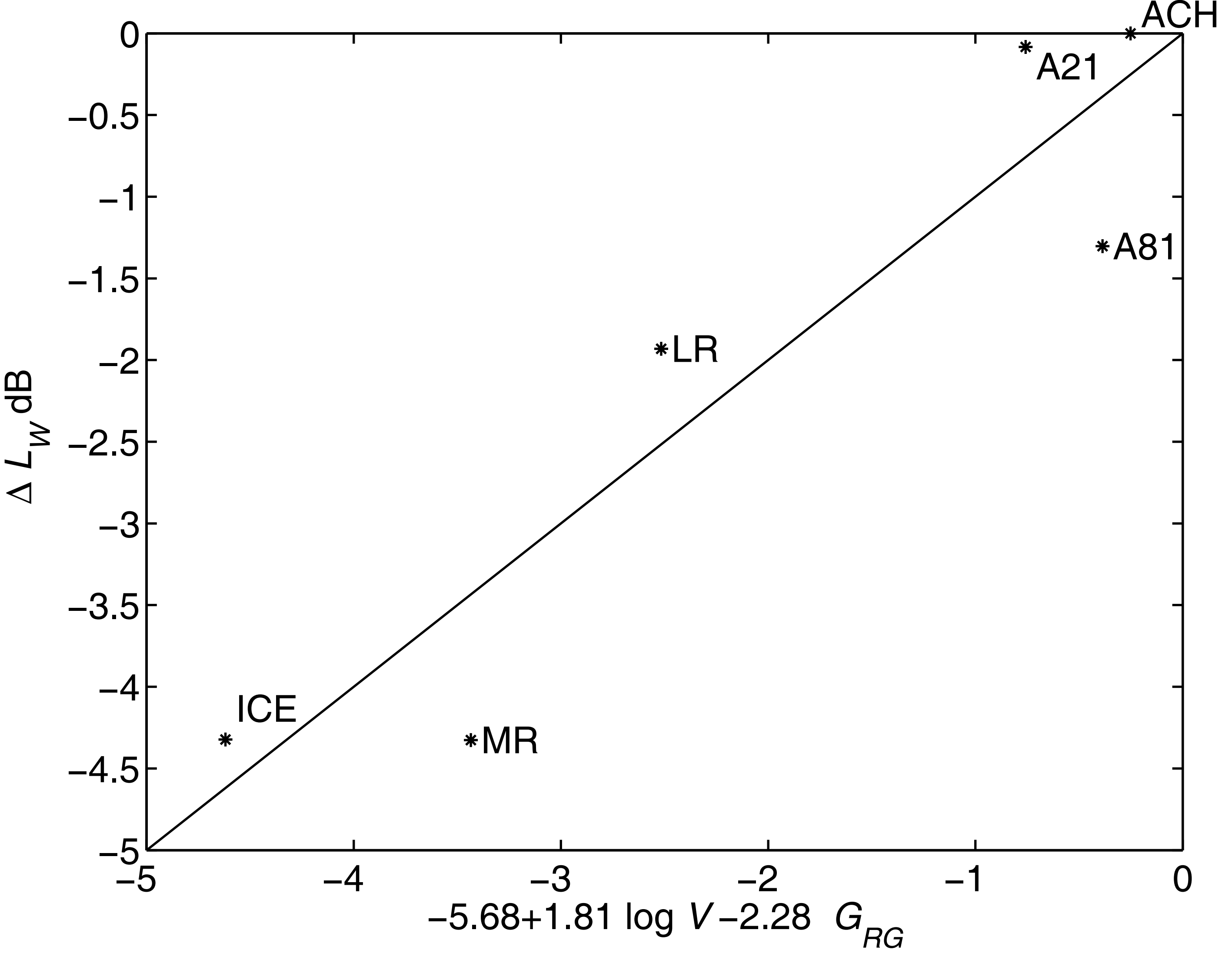

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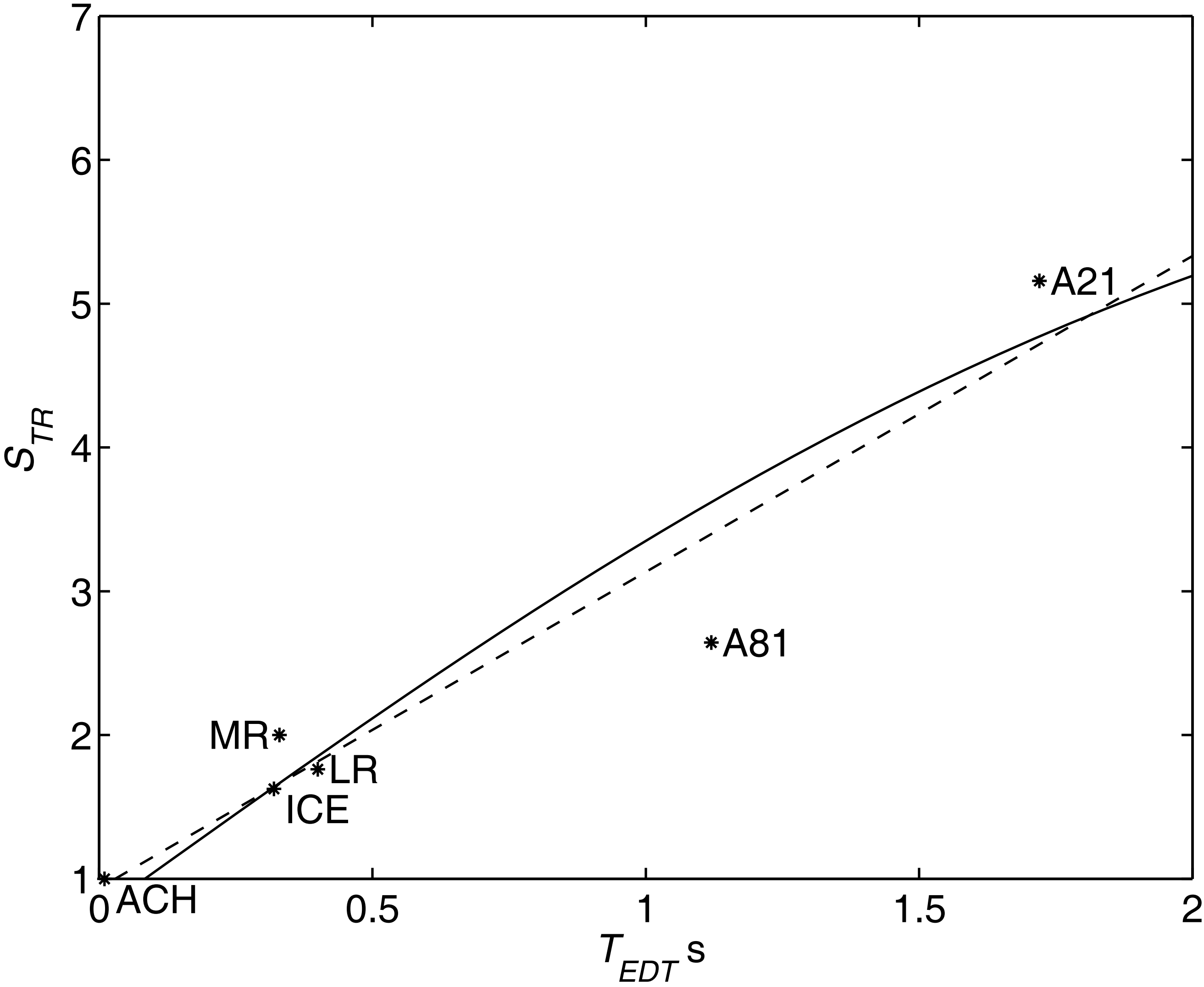
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