ARCHITECTURE IN MOTION: A MODEL FOR MUSIC COMPOSITION

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ABSTRACT

The architectural acoustics' data obtained from an enclosed space provides a unique numerical description of the aural properties of that specific space. These properties – like music – are in the realm of frequency, time and amplitude. This model proposes a system that "translates" the acoustical data of a room into musical terms, transforming the merely numerical acoustical values into the identity of a musical composition.

INTRODUCTION: PARAMETERS OF ROOM ACOUSTICS AND THEIR APPLICATION

These parameters are organized according to the pitch, time and amplitude domains. All values correspond to the tables and floor plan provided in the Appendix.[1]

1. PITCH: FREQUENCY RESPONSE AND CENTROID

The frequency response of a room is the measure of the spectrum output of its response to a signal input (impulse). The centroid is where the center of mass of that spectrum is located, calculated as a weighted mean of the frequencies and their corresponding amplitudes. In this section of the model, the fundamental frequency that corresponds to a tone is the only element taken into account for the calculation of the weighted mean. All the remaining partials of the spectrum are disregarded.

The collected data shows that the spectrum content of any source performed on stage is perceived differently depending on the location of the receiver. Therefore, the room centroid value is an overall average between the centroids of eight different impulse locations within the room.[2]

Table 1. Room formants and centroid values for the different S and R locations.[3]

Location	Formant peak (in Hz)	Centroid (in Hz)
S1 R1	366	357
S1 R2	279	399
S1 R3	259	315
S2 R1	298	336
S2 R2	298	262
S2 R3	429	310
S3 R1	236	241
S3 R2	214	326
Average	298	319

1.2. Orchestrating the Centroid Values

The centroid is calculated as a weighted medium. However, this model proposes the inverse process, where the centroid value obtained from an enclosed space is the value around which many chords[4] can be orchestrated. The averaged centroid value obtained from the

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[1] The room selected for the initial application of the proposed model is the Baughman Meditation Pavilion at the University of Florida.

[2] According to the S (source) and R (receiver) locations in the Appendix).

[3] Measurements obtained using PVC, sound analysis and processing software, created by Paul Koonce.

[4] In this section of the study, the terms "chord" and "complex" refer to the same concept and are, therefore, interchangeable: group/s of two or more pitches that occur simultaneously.

impulses in the Baughman Center is less than 10 Hz off the 329 Hz or E4.

This example shows an ideal situation where the median of this chord is also the chord's centroid (E4) because the two pitches have an identical dynamic indication.

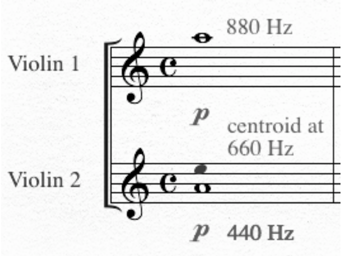

Figure 1. Orchestrated centroid (I).

In the next example, the centroid also equals the median because all the frequencies evaluated are at the same dynamic.

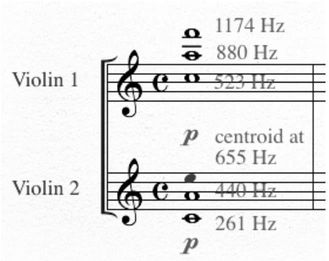

Figure 2. Orchestrated centroid (II).

The calculation gets more complex when each pitch has a different amplitude and duration; for that case we will use the formula of the weighted mean in order to obtain a precise result.

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i}.$$

Figure 3. Weighted mean formula used.

In this case the centroid will increase in the direction of the pitch with higher amplitude. The high A at 880 Hz is four times louder than the lower one[5], pulling the centroid upwards to 693 Hz, getting to an absolute frequency that is almost a half step above (F4) from the previous example with two notes at the same dyamic.

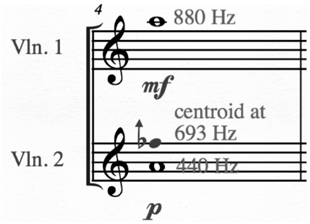

Figure 4. Orchestrated centroid (III), with weighted dynamics.

Those orchestrational concepts can also be applied in a more dynamic way by following the curve reflected by the values obtained in the actual room. We can use orchestration to gradually change (increse or decrease) the centroid. The following excerpt shows how the increasing amplitude of the lower pitch has a direct influence on the value of the centroid, pulling it down. The inverse effect would occur if the higher pitch increased in amplitude.

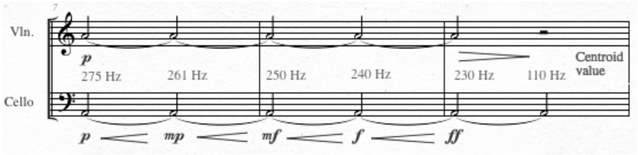

Figure 5. Weighting dynamics and varying centroid value (I).

To actually "tune the music to the room" the process of orchestrating the centroid values can be expanded even more. The center frequency of a room can be used to create chords that, despite their different configuration, share the same centroid. The following excerpt shows a series of chords that have the same centroid of 440 Hz (with a maximum margin of error of 10 Hz). Each note has its own dynamic indication for the sake of clarity and consistency of the example.

Figure 6. Weighting dynamics and varying centroid value (II).

This concept could be further developed by calculating the centroid of a sub-group of the components of the resulting chords in a sort of chain of centroids or "centroid of the centroid".

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[5] According to the table of equivalencies proposed in the Appendix C.

That concept ("centroid of the centroid") is a compositional device that focuses on the gravitational point of a note, frequency or array of them; pitches are consirered as a whole along with their amplitudes (dynamics) that influence the location of the center of mass of a chord. In the following example, the initial centroid value is 660 Hz (equivalent to E5).

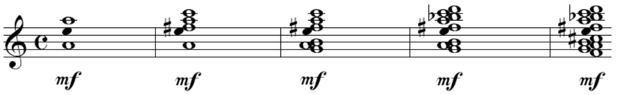

Figure 7. Example of a single centroid value (E5 or 660 Hz) through a series of complexes at the same dynamic level.

The upper and lower pitches (880 Hz and 440 Hz respectively) are at the same dynamic and do not alter this value. If we consider these last two pitches as new centroid values, we could think about them as new centroids and orchestrate chords around them and, therefore, still keep the overall 660 Hz of the complex unchanged.

It is important to clarify that the centroid of the centroid needs to be calculated prior to the calculation of the centroid value of the overall complex. Otherwise the values do, in fact, change.

This approach becomes more intricate when each pitch component is performed at a different dynamic (amplitude). Each pitch gets weighted by 10 dB per dynamic indication[6]. In order to keep the same centroid value on an E5, the complexes in the following example justify the implementation of micro-tuning. The development of the complex is similar but with a different interval configuration.

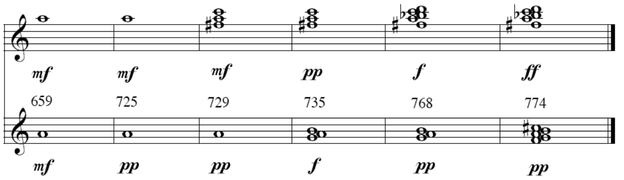

Figure 8. Weighting dynamics and varying centroid value (III).

The frequencies that correspond to the center of weight of the complexes respond to the weighting values coming from the amplitude domain. In addition to that, it is a remarkable fact that those centers correspond to pitches that are not present in the complexes, E5 (≈ 659 Hz) in the first one and G5 (774 Hz) in the last one. This compositional system facilitates the elaboration of pieces around pitch centers that are, potentially, never revealed. Unlike musics in which the center of gravity establishes its aesthetic primacy as it emerges, this model proposes the opposite approach, where the center of weight can never surface and still remain the essence of the musical composition.

2. TIME I: REVERBERATION TIME - RT

The Baughman Center has an average reverberation time (between frequency bands and different locations of source and receiver) of 2 seconds. If we only consider the bands where the human ear is most sensitive (250 Hz – 4000 Hz), the averaged result is slightly longer, 2.2 seconds. The RT envelope's data (regarding frequency, time, and amplitude) is the source for the orchestrational models.

2.1. Orchestrating the Reverberation

In this musical example, we can see the performed sound and the actual result with a 2.2 second reverberation time that corresponds to the values obtained from the Baughman Center.

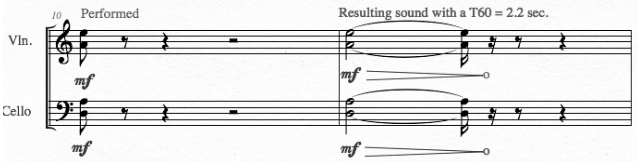

Figure 10. Orchestrated RT (I).

The tempo marking of (MM = 60) facilitates the translation between musical values and RT. The RT value obtained from the Baughman Center can now be embedded in the music through the orchestration.

When two chords are performed in succession, meaning the attack of the second one within the decay tail of the first one, the result is

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[6] According to Appendix C.

of particular interest. The excerpt in Figure 11 shows a standard accompaniment pattern for string players and its orchestrated aural result as if performed in a room with a RT of 2.2 seconds.

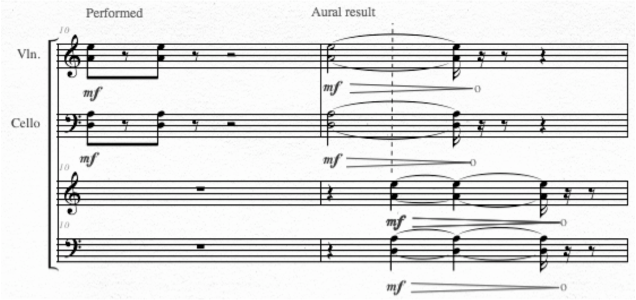

Figure 11. Orchestrated RT (II).

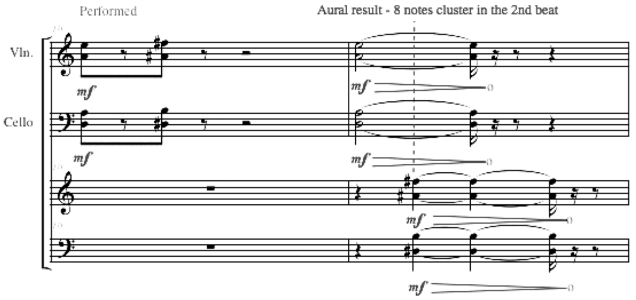

Figure 12. Orchestrated RT (III).

In Figure 12, the RT of 2.2 second creates - through the orchestration - the aural illusion of an 8-note cluster on the second beat of the measure, which is something presumably never intended by the composer using the original pattern.

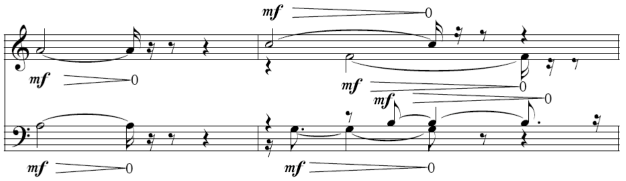

Figure 13. Orchestrated RT per frequency band (I).

The excerpt in Figure 13 is a simultaneous complex that is performed at the same dynamic and that is equally spread along all the frequency bands. As those bands decay at different times, the result becomes evocative of the space's frequency response. The excerpt's complex is built around the centroid value of the room at ≈ 329 Hz or E4 combining data from both the time and frequency domains. The tempo is MM = 60. The whole passage recreates in musical notation the acoustical data taken from the Baughman Center.

The following example considers not only the centroid value obtained from the room, but also the RT per frequency band. Now, the decay times respond not to the average RT value, but to the specific values per band as shown in the Appendix B.

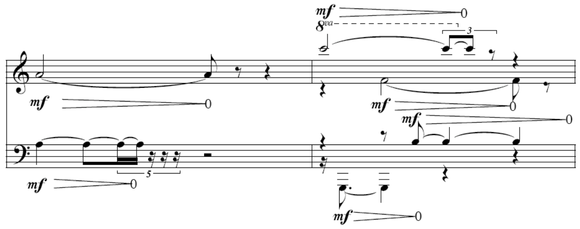

Figure 14. Orchestrated RT per frequency band (II).

Due to the particularities of the collected data and for orchestrational purposes, the RT values are averages from all impulses in three main band subgroups (63 to 125, 250 to 1000, 2000 to 8000). The values per group are (in seconds) 1.7, 2.5 and 1.65 respectively. The orchestration example was composed using the same centroid value with different pitch distribution, and independent RT per band.

3. TIME II: RHYTHM OF THE EARLY REFLECTIONS

The rhythmic implication of the RT is only limited to duration and enveloping. Rhythm, as the succession of sonic events in time, is not taken into account. Even though, the "rhythmic identity" of an enclosed space can be extracted from the temporal succession of the early reflections of an impulse. The early reflections were chosen for the proposed model because they unequivocally define the dimensions of the enclosed space. As they travel a longer path, the amount of time it takes the first reflected sounds to reach our ears gives us clues as to the size and nature of the listening environment.

For the proposed model, the impulse S1 R1 was utilized. The Acoustic Tools software helped to measure the time between the first 10 reflections after the direct source. Those reflections were separated by the following times (in milliseconds):

Table 3-4. Delay times of the first 10 early reflections.

Reflection	1	2	3	4	5	6	7	8	9	10
Delay	3	4	5	8	9	12	22	24	25	29

These minute time delays are initially irrelevant for the human ear, as reflected energy arriving at the ear within 25 ms is integrated with the direct sound and is perceived as part of it, opposed to the reverberant sound. These early reflections also increase the loudness of the sound source.[7] Despite that fact, the proportions and placement in time of the "attacks" of each of the reflections can easily become a relevant compositional consideration. In order to fully extract the rhythm of the reflections, we need to remove the initial time reference to the direct sound, starting from 1. That will give us a "prime" set of values that are completely isolated from their source and original measuring unit.

Table 3-5. Values of the first 10 early reflections.

Reflection	1	2	3	4	5	6	7	8	9	10
Value	1	2	3	6	7	10	20	22	23	27

The sequence of values corresponds to the architectural design of the Baughman Center and the location of the S1 R1 impulse. The first five values come from the closer side walls and the stage (in relation to the location S1, see Figure 3-2), the following values are increasingly more separated corresponding to the reflections coming from the back walls (from the building's entrance). The difference between reflections 6 and 7 is noteworthy and represents one of the "rhythmic" characteristics of a specific location within this particular room.

3.1. Orchestrating the Rhythm of the Early Reflections

The translation of the obtained values into rhythm can be achieved in different ways. If the values originally come from delay times in ms, the musical translation of them could simply be $v * 1000$. In that way, we keep the time proportion between events as well as their temporal origin. Thus, this 10-values-27-seconds rhythmic pattern is acoustically related to the studied room and at the same time musically significant.

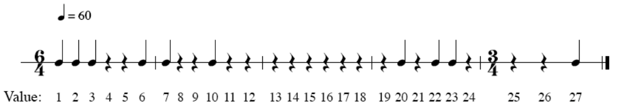

Figure 15. Rhythmic structure extracted from the early reflections.

Another approach is to only keep the temporal proportions between the obtained values without any reference to the original unit of time. The composer can now freely choose a time unit with the corresponding dissimilar result; the ten events (corresponding to the reflections) are placed in a varying time spam. Those events occur at the same rate as the early reflections but are expanded or compressed according to the composer's chosen unit. Durations and pitches could be freely decided provided that they do not compromise the placement of the attacks.

The excerpt on Figure 16 is built upon the pitch classes of an ascending chromatic scale (F# to D#) that are organized in time according to the proportions extracted from the early reflections of the Baughman Center.

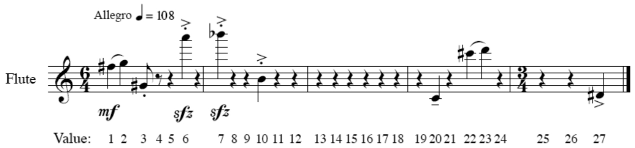

Figure 16. Orchestration of the rhythmic structure extracted from the early reflections (I).

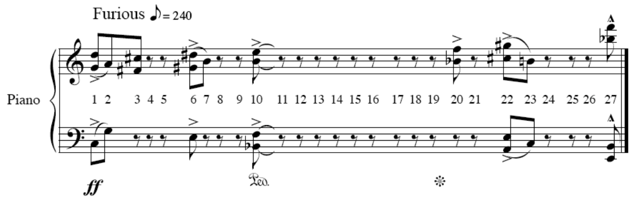

Figure 17. Orchestration of the rhythmic structure extracted from the early reflections (II).

The integral application of the rhythmic elements results in a musical example that takes into account the placement of the attacks of the sonic events (coming from the early reflections) as well as their resonances, which come from the RT value.

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[7] F. Alton Everest (2008), *"Master handbook of acoustics"*.

Figure 18. Orchestration of the rhythmic structure extracted from the early reflections (III). For string quartet, also considering the room's RT value of 2.2 s.

4. AMPLITUDE: MUSICAL DYNAMICS AND THE G FACTOR

This criterion differentiates the amount of sound pressure coming directly from the source from the one that is added by the room.[8] Its musical application is vital as it permits the use of *crescendos* (when the G value is positive) that otherwise would remain unavailable for the composer.

4.1. Orchestrating the G Factor

The implementation of the G factor in the proposed model refers to the ratio between the G values of certain frequencies. Specifically, the mid-low bands 63, 125, 250 and 500 divided by the mid-high ones 1000, 2000, 4000 and 8000. That operation returns a ratio of 1.35 meaning that the room's loudness has a higher ratio of lower frequencies within the overall G factor. This choice was made in order to accurately represent the room's spectral color, which in this particular case is clearly oriented towards the mid-low bands.

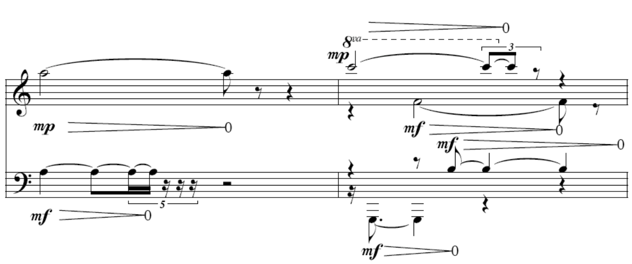

Figure 19. Combinatorial example (I).

Figure 19 shows an application of the preceding principle. The problem here is that the equivalencies (Appendix C) between amplitudes and dynamic indications established initially for the model, are structured in doubling values (***p*** is twice as loud as ***pp*** or 10 dB more), and the ratio shown by the room measurements is less than 2. In this case, and to make the translation musically interesting, the G value between mid-lows and mid-high is rounded to 2, so the frequencies below 500 Hz are orchestrated twice as loud in relation to the high ones.

Another feasible and musically relevant application would be to consider the G factor more strictly related to the direct sound, suggesting through the orchestration the idea of the reflected sound ending somehow embedded in the direct source. In order to achieve that effect, a polyrhythmic and monophonic texture is necessary as well as an accurate dynamic relation between direct and reflected sources.

The example on Figure 22 shows one of the three possible scenarios. The excerpt orchestrates a negative G value (louder direct source, doubles the amplitude of the reverberated sound). Despite that fact, the G factor could be positive (the reverberated sound is louder), or equal 0 (when direct and reverberated are equal).

Figure 20. Combinatorial example (II).

That hypothetical data could be easily translated into the same excerpt by simply adapting the dynamic indications. This particular example embeds an unambiguous aural

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[8] Leo Beranek, Ibid. 509.

representation of a direct sound source and its posterior reflection. The tempo is MM = 60 and it could be a potential fragment of a composition for two pianos, or string ensemble.

We naturally arrive at a creative application of the model, in which the acoustical data is no longer evident but still present. The resonances are orchestrated with a decreasing G factor also taking advantage of the idiomatic orchestration resources of the string ensemble; the evocation of the decreasing reflections is also achieved by the *non-vibrato* effect, which helps differentiate them from the original source. The bowings also help to reinforce the idea of what is direct source and what is not, the down-bows are utilized to give more emphasis to the direct sources and up-bows to suggest the milder attack of the resonances. Color contrasts are also reinforced with the *sul-ponticello* effect.

The initial centroid value (as seen in Table 1) developed into a musical excerpt of 10 seconds of duration that could continue to evolve in complexity and musical interest with the implementation of other simultaneous complexes and volumes of orchestration.

Figure 21. Combinatorial orchestration example of the G factor for string ensemble.

5. CONCLUSION

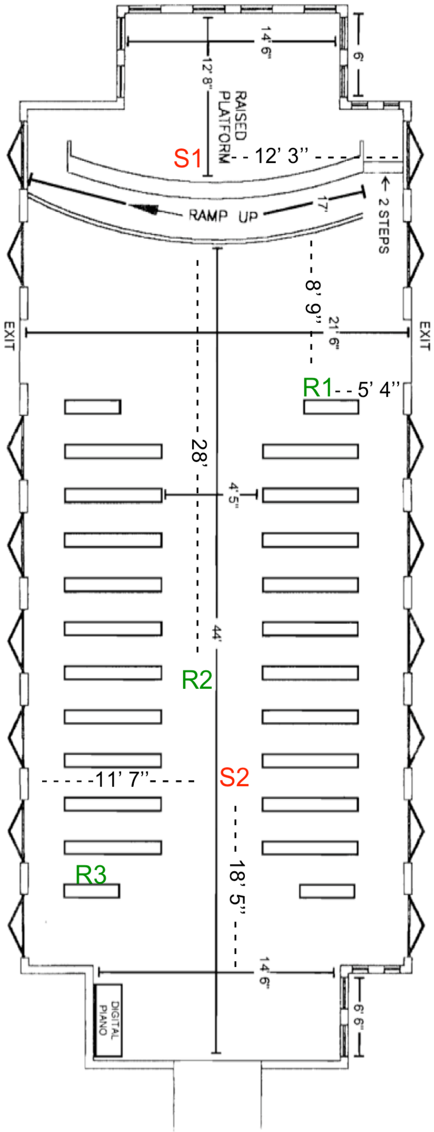
This paper has proposed a model for musical composition based on measurements from architectural acoustics. Although not exhaustive, the proposal opens a very concrete set of guidelines for interdisciplinary collaboration in the arts.

6. REFERENCES

1. Beranek L. *Concert and Opera Halls. How they sound*. New York: Acoustical Society of America through the American Institute of Physics, 1996.
2. Blesser, B. & Salter, L. R. *Spaces speak, are you listening?* Cambridge: MIT Press, 2007.
3. Everest, F. A. *The Master Handbook of Acoustics* (2nd ed.). Blue Ridge Summit, PA: TAB Books Inc., 1989

APPENDIX

A) Baughman Center Floor Plan.



A) Baughman Center Meditation Pavilion floor plan with exact location of the Sources (S) and Receivers (R) utilized for the impulses and the data collection. Plan by Zona, Humburg & Associates Architects.

B) Data collected from the Baughman Center.

S1 R1

F(Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
snr(dB)	3	22.5	30.1	30.7	26.7	30.7	35	39.8
edr(dB)	15.7	33.3	41.6	40.8	37.4	42.6	47.3	53
EDT(s)	1.38	1.55	2.62	2.55	2.17	1.6	1.49	1.06
T30(s)	2.17	1.86	2.37	2.65	2.45	1.84	1.69	1.34
corr	-0.99	-0.996	-0.999	-1	-1	-0.999	-1	-0.999
T20(s)	2.17	1.72	2.38	2.68	2.41	1.76	1.65	1.28
corr	-0.99	-0.992	-0.998	-0.999	-0.999	-0.999	-1	-0.999
Tc(ms)	192	119	174	173	139	90	68	39
C80(dB)	2.5	0.7	-2	-2.2	-0.6	1.8	4	7.1
D50(%)	40	45	30	30	37	50	63	76
G(dB)	56.9	59.3	62.2	61.4	51.1	47.5	45.2	43

S1 R3

F(Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
snr(dB)	7.9	24.1	30.2	28.1	29.5	35.2	36.7	38.1
edr(dB)	25.2	33.9	40.3	38.5	40.6	48.4	49.6	51.4
EDT(s)	1.18	1.37	2.25	2.61	2.09	1.82	1.63	1.33
T30(s)	1.02	2.22	2.48	2.77	2.38	1.99	1.71	1.39
corr	-0.994	-0.995	-0.999	-1	-0.999	-1	-1	-1
T20(s)	1.02	2.04	2.38	2.77	2.27	2	1.68	1.37
corr	-0.995	-0.989	-0.999	-1	-1	-1	-1	-1
Tc(ms)	106	108	168	202	166	142	130	102
C80(dB)	2.2	1.4	-1.1	-4.4	-2.6	-1.4	-1.3	0.5
D50(%)	43	46	36	19	19	24	26	34
G(dB)	58.3	59	60	57.4	51.1	48.6	43.7	38.4

S2 R1

F(Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
snr(dB)	-5.7	10.9	25.2	24.8	22.3	27.1	27.6	31
edr(dB)	15.4	24.2	36.6	36	34.4	39.8	40.3	45.5
EDT(s)	0.85	1.69	2.19	2.51	2.23	1.77	1.58	1.25
T30(s)	1	1.97	2.32	2.57	2.33	1.85	1.73	1.36
corr	-0.986	-0.998	-0.999	-0.999	-1	-1	-1	-1
T20(s)	1	1.97	2.4	2.57	2.38	1.8	1.69	1.36
corr	-0.986	-0.998	-0.997	-0.999	-1	-1	-1	-1
Tc(ms)	176	147	168	171	156	128	111	88
C80(dB)	1.5	-1.4	-2.1	-2.5	-1.3	-0.2	0.2	1.6
D50(%)	54	32	16	27	29	31	37	44
G(dB)	60.9	56.8	59	56.7	46.7	43	38	34.1

S2 R2

F(Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
snr(dB)	7.8	23.3	31.9	31.3	29.9	36.8	39.8	42.8
edr(dB)	22.3	35.5	42.5	41.9	40.7	49.4	52.5	56.4
EDT(s)	1.6	1.57	2.18	2.69	2.13	1.47	1.33	0.99
T30(s)	1.62	1.9	2.29	2.65	2.51	1.8	1.64	1.33
corr	-0.998	-0.997	-0.998	-0.999	-0.999	-0.999	-1	-1
T20(s)	1.62	1.89	2.18	2.54	2.43	1.76	1.6	1.31
corr	-0.998	-0.991	-0.999	-0.999	-0.999	-0.999	-1	-0.999
Tc(ms)	100	115	135	136	104	80	61	40
C80(dB)	4.3	0.4	-0.3	1.2	1.6	2.6	4.8	6.9
D50(%)	68	37	41	44	55	55	65	76
G(dB)	58.7	57.2	58.8	54.7	45.4	43.6	41.1	37.4

S2 R3

F(Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
snr(dB)	8.5	23.3	32	31.8	32.3	37.8	39	41.9
edr(dB)	25.4	37.3	43.4	43	43.5	51.2	51.9	55.5
EDT(s)	1.15	1.75	2.16	2.42	1.84	1.53	1.38	1.07
T30(s)	1.22	1.8	2.51	2.72	2.46	1.76	1.69	1.35
corr	-0.994	-0.999	-0.999	-1	-0.999	-1	-1	-1
T20(s)	1.22	1.82	2.53	2.7	2.32	1.72	1.66	1.3
corr	-0.994	-0.998	-0.998	-0.999	-0.999	-0.999	-0.999	-0.999
Tc(ms)	67	95	119	104	85	81	82	62
C80(dB)	5.3	3.6	1.4	2.4	3.7	3.2	2.7	4.5
D50(%)	77	56	49	60	62	58	52	61
G(dB)	56	56.1	57	55.9	47.5	44.8	39.7	36

C) Table of equivalencies.

Dynamic indication *(musical notation)*	**Musical meaning**	**Decibels**
ppp	*Pianississimo* – extremely soft	40
pp	*Pianissimo* – very soft	50
p	*Piano* – soft	60
mp	*Mezzo piano* – medium soft	70
mf	*Mezzo forte* – medium loud	80
f	*Forte* – loud	90
ff	*Fortissimo* – very loud	100
fff	*Fortississimo* – extremely loud	110