THE IMPORTANCE OF THE HIGH FREQUENCIES OF CLARITY INDEX FOR THE PERCEPTION OF MUSICAL CLARITY

F del Solar Dorrego Graduate Program in Acoustics, The Pennsylvania State University,
University Park, Pennsylvania, USA
MC Vigeant Graduate Program in Acoustics, The Pennsylvania State University,
University Park, Pennsylvania, USA

1 INTRODUCTION

The seminal work conducted by Wallace C. Sabine at the turn of the XXth century [1], provided acousticians with the first set of scientific rules to predict a specific aspect of the acoustics of a room, its reverberation time (T30). Sabine's work was limited to the study of reverberation and its subjective counterpart, reverberance, but more recent findings highlighted the fact that other perceptual aspects are important for the appreciation of room acoustics besides reverberance. The importance of the temporal structure of sound fields for the perception of clarity of speech and music, was highlighted by a series of studies conducted in the 1950s and 1960s [2] [3] [4]. The clarity index metric (C_{80}) was proposed as an objective parameter that can quantify the degree of musical clarity in a sound field, based on the early-to-late ratio of sound energy in the room impulse response (RIR) [4]. Clarity index is a well-established metric and has been included in the Annex A of the ISO 3382-1 standard [5], along with other metrics derived from the RIR. However, there is little information of which octave bands of C_{80} have more influence on the perception of musical clarity. In the past, recommendations on how to average different octave bands of C_{80} to obtain a value better correlated with the perception of clarity have been proposed [5] [6] [7], but these recommendations have often been made without sufficient scientific validation. The purpose of the present study was to propose a weighted average of the octave-band values of C_{80}, called a single-value frequency-averaged metric (SVFA), to obtain a metric better correlated with perceived musical clarity.

2 PREVIOUS RESEARCH ON PREDICTORS OF CLARITY

Starting in the decade of 1950, a series of studies conducted in Germany analysed the effect of sound reflections on the appreciation of the acoustic character of speech and music signals. A general analysis of the influence of the delay and relative amplitude of sound reflections on the perceived acoustics, was undertaken by Thiele [3], who highlighted the importance of "useful" reflections, associated with the early sound, versus "detrimental" reflections associated with the late sound. Reichard and Kussev [4] set the integration value for the useful reflections at 80 ms after the direct sound, based on the observation of the duration of musical notes and transients of musical instruments. The C_{80} metric was defined as the ratio of the energy of the RIR up to 80 ms, and the energy of the sound reflections after 80 ms, in decibels.

Several studies have proposed averaging schemes for the different octave-band values of C_{80} that are better correlated with perceived clarity. Soulodre and Bradley [8] conducted a subjective study in which they evaluated the correlations between different combinations of the octave band values of C_{80} and musical clarity. In their investigation, the highest correlation with musical clarity was found for the average of the 500 and 1000 Hz octave band values of C_{80}. Beranek [6] and Barron [7] recommended, without rigorous scientific validation, that averaging the values of the 500, 1000, and 2000 Hz octave bands of C_{80} yields a metric, $C_{80(3)}$, that has a high correlation with musical clarity. Barron [7] justifies this operation since the human ear has a low temporal resolution for frequencies below 500 Hz. The ISO 3382-1 standard [5] proposes the average of the 500 and 1000 Hz octave band values of C_{80} to obtain a SVFA measure that is better correlated with musical clarity.

More research is needed to elucidate the dependency of musical clarity upon the different frequency ranges of C_{80}. The present work proposes a SVFA of C_{80} that can better predict musical clarity based on a subjective study using realistic auralizations of concert hall acoustics.

3 EXPERIMENTAL OVERVIEW

The investigation presented in this paper is separated into three tasks. The first task, Task 1, was designed to obtain a regression model that can predict subjective ratings of clarity from the octave band values of C_{80} of an arbitrary RIR measured in a hall. The stimuli used in Task 1 were composed of a base case spatial room impulse response (SRIR) extracted from a database of concert hall acoustics measurements [9] [10], which was computationally modified to obtain an additional set of stimuli with specified values of C_{80} in different pairs of octave bands. Since changes in C_{80} were made in individual pairs of octave bands, Task 1 will be referred to as the “one-factor-at-a-time” (OFAT) task, since each factor (pair of octave bands) was modified individually.

Task 2, referred to as the “validation task”, consisted of the validation of the regression model obtained in Task 1. Seven SRIRs, corresponding to a representative sample of seven halls from the same database used in Task 1, were used as the stimuli. These SRIRs were rated by the subjects in terms of perceived clarity, and the obtained ratings were compared with those predicted by evaluating the regression formula obtained in Task 1 with the C_{80} octave band values of these halls.

In Task 3, a correlation analysis was performed between the ratings of clarity of the seven halls used in the validation task (Task 2) and their octave-band C_{80} values. The purpose of the correlation analysis was to further assess the level of association between the different frequency ranges of C_{80} and the perception of clarity in the acoustics of concert halls.

A direct scaling method was selected to quantify the sensory impression. The subjective testing was conducted in an anechoic chamber located at Penn State’s campus, using third-order Ambisonics [11]. Twenty-four subjects participated in the listening test, having, on average, 14 years of musical training. For each task, the subjects rated the clarity of the stimuli on a scale from 0 to 100. Multiple linear regression analysis was used to create the statistical model that can predict subjective ratings of clarity from the values of pairs of octave bands of C_{80}.

4 SELECTION OF STIMULI FOR THE SUBJECTIVE TEST

4.1 Selection of stimuli for OFAT task

In the OFAT task, the base case SRIR was computationally modified to attain target values of C_{80} in pairs of octave bands, to create the set of stimuli used in the subjective study. To select a base case SRIR for this task from the concert hall database, two criteria were established. The first criterium required that the C_{80} spectrum of the selected SRIR, comprising the octave bands from 63 to 8000 Hz, should be representative of the average spectrum of this acoustical parameter found in the halls of the concert hall database. The second criterium was based on the premise that the modified octave band values of C_{80} of the selected SRIR should not greatly exceed the extreme values of this parameter found in the SRIRs of the database.

To obtain an SRIR that would comply with the first criterium, a computational procedure was used with the purpose of identifying SRIRs whose C_{80} spectrum had minimal differences with the overall average value of these parameters across the database. The omni IR is the omnidirectional RIR of each measured SRIR, equivalent to a RIR measured with a diffuse field microphone. This RIR was used to calculate the values of C_{80} upon which the selection process was conducted. For each candidate SRIR, the procedure was based on calculating the absolute difference in C_{80} values between the candidate SRIR and the average value of this parameter in the database. This analysis was conducted in each of the eight octave bands from 63 to 8000 Hz, and the results from each band were then summed for each candidate SRIR. By observing which SRIRs had the smallest values of these sums of differences, a representative SRIR was obtained. The selected SRIR for the C_{80} analysis is shown in Figure 1a along with the scatter of C_{80} values of the entire database.

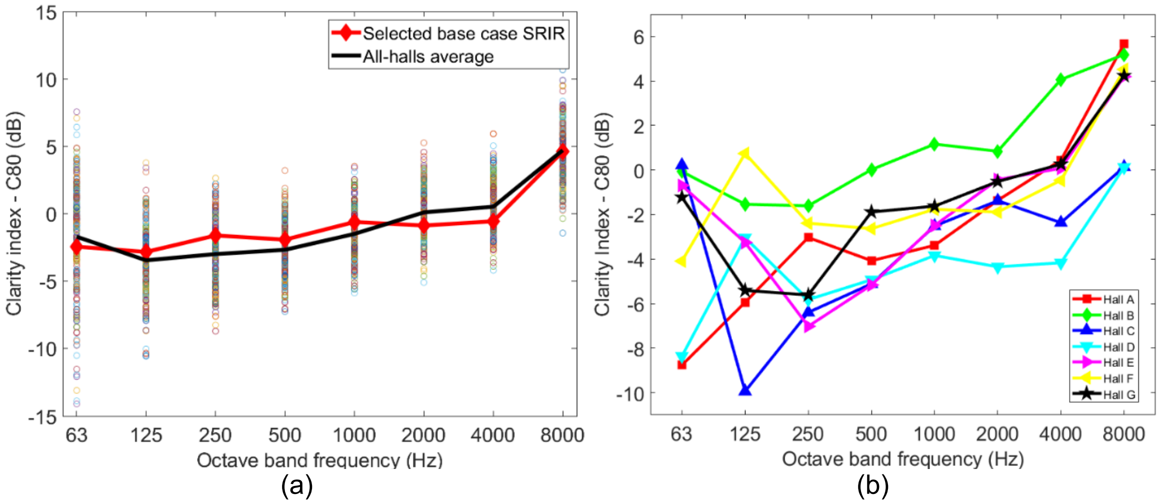

Figure 1: a) Base case SRIR used for the C_{80} OFAT task, along with the individual octave band C_{80} values of all halls and receiver positions in the concert hall database and the overall average. b) C_{80} spectra of the seven halls selected for Task 2.

4.2 Selection of stimuli for the validation task

The selection of the SRIRs for the validation task was undertaken by analysing the C_{80} values of all the receiver positions of the halls in the concert hall database. Since a varying number of receiver positions were measured in each hall, and in an effort to better analyse the data, “representative” receiver positions were determined for each hall. These representative positions were obtained for each hall and each octave band, based on the premise that they should have minimal deviations from the mean values of C_{80} found in the SRIRs of the concert hall database.

The fundamental criterion used for the selection of SRIRs for the validation task, was that the selected SRIRs should be representative of the existing correlations between the early decay time (EDT) and C_{80} values found in the concert hall database. In addition, the candidate receiver positions should belong to different concert halls since it was desired to conduct the validation task with SRIRs from different halls. The procedure used to obtain SRIRs based on the representative receiver positions is described in [12]. A total of seven halls were selected, and the C_{80} spectra obtained from their SRIRs are shown in Figure 1b. This number of halls struck a balance between a large enough sample to satisfactorily validate the OFAT regression model, and avoiding having too lengthy listening tests which might induce listener fatigue.

5 MODIFICATION OF THE OFAT STIMULI

The OFAT task was based on an experimental design in which a base case SRIR was computationally modified to create changes in the values of C_{80} of pairs of octave bands, controlling for changes in other acoustical parameters. This approach limits the influence that changes in other perceptual aspects might have in the perception of clarity, thus strengthening the validity of the association between the explanatory and response variables.

An algorithm was developed that could a make an arbitrary RIR attain specific values of C_{80} in different octave bands by modifying the amplitude of the early (up to 80 ms after the arrival of the direct sound) or late (after 80 ms relative to the direct sound) energy of the RIR [12]. The proposed algorithm uses a technique to modify C_{80} in specific octave bands which can be described as a “double-ramp amplification/attenuation" technique. The algorithm multiplies the amplitudes of the samples of the RIR by two time-domain linear ramp functions. The first ramp function starts at the beginning of the RIR and extends up to 80 ms, while the other ramp extends from 80 ms until the end of the RIR. The amplitude of the ramp functions determines the amplification/attenuation factor with which the samples are multiplied. The modification process was applied to each octave band of the RIR.

The changes enforced in the C_{80} values of the pairs of octave bands should be large enough to elicit a change in perceived clarity, by exceeding its associated just noticeable difference (JND). While some studies have obtained the broadband C_{80} JND [13] [14] [15], the authors of the present paper have no knowledge of any study that has tried to obtain the C_{80} JND for individual or groups of octave bands. The task of determining the change in C_{80} in pairs of octave bands that creates a change in perceived clarity was undertaken in the piloting sessions of this study through trial and error, where the necessary change was found to be close to ±8 dB

To create the stimuli for the subjective study, a ±8 dB change in C_{80} was applied to the following pairs of octave bands of the base case SRIR: 63 and 125 Hz, 250 and 500 Hz, 1000 and 2000 Hz, and 4000 and 8000 Hz. The lack of perfect convergence to the target C_{80} values was encountered when manipulating the SRIR with the algorithm. The average tolerance in C_{80} values in all octave bands, for all stimuli, was 0.15 dB, and the standard deviation was 0.21 dB. Creating changes in C_{80} in a RIR by modifying the amplitude of the early reflections has an inevitable impact on the value of other acoustical parameters which are dependent upon the early sound, such as EDT. The average change in EDT across the nine stimuli was 0.13 s and the standard deviation was 0.93 s.

6 STIMULI REPRODUCTION FACILITY

The stimuli were auralised at the AUralization and Reproduction of Acoustic Sound fields (AURAS) facility, located at Penn State's campus. The facility houses a loudspeaker array composed of 30 two-way loudspeakers, and two large subwoofers for reproduction of low-frequency sound [16] located in an anechoic chamber. The 30 loudspeakers in the facility are situated in an almost spherical distribution, distributed in four rings of different elevations. Since the loudspeakers are not positioned in a perfectly spherical distribution around the listening position, individual adjustments in level and delay are applied to each speaker to compensate for this limitation. When combining the two-way loudspeakers with the two subwoofers, the frequency range of the system is flat down to 20 Hz.

7 EXPERIMENTAL PROCEDURE

7.1 Subject information and selection criteria

The listening test was conducted with 24 participants (13 female, 11 male) with an average age of 28 (SD = 14) and 14 years of musical training. One of the requirements for inclusion in the subjective testing was that subjects had at least 5 years of musical training and currently be practicing an instrument. In addition, all participants were screened to have at least a minimum hearing threshold of 15 dB hearing level (HL) in the octave bands from 250-8000 Hz.

7.2 Listening test

After completing an informed consent, participants viewed a tutorial with a set of slides explaining the testing procedure. The concept of clarity was presented to the subjects as "the degree to which instrument notes that follow one another stand apart". As part of the subject's preliminary training, the tutorial provided two audio excerpts of music in rooms with opposite degrees of musical clarity, i.e., a very "clear" acoustics versus a highly "blurred" acoustics. These audio excerpts were presented to the participants over headphones. The technique of presenting extreme cases of the stimuli to be rated before the actual listening test is recommended in [17]. The computer tutorial also showed the subjects how to use the testing interface which ran on a tablet PC.

In the test, the subjects listened to each of the nine stimuli corresponding to the OFAT study and rated them with the interface in terms of clarity, on a scale from 0 to 100. Subjects were instructed to use the full scale to rate the stimuli, i.e., rate the clearest stimulus in the set with 100 and the least clear one with 0. Subjects could also switch between the music samples without stopping the playback of the music to allow quick comparisons between the stimuli.

The test was organized into four sets with a 5-minute break after the first set. The first set presented to the subjects was a practice set, in which subjects rated in terms of clarity four stimuli that were extracted from the set of stimuli for the OFAT study. After the break, in which the test administrator checked that the test subject was comfortable in the chamber and that he or she understood the testing procedure, a hidden practice set was presented. In this set, the subjects rated four stimuli extracted from the set of stimuli of the OFAT study. The four stimuli in the hidden practice set were composed of the unmodified SRIR, a stimulus where the 63 and 125 Hz octave bands of C_{80} were decreased by 8 dB, and two stimuli in which the 4000 and 8000 Hz octave bands of C_{80} were increased and decreased by 8 dB, respectively; all these changes were relative to the octave-band values of C_{80} of the base case. After completing the hidden practice set, the subjects were presented with either the full OFAT (Task 1) set or the validation (Task 2) set. The order in which the OFAT set and the validation set were presented was randomized for each subject.

8 STATISTICAL ANALYSIS TECHNIQUES

8.1 Multiple regression analysis

The purpose of regression analysis is to explore the relation between two variables in such a way that an outcome, or response variable, can be predicted by one or more independent or explanatory variables. When building the regression model, the selection of the explanatory variables included in the model is dictated by theoretical considerations or past experience in the field. In the present case, due to the proven effectiveness of C_{80} in predicting perceived clarity, the only explanatory variables included in the regression model were the different pairs of octave bands of C_{80}. The true functional relationship between the octave band values of C_{80} and predicted clarity is unknown, but the Taylor series theorem from elementary calculus demonstrates that a linear model is always an appropriate first order approximation of any curvilinear function.

The coefficient of multiple determination, R^2, can be used to assess the fit of the model, since it indicates the amount of variance that is reduced in the model by introducing the explanatory variables. The adjusted coefficient of determination, R_a^2, is a better descriptor of the fit of the model, because the addition of explanatory variables to the model always results in a reduction of unexplained variance, with a subsequent increase of R^2.

8.2 Correlation analysis

The amount of linear association between two variables can be assessed by means of correlation analysis. The correlation coefficient measures the strength of the monotonic increase or decrease of one variable when the other one increases. The Pearson product-moment correlation coefficient [18] (r) quantifies the strength of the linear association between two random variables. The Pearson correlation coefficient assumes that the two variables being correlated are continuous, jointly normally distributed, random variables. Additionally, the sample from which r is calculated should be free of outliers and influential points which might have an undue influence in the value of the coefficient.

9 RESULTS AND DISCUSSION

9.1 OFAT study results

A linear regression model was fitted to the clarity data from the subjective test described in section 7.2. Equation 1 shows the statistical model, with the four independent variables, namely $\overline{C_{80}}_{63Hz\,\&\,125Hz}$, $\overline{C_{80}}_{250Hz\,\&\,500Hz}$, $\overline{C_{80}}_{1kHz\,\&\,2kHz}$, and $\overline{C_{80}}_{4kHz\,\&\,8kHz}$, and a dependent variable, $clarity$.

$$clarity_{i,j} = \beta_0 + \beta_1 \overline{C_{80}}_{63Hz\,\&\,125Hz(i)} + \beta_2\, \overline{C_{80}}_{250Hz\,\&\,500Hz(i)} + \beta_3 \overline{C_{80}}_{1kHz\,\&\,2kHz(i)} + \beta_4 \overline{C_{80}}_{4kHz\,\&\,8kHz(i)}, \quad (1)$$

where $clarity_{i,j}$ is the predicted rating of clarity for the i^{th} level of the predictor variables and for the j^{th} subject, β_i are the model parameters of the population, and $,\overline{C_{80}}_{\mathrm{XX}\,\&\,\mathrm{YY}(i)}$ is the i^{th} level of the predictor variable obtained from the average of the C_{80} values of octave bands XX and YY.

The model was fitted to the data from the 24 subjects. The fitting method was least-squares, implemented with the SPSS v28.0.1.0. statistical software [19]. A total of 216 data cases, a number which results from the multiplication of the number of levels of the explanatory variables in the C_{80} OFAT study (9 levels) and the total number of subjects (24 subjects), were used to perform the least-squares fit. Equation 2 shows the fitted model:

$$clarity = 54.99 - 0.43\overline{C_{80}}_{63Hz\,\&\,125Hz} + 0.99\, \overline{\mathrm{C}_{80}}_{250Hz\,\&\,500Hz} + 3.07\, \overline{\mathrm{C}_{80}}_{1kHz\,\&\,2kHz} + 4.16\overline{C_{80}}_{4kHz\,\&\,8kHz}. \quad (2)$$

The R^2 value was equal to 0.470 and the adjusted coefficient of determination R_a^2 was equal to 0.460. The Durbin-Watson statistic was equal to 2.012, very close to 2, indicating that the residuals of the regression model can be considered to be statistically independent. A visual inspection of the residual plots showed that the residuals were normally distributed, and this assumption was further confirmed by the insignificant *p*-values of the Kolmogorov-Smirnov test and the Shapiro-Wilk test. From Equation 2, it can be observed that the high frequencies of C_{80} have the largest influence on the prediction of musical clarity. In particular, the average of the 4000 and 8000 Hz octave bands were found to be the most important ones for the prediction of clarity. This result is in agreement with the findings of Beranek and Schultz [20] in their study of the desired frequency content of early reflections in concert halls.

9.2 Validation task results

The validity of the regression model obtained in section 9.1 was tested by using it to predict the ratings of clarity of arbitrary RIRs. The regression model was evaluated with the average value of C_{80} of pairs of octave bands of the SRIRs of the seven halls selected for the task, and the resulting ratings of clarity were compared with the average ratings of this subjective impression obtained in the listening test described in section 7.2, as shown in Figure 2. Values close to the diagonal indicate good agreement between ratings and predicted ratings.

In general, good agreement was found between the predictions from the regression model and the ratings of the halls from the listening test. A figure of merit is the mean square error between rated and predicted values of clarity, which was found to be equal to 10.5 scale points. This result indicates that, on average, an error in predicted clarity of 10.5 scale points is made when using this model.

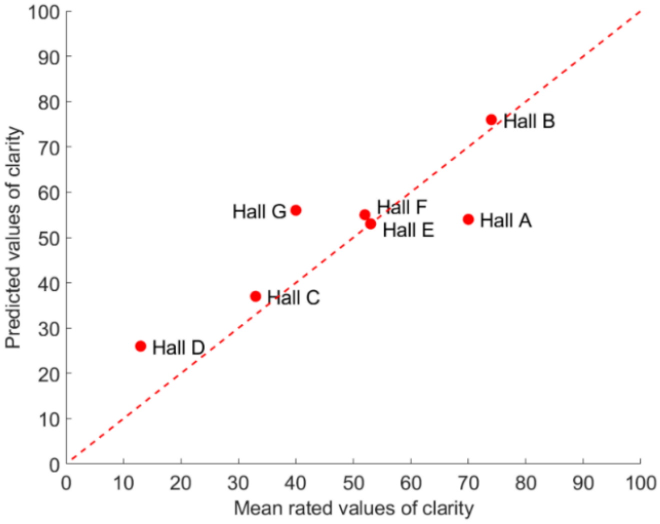

Figure 2: Comparison between predicted values of clarity, obtained from the regression model, and mean ratings of clarity for each hall.

There are two evident outliers in the data, Halls “A” and “G”. The reason why Hall “A” might have a rated clarity value that is substantially larger than the predicted rating is due to its very high value of C_{80} at the 8000 Hz octave band (5.7 dB) and a comparatively low C_{80} value in all the other octave band frequencies. Clarity is very highly correlated with C_{80} at 8000 Hz, and Hall “A” has the highest value (5.67 dB) of this parameter of the set of seven halls.

Hall “G” has dissimilar predicted and rated values of clarity. The mean rated value of clarity was 40 scale points for this hall, while the predicted value was 56 scale points. To analyse this discrepancy, it can be noted that Hall “F” has a similar C_{80} spectrum than Hall “G”, but the rated value, 52 scale points, was closer to the predicted rating of clarity for this hall, 55 scale points. This inconsistency may be attributed to the fact that Hall “G” is more reverberant than Hall “F”, as evidenced by the higher average of the mid-frequency (500 Hz and 1000 Hz) values of EDT of Hall “G” (2.6 s), compared to that of Hall “F” (2.2 s). Research conducted to obtain SVFA measures of EDT [12] show that these two pairs of octave bands are highly correlated with reverberance, which is negatively correlated with clarity. The regression formula for predicting the clarity ratings is only based on the C_{80} octave band values of each hall, not including the influence of EDT or other acoustic parameters, which might explain the discrepancy between the predicted and rated values of clarity for Hall “G”.

9.3 Correlation analysis results

A correlation analysis was conducted in which pairs of octave band values of C_{80} of the seven halls selected for the validation task were correlated with the ratings of clarity for these halls obtained from the listening test. The set of clarity ratings from the sample was not found to be normally distributed, so the correlations were performed using non-parametric statistics, such as the Spearman [21] correlation coefficient (r_s). This correlation coefficient is robust to the violation of the assumption of normality. The results of the correlations using the Spearman correlation coefficients is shown in Table 1. The $C_{80(3)}$ metric, proposed by Beranek, which can be obtained by averaging the 500, 1000 and 2000 Hz octave bands of C_{80}, was also correlated with perceived clarity. A high correlation coefficient was found for the association between the high-frequency pairs of octave bands of C_{80} and perceived clarity. The Spearman rank correlation coefficient was equal to 0.709 for the 4000 and 8000 Hz pair of octave bands. The $C_{80(3)}$ metric proposed by Beranek didn’t show a particularly high correlation with perceived clarity, with a correlation coefficient equal to 0.459.

Table 1: Spearman correlation coefficient of the correlations between clarity ratings and pairs of octave band values of C_{80}.

	C_{80} pair of octave bands				
	63 Hz & 125 Hz	**250 Hz & 500 Hz**	**1 kHz & 2kHz**	**4 kHz & 8 kHz**	$\boldsymbol{C_{80(3)}}$
Spearman rank correlation (r_s)	0.235	0.417	0.363	0.709	0.459
Significance (2-tailed)	0.002	< 0.001	< 0.001	< 0.001	< 0.001

When comparing the results of the regression analysis with the results of the correlation analysis, it is important to understand that these two analysis techniques have different statistical interpretations. The regression coefficient of an independent variable belonging to a regression model measures the importance of that variable in the prediction of the outcome variable, while the correlation coefficient measures the degree of linear association between the two variables. Disregarding the fact that there is a conceptual difference between these two coefficients, it can be observed that a good agreement was be found between the regression and correlation analysis, highlighting the importance of the high frequencies of C_{80} for the perception of clarity.

10 SUMMARY AND CONCLUSIONS

The purpose of the present study was to analyse the relative importance of the different frequency ranges of C_{80} for the prediction of musical clarity. This task was accomplished by means of a listening test in which 24 subjects with normal hearing and musical background rated stimuli in terms of musical clarity. Two different sets of stimuli were rated: one set was composed of SRIRs that were computationally modified to attain specific values of C_{80} in individual pairs of octave bands, while the other set was composed of SRIRs obtained from seven different concert halls. The ratings of clarity obtained for the first set of stimuli were regressed with the average C_{80} values of pairs of octave bands of their SRIRs. The obtained regression model can be used to predict a rating of musical clarity on a scale from 0 to 100 from an arbitrary RIR. The model was tested by comparing the predicted ratings when evaluating the regression formula with the octave band values of C_{80} of the seven halls, with the mean values of the ratings of clarity of these halls. It was found that the average error in the predictions of regression model relative to the actual ratings was approximately 10.5 scale points.

A correlation analysis was conducted between the ratings of clarity of the seven halls and their octave band values of C_{80}. It was found that the average of the 4000 and 8000 Hz octave band values of C_{80} had the highest correlation with musical clarity (r_s = 0.71), while the correlation between clarity and the $C_{80(3)}$ metric proposed by Beranek was not particularly high (r_s = 0.46).

The present study has helped in elucidating the relative importance of the different frequency ranges of C_{80} in the perception of musical clarity. In the past, several averaging schemes of the octave-band values of C_{80}, which were believed to be highly correlated with clarity, have been proposed. However, these SVFA measures of C_{80} originated in the practical experience of acoustical consultants and the literature is limited in this area. Both the obtained regression model and the results of the correlation analysis presented in 9.3, indicate that the high frequencies of C_{80} are very important for the perception of musical clarity. By using these results, the concert hall designer has an improved method to predict the impact that a change of C_{80}, due to the modification of the geometry or the materials of the hall, will have in perceived clarity.

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