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Concert Hall Sound Clarity: A Comparison of Auditory Judgments and Objective Measures

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The purpose of the study was to compare auditory judgments of sound clarity of music examples recorded in a concert hall with predictions of clarity made from the impulse response signal recorded in the same hall. Auditory judgments were made with the use of two methods: by rating sound clarity on a numerical scale with two endpoints, and by absolute magnitude estimation. Results obtained by both methods were then compared against the values of clarity indices, C_{80} and C_{50}, determined from the impulse response of the concert hall, measured in places in which the microphone was located during recording of music examples. Results show that auditory judgments of sound clarity and predictions made from the C_{80} index yield a similar rank order of data, but the relation between the C_{80} scale and perceived sound clarity is nonlinear. The data also show that the values of C_{80} and C_{50} indices are in very close agreement.

Keywords: sound clarity, room acoustics, psychoacoustics.

1. Introduction

This article reports a study carried out to compare auditory judgments of sound clarity of music examples recorded in a concert hall with predictions of clarity made from the impulse response signal recorded in the same hall. Clarity, a term used in sound quality studies, refers to the perceived resolution of the auditory image, that is the precision with which the details of sound can be heard. Beranek (2004) defined clarity as “the degree to which a listener can distinguish sounds in a musical performance.”

Clarity, a basic criterion for sound quality assessment of concert halls, may be estimated by means of auditory evaluation or with the use of objective measurement methods. Auditory evaluation may be made by expert listeners during a live performance of music in a hall (e.g., Marshall, 1994) or in an experiment carried out with the use of test examples recorded in a hall (e.g., Höhne, Schroth, 1995), or presented in synthesized sound fields (Reichardt *et al.*, 1975). In objective measurements clarity is predicted from the value of clarity index, C_{80} (Marshall, 1994), also called early-to-late sound index (Barron, 1993). Clarity index has been defined as the logarithmic ratio of sound energy during the first 80 ms in the impulse response to the energy after 80 ms, expressed in decibels (Reichardt *et al.*, 1975). An index based on a similar measurement principle, C_{50}, defined as the ratio between the energy in impulse response before and after 50 ms, is used for prediction of speech clarity in auditoria (Reichardt *et al.*, 1974). The C_{80} and C_{50} metrics are applied to unoccupied halls (e.g., Gołaś, Suder–Dębska, 2009).

Room acousticians generally agree that C_{80} is a good predictor of sound clarity of music perceived by the audience in concert halls. The belief about the validity of C_{80} has been mainly based upon practical experience gained from designing concert halls, but the quantitative relation between the impression of sound clarity perceived by a listener and the clarity index value has never been thoroughly examined in a systematic way.

The most widely known study on the validity of clarity index was published by Reichardt *et al.* (1975). The subjects who participated in that study listened to an excerpt of symphonic music presented in various synthesized sound fields and indicated whether sound clarity was "useful" or "useless". By comparing those two categories of responses against the values of C_{80} determined for each sound field Reichard and his coworkers distinguished three categories of clarity: a category of "bad clarity" represented by C_{80} values below -1.6 dB, a "border category" with C_{80} ranging from -1.6 to 1.6 dB, and a category of "good clarity" with C_{80} values above 1.6 dB.

Marshall (1994) proposed a scale describing the relation of C_{80} to sound clarity in five gradations, from bad to excellent, but he did not conduct any methodologically systematic listening tests to verify the validity of that scale; he only noted that the values of C_{80} were consistent with his impression of sound clarity experienced during a rehearsal of a symphony orchestra in an unoccupied concert hall. Other psychoacoustic studies of sound clarity were concerned with the difference limen for C_{80} and maximum permissible variations of C_{80} values across seats in auditoria (Höhne, Schroth, 1995; Cox *et al.*, 1993).

In the present study sound clarity of short music examples recorded with a dummy head in various places in a concert hall was assessed with the use of two psychophysical methods: by rating the sensation magnitude on a numerical scale with two endpoints, and by absolute magnitude estimation. The judgments obtained from a panel of expert listeners were then compared against the values of C_{80} and C_{50} measured in the concert hall, in places in which the sound material used for listening tests was recorded with the dummy head.

2. Method

2.1. Sound material used in listening tests

The judgments of sound clarity were made for four music examples. Two of them were excerpts from Fréderic Chopin's piano pieces: *Waltz* in C-sharp Minor, Op. 64 No. 2 (bars 32–48, lasting 12 s), and *Fantasie-Impromptu* in C-sharp Minor, Op. 66 (bars 37–46, lasting 22 s). The third excerpt was from a solo violin piece (*Obertas* Op. 19 No. 1, by Henryk Wieniawski, bars 1–11, 16 s in duration), and the fourth one was from a piece for violin and piano (*Romanian Dance* No. 5, by Béla Bartók, bars 1–16, 16 s in duration). The excerpts were performed by professional musicians in an unoccupied concert hall, at the Royal Castle in Warsaw. The hall is used for concerts of solo and chamber music so the sound examples selected for listening tests represented the kind of music typically performed in that hall.

Figure 1 shows the plan view of the concert hall. The hall was 2300 m^3 in volume and had a floor area of 195 m^2; its reverberation time, T_{30}, ranged from 2.7 to 1.6 s (125–4000 Hz). Music examples performed in the hall were recorded with a Neumann KU 100 dummy head, a model of the human head with a microphone placed on each side in a pinna, with no simulation of the ear canal. The recordings were made in five places in the auditorium area and in one place on the stage, as shown in Fig. 1. In all placements the microphones of the dummy head were positioned at a height of 1.2 m above floor. The sound was captured with the same dummy head in all six places in the hall therefore the musicians repeated the performed material several times during the recording session.

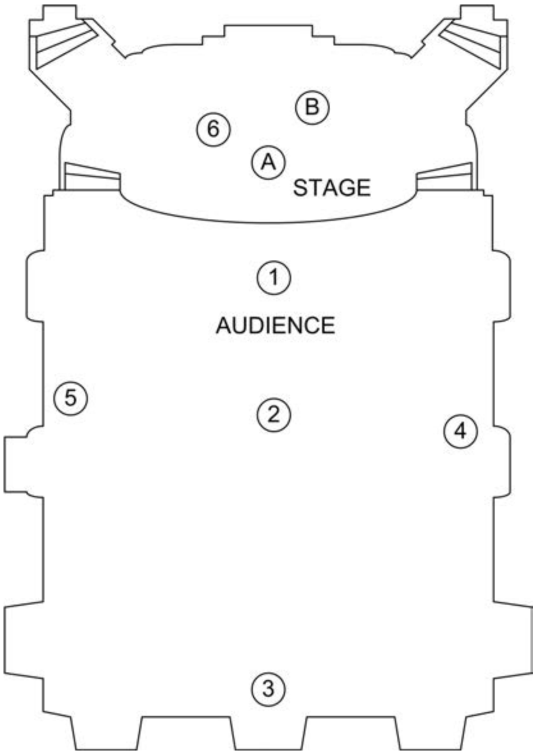

Fig. 1. Floor plan of the concert hall. The numbers show six placements of the dummy head during recording of the sound material used in listening tests. Letters A and B indicate the positions of a dodecahedron loudspeaker system used for the measurement of impulse response of the hall (see Subsec. 2.3).

2.2. Procedure for listening tests

Judgments of sound clarity were made in individual listening sessions, in a sound-insulated room. The recordings of music excerpts were stored in audio format on CD-R disks. Each set of six recordings of a music excerpt, separated by 5-s intervals of silence, was recorded on a separate track. The order of tracks and the order of sound samples within tracks was different on disks prepared for each listener. The recordings were played back from a Marantz 74CD72/02B CD player, through a Beyerdynamic DT 990 headphone set. The gain of the headphone amplifier was set such as to reproduce the original sound pressure levels measured in the position of the dummy head during recording of the samples in the concert hall. A set of 24 samples (4 tracks with different music excerpts × 6 microphone placements) was played back from CD and the listener had to write down his/her judgment of sound clarity on a response form, during the 5-s silence interval after the presentation of a sample.

The listening test comprised two parts. In the first part the judgments of sound clarity were made using the method of absolute magnitude estimation (Zwislocki, Goodman, 1980). The listeners were asked to assign a number to each sound sample in such a way that their impression of the size of the number reflected their impression of the clarity of sound. According to the principles of absolute magnitude estimation method the estimates were made with no reference standard. The listeners were instructed to use positive numbers in their judgments: whole numbers, decimals, and fractions, but beside this requirement, no restrictions as to the range of numbers were imposed. The listeners were also instructed to judge each sound sample separately, and not to think about numbers assigned to preceding samples in a series, while making a judgment.

In the second part of the test the listeners rated sound clarity on a numerical scale, extending from 0 to 10. The procedure of judgment was modeled after rating procedures used for sound quality assessment of concert halls (Barron, 1988) and sound reproduction equipment (Gabrielsson, Sjögren, 1979). The scale was presented in form of a horizontal line on an answer sheet, with numerical labels, and the listener indicated his/her judgment by placing a checkmark on the line. In succession of two tests, rating was conducted as second to avoid any possible influence of the rating scale's numerical range on the listener's choice of numbers in the absolute magnitude estimation task.

In both parts of the test judgments of sound clarity were obtained from 12 listeners. The listeners were recent graduates and graduate students of sound engineering at the Fryderyk Chopin University of Music in Warsaw and had extensive experience in sound quality assessment of music recordings.

2.3. Measurement of C_{80} and C_{50} indices

The values of C_{80} and C_{50} indices were determined from the impulse response of the concert hall. Impulse response was measured with the use of maximum length sequence (MLS) signal reproduced through a dodecahedron, omnidirectional, wideband loudspeaker system. The measurements were made for two positions of the loudspeaker system, indicated by letters A and B on the hall's plan (Fig. 1). The measurement signal reproduced from the loudspeaker was recorded in six places in the hall, which corresponded to the placements of the dummy head during recording of music excerpts (points 1–6 in Fig. 1). The signal was captured by a Brüel&Kjær 4155 measurement microphone, fed through the pre-amplifier of a Brüel&Kjær 2230 sound level meter to an audio interface (RME Fireface 400), and stored on a hard disk. A single MLS signal lasted 5.9 s. Each measurement was based on an analysis of eight MLS signals.

The analysis of recorded signals and the calculations of clarity indices were made with the use of EASERA 1.1.3 software package for acoustic and electronic measurements. Clarity index, C_{80}, was calculated according to the following formula (Reichardt *et al.*, 1975):

$$C_{80} = 10 \log \frac{\int\limits_{0}^{\mathrm{T}} h^2(t)\,\mathrm{d}t}{\int\limits_{\mathrm{T}}^{\infty} h^2(t)\,\mathrm{d}t}, \tag{1}$$

where T (80 ms) is time elapsed after arrival of direct sound wave, and $h(t)$ is the impulse response. For calculation of speech clarity index, C_{50}, the constant T was changed from 80 to 50 ms in Eq. (1).

3. Results

Figure 2 shows the values of sound clarity obtained by the method of rating. Labels on the abscissa indicate the placement of the dummy head during recording, as shown in Fig. 1, and the ordinate axis represents the rating scale, extending from 0 to 10. Results obtained by absolute magnitude estimation are plotted in Fig. 3.

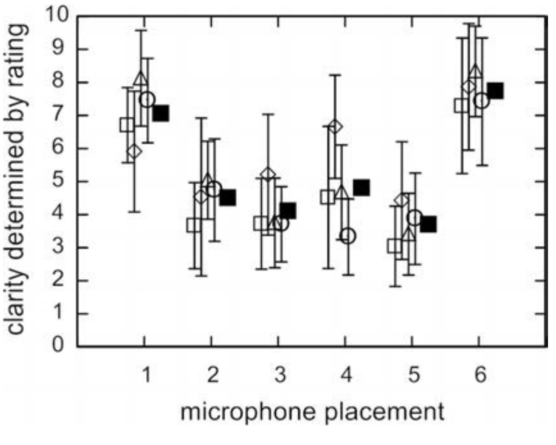

Fig. 2. Results of rating of sound clarity on a scale from 0 to 10. Open symbols show arithmetic means of 12 judgments obtained for individual musical excerpts: *Waltz* (piano) – squares, *Fantasie-Impromptu* (piano) – diamonds, *Obertas* (violin) – triangles, *Romanian Dance* (violin and piano) – circles. Error bars represent the standard deviation of the mean. Filled squares show arithmetic means calculated across musical excerpts.

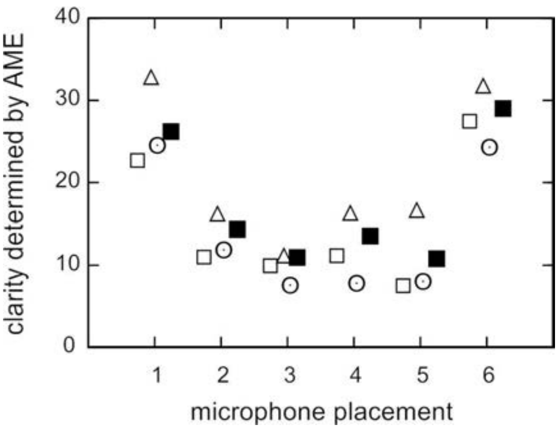

Fig. 3. Results of absolute magnitude estimation of sound clarity. Open symbols show geometric means of 12 judgments obtained for individual musical excerpts. Symbol indications of the excerpts are same as in Fig. 2. Filled squares show geometric means calculated across musical excerpts.

To estimate statistical significance of the effect of microphone placement in the concert hall and the effect of musical piece on the judgments of sound clarity, a two-way analysis of variance was applied to the results of the experiment. The analysis was made separately on raw numerical judgments obtained by rating and on log-transformed judgments obtained by absolute magnitude estimation. The results of analysis of variance indicate that for both methods the effects of microphone placement and musical excerpt were statistically significant [rating: microphone placement $F(5, 11) = 53.5$, $p < 10^{-37}$, excerpt $F(3, 11) = 5.32$, $p < 0.01$; AME: microphone placement $F(5, 11) = 6.33$, $p < 0.0001$, excerpt $F(3, 11) = 3.81$, $p < 0.05$].

The data plotted in Figs. 2 and 3 indicate that sound clarity considerably differed across the measurement points in which the musical excerpts were recorded in the concert hall. At point 1, located in the first row of audience seats and at point 6, located on the stage, sound clarity was considerably higher than at points 2–5, placed at a further distance from the stage. Such a clear-cut difference in sound clarity was expected. The hall's critical distance was 1.8 m, so points 1 and 6 were placed in direct sound field and points 2–5 in reverberant field.

The overall pattern of data across the measurement points is, by and large, similar for all musical excerpts (Figs. 2 and 3). It may be therefore assumed that averaging of data across musical excerpts may give a general view of the variability of sound clarity across measurement points, despite that the effect of music appeared to be statistically significant. A comparison of averaged data, represented by filled squares in Figs. 2 and 3 demonstrates that quantitative relations between the values of sound clarity across measurement points are similar for both methods.

The values of clarity indices, C_{80} and C_{50}, calculated for two positions of the loudspeaker system and six measurement points are given in Table 1. The C_{80} values were obtained by averaging data for octave bands centered at 500, 1000, and 2000 Hz, as recommended by Marshall (1994). The C_{50} values were calculated by multiplying the data for octave bands centered at 500, 1000, 2000, and 4000 Hz by weighting factors of 0.15, 0.25, 0.35, and 0.25, and summing the products (Marshall, 1994).

Table 1. Clarity index, C_{80}, and speech clarity index, C_{50}, determined for two positions of the loudspeaker system and six measurement points in the concert hall.

loudspeaker placement	measurement point	clarity index C_{80} [dB]	speech clarity index C_{50} [dB]
A	1	−0.1	−1.3
A	2	−1.8	−2.9
A	3	−1.7	−3.7
A	4	−2.3	−4.9
A	5	−2.4	−3.8
A	6	3.7	3.4
B	1	−0.9	−1.8
B	2	−1.8	−4.5
B	3	−2.0	−4.5
B	4	−2.5	−4.4
B	5	−0.6	−2.3
B	6	4.6	5.3

The values of C_{80} and C_{50} given in Table 1 are plotted in Fig. 4 against the results of auditory judgments obtained by rating (upper panel) and by absolute magnitude estimation (lower panel), averaged across musical excerpts. It is apparent in Fig. 4 that the values of C_{80} and C_{50} indices are in fairly good agreement with results of auditory judgments of sound clarity obtained with the use of both methods. "Fairly good" agreement means in this case that clarity indices correlate with the rank order of sound clarity values derived from the results of auditory judgments, but do not reflect their quantitative relations, such as ratios or differences.

The patterns of data shown in Fig. 4 provide an example attesting to the limited validity of C_{80} and C_{50} indices for prediction of the results of auditory judgments of sound clarity. The cluster of four symbols, seen second from right in both panels, represents the data obtained for point 1, located in the first row of audience seats, very close to the stage. Results of auditory judgments indicate that sound clarity was at point 1 only slightly poorer than at point 6, located on the stage, but substantially better than at all the other points in the auditorium. The measurements of

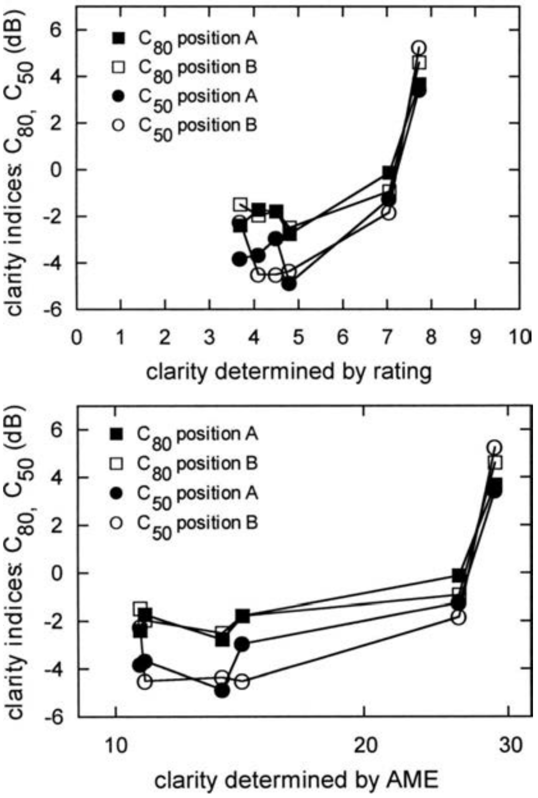

Fig. 4. Clarity indices C_{80} and C_{50}, determined for two positions of the loudspeaker system (A and B), plotted against the results of auditory judgments of sound clarity obtained by rating (upper panel) and absolute magnitude estimation (lower panel). The abscissae are data averaged across musical excerpts, replotted from Fig. 2 (upper panel, rating) and Fig. 3 (lower panel, AME method). The ordinate shows C_{80} and C_{50} values determined for six microphone placements.

C_{80} and C_{50} do not reflect such a relation as the values obtained for point 6 are considerably higher than those for point 1 and the difference between the C_{80} and C_{50} values at point 1 and those measured for points 2–5 is much smaller than indicated by the results of auditory judgments.

Figure 5 shows results of auditory judgments of clarity made with the methods of rating (upper panel) and absolute magnitude estimation (lower panel), plotted against the values of clarity index, C_{80}. The values shown on the abscissa are arithmetic means of two C_{80} values given in Table 1, determined for different positions of the loudspeaker system during the measurement. As seen in Fig. 5, the relation between the C_{80} value and perceived clarity is nonlinear. When C_{80} in decibels increases from negative values to about zero, the corresponding increase in perceived clarity is considerable, but further increase of C_{80} beyond zero is reflected only by a slight growth of perceived clarity.

The present experiment provides some new insight into the methodology of the assessment of concert hall sound clarity. Sound clarity of music is typically predicted from the C_{80} value. The data plotted in Fig. 4 show that the C_{80} and C_{50} values are in close agreement which suggests that sound clarity of music may be predicted with similar accuracy from both indices. When using the C_{80} and C_{50} indices one must keep in mind that they can be used to compare sound clarity on an ordinal measurement scale and do not reflect neither the differences nor the ratios of sound clarity perceived by a listener. Nevertheless, an ordinal-type scale of sound clarity is sufficient in most applications in the design and evaluation of concert halls, especially that it has been determined what ranges of C_{80} are preferred for certain types of music (Marshall, 1994).

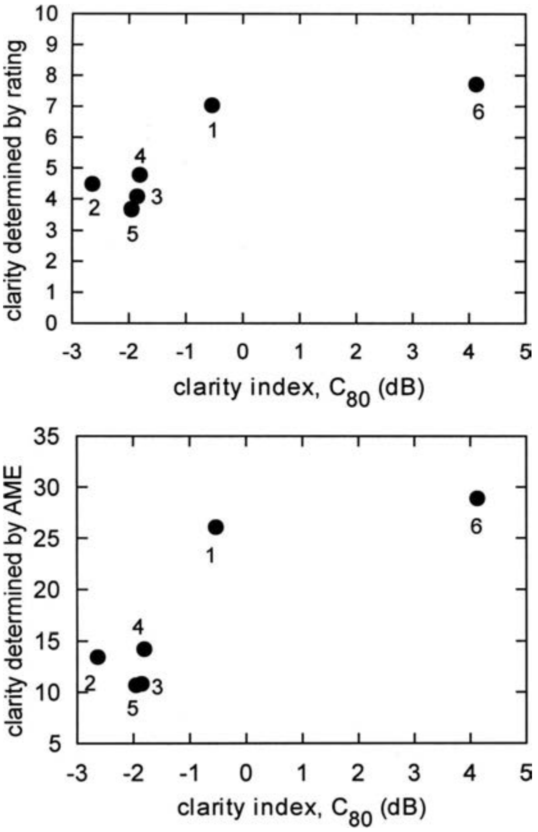

Fig. 5. Results of rating (upper panel) and absolute magnitude estimation (lower panel) of clarity, plotted against the values of clarity index, C_{80}. The data on the abscissa are arithmetic means of C_{80} values determined for two positions of the loudspeaker system (see Table 1). The values on the ordinate are results averaged across musical examples, replotted from Figs. 2 and 3. Numbers (1–6) indicate the microphone placements shown in Fig. 1.

In applied studies consisting in auditory assessment of concert hall sound quality, clarity is usually evaluated by rating on a numerical scale with two endpoints. The present data demonstrate that results of rating are consistent with the results obtained by absolute magnitude estimation. Absolute magnitude estimation is a psychophysical scaling method typically used in basic research in psychoacoustics, especially in experiments sought to determine the relation of sensation magnitude to a physical variable of sound. The advantage of absolute magnitude estimation over rating procedures is that it yields data that represent the sensation magnitudes on a ratio scale whereas rating leads at most to the construction of an interval scale.

Representation of sensation magnitudes on a ratio scale is particularly desirable when the data are related to a psychoacoustic model of signal processing in the auditory system. The C_{80} and C_{50} indices have been based on a simple empirical finding that sound clarity is correlated with the energy ratio of early and late sound wave reflections and have no foundations in psychoacoustic models. Further investigations would be needed to describe the underlying physiological and perceptual mechanisms of the impression of sound clarity, such as the effects of auditory signal filtering, masking, and temporal integration of energy. Such investigations should also take into account the effect of musical factors on sound clarity. Marshall (1994) presented a general classification of C_{80} values optimal for various kind of musical ensembles, yet he made it clear that optimal clarity also depends on the style of music and its instrumental texture.

4. Conclusions

The main findings of the present study may be summarized as follows.

1. Auditory judgments of sound clarity obtained by rating on a numerical scale with two endpoints are in general agreement with sound clarity values determined by absolute magnitude estimation. Agreement means in this case that the results of rating, presented on a linear scale, yield similar patterns of data when compared with the results of absolute magnitude estimation plotted on a logarithmic scale.
2. The values of C_{80} and C_{50} indices used for prediction of sound clarity generally agree with the results of auditory judgments of sound clarity. The agreement of both types of data is restricted to their convergence on an ordinal scale which means that the order of sound clarity values predicted from the C_{80} and C_{50} indices is consistent with the order determined from auditory judgments.

Acknowledgment

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