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ACOUSTICS IN 29 SPORTS HALLS MEASURED

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Physical Education (PE) teachers risk noise-induced hearing loss and other health problems due to high sound levels. The acoustic conditions in the sports hall are a potential factor of influence. However, no literature was found that confirms the relationship between occupational noise levels and acoustic conditions. Therefore, the acoustic conditions of 29 different sports halls have been measured during a multidisciplinary research project in the Netherlands on noise in sports halls focusing on specialist PE teachers in primary schools. Reverberation Time T_{20}, Sound Strength G and Speech Transmission Index STI are evaluated and compared to Room Volume, Equivalent Absorption Area and Average Absorption Coefficient. A clear relationship between Sound Strength and Equivalent Absorption Area is found as can be explained by diffuse sound field theory, even though the rectangular room shapes cause flutter echo behavior (not diffuse). Also, Speech Transmission Index and Average Absorption Coefficient show a relationship. In 7 sports halls, reflection studies have been conducted using an acoustic camera as a new method to visualize reflective, absorptive and diffusive properties of materials in the hall. Results are presented in this paper. Future research will focus on measuring occupational noise levels in the sports halls to investigate the relationship between sound levels in the same sports halls in use and acoustic conditions. The end goal of the project is to inform Physical Education (PE) teachers how they can protect their hearing during class.

Keywords: reverberation, strength, speech, sports, teachers

1. Introduction

Physical Education (PE) teachers risk noise-induced hearing loss and other health problems due to high sound levels [1]. The acoustic conditions in the sports hall are a potential factor of influence. However, no literature was found that confirms the relationship between occupational noise levels and acoustic conditions. In this partial research, the acoustic conditions of 29 different sports halls have been measured during a multidisciplinary research project in the Netherlands on noise in sports halls focusing on specialist PE teachers in primary schools. A detailed introduction of this research project was presented at Forum Acusticum 2023 [2]. Another paper by Lüthi and Desarnaulds on the same conference [3] showed measured reverberation times for 63 sports hall configurations from various researchers and compared them to different international standards, including the Dutch guideline by NOC*NSF [4] which is the strictest. It is striking that none of these 63 sports halls meet the Dutch guideline for reverberation time.

In the Netherlands the NOC*NSF guideline already exists for almost 20 years. This has led to a considerable improvement in acoustic conditions in newly build sports halls, where it is now common practice to provide sound absorption in the ceiling and at least 2 adjacent lower walls, as was not the case for the 63 configurations presented by [3]. Furthermore, they discuss difficulties with predicting reverberation time in sports halls because of limitations in computer modelling, which was also discussed by one of the authors of the current paper [5]. Parallel surfaces and uneven distribution of sound absorption make the sound field non-diffuse and more difficult to predict. Also, the estimation of input parameters such as (angle dependant) sound absorption and scattering characteristics of materials can be difficult.

In the current paper, the results from acoustic measurements are presented for 29 different sports halls. Reverberation Time, Sound Strength and Speech Transmission Index are evaluated and compared to Room Volume, Equivalent Absorption Area and Average Absorption Coefficient. Besides, reflection studies have been conducted using an acoustic camera as a new method to visualize reflective, absorptive and diffusive properties of materials in the hall. Future research will focus on measuring occupational noise levels in the sports halls to investigate the relationship between sound levels in the same sports halls in use and the currently presented acoustic conditions.

2. Room acoustics measurements

2.1 Halls

For the research 10 sports halls were selected. Corresponding the size and volume categorisation of the NOC*NSF standard [4] (category A – E) four of the selected sports halls are under category A, three under B and three under C. Most halls can be split in 1/3 and/or in 2/3 halls, except the ones in category A, which led to a total number of 29 configurations measured. Each category contains older halls (built before 2000) and new halls (built after 2015), which were selected such that potentially half of the halls would comply with the standard. Table 1 shows an overview of the categories that exist in the standard together with the reverberation time (RT) requirement, averaged over 125-4000 Hz octave bands. Additionally there is a requirement for maximum deviation per band f_b which is $T_{avg.} : T_{max,fb} \geqslant 0.7$.

Table 1: Sports halls categories NOC*NSF and number of measured halls per category, per NOC*NSF pass/fail.

Cat.	Description (in Dutch)	L [m]	W [m]	H [m]	Volume [m^3]	RT	Pass	Fail
A.1	gymnastieklokaal	14	22	5.5	≤ 1,700	≤ 1.0	2	1
A.2	sportzaal	13	22	7	1,701-2,100	≤ 1.1		
A.3	1/3 sporthal or sportzaal	14	24	7	2,101-2,400	≤ 1.2	4	
B.1	sportzaal	16	28	7	2,401-3,200	≤ 1.3		2
B.2	sportzaal	22	28	7	3,201-4,350	≤ 1.4	3	5
B.3	1/2 sporthal	32	28	7	4,351-6,300	≤ 1.5	3	1
C.1	sporthal	24	44	7	6,301-7,400	≤ 1.7	2	2
C.2	sporthal	28	48	7	7,401-9,500	≤ 1.8		
C.3	sporthal	28	48	9	9,501-12,400	≤ 1.9	1	1
D.1	sporthal	28	88	7	12,401-17,250	≤ 2.0	2	
D.2	sporthal	32	88	10	17,251-29,000	≤ 2.3		
E	overig				≥ 29,001			
					Total		**17**	**12**

2.2 Parameters

The reverberation time (RT) is a common measure to describe the room acoustics of a room and relates to the perception of reverb and the amount of sound absorption in the room (in a diffuse sound field). Sports halls have often not diffuse sound fields and contain specific so-called flutter echoes caused by sound bouncing back and forth between parallel reflective walls. There is no acoustic measure to objectively describe flutter echoes, however indirectly the RT does take them into account. Usually, a sports hall that meets the NOC*NSF requirements for RT requires sound absorption on (lower) walls that also reduces the intensity of the flutter echoes. The NOC*NSF requirements are based on a surface averaged sound absorption coefficient (in this paper denoted "alpha$_{S\text{-avg}}$") of 0.25 leading to a reverberation time based on the Sabine model (approx.).

The Sound Strength (G) is a measure to describe the amplification of sound by a room. It compares the measured sound level from an omnidirectional sound source in the room to its sound level at 10 m in the free field. It can be expected that the higher G is, the louder the sounds from sports activities will be in the sports hall. This makes G an interesting acoustic parameter in this study. Fig. 1 shows the theoretical relationship between RT and G in case the alpha$_{S\text{-avg}}$ is constant (0.25 is the blue line), also showing the relationship between alpha$_{S\text{-avg}}$, RT and room volume, V. It shows that sound strength is expected to be higher in smaller sports halls, if alpha$_{S\text{-avg}}$ is constant for each room volume and shape (V/S).

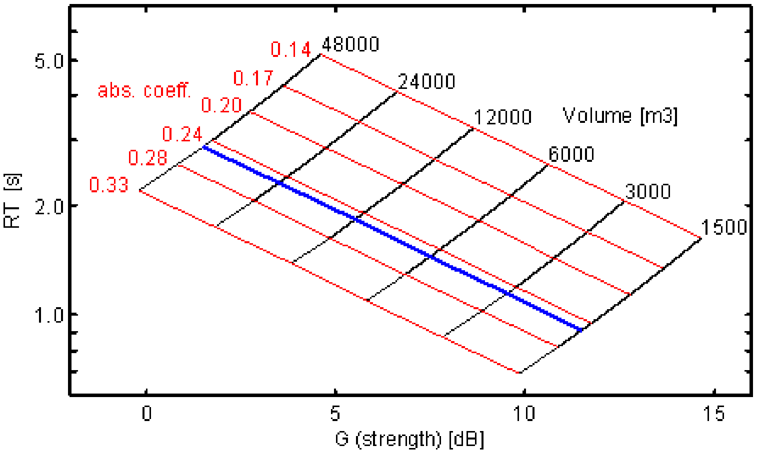

Figure 1: diffuse field relationship between RT, G, alpha$_{S\text{-avg}}$ and V [4,6].

The Speech Transmission Index (STI) is a measure to describe speech intelligibility and is affected by the room response (reverberation, echoes), the received sound level from the source and the background noise ($L_{A,eq}$). In this study, the STI is an important parameter to establish working conditions for the PE teachers. Possibly, a poorer speech intelligibility leads to the (perceived) need of using loud whistling and using a shouting voice affecting the noise exposure and voice load of the teacher.

2.3 Equipment and positions

Measurements to determine the RT and G have been carried out using an omni-directional sound source and microphone. Measured impulse responses (IRs) were obtained by using a deconvolution technique using DIRAC 6 Software. The microphone was also used to measure the background noise levels in the halls. Measurements of the IRs were performed for source and receiving positions in accordance with the NOC*NSF standard, see Fig. 2. Source- receiver distance is beyond the critical distance.

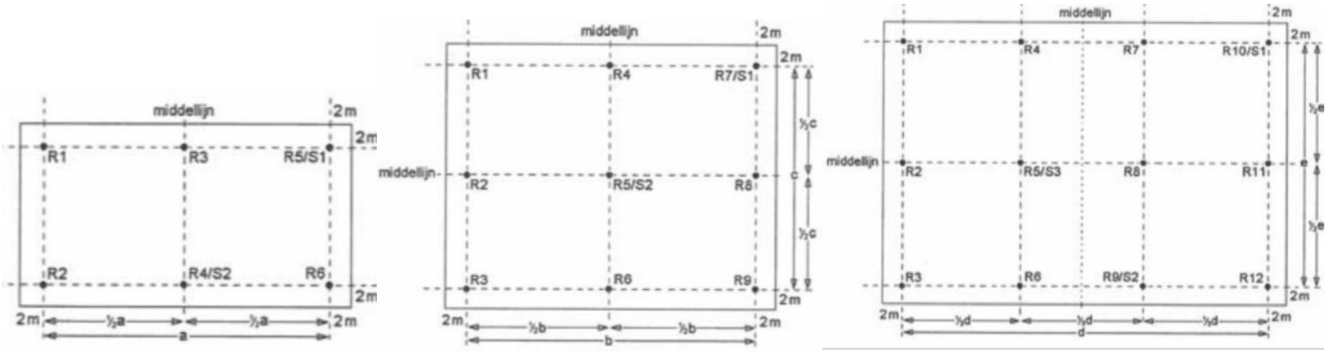

Figure 2: measurement grid used in sports halls. Left: A. Centre: B. Right: C, D, E

The STI is derived from measured impulse responses using the directional loudspeaker ECHO Speech Source (B&K 4720), an omni-directional microphone and DIRAC 6.0. The used speech level is the spectrum of a male voice with a normal voice effort of 60 dB(A) at 1 meter distance in accordance with IEC 60268-16. The receiving positions are positioned with 45 degree steps along semicircles with the source in the centre point; the first semicircle at a distance of 1 m from the source and the subsequent ones at a distance of 2 m in between. The source position is positioned on the long side of the hall. To compare the halls independently the STI was calculated using the signal-to-noise ratio for a background noise level based on the Noise Rating curve NR30 and 38 dB(A). The NOC*NSF requirement is < 40 dB(A).

Detailed information about the measurements can be found in the bachelor thesis by Beijer [7].

2.4 Results

On the next page, Fig. 3 shows the large difference in RT for sports halls that fail and pass the NOC*NSF requirement. In all cases, the difference between fail or pass can be explained by the absence or presence of sound absorption on the walls (while all halls have a sound absorbing ceiling). In the right graph showing Sound Strength, results from both “RT Fail” and “RT Pass” overlap because a smaller halls with low RT can have a higher G than large halls with high RT.

Fig 4. shows the correlation between Sound Strength directly measured and when predicted based on RT using two different statistical diffuse field models: Sabine and Eyring. With an average deviation of +/- 1.1 dB, the Eyring model can predict the average G reasonably accurate, while the Sabine model always underestimates G by 1.4 dB on average. The only model input required is measured RT and the room dimensions L, W, H and V. This suggests that G does not have to be measured, which would be convenient because a laboratory calibration of the measurement sound source is otherwise required.

Fig. 5 compares the measured Speech Transmission Index to the surface averaged sound absorption coefficient, without and with the effect of background noise. It should be noted that the absolute value of STI is somewhat arbitrary because the value is averaged over distance and STI strongly depends on distance. A general trend can be observed that average STI increases when alpha$_{\text{S-avg}}$ is higher. Larger halls > 3.000 m^3 that fail the RT requirement can have a similar STI to small halls <3.000 m^3 that (just) meet the RT requirement. It is clear that the small halls with low average absorption have the lowest speech intelligibility. Small halls can have a relatively high STI (0.65 with background noise) when reverberation time is very low (one example is a 1,500 m^3 hall with a RT of 0.7 s. while 1.0 s. is required).

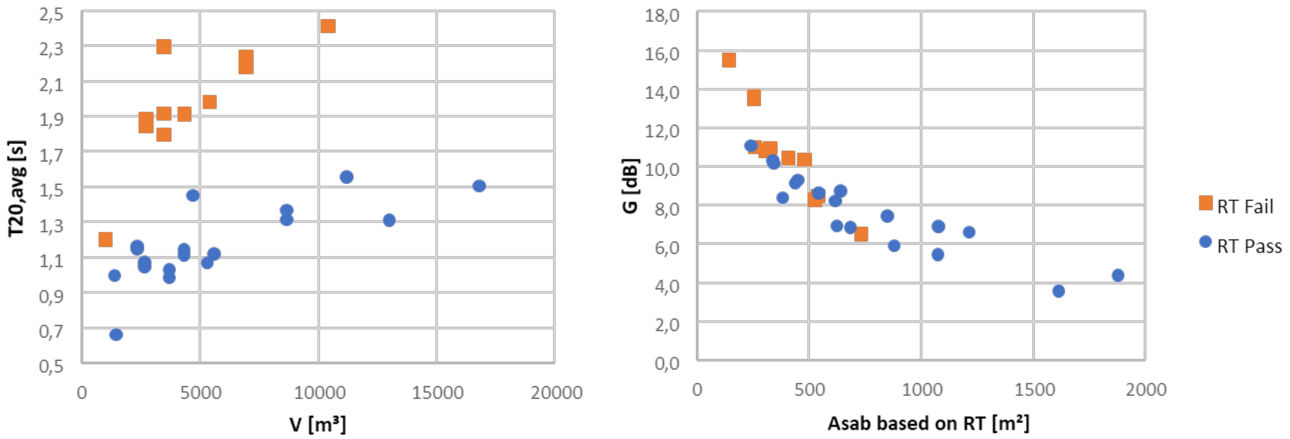

Figure 3: Blue/Orange: pass/fail NOC*NSF requirement RT. Left: Reverberation Time T_{20} vs room volume V. Right: Sound Strength G vs Equivalent Sound Absorption A_{sab} ($A_{sab} = 0.161\ V/T_{20}$) [7]

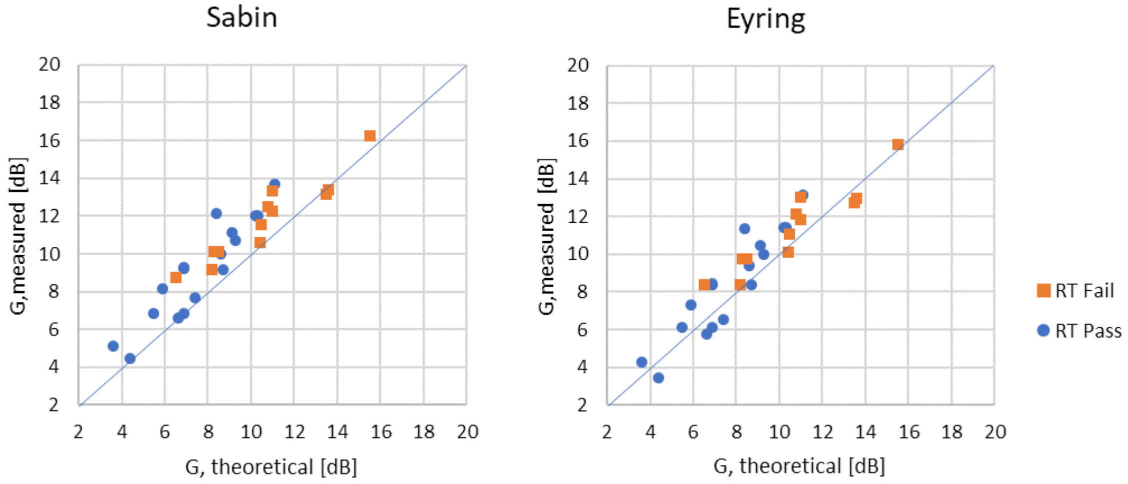

Figure 4: Measured Sound Strength vs Predicted Sound Strength. Blue line is equal $G_{measured}$ and $G_{theoretical}$
Left: Sabine model $G = 31 + 10 \log (4 / alpha_{S\text{-}avg} *S)$, average deviation 1.4 dB.
Right: Eyring model $G = 31 + 10 \log (4*(1- alpha_{S\text{-}avg}) / alpha_{S\text{-}avg} *S)$ (average deviation 1.1 dB).

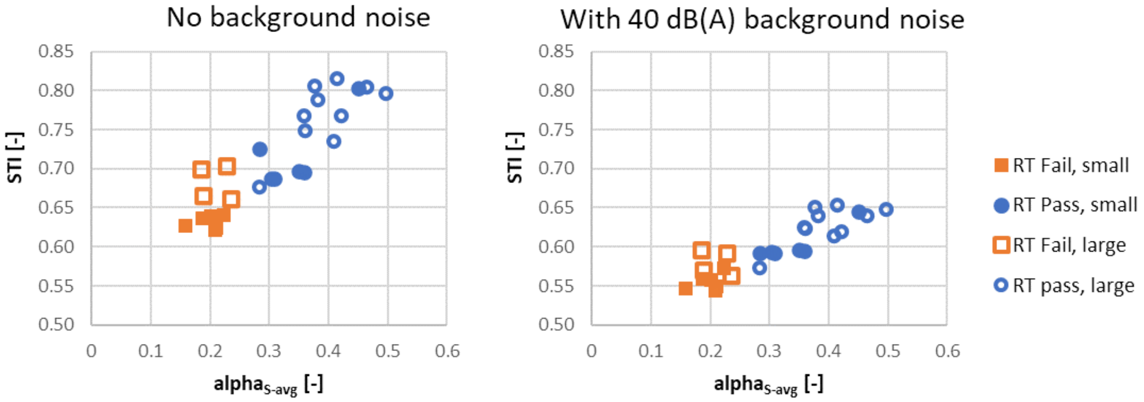

Figure 5: Speech Intelligibility Index STI vs $alpha_{S\text{-}avg}$ (Sabine). STI average, 16 pos., 2 to 8 meter, 5 directions.
Left: Voice only, background noise level none. Right: Voice 60 dB(A) at 1 m, background noise 40 dB(A). [7]

3. Acoustic camera analysis

3.1 Aim

Reflection studies have been performed using an acoustic camera (Sorama CAM iV64) as a new method to visualize reflective, absorptive and diffusive properties of materials in the sports halls under test.

The camera contains of a microphone array of 64 microphones and uses a measurement technique called 'acoustic beamforming' to display the location of sound with the highest amplitude over a certain frequency selection. The Sorama CAM iV64 visualizes the sound with a heatmap, making insightful where the most dominant sound is located. With this map it became clear where reflections occurred on surfaces in the sports hall and what the magnitude of the reflections was.

Important frequencies regarding this research are the resonating frequencies of the vocal tract of children, which are known as formants. The formant F2 is active in the frequency range of 1.5 kHz – 1.9 kHz [8]. The camera can perform acoustic beamforming accurately in this frequency range and therefore it was chosen to investigate the reflections in the sports halls in this frequency range.

The results described in this chapter revolve around two B.2 category sports halls. Both sports halls have similar dimensions and were therefore the best comparable. These sports halls are labeled as ADO and OV. The mayor difference between these two sports halls is that ADO is equipped with sound absorption on the lower walls (Micro Perforated Panels), while OV is not.

3.2 Method

To create a map of reflections on the walls of the sports halls, the camera was positioned at a fixed distance (of 6 meters) aimed towards the wall under test. Behind the camera an omni-directional loudspeaker (AcouTronics DS303) was positioned at a distance of 5 meters to the back of the camera. The speaker played a stationary white noise signal in the frequency range of 40 Hz to 8 kHz (which covers the 1.5 kHz – 1.9 kHz range that is the interest of this research).

The Sorama CAM iV64 was surrounded with a shield that had the function of limiting direct sound which could reach the camera via a direct path through the air. As a result, sound that is localized by the camera is due to the reflection of sound on the wall the camera is pointing towards. The same steps were repeated for each wall under test, resulting in a sound map of reflections of all the walls in the sports hall. This measurement setup therefore simulates the situation of a PE teacher standing near the sidewalls of the sports hall while children are doing their activities near the center of the sports hall.

Fig. 6 depicts the measurement setup as used for the measurements in sports hall OV.

Figure 6: The measurement setup to gather a sound map of reflections in sports hall OV. On the left is the Sorama CAM iV64 acoustic camera surrounded by the shield. On the right is the omni-directional speaker.

3.3 Results

Fig. 7 and Fig. 8 present the sound maps of the reflections measured in sports hall OV and ADO. The sound maps consist of colours. A red color means a high sound pressure level (SPL), while a blue color describes a lower SPL. This means the more intense the color of the sound image is, the higher the SPL related to the reflection is. The sound map's colors are equally scaled, meaning that all measurements have the same upper and lower SPL limits and are one-to-one comparable.

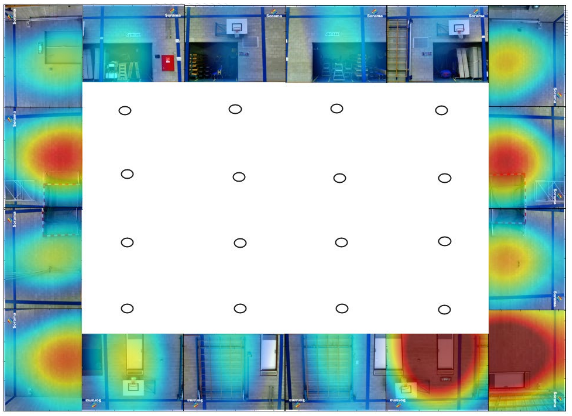

Figure 7: Sound map of reflections of sports hall OV (V = 2,700 m^3, T_{20} = 1.9 s, G = 13.5 dB)

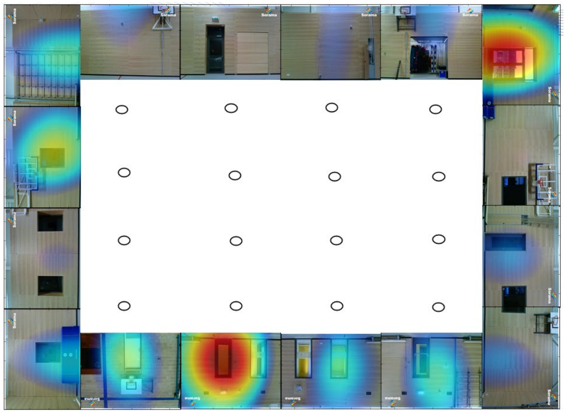

Figure 8: Sound map of reflections of sports hall ADO (V = 2,600 m^3, T_{20} = 1.1 s, G = 9.1 dB)

It can be seen that in sports hall OV the majority of the walls show reflections with a much higher SPL compared to sports hall ADO, since the color intensity of the sound image is much higher. Any reflections in sports hall ADO that are similar in magnitude to sports hall OV are caused by flat surfaces, such as big glass windows and doors, or a pile of landing mats. This comparison confirms that the sound absorption on the lower walls reduces reflections of sound waves at frequencies of children's speech.

The sound map of sports hall OV provides more interesting information. The reflections near the climbing frames and the equipment storage have a lower magnitude compared to other locations in the sports hall. In particular, the SPL of the reflections near the equipment storage are visibly lower than on other spots. Computed over the range of children's speech (1.5 kHz – 1.9 kHz), the SPL on the location of the reflection is 6 dB lower when comparing the location near the equipment storage with the location in the corner with the most dominant reflections. This means that the SPL of children's speech reflected via a single wall towards a PE teacher is less when standing near or in the equipment storage's opening compared to when standing in the corner with the most dominant reflections.

A similar result is present in the sound map of reflections of sports hall ADO. When standing in front of a wall with sound absorption instead of near one of the doors or windows with the most dominant reflections, the SPL due to reflections over the frequency range of children's speech could (in the best case) lead to a reduction of 7 dB. This would correspond to the reduction achieved by a surface with a sound absorption factor of 0.8.

4. Discussion and conclusion

The various measurements of room acoustic parameters (T_{20}, G and STI) and the reflection studies using an acoustic camera (SPL mapping) confirm what can be expected based on theory. The complex relationship between the room acoustic parameters depends on the room volume and the total or average sound absorption present. For instance, a small hall with a relatively low reverberation time can have a higher sound strength than a large hall with a relatively high reverberation time. And, speech intelligibility STI in a small hall with low reverberation may be similar to STI in a large hall with long reverberation because of differences in the direct/diffuse ratio at the fixed source-receiver distances. Nevertheless, room volume dependent reverberation time is a useful starting point for evaluation of sports halls, because other parameters can reasonably be predicted once reverberation time and room geometry is known.

Reflection studies have been performed using an acoustic camera as a new method to visualize reflective, absorptive and diffusive properties of materials in the sports halls under test. Sound maps of the reflections make insightful that avoiding standing near flat surfaces such as windows, doors and walls without sound absorption, and instead standing near a wall with sound absorption, but especially near or in the equipment storage's opening would reduce the SPL due to reflections over the frequency range of children's speech between 6 and 7 dB. This confirms that an inevitable starting point for any sports hall design should be to include sound absorption on most available lower wall surfaces.

The combination of acoustic parameters and the sound camera can provide valuable information about modifications to the hall that will improve hall acoustics. A prolonged reverberation time adversely affects sound perception and educational teachers are at risk for noise related health issues like stress, vocal problems, and hearing loss [1,9].

Yet, it remains uncertain whether halls that meet the NOC*NSF standard for reverberation time exhibit notably reduced sound levels during physical education lessons. It is common that PE teachers are using large sports halls subdivided into smaller sports halls by moveable walls. In this context, room volume can vary between 900 and 4,200 m^3. One of the largest single halls (3,700 m^3) that passes the NOC*NSF standard has a sound strength of 7 dB compared to a small hall (900 m^3) that just exceeds the standards' reverberation time limits which has a considerably higher sound strength up to 15 dB. Whether these differences in Sound Strength would lead to similar differences in noise exposure is unknown.

Therefore, further research is needed to investigate the relationship between sound strength, room reflections and the sound levels that occur during sports lessons.

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