15th International Congress on Acoustics
Trondheim, Norway 26 - 30 June 1995

BACH, A NEW BINAURAL PARAMETER

António Pedro O. Carvalho, Ph.D.
Acoustical Laboratory, Faculty of Engineering, Univ. of Porto, Portugal

SUMMARY

This study reports on acoustical field measurements made in a major survey of 41 Catholic churches in Portugal built in the last fourteen centuries. Binaural measurements were taken in each church using a dual channel real time frequency analyzer to calculate the *coherence* values between the signals at both ears in 1/3 octave frequency bands. From the *coherence* values a new binaural acoustical measure was developed and called *BACH* (*Binaural Acoustical CoHerence).* Monaural acoustical measurements were also taken at several source/receiver locations using the impulse response method. *BACH* was shown to be an orthogonal parameter in statistical tests with nine other monaural acoustical measures (RT, EDT, C80, D, TS, L, BR_RT, BR_L and RASTI) and fifteen architectural parameters. Information was collected regarding the quality of music in each church. ANOVA tests were performed to examine the significance of the differences among the groups of equal subjective quality ratings. The author wanted to test the hypothesis that this new binaural acoustical measure can be useful in estimating the general subjective quality of churches regarding music. A linear correlation coefficient near 0.7 was found between the *BACH* and the subjective quality ratings that supported the stated hypothesis.

INTRODUCTION

The purpose of this document is to study the interaction between personal feelings regarding musical performances in churches and a new physical quantity to measure it. The main investigation is focused on the Roman Catholic churches of Portugal. Portugal is one of the oldest European countries and played a prominent role in some of the most significant events in world history. It presents an almost perfect location to trace the history of Catholic church buildings in the world. Portuguese churches can be considered a representative example of Catholic churches in the world. This study reports on acoustical field measurements in a major survey of 41 Roman Catholic churches that were built between the 6th century and 1993. The churches were selected to represent the main architectural styles found throughout Portugal and to represent the evolution of 14 centuries of church construction. For more uniformity of the sample and due to the sound power limits of the sound source, only churches with a maximum volume of less than 19000 m^3 were selected for the study. Acoustical measurements were taken in similar numbers of churches grouped by large periods of history: 12 *Visigothic* or *Romanesque* churches (6th-13th centuries), 16 *Gothic* or *Manueline* churches (13th-16th centuries), 13 *Renaissance, Baroque* or *Neoclassic* churches (16th-19th centuries) and 4 *Contemporary* churches (20th century). The main architectural features of these churches are displayed in Table 1.

TABLE 1- Simple statistics for all churches tested.

ARCHITECTURAL FEATURE	Minimum	Maximum	Mean	Median
VOLUME (m^3)	299	18674	5772	3918
AREA (m^2)	56	1031	450	427
MAX. HEIGHT (m)	7	39	15	13
MAX. LENGTH (m)	12	62	33	31
WIDTH NAVE (m)	4	38	13	11

PROCEDURE

Binaural measurements were taken in each church using a dual channel real time frequency analyzer. In the simultaneous analysis of signals it is no longer the signals themselves that are of primary interest, but rather the properties of the physical system responsible for the differences between them. The idea was to use both instant spectra (channels A and B inputs) and their cross spectrum to find the *coherence* values. Channels A and B are microphones held outside both ears of a person in the center of the longitudinal axis of the church. A *pink noise* source was used with the loudspeaker in front of the altar at a height of 0.8 m and with SPL of 88-104 dB measured at the receiver. he churches were measured while unoccupied.

The *coherence* gives a measure of the degree of linear dependence between the two signals as a function of frequency. It is calculated from the two autospectra and the cross spectrum. It can also be interpreted as a squared correlation coefficient expressing the degree of linear relationship between two variables. If the *coherence* is 1 there will be a perfectly linear relationship between the signals at both ears. If it is 0, there is no relationship whatsoever between signals at the two ears. In each church, three spectra were recorded in the same position (only one position was used - in the middle of the longitudinal axis). The values were then averaged for further analysis.

Very basic qualitative information was collected in each church by an interview with the local priests and other members of the staff. Answers were requested to simple questions such as if the church had a *good* acoustics or *good* sound, if music sounded *good* in the church, if there were musical performances in the church, which type of musical performances occurred in the church, if the performers like the *sound* of the church, etc. The churches were finally rated on a five level scale: *very bad, bad, normal, good* or *very good* acoustics.

The equipment used was: sound level meter *Brüel & Kjær* (*B&K*) 2231; 1/3-1/1 octave filter set *B&K* 1625; module Room Acoustics *B&K* BZ7109; sound source *B&K* 4224; microphone 1/2" *B&K*; computer *Compaq* LTE386-25 MHz; application software Room Acoustics *B&K* VP7155; speech transmission meter *B&K* 3361 and microphone 1/2" *B&K* 4129; dual channel real-time frequency analyzer *B&K* 2144; two 1/2" microphones *B&K* 4165; two microphone preamplifiers *B&K* 2639; and application software B&K 5306.

BACH

Using the *coherence* values obtained in twenty-eight 1/3 octave bands a new measure was sought. Figure 1 presents the graphical representation of all bands considering the average of all churches tested. In this graph describing the general behavior of the *coherence* in all the churches tested, four areas can be identified. At very low frequencies the *coherence* is almost constant and equal to 1.0; from 200 to 800 Hz the *coherence* decreases with a roll-off of nearly 0.3/octave; at mid frequencies (1 to 2.5 kHz) there is a constant level for the coherence around 0.28; finally to higher frequencies (3.15 to 10 kHz) a *V* shaped behavior appears with a drop to a *coherence* of 0.15 near 5 kHz. To analyze which of these characteristics could be related to the subjective quality of the room, the Pearson correlation coefficients were calculated between *Subjective* rating and *Coherence* (28 frequency bands). The highest R was found with *Coherence 3150 Hz* (R = 0.55). But this is still a low R and other factors must be involved in the variance of the subjective quality ratings.

Studying the general behavior of the *coherence* values in churches (Fig. 1), 22 combinations of coherence were tested to find the best suited to represent or explain the variance in the subjective quality scores using the R coefficients regarding the linear smoothing between the *Subjective* rating and these 22 equations. The highest |R| found was 0.684. The plot of this relationship is shown in Fig. 2. This is the new binaural measure sought and was called BACH, *Binaural Acoustic CoHerence*.

Considering the ratings of subjective acoustical quality by the priests of the churches, this R ≈ - 0.7 seems very reasonable to accept as a good relationship and supports the idea that subjective quality in churches regarding music can be assessed by the use of this new binaural measure. Therefore it seems that the overall subjective quality of churches for music can be inversely proportional to the following formula.

$$\text{BACH} = (\text{Coh } 50\text{ Hz} + \text{Coh } 63\text{ Hz} + \text{Coh } 80\text{ Hz}) / (\text{Coh } 3150\text{ Hz} + \text{Coh } 4\text{ kHz} + \text{Coh } 5\text{ kHz})$$

by the next relation: SUBJECTIVE = 5.374 - 0.310 BACH (Standard error of estimate = 0.88).

That is, the greater the difference between the *coherence* at the high and very low frequencies, the lower the church was rated regarding the overall subjective impression of music quality. The explanation for this result is hypothesized to be in the combination of several factors. Considering that not many musical instruments use those high frequencies (4 and 5 kHz), it is perhaps the effect of overtones or upper partials that it is present. It may also be the effects in the perception of treble and timbre or tone color that are also been weighted. In fact only a few instruments such as the xylophone, glockenspiel, harp, piccolo and naturally the organ can give such high notes. Or it may be that a similarity of sounds at both ears, over a wide range of frequencies, are considered to be preferable in live performances as opposed to the enjoyment of a musical piece when listened to using stereo headphones or loudspeakers. It does not appear that this effect can be very important in explaining speech reception because those frequencies (3 to 6 kHz) are above the frequencies most significant to the understanding of speech. For most speech communication the critical frequency range is 0.3-3 kHz although some speech cues occur as high as 8 kHz. Some of these facts describe subtle details of listening to music. It is questionable if the subjective ratings obtained could discriminate. More data is necessary to validate a more positive explanation.

ANOVA tests were performed to examine the significance of the differences among the groups of equal subjective quality ratings. The 3 options (Fig. 3) were: OPTION A - 5 groups of equal subjective quality; OPTION B - 3 groups of equal subjective quality, labelled: *1*-BAD (=*1+2* of opt. A), *3*-NORMAL (=*3* of option A), *5*-GOOD (=*4+5* of opt. A); OPTION C - 2 groups equal of subjective quality, labelled: *2*-BAD (=*1+2+3* of opt. A); *4* -GOOD (=*4+5* of opt. A). Using ANOVA results, the conclusion is that the 5-group system of rating (Fig. 3a) is too narrow to give statistically significant differences (with a p-value < 0.20). The use of a 3-group rating method (Fig. 3b) gives statistically differences in all possible pairwise comparisons (for a p-value < 0.20). The use of a 2-group rating method (Fig. 3c) gives a statistically difference in the only possible pairwise comparison (but now for a p-value < 0.05). Therefore it can be stated that a 3-group rating of subjective quality in churches in the method used in this study is an acceptable choice.

In order to verify the importance of all the parameters in the subjective ratings, a general linear model was performed. The goal was to relate the *SUBJECTIVE* rating to some of the other parameters used in this study. Therefore the model was done with the 28 coherence bands, 39 acoustical measures (all frequency bands), 15 architectural parameters and 22 tentative BACH formulas for a total of 104 parameters. With an α-to-enter/remove equal to 0.05 the final model using a forward stepwise procedure only presented the chosen BACH as a predictor of the *SUBJECTIVE* rating (with $R^2 = 0.47$ and standard error of the estimate = 0.88). Using an α-to-enter/remove equal to 0.1 the final predictors will now include BACH and COH80 but the R^2 only improved to 0.52 with a standard error of the estimate = 0.84. Consequently, no other parameter tested in this study could be used as a substitute for BACH to give the same type of information. This increases the validity and interest of this new measure and its individuality.

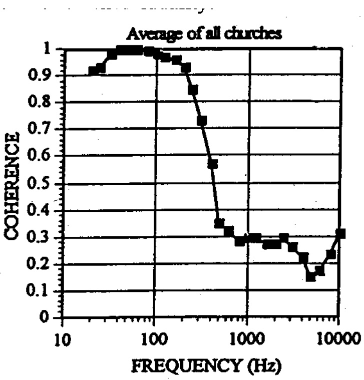

Fig. 1- Spectrum of averaged *coherence* (*y* axis) for all churches in 1/3 octave frequency bands (*x* axis).

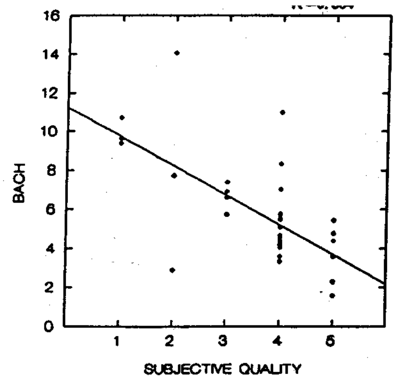

Fig. 2- Subjective quality ratings (1-*V. Bad*, 2-*Bad*, 3-*Normal*, 4-*Good*, 5-*V. Good*) vs. BACH with linear regression model and correlation coeff.

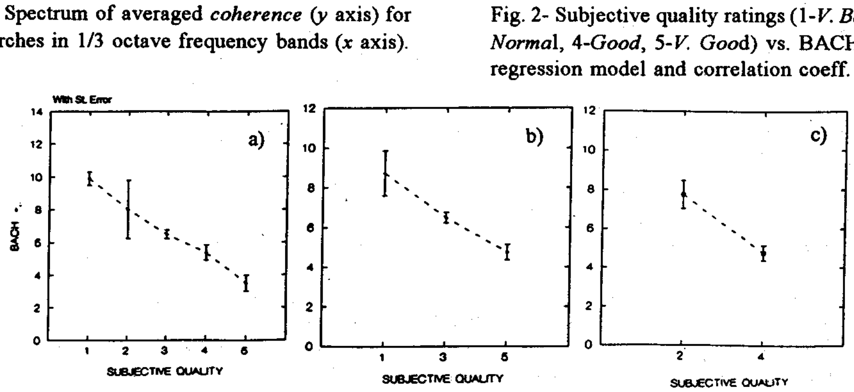

Fig. 3- BACH vs. 3 methods of grouping subjective quality ratings with standard error confidence interval. a) 5 level scale (1-*V. Bad*, 2-*Bad*, 3-*Normal*, 4-*Good*, 5-*V. Good*); b) 3 level scale (1-*Bad*, 2-*Normal*, 3-*Good*; c) 2 level scale (1-*Bad*, 2-*Good*).

BACH AND OTHER ACOUSTICAL MEASURES AND ARCHITECTURAL PARAMETERS

To check the relationship between BACH and other acoustical measures, six well established monaural acoustical measures were taken: Reverberation Time (RT), Early Decay Time (EDT), Early to Late Sound Index or Clarity with a time window of 80 ms (C80), Early to Total Energy Ratio, Definition or *Deutlichkeit* with a time window of 50 ms (D), Center Time (TS) and Loudness, Total Sound Level or Strength of arriving energy (L). Also 3 other measures were calculated: Bass Ratio based on Reverberation Time {BR_RT = [RT(125) + RT(250)] / [RT(500) + RT(1k)]}, Bass Ratio based on Loudness {BR_L = [L(125) + L(250) - L(500) - L(1k)] / 2} and Rapid Speech Transmission Index (RASTI).

The method used to calculate the acoustical measures is based on the integrated impulse-response method described by Schroeder. A limited-bandwidth noise-burst is generated and transmitted into the church by a loudspeaker via an amplifier. The room's response to the noise-burst (called the impulse response) is then sampled from the RMS detector output of the sound level meter. Each measurement was calculated from an ensemble of three and four pulse responses in each position. Five receiver positions were, on average, used, depending on the width of the church. The microphone at each location was placed at 1.30 m above the floor. In total, nearly 8000 values were determined (all combinations of frequency bands and source/receiver locations).

To check the relationship between BACH and the acoustical measures, the Pearson correlation coefficients were calculated for all the octave bands involved (Table 2). With these results there are no strong and evident relations between any of the 39 acoustical measures and the new binaural measure. This increases its individuality.

To check the relationship between BACH and the architectural features of the churches, fifteen architectural parameters were used and the architectural parameters, the Pearson correlation coefficients were calculated for all the architectural parameters (Table 2). With these results there are no evident relationship between any of the fifteen architectural parameters and the new binaural measure. This again, augments its uniqueness.

TABLE 2- Correlation coeff. for the relationships between BACH and the acoustical meas. or architectural param.

Measure	R	Measure	R	Measure	R	Measure	R
RT 125	0.315	EDT 2k	0.513	D 500	-0.364	L 125	0.033
RT 250	0.299	EDT 4k	0.524	D 1k	-0.443	L 250	0.040
RT 500	0.396	C80 125	-0.296	D 2k	-0.456	L 500	0.035
RT 1k	0.436	C80 250	-0.163	D 4k	-0.440	L 1k	0.052
RT 2k	0.494	C80 500	-0.391	TS 125	0.332	L 2k	0.021
RT 4k	0.517	C80 1k	-0.504	TS 250	0.305	L 4k	-0.105
EDT 125	0.280	C80 2k	-0.543	TS 500	0.433	BR_RT	-0.162
EDT 250	0.284	C80 4k	-0.485	TS 1k	0.507	BR_L	-0.006
EDT 500	0.410	D 125	-0.206	TS 2k	0.538	RASTI	-0.481
EDT 1k	0.473	D 250	-0.006	TS 4k	0.544		

PARAMETER	R	PARAMETER	R	PARAMETER	R
VOL. TOTAL	-0.016	LENGTH NAVE	0.084	WIDTH AVG.	-0.111
VOL. NAVE	-0.004	HEIGHT MAX.	0.075	SEATS	-0.009
AREA TOTAL	-0.046	HEIGHT NAVE avg.	0.183	ABSORP. TOTAL	-0.253
AREA NAVE	-0.037	HEIGHT AVG. TOTAL	0.158	R LOCAL	-0.271
LENGTH MAX.	0.148	WIDTH NAVE	-0.080	ALPHA AVG.	-0.293

CONCLUSIONS

The definition of a new binaural measure is believed to be an important step in studying the interaction between personal feelings regarding musical performances in churches and a physical quantity to measure it. Using binaural measurements and subjective information collected in 41 churches, Binaural Acoustical CoHerence (BACH), a new binaural measure was presented as a ratio of coherence values (1/3 octave bands) between low (50, 63 and 80 Hz) and high (3.15, 4 and 5 kHz) frequencies. It was found to be orthogonal among the other 104 acoustical measures and architectural parameters ($R^2_i < 0.3$). A linear correlation coefficient near 0.7 was found between the BACH measure and a five point subjective quality rating regarding music in churches (*V. Bad, Bad, Normal, Good*, and *V. Good*), supporting the hypothesis that this measure can be useful in predicting the subjective quality of music heard in churches. A three-point (*Bad, Normal*, and *Good*) method of rating the subjective quality of music in churches was found to be more acceptable than the five-point scale used.