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ACOUSTIC CLARITY AND AUDITORY ROOM SIZE PERCEPTION

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Abstract

Studies of auditory room size perception have sometimes found clarity index to be a good first order predictor of subjective ratings, with a negative correlation coefficient. However, for rooms of fixed reverberation time, the slope of the function relating clarity index to room volume is positive (for a given source-receiver distance). This paper considers how clarity index relates to room volume for realistic rooms, and why it can be an effective predictor of perceived room size.

1. INTRODUCTION

Acoustic indicators of the size of rooms may include density and strength of early reflections, room mode density, reverberation time, strength factor, and the presence and timing of echoes. Auditory and physical acoustic analysis are not the same process, so the auditory cues for room size perception may not concur with acoustic indicators. Kuster [1] has shown that Baron and Lee's 'revised theory' [2] of diffuse field energy relations in rooms can be used for the computational estimation of room size using source-receiver distance, reverberation time, direct sound level and reverberant sound level. Extracting this information from room impulse responses, Kuster verified this using twelve rooms ranging from 10 m^3 to 20000 m^3. However, in auditory perception, source-receiver distance is more difficult to estimate and is affected by several factors [3], and there is not a clear perceptual separation between the concepts of reverberation time and reverberant sound level. Furthermore, auditory room size perception and physical room volume do not need to correspond (since one is subjective, and the other objective) – just as a darkly painted room might be interpreted visually as being smaller than the same room painted white.

Several experiments of auditory room size perception have found clarity index to be the best of the common room acoustical parameters in predicting subjective response [4-6]. Clarity index is the ratio of early to late sound energy in a room impulse response, expressed in decibels. The variants of clarity index C_{50} and C_{80} are commonly used in room acoustics, where 50 ms and 80 ms are taken as the respective boundaries between early and late energy. These room size perception experiments have generally been conducted using rooms of moderate size, yielding strong negative correlation coefficients of up to r = -0.97 between subjective responses and clarity index. Some experiments have used systematically controlled variables (e.g., room volume, source-receiver distance and reverberation time), and some using real rooms with a mixture of controlled and incidental variable values. However, the finding that clarity index correlates negatively with perceived room size is at odds with the fact that for a fixed reverberation time and source receiver distance, clarity index correlates positively with room volume. Like other aspects of spatial hearing, it can be postulated that auditory room size perception develops in an individual though learning in their everyday experience. If auditory cues for room size are learnt from everyday experience, then the role of clarity index as an acoustic predictor of room size rating provides something of a puzzle. Therefore this simple paper considers this relationship in more detail in an effort to provide more of an explanation for this apparent relationship between clarity index and perceived room size.

2. THEORETICAL MODEL

Using the diffuse field theory of Barron and Lee [2], clarity index can be predicted from:

$$C_{80} = 10\log\left(\frac{E_{direct} + E_{early}}{E_{late}}\right) \tag{1}$$

Where E_{direct} is the direct sound energy, E_{early} is the early reflection energy up to 80 ms after the direct sound arrival, and E_{late} is the late reflected energy after 80 ms, which are calculated thus:

$$E_{direct} = \frac{100}{r^2} \tag{2}$$

$$E_{early} = \left(\frac{31200T}{V}\right) e^{-0.04r/T}\left(1 - e^{-1.11/T}\right) \tag{3}$$

$$E_{late} = \left(\frac{31200T}{V}\right) e^{-0.04r/T} e^{-1.11/T} \tag{4}$$

Here T is reverberation time (in seconds), V is room volume (cubic metres), and r is source-receiver distance in metres (the source and receiver are omnidirectional).

Figure 1 evaluates this for reverberation times of 0.5 s, 1 s and 2 s, with a source-receiver distance of 2 m, as a function of room volume. While clarity index correlates positively with room volume, the effect is weak in the small room volume range (up to 160 m^3). If the source-receiver distance is reduced, the extent of this flattening out of the function at small room volumes is reduced. As mentioned in the Introduction, the positive correlation runs counter to experimental results on auditory room size perception.

Experience of source-receiver distances in everyday room use is not independent of room volume. Large source-receiver distances are not possible in small rooms, but are in large rooms. Therefore a fairer analysis of clarity index as a function of room volume could be conducted by increasing the source-receiver distance with volume. This is done in Figure 2, which shows a much smaller positive correlation between clarity index and room volume for the reverberation times of 0.5 s, 1 s and 2 s. Source-receiver distance is taken as half the cube root of the volume.

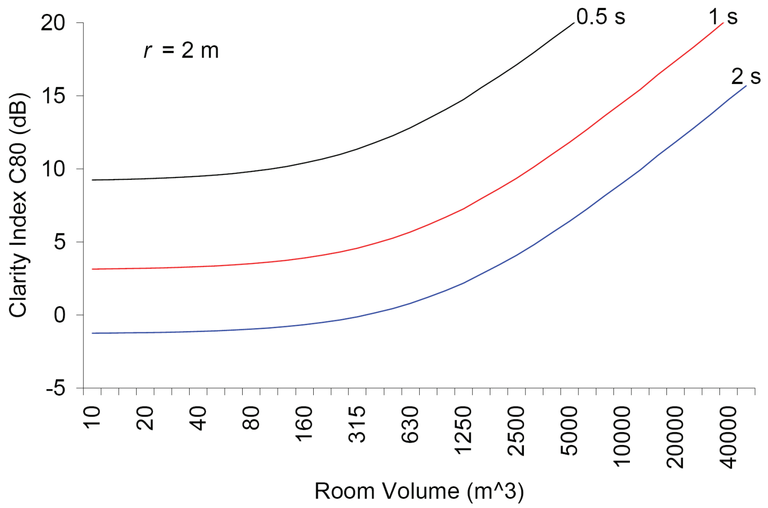

Figure 1. Clarity index as a function of room volume for a source-receiver distance of 2 m. Functions are for constant reverberation time.

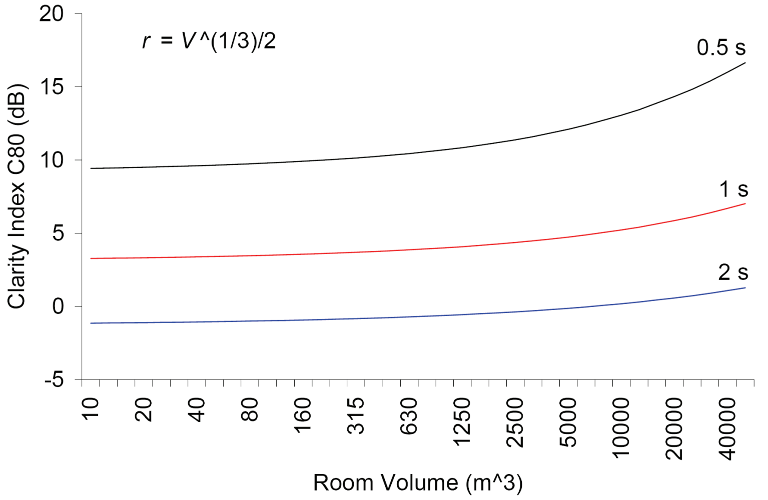

Figure 2. Clarity index as a function of room volume for a source-receiver distance that is proportional to the room's linear dimension. Functions are for constant reverberation time.

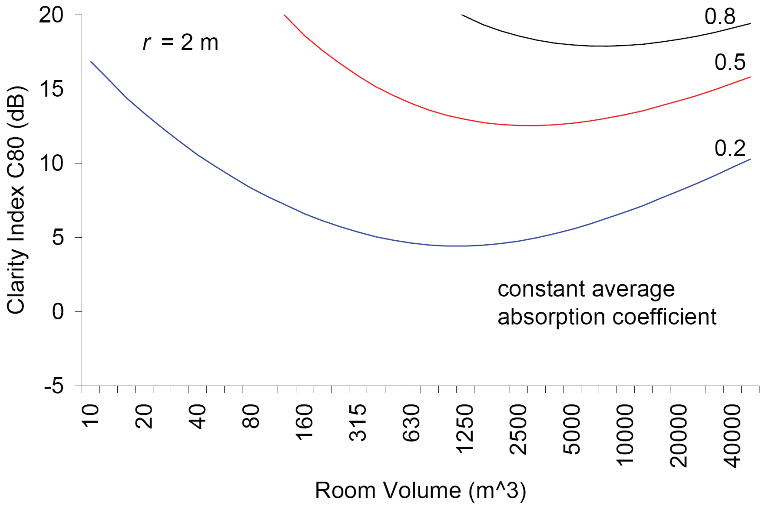

Figure 3. Clarity index as a function of room volume for a source-receiver distance of 2 m. Functions are for constant absorption coefficient.

In practical rooms, reverberation time is not independent of room volume, but tends to increase with volume when similar building fabrics and furnishings are used. For a source-receiver distance of 2 m, Figure 3 shows the relationship between clarity index and room volume for approximately cubic rooms with average absorption coefficients of 0.2, 0.5 and 0.8. In this case clarity index initially decreases with room volume, but then increases for the large volumes.

Combining the concept of constant absorption coefficients and a source-receiver distance that grows with room volume, Figure 4 shows a clear negative correlation between volume and clarity index, which agrees in general terms with the results of experiments on auditory room size perception.

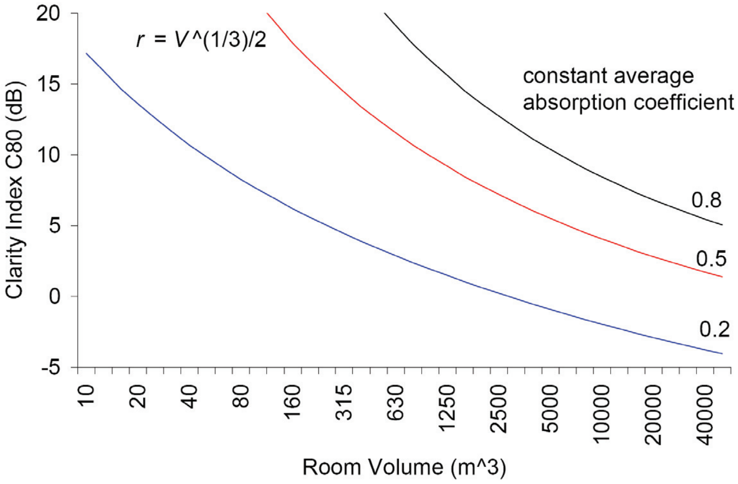

Figure 4. Clarity index as a function of room volume for a source-receiver distance that is proportional to the room's linear dimension. Functions are for constant absorption coefficient.

3. RECOMMENDED VALUES

The assumption of constant average absorption coefficient is probably too extreme. A more subtle approach is to consider how reverberation time changes with room volume in realistic rooms. A simple way of considering this is to model the clarity index that results from recommended reverberation times for particular room uses as a function of room volume. AS2107 presents recommended reverberation times for 'rooms for speech', 'cabarets and theatre restaurants' and 'music studios' each as a function of room volume [7]. The recommended reverberation time increases with volume, and the calculated clarity index for a constant source-receiver distance of 2 m is shown in Figure 5. Here there is mainly a positive correlation between room volume and clarity index.

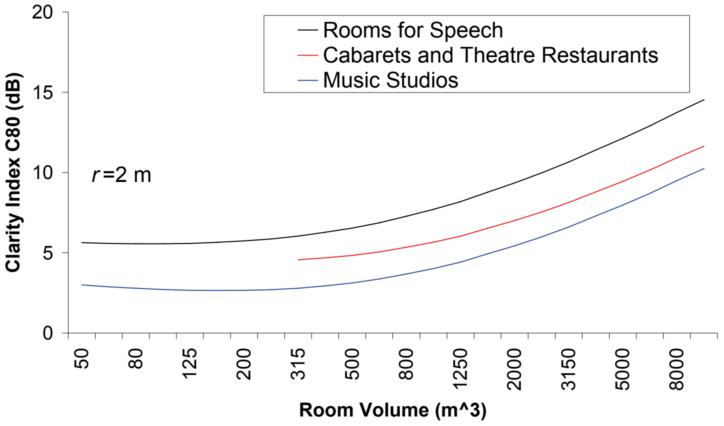

Figure 5. Clarity index as a function of room volume for a source-receiver distance of 2 m. Functions are the recommended reverberation times in AS2107.

A variation of the above is to vary the source-receiver distance with room volume, as was done in the previous section. Figure 6 shows this for the AS2107 recommended reverberation times. The relationship between clarity index and room volume is very weak in that case.

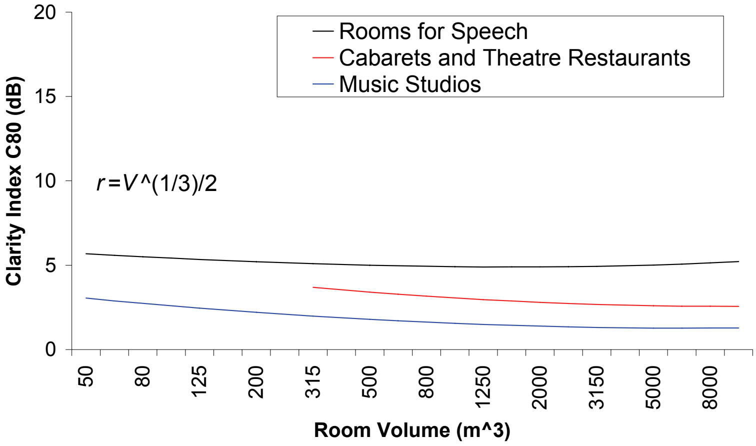

Figure 6. Clarity index as a function of room volume for a source-receiver distance proportional to the room's linear dimension. Functions are the recommended reverberation times in AS2107.

Neither of these models offers anything to support the relationship between clarity index and auditory room size perception data referred to in this paper. The functions of Figure 5 probably reflect the intent of the recommended reverberation times – which is to maintain an appropriate degree of acoustic clarity for a given application regardless of room volume. However, recommended reverberation times do not necessarily correspond to the actual reverberation times experienced by people in everyday life. Furthermore, people do not restrict themselves to particular types of rooms, but instead move between a wide variety of room types. Therefore a better approach would be to compare clarity index values to room volumes for such a variety of room types.

4. MEASURED VALUES

In 2006, the author measured 16 everyday acoustic environments using fixed source-receiver distances (in Kobe, Japan) [8]. If outdoor environments and rooms of undefined volume (corridors) are removed, these data provide a small insight into how clarity index varies with room volume. Figure 7 shows clarity index (in the 500 Hz octave band) for a source-receiver distance of 1.5 m in 10 everyday rooms, including a small shoe room, a small public lavatory, office rooms, domestic rooms, seminar rooms, a library and a 150-seat auditorium.

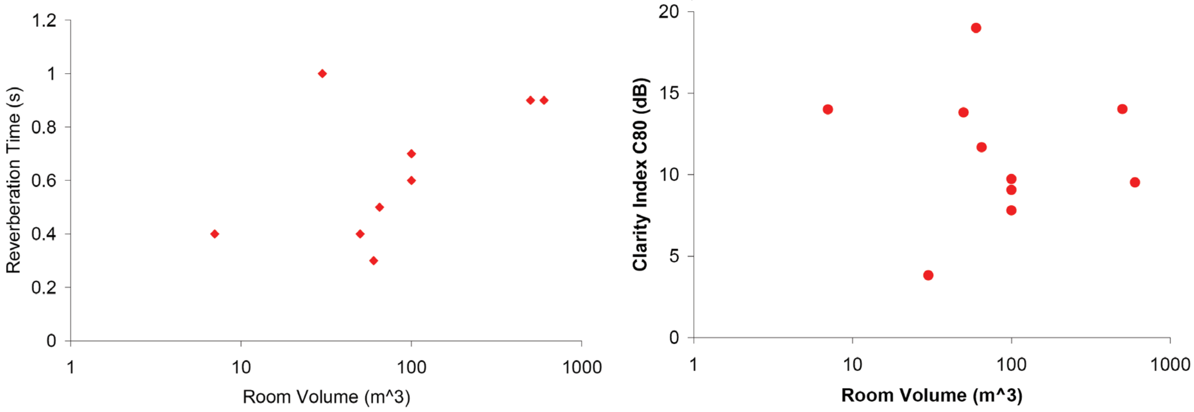

Figure 7. Measured data for ten everyday rooms in the 500 Hz octave band.

There appears to be no consistent relationship between room volume and clarity index in these data. Figure 7 also shows the relationship between room volume and reverberation time for these rooms, showing a positive correlation (with two outliers).

As has been noted previously, the association of constant source-receiver distance with variable room volume does not correspond well to practical experience in rooms. Therefore the measurement results are re-analysed, using measured reverberation times and a variable source-receiver distance to predict clarity index based on Barron and Lee's theory. The results, shown in Figure 8, still show significant scatter. Nevertheless, there is some negative correlation between room volume (logarithmic units) and clarity index (r = -0.49), which is strengthened to r = -0.69 with the removal of one outlier. Hence these data are broadly consistent with the notion being investigated.

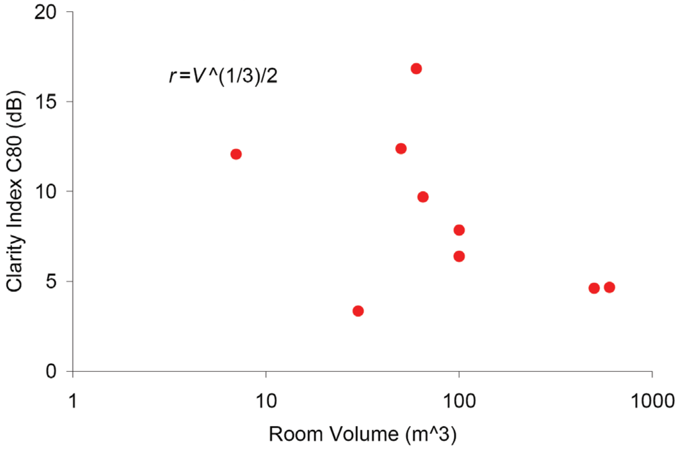

Figure 8. Predicted clarity index for a source-receiver distance proportional to the room's linear dimension for the ten everyday rooms.

The same calculations can be made for reverberation time and room volume data published elsewhere. Diaz and Pedrero [9] present data for 8246 furnished bedrooms and 3211 furnished living rooms with room volumes between 10 m^3 and 100 m^3. Figures 9 and 10 show that there is a negative correlation between room volume and clarity index predicted from the regression function of these data (1 kHz octave band). The other data on Figures 9 and 10 are 56 listening rooms for audio monitoring (some high outliers have C80 values greater than 30 dB) [10], 8 music practice rooms [11], 32 classrooms [12], 52 concert halls [13] and 24 opera halls [14].

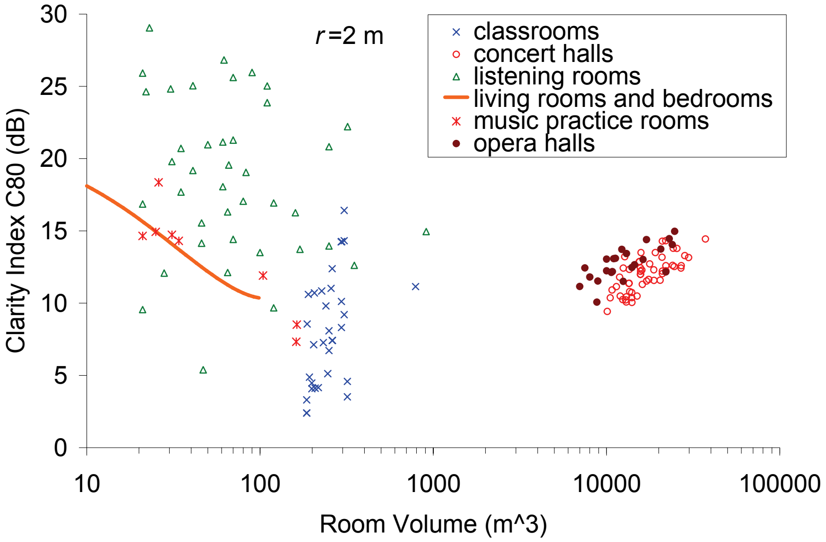

Figure 9. Predicted clarity index for published reverberation time data (r=2 m).

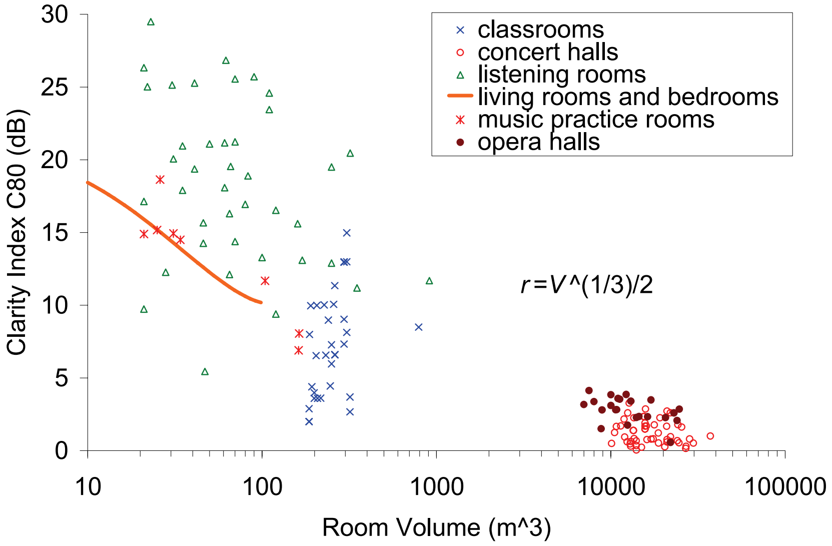

Figure 10. Predicted clarity index for published reverberation time data (distance proportional to the room's linear dimension).

Taken together, these data are consistent with the concept that there is a negative correlation between clarity index and room volume when the source-receiver distance is proportional to the room's linear dimension (Figure 10). Some of the negative correlation remains for constant source-receiver distance (Figure 9), but the data suggest a 'U' function like the equivalent theoretical model of Figure 3.

5. DISCUSSION AND CONCLUSION

While there exist many surveys of the acoustical characteristics of special purpose rooms (such as concert halls and classrooms), surveys covering the statistical distribution of everyday rooms that would be experienced by people regularly are scarce. Yet if the auditory perception of room size is based on learning from everyday experience, then this learning takes place in everyday rooms. This paper presents preliminary data that lend a little support to the hypothesis that the negative correlation between auditory room size ratings and clarity index in formal experiments can be explained by learning from everyday acoustic environments. However, an important aspect of this is that greater distances are experienced in larger rooms – the hypothesis fails or partly fails both theoretically and empirically if source-receiver distance is kept constant.

In listening, people do not literally hear clarity index as it is defined acoustically. Similarly, they do not literally hear reverberation time. Instead a complex and subtle impression is formed from multiple cues, and often it is hard to describe the auditory impression of a room in words, let alone to quantify it subjectively in terms of independent parameters. Clarity index might be thought of providing a crude measure of one aspect of the subjective impression of reverberation, which is sometimes called reverberance. The numerator of the clarity index ratio represents energy that is integrated with the direct sound, and so contributes to the loudness and clarity of the source. The denominator represents the energy that is heard as reverberation. Hence clarity index might be thought of as the inverse of the relative reverberance of a space. Studies of auditory room size perception have found that both reverberation time and reverberation 'strength' (i.e., the excess level produced by the room reflections, compared to the anechoic condition) can influence room size perception, and sometimes the influence of one or the other varies between individuals. Clarity index provides a measure that combines reverberation time and strength into a single number, and in this sense the negative correlation between clarity index and auditory room size perception reflects the idea that people associate reverberance with large rooms.

This paper offers a potential explanation for experimental results in auditory room size perception, and a much more extensive survey of everyday acoustic environments is required to verify this explanation.

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