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The effect of occupancy in the speech intelligibility in churches

Victor Desarnaulds [1], António P. O. Carvalho [2], Gilbert Monay [3]

[1] E. P. F. Lausanne (EPFL), 1015 Lausanne, Switzerland (desarnaulds@ monay.ch)
[2] Univ. of Porto, Fac. of Engineering, 4200-465 Porto, Portugal (carvalho@fe.up.pt)
[3] Bureau G. Monay, 25 Vinet, 1004 Lausanne, Switzerland (monay@monay.ch)

Abstract

Measurements were done in four churches with and without occupancy (mean volume of 6314 m^3 and mean occupancy of 155 persons) to test the effect of occupancy in the *STI* values. The results show that occupancy induces a mean increase for the speech intelligibility of *DSTI* (*STIoccup* - *STIunoccup*) of 0.05 with the use of a public address system (PA) and 0.027 without a PA. This increase is caused mainly by the reduction of the room reverberation time (*RT*), due to the additional sound absorption by the presence of persons. The reduction in the *RT* values in a church depends mainly on its volume and on the *RT* of the unoccupied room as well as on the number and dispersion of the persons in it. The mean sound absorption by person (*Apers*) calculated for the average *RT* calculated for each church, equals to 0.57 ± 0.09 m^2. The decrease in the *S/N* ratio (due to the background sound level augmentation by the presence of people and to the sound level decrease with the distance in the congregation area) could reduce the *STI* gain in particular cases. The variations of humidity and temperature by heating in churches induce a weak variation of the *RT* values (less than 0.2 s). These effects are generally negligible for the *STI* values.

The variations in the *STI* values with occupancy can be predicted in churches (mean error *DSTI* < 0.005) by empirical formulations based on *RT* in occupied and unoccupied churches:

DSTI = 0.276*ln(*RTunocc (2kHz)* / *RToccup (2kHz)*) – 0.052 with a PA (R^2 = 0.96), and

DSTI = 0.045*ln(*RTunocc (2kHz)* / *RToccup (2kHz)*) + 0.012 without a PA (R^2 = 0.34).

1. Introduction

For reasons of convenience, the measurement of speech intelligibility using objective parameters takes place generally in unoccupied rooms. Under normal conditions of use, the room occupation can increase or decrease the speech intelligibility.

This paper concerns a study that aims at determining the effect of the occupation on speech intelligibility based on comparisons made with the *STI* (Speech Transmission Index) measured in unoccupied and occupied churches. The analysis of the various effects induced by the presence of the congregation on the speech intelligibility will result in proposing a model to predict the occupied *STI*.

2. Measurement Description

In order to disturb the least possible the church assembly during ceremonies and to allow the collection of a maximum of information, a measuring system of type MLS (MLSSA) was used with an asynchronous data processing except for St. John church measured with B&K 3361 [1]. The data presented in this study relate mainly the speech intelligibility expressed by the *STI* with the reverberation time (*RT)* but also the background noise and the sound levels during the ceremonies. The field measurements took place in four churches (unoccupied and occupied) whose main characteristics and results are given in tables 1 and 2.

Church	Place, country	Confession	Volume (m^3)	Occupation (persons)	*RTunocc* 2 kHz (s)	*RTocc* 2 kHz (s)
Sacré-Cœur	La-Chaux, Switzerland	Catholic	9137	183	5.9	3.5
Pasquart	Bienne, Switzerland	Protestant	4472	114	2.5	2.2
Fille-Dieu	Romont, Switzerland	Catholic	5600	124	2.8	2.6
St. John	Porto, Portugal	Catholic	6048	200	2.7	1.9
		Mean	6314	155	3.5	2.6
		St. deviat.	1995	43	-	-

Table 1: Main characteristics and *RT* values of the churches sampled

Church	Condition	*STI occup.*	*STI unocc.*	Δ*STI* =*STIoccup-STIunoccup*	Standard deviation
Sacré-cœur	Without PA	0.278	0.242	0.036	0.035
	With PA 1 (high DI)	0.472	0.410	0.062	0.043
	With PA 2 (low DI)	0.405	0.332	0.073	0.049
Pasquart	Without PA	0.523	0.495	0.028	0.013
	With PA	0.576	0.558	0.018	0.029
Fille-Dieu	Without PA	0.313	0.290	0.023	0.015
St. John	Without PA	0.435	0.415	0.020	0.045
	With PA	0.555	0.508	0.048	0.029
Mean values	Without PA	0.387	0.361	0.027	0.006
	With PA	0.534	0.492	0.050	0.024

Table 2: *STI* results for the churches sampled (PA = Sound system, DI = Directivity index)

3. Analysis

The *DSTI* results shown in table 2 highlight an increase in the speech intelligibility values with the occupation. This improvement is more significant when the sound system is used:

$\Delta STI = STIoccup - STIunoccup$ = 0.027 ± 0.006, without a sound system;
= 0.050 ± 0.024, with a sound system.

The measurements of *RT*, shows a reduction in the *RT* values by the occupation of 1.2 ± 0.7 second that is 29 ± 8%. The church occupancy induces a significant decrease in the *RT* values, particularly in the 1 kHz frequency band, which is one of the most significant for the speech intelligibility quality. The variation in the speech intelligibility values (Δ*STI*) correlates well with the reduction in the *RT* values (or more precisely with the factor: *ln(RTunocc/RTocc)*), and this particularly when the sound system (PA) is used. Without the use of a sound system, the improvement of the *STI* is relatively constant and increases slightly with the reduction in the *RT*. This decrease in the *RT* values can be explained by several effects as described below.

3.1.1 Increased sound absorption due to the audience

The reduction in the *RT* values comes primarily from the increased sound absorption brought by the audience. The value of that reduction in the *RT* values in a church depends mainly on its volume and on the *RT* of the unoccupied room as well as on the number and dispersion of the persons in it.

For the sampled churches, the average equivalent sound absorption values *Apers* (calculated using the Sabine equation) and the optimised *Apers'* values (calculated using the least square method) are given in table 3.

The mean sound absorption by person (*Apers*) calculated for the average *RT* (0.5-1 kHz) and for all the churches, equals to 0.57 ± 0.09 m^2. When the persons are grouped in a church, the sound absorption at the highest frequencies (*f* > 2 kHz) is about 0.45 m^2. On contrary, when the faithful are dispersed the sound absorption per person in the highest frequencies (*f* > 2 kHz) practically doubles (about 0.9 m^2).

The optimised *Apers'* values with the Sabine equation allows a satisfactory estimate of the occupied *RT* (average error *RT(calc)-RT(meas)* < 0.1 s).

The values obtained for *Apers* are generally higher than those available in the literature for a seated person, because of the low occupation density in the occupied churches compared to the ones calculated using a reverberation chamber or a concert hall (edges effect).

Frequency (Hz)	125	250	500	1k	2k	4k	avg. 500-1k
Mean calculated values *Apers* (m^2)	0.24	0.43	0.51	0.65	0.44	0.65	0.57
Standard deviation (m^2)	0.18	0.22	0.06	0.17	0.32	0.25	0.09
Optimised calculation *Apers'* (m^2)	0.13	0.52	0.53	0.72	0.75	0.86	0.62

Table 3: Equivalent sound absorption by person (*Apers*) according to frequency

3.1.2 Background noise

In a preceding study [2], the background noise in 44 unoccupied churches was measured according to the surrounding environment (*urban* or *rural*) (table 4). The equivalent sound levels and the *S/N* were also measured during and after religious ceremonies.

It was noted that the background noise increases by 10 ± 4 dB with the occupation. When the churches are unoccupied, the *S/N* is higher than necessary (> 25 dB) but when occupied the *S/N* remains in general sufficient (> 15 dB) not to disturb the speech intelligibility. In spite of the systematic use of a sound system in the large churches or in those with a high background noise, the *S/N* can be insufficient in certain particular cases. This can be due to an emitted low sound level (bad adjustment or absence of sound system) or to a high background noise made by the public. In winter, many churches require the use of heating for the religious services that can also generate a considerable noise within the church.

Church environment	$L_{eq(20\ s)}$ mean values		Standart deviation	
Urban	35 dB(A)	56 dB(Lin)	7 dB(A)	5 dB(Lin)
Rural	23 dB(A)	46 dB(Lin)	4 dB(A)	5 dB(Lin)

Table 4: Mean values regarding the sound equivalent background noise in 44 Swiss churches [2]

3.1.3 Sound attenuation within the congregation area

The variation of *RT* values due to the occupation (and possibly to the heating) involves an attenuation of the sound level in the reverberated field that can be expressed approximated by *DL* (dB) ≈ 10*log (*RTocc* / *RTunocc*). According to the performed *RT* measurements, the decrease of the reverberated sound level varies from 1.1 and 1.9 dB.

According to the *SPL* measurements, the additional attenuation (*DL*) with the distance due to the public is in fact less than 1 dB and this for large distances from the sound source (d > 10 m). In general, the improvement of speech intelligibility (Δ*STI*) is practically not linked with the distance to the main sound source.

3.1.4 Effect of the heating

In winter, the church heating during ceremonies induces several favourable effects in the speech intelligibility values, such as:

- A small increase in the air absorption ($f \leq 2$ kHz) is present that involves a weak reduction in the *RT* values at these frequencies. At the highest frequencies ($f > 2$ kHz), the opposite phenomenon is observed.
- An increase in the speed of sound propagation that involves a reduction in the room *RT*.

For a church of 6000 m^3 (as an example) with a *RT* (non occupied) of 4 s, the two effects induced by the heating involve a reduction in the *RT* at medium frequencies of less than 0.2s.

4. Empirical model

From the measured data, an empirical model can be stated that allows to determine the variation on *STI* values with the church occupancy based on the main effect present. For this calculation, the 2 kHz frequency band was chosen for a representative single-number *RT*, not only because it is the most important regarding speech intelligibility but also because it showed to have the best correlation values of all the average *RT* hypotheses tested.

The field results of this study showed that the principal factor influencing *STI* was the *RT* variation. Therefore the proposed logarithmic model is: *DSTI= a*ln(RTunocc/RToccup) + b* where parameter "*a*" takes into account the contribution of the variation of *RT* values and the parameter "*b*" gathers the other diverse contributions. The optimisation of these two parameters (for the sampled medium size churches) gives the following formula:

DSTI =0.276*ln(*RTunocc (2kHz)*/*RToccup (2kHz)*)–0.052, with a PA (R^2 = 0.96), and

DSTI =0.045*ln(*RTunocc (2kHz)*/*RToccup (2kHz)*)+0.012, without a PA (R^2 = 0.34).

The reduction of the additional *RT* induced by the PA (using loudspeakers with strong directivity oriented to the congregation area) could explain the high slope obtained empirically with PA.

References

1. A. Carvalho, "*The significance of the Church Occupancy in the RASTI values in a Catholic Church*", Congrès Français d' Acoustique CFA2000, 2000, Lausanne, 477-480.
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