Influence of Size and Composition of the Orchestra on the Perception of Room Acoustical Quality

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Abstract:

Analysing the results of subjective listening tests in real halls, the sound power levels of the different orchestral ensembles as sound sources for the listening tests are shown to be an important factor. Correspondence between objective measurements and subjective evaluation, especially for the question of loudness of the hall, turns out to be very good when the effective sound pressure level at the listeners' positions is taken as the objective parameter. This means that in order to explain subjective judgments on the loudness of a hall not only the objective measure of the amplification of the hall, but also the sound power of the orchestra has to be taken into account. On the contrary, judgments of subjective loudness turn out to be independent of orchestral ensemble for halls of auditorium type, indicating that for the evaluation of chamber music a change in response strategy of the listeners occurs. The regression constants for the subjective changes due to either a change in the amplification of the hall or a change in the sound power of the orchestral source are estimated and found to be reasonably close.

Introduction

During the last few years, the room acoustics laboratory at Ircam, Paris, has undertaken a series of objective measurements as well as subjective listening tests in a number of different halls throughout Europe [1]. As the measurement campaign included major concert halls as well as operas and smaller-sized auditoria, the question of normalization of the sound level in the different halls occurred. Measurements of impulse responses were made using a calibrated loudspeaker emitting a constant sound power, resulting in sound levels for smaller auditoria several dB in excess of the values for concert halls. For the listening tests, on the other hand, the type of music, and thus the number of musicians on stage, varied from chamber music to symphony. We hence proceeded to calculating the sound pressure levels at the individual listening locations, using estimates of the sound power levels of the various orchestral ensembles on stage.

Sound Power Calculations

Measurements of the sound power level as well as of dynamics and directivity of musical instruments can be found in the literature. Especially the writings of Jürgen Meyer [e.g. 2,3] provide ample information on most orchestral instruments. To retain but a single number per instrument, it was decided to follow his proposal and use the values for a ``good forte'' in a typical tonal range of the instrument.

Few equivalent measures exist for the piano or for singers. Additionally, establishing a single value for their sound power seems a near to impossible task when considering possible variations between a Steinway concert grand piano and a chamber-music type piano, or between a soloist in a Wagnerian opera and an amateur choir singer. For these cases, however, an evaluation by comparison rapidly converges to reasonable answers that will respect at least the order of magnitude. For example, the sound power of a concert piano was determined as being equivalent to the sound power of a small string orchestra by observing the equilibrium of the strings and the solo piano in a concerto by Mozart or Beethoven. The sound power level of a single choir singer was inferred from an equivalence of the sound power of the choir and the full orchestra for Beethoven's 9th Symphony (with a choir of 90) and Mahler's 2nd Symphony (with a choir of 150). The following table gives a summary of the estimated sound power levels (always for a ``good forte") for all the instruments that had to be considered in the calculation of the sound power levels of the different orchestral ensembles.

violoncello	90 dB	clarinet	93 dB	trombone	101 dB
double-bass	92 dB	bassoon	93 dB	tuba	104 dB
timpani	100 dB	piano solo	102 dB	solo singer	99 dB
percussion	99 dB	accompanying piano	99 dB	choir singer	93 dB

Table 1: Sound power levels of musical sound sources

The emitted sound power of an orchestra depends on its size and composition as well as the manner the different instruments are employed within the musical work. The second influence being extremely difficult to measure, only the first influence is taken into account. The sound power of the orchestral ensemble is calculated as a linear addition of the sound powers of the individual instruments. This is equivalent to considering that all of the musicians play at the same time, rare in real musical works. But, on the other hand, subjective judgments of the loudness of a hall will to a large extent be based on the loudest moments in a musical work, and for these moments the approximation of all instruments playing simultaneously will approximately be fulfilled.

The size and composition of the orchestral ensembles were mostly noted during the listening tests. Otherwise, the scores were consulted yielding a sufficiently exact determination of the numbers of players physically present on stage. For auditoria sound power levels ranged from 95 dB (string quartet) to 107 dB (chamber orchestra), for concert halls a typical variation within a single hall was from 111 dB (classical concerto) to 115 dB (late romantic symphony).

On average, sound power levels of the orchestral ensembles for the auditorium type were down by 12 dB when compared to concert halls. This has to be compared to differences in the amplification of the hall of on average 8 dB. Within a concert hall differences of 3 or even 4 dB of the sound power level of the orchestra are commonplace. Do corresponding differences occur in the subjective evaluation of the halls?

Influence of the Musical Work

The responses to the structured questionnaire used in the subjective listening tests were separated by musical work and the judgments for identical places, but differing musical works, were analysed. A number of statistically significant differences could be observed in addition to the question of subjective loudness.

So, for example, when listening to ``Rosamunde", a ballet music by Franz Schubert, performed by a moderately sized orchestra, the Berlin Philharmonie was not only judged as being less ``loud", but also as having smaller dynamics and being less brilliant and enveloping than when listening to the three orchestral pieces op. 6 by Alban Berg. Similar observations could be made in other halls. On the other hand, in the Auditorium du Louvre in Paris two distinct listening tests were performed, using exactly identical listening locations, but partially different listeners, one with a duo of violoncello and piano, the other with a chamber orchestra. In this case, no significant difference in subjective loudness could be observed in spite of a major change in the number of musicians on stage.

Studying the subjective attribute of reverberance revealed further influences. When listening to the first piano concerto by Brahms the Berlin hall was, for the seats in front of the orchestra, judged as being less reverberant than when listening to e.g. the orchestral pieces by Berg. This is linked to the strong directivity of the piano, diminishing the importance of the late reverberation in the hall. On the contrary, the Vienna Musikverein was judged as being more reverberant for a Beethoven piano concerto than for the Pastorale symphony - but in this case the piano was turned towards the orchestra and the lid was taken off, so as to allow the pianist Daniel Barenboim to conduct the Vienna Philharmonic at the same time as playing the solo part. This layout enhances the importance of the late reverberated sound field and hence augments the subjective impression of reverberance.

Relationships with Objective Criteria

The relationships with objective criteria will only be discussed for the question of ``loudness''. Figure 1 shows the relation of the subjective judgments of loudness vs. the objective parameter of the calculated sound pressure level, separated by musical work but averaged over all tested positions in each hall. Correspondence is very good for the concert halls (A,B,P,V) as well as for the operas (C,G,M), but subjective judgments for the auditoria (L and O) are surprisingly constant even for major changes in sound pressure level.

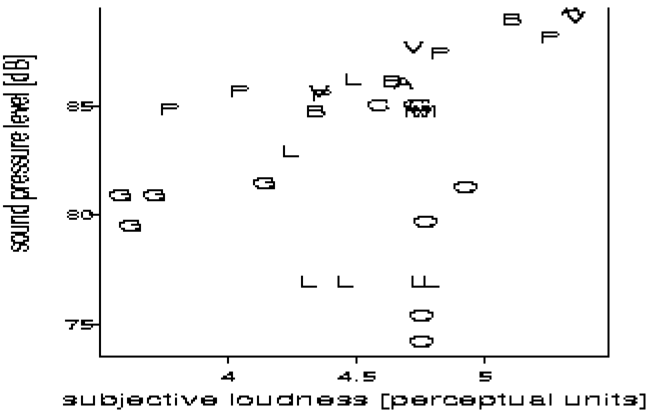

Figure 1: Subjective loudness vs. sound pressure level for the means of the halls, by musical work.

One could argue that for chamber music the calculation of the effective sound power level of the orchestral ensemble is no longer valid. A soloist will tend to play louder than a tutti orchestra player and whereas in symphony music rarely all of the musicians will play at the same time, this no longer holds for chamber music. This will largely diminish the difference between smaller and bigger ensembles when calculating some kind of an average sound pressure level. But in this way the relative constancy of the judgments for the loudness of the auditoria can still not be explained. The results hence rather indicate that a change in response strategy occurs. Whereas for symphonic music the results strongly suggest that subjects evaluate the sound pressure level rather than the amplification of the hall (which would mean making abstraction of the musical message), it seems that for chamber music a relative judgment is performed, taking into account the expected sound power of the clearly visible instruments on stage.

Except for auditoria the correspondence with the objective parameter of sound pressure level is excellent. Taking one musical work at a time, there is no significant correlation between subjective loudness and the average value of G within a concert hall, see fig. 2a. But there is a high correlation (r = 0.8) between subjective loudness and the calculated sound pressure levels, fig. 2b.

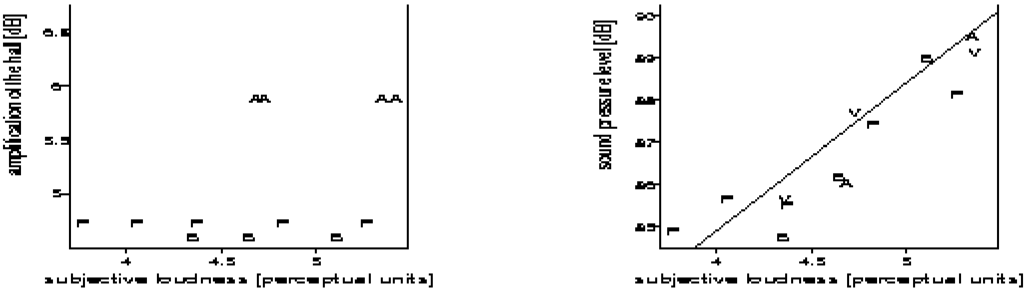

Figure 2: Subjective loudness vs. amplification of the hall G (left figure), and vs. sound pressure level (right figure), both at mid-frequencies. Each data point is the average over all seats in a hall, for one musical work, concert halls only.

The influence of a varying source power can equally be seen when considering individual places within a hall. In figure 3 each data point is the mean of the responses for one musical work, for different places in the Berlin Philharmonic Hall. The correlation coefficient of about $r = 0.5$, when relating to the amplification of the hall *G*, at mid frequencies, is increased to $r = 0.8$ when including the correction for the sound power levels of the orchestral sources.

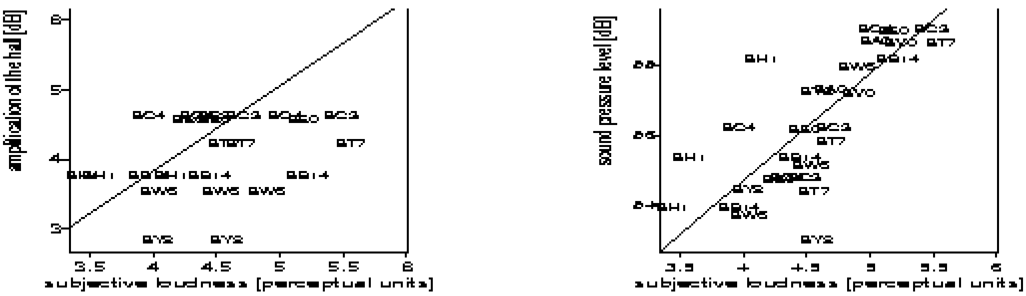

Figure 3: Subjective loudness vs. amplification of the hall G (left figure), and vs. sound pressure level (right figure), for the Berlin Philharmonic Hall. Individual places, separated by musical work.

What are the regression constants for the different objective changes of amplification of the hall and of source power? And will the regression constants be similar for changes within a room or across rooms, i.e. comparing questionnaires that were either completed within 24 hours (within a hall) or with a time lag of several weeks between tests (different halls)? The findings were:

- Variation of the amplification of a hall G, short-term comparisons. Derived from the changes within a hall, the average source power is thence constant. The regression constant can be estimated as 2.00.5 dB per perceptual unit.
- Variation of the amplification of the hall, long-term comparisons. Derived from the means of the concert halls, averaged over the musical works. The number of data points is not sufficient to establish the regression constant with certainty, but it can be estimated to about 52 dB per perceptual unit.
- Variation of the sound power of the source. Derived from changes of the sound source within a hall, the amplification of the hall at the different places will hence remain unchanged. The regression constant can be estimated as 41.5 dB per perceptual unit.

The difference in the average judgments of the halls indicate that even over a span of several months subjects are able to give reliable judgments. But a partial adaptation to sound pressure level occurs, and the difference in regression constants can be translated into a difference in sensitivities between short-term (not instantaneous) and long-term comparisons by a factor of about two or three.

The regression constants for variations of source power or of amplification, both within a hall, indicate that a change in the amplification of the hall and a change in the sound power of the source will produce similar effects. The remaining difference of 2 dB against 4 dB can be explained by the calculation of the total sound power of the orchestra as a linear addition of the sound power of all the instruments, inevitably overestimating the ``real'' mean sound power levels for the bigger orchestral ensembles. Furthermore, the objective measurements were made in unoccupied halls, differences between the loudest and the quietest seats tend to increase in an occupied hall when compared to the unoccupied state.

Conclusion

Absolute sound pressure level at the listeners' positions turned out to be a good correlate to the subjective notion of ``loudness'' of the hall, at least for the concert halls and the operas. In order to estimate the effective pressure levels, the sound power levels of the different orchestral ensembles were calculated, and an outline of the method was given. Currently, other criteria integrating the masking of parts of the impulse response are under study to further optimize the relation with the subjective impressions.

The regression constants for different objective changes as well as the ratio of the sensitivity between reasonably short-term comparisons (change in a concert or the following day) could be estimated.

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