Psychoacoustic perception of transient effects of resonance modes at low frequencies in a listening environment

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ABSTRACT

Verifying the results of previous listening tests performed on headphones, regarding the perception of the effect of resonance modes at low frequencies on musical transient sounds. A complete acoustical analysis of the University of Bologna new listening room was carried out before its optimization and problematic frequencies were identified under 100 Hz. Test sounds were developed specifically, thirty-eight expert listeners were asked to answer simple question regarding the perceived volume and resonant quality of real tones. Test musical sounds (pure tones, kick drums and bass notes) were played on loudspeakers in the listening room and listeners seated in the sweet spot.

Results are generally in accordance to the ones obtained in the previous headphone tests. In a direct comparison, listeners seem to be more sensitive to a difference in resonance rather than volume on complex tones and the opposite on pure tones. Fundamental frequency, note duration, and number of repetitions of the sound impact on human perception, confirming the influence of the room's transient energetic phenomena on the beginning of the sound in the perception of the volume, and also the correlation between the presence of a resonance and the perceived quality of the sound. The study confirms the importance of accurate frequency analysis rather than band analysis at low frequency.

Keywords: LF Perception; room modes I-INCE Classification of Subjects Number(s): 23.6

1. INTRODUCTION

A complete acoustical analysis of the University of Bologna new listening room was carried out before its optimization and problematic frequencies were identified under 100 Hz. This allowed to test the perceptibility of room mode on listening to musical sounds. The analysis has been carried out on the "sweet-spot" listening position (i.e. the vertex of the equilateral triangle that has, on the other vertices, the loudspeakers' positions). This point is important for critical listening but it is also useful to study the room response on a single specific position, in order to understand local behavior of room response al low frequencies correlated to human perception.

2. LISTENING ROOM ANALISYS

2.1 Geometrical characteristics

The listening room under investigation is 7.20 m long, 5.09 m wide and 2.81 m high, for an overall volume of 103 m^3. The room geometry is slightly different from the classic shoe-box shape: two symmetrical parts of the ceiling are inclined toward the front wall. The room is almost completely symmetrical to the main longitudinal axis and it is empty of furniture.

All the walls and the ceiling are covered with sound absorbing panels (5 cm thick). On the floor is placed a carpet.

The overall room volume is 103 m^3 while the floor area is 35 m^2: the room meets the specifications of ITU-R BS.1116-1 (1) where, for a stereo listening room the floor area has to be 20 to 60 m^2.

However, the listening room is "acoustically small" and its acoustic response is strongly influenced by modal resonances in the low frequencies, one theoretical limit is the Schroeder Frequency above which the room's sound field can be considered statistically, and the frequency response varies to a smaller degree around the room. For the room under study the Schroeder Frequency is given by:

$$f_{Schroeder} = 2000\sqrt{\frac{T_R}{V}} = 2000\sqrt{\frac{0.26}{103}} = 100 \text{ Hz} \tag{1}$$

Where TR is the reverberation time (2, 3).

Inside small rooms, the acoustic analysis tools used for theaters and auditoria are not suitable, but it necessary to use ad-hoc tools specifically designed for that purpose: Schroeder Frequency is often optimistic proposing a limit that is too low.

2.2 Third-octave bands analysis

The ITU-R BS.1116-1 (1) and the EBU 3276 (4) propose an upper and a lower bound for the "Operational room response curve", i.e. the one-third octave band frequency response given by the sound system in the listening point.

These tolerance limits are placed at +/- 3 dB from an average level L_m which is the mean value of the levels of the 1/3–octave bands with center frequencies from 200 Hz to 4 kHz. In the Figure 1 below, is reported the "Operational room response curve" for right channel of the main audio monitors (in red) and left channel (in black) from 40 to 315 Hz.

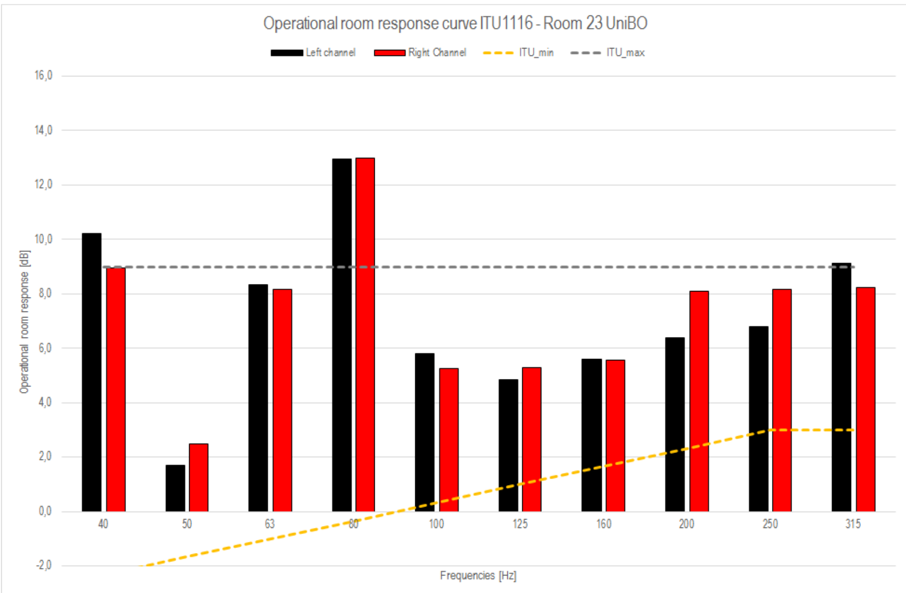

Figure 1 –Operational Room Response for the listening room at the listening position

The overall behavior of the room response is positive with exceedances of the upper limit in the one-third octave frequency bands of 40 Hz, 80 Hz (high exceedance) and 315 Hz (slight exceedance). The room behavior is positive above 100 Hz.

2.3 Low frequency modal analysis

The authors believe that a third-octave band analysis does not have the degree of resolution necessary to perform an in-depth investigation of the room acoustic characteristics. In order to verify the room response in the 32 to 250 Hz octave bands, an accurate modal analysis (resonance frequencies) is more appropriate: 5 room impulse responses, measured 10 cm around the listening position, have been averaged in the frequency and phase domain in order to overlap the obtained spectra to theoretical resonance modes, calculated for shoe-box shaped rooms. Indeed, in the low frequencies end, the modal resonance frequencies deeply influence the room response as expected.

By averaging the measured room impulse responses, a signal more similar to the one perceived by our ears is obtained. This traditional analysis (performed using FFT) is useful to analyze the stationary steady-state response of the room, i.e. valid while listening to notes and long lasting sounds.

In Figure 2 the room frequency response amplitude H(f) is reported, obtained by overlapping the right channel response (in red), the left channel response (in black) and the stereo response (in blue). The spectra are showed in the 30 Hz to 150 Hz range: inside rooms with volume similar to the analyzed one, in that frequency range, the resonance modes are dominant and the Sabine assumptions clearly lose their value.

As known from the authors experience, inside room with similar dimensions, without furniture as the listening room under study, tangential modes play a key role in the room response building. In Figure 2, the tangential modes (in blue vertical lines) are overlapped to axial modes (in green): note that the correspondence between resonance peaks and modes position is accurate thanks to tangential modes and that the left / right symmetry is well respected inside the listening room.

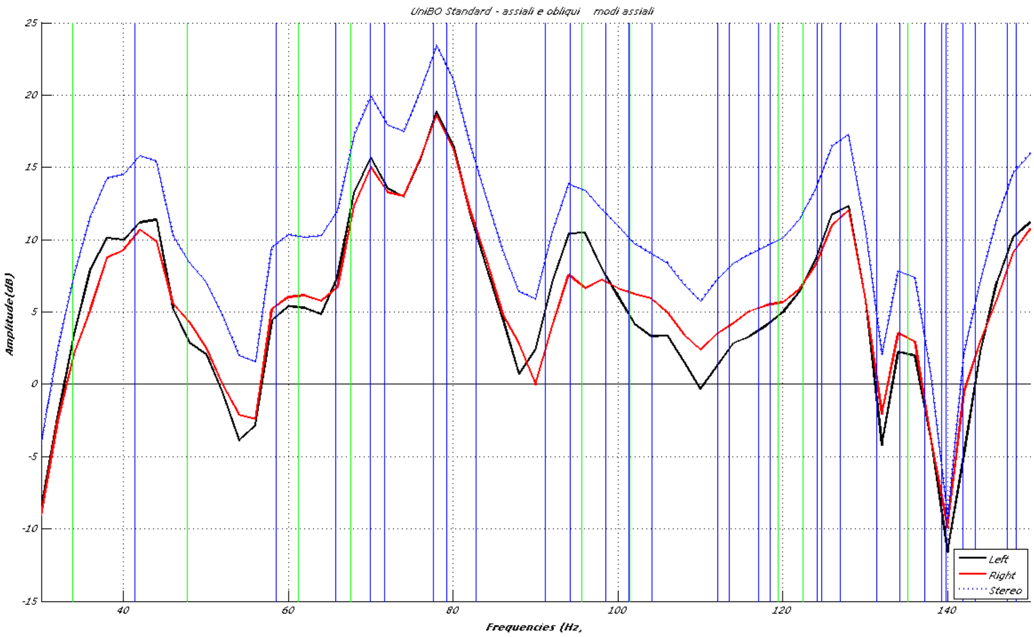

Figure 2 –FFT response overlapped to axial and tangential room modes

Observing Figure 2, maxima, or high resonance peaks (high Q factor) can be observed at the following frequencies:

- 42 Hz
- 70 Hz
- 78 Hz
- 128 Hz

Minima, deeps in the FFT response (i.e. anti-node energetic areas are present due to the lack of modal sustain – low Q factor) can be observed at the following frequencies:

- 54 Hz
- 90 Hz
- 140 Hz

This happens at the listening position: it is clear the phenomena pass above the Schroeder Frequency.

2.4 Modal decay analysis

Because the FFT analysis, reviewed in the previous paragraph, is useful only to explore the steady-state response of the room, that is the room response while listening to note and sound of long duration, it is necessary to investigate the transient response of the room at low frequencies, performing a detailed analysis of sound attack and sound decay. This analysis is fundamental for short and repeated sound (drum kick or bass guitar riffs) and for natural sounds in general: these sounds should have rapid attack and decay time in order to avoid overlap between the end of a sound and the beginning of the next. This kind of overlap causes a degradation of the perceived music quality.

Reverberation time is a wrong concept at low frequencies because no small-room is Sabinian when standing waves dominate the sound-field.

The first step of this analysis method proposes the computation of decay times for all frequencies in the range between 30 and 300 Hz. This kind of accurate resolutions cannot be reached with traditional one-third octave band analysis. Decay times were computed for all frequencies with a Schroeder Backward Integration using the slope over a fall in amplitude of 20 dB from the steady state value and multiplied by 3 to estimate a 60 dB drop. The obtained curve is compared with the perceptual threshold of detection of modal decay proposed by Avis et al. in (5), further analysis on the topic has been recently presented by Fazenda et al. in (6), both studies defined a limen curve with headphones listening tests. The accuracy of this procedure is not comparable to that offered by traditional one-third octave band reverberation time analysis, where the important connection between a specific resonance mode and its intrinsic temporal decay is completely lost (small rooms can host two or more resonance problems in one single third octave band). The analysis reported in Figure 3 (modal decays obtained from the average of impulse responses in stereo configuration) confirms some considerations derived from analysis FFT. In red is stemmed the one-third octave band reverberation time. Note that the proposed decay analysis is more detailed.

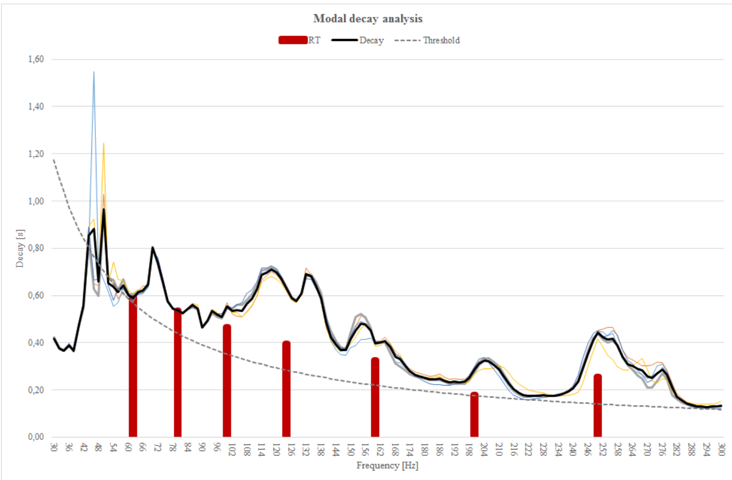

Figure 3 –Modal decay analysis, 3rd octave RT and delay detection threshold [3]

At 42 Hz there is a slow modal decay, in correspondence of a resonance peak, highlighted also by the FFT analysis. Correspondences can be found also at 70 and 120 Hz. It has to be noticed that the most modal decays are slow. The correspondence between FFT resonance peaks and long modal decays is known from the Green function (7) and it implies that, for the identified frequencies (potentially problematic in critical listening of musical material) a specific acoustic treatment is necessary. The proposed listening tests have been based near the identified problematic frequencies (peaks at 42, 76 Hz, and valleys at 52, 88, 92 Hz).

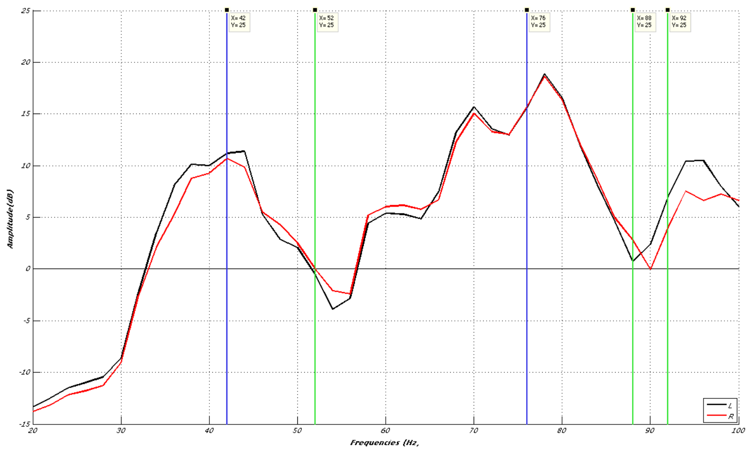

Figure 4 – Room LF response and tested frequencies (light blue: peaks, green: valleys)

3. DSP algorithms for modal decay analysis

The Acoustic Quality Test (AQT) algorithm was refined by Farina et al. (8), first by creating its virtual counterpart, and then by developing the AQT 2 method, which offers more solid results.

The AQT 2 algorithm creates short sine bursts at increasing frequencies, and synthetically convolves each one of them separately with the environment's impulse response. The output of each convolution (which, all together, create the 3D EFT plot) is the temporal evolution of each frequency in the room at the measurement positions. The envelope of these signals will be referred to as "Response Envelope" in the following: it allows to see, the transient behavior, for short sounds clearly, which is important for level and tone perception.

When analyzing a room using this algorithm, three main different behaviors can be found, as Figure 5 shows:

- On the peaks of the FFT curve, Response Envelopes are quite slow both in rising to and decaying from the steady state; for short tone bursts, they often fail to reach the actual steady state value (yellow line): these frequencies will be referred to in the following as "slow" frequencies, and the room has a typical over-damped, "capacitive" behavior.
- In some rooms, Response Envelopes of peaks reach their steady state also for short bursts. This behavior defines "fast" frequencies and it is related to good acoustic correction.
- On the valleys of the FFT curve, Response Envelopes are faster both in rising to and decaying from the steady state, and they show an overshoot behavior, meaning that there is a peak higher than the steady state level in either or both the initial and final part of the Response Envelope. The lower steady state value, instead, is caused by the interference between direct and reflected field in the definition of the standing wave anti-node (6). These frequencies will also be referred to as "fast frequencies", but show an under-damped behavior.
- On intermediate frequencies, the behavior changes gradually between the one on peaks and on valleys

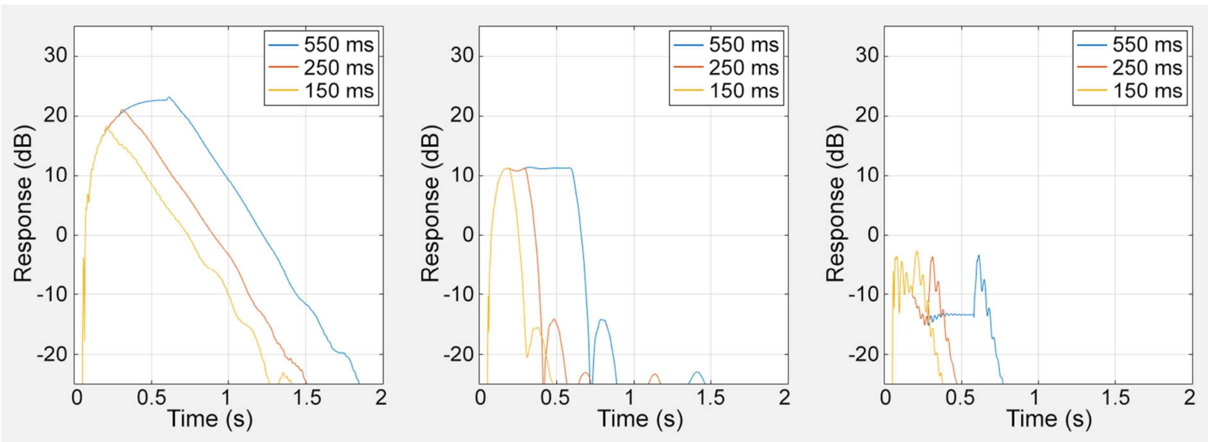

Figure 5 – Different pure tone burst response

3.1 Room Inertia

In a previous study (9), a parameter called "Room Inertia" was introduced by the authors. This curve shows, for each frequency, the time passing between the end of the tone burst and the moment when the Response Envelope reaches a fixed, "target" value which is initially set to be the minimum value in the frequency response between 30 and 300 Hz, minus 1 dB in order to ensure that the R.I. value is always greater than zero. This curve allows to see intuitively which frequencies decay more rapidly and it can be more useful than a decay time defined as a 20 dB or 30 dB drop.

3.2 Room Slowness

Similarly in (9), a parameter called "Room Slowness" was introduced. This curve shows, for each frequency, the time passing between the instant when the test tone is started, and the moment when the Response Envelope reaches the steady state value minus a fixed value. Four different computations were done by setting the threshold at different values (0.1, 2, 6 and 10 dB) in order to obtain a different precision: the more the threshold is close to the steady state value, the more this measure takes into account the last part of the rise, which is usually slower; when the threshold is quite low, the measure mainly accounts for the initial slope of the Response Envelope. When combined together, they offer an intuitive view of how each frequency grows with time. As expected frequencies that have high Slowness values also have high Inertia values, and are mainly the, already defined, “slow frequencies”. Instead, “fast frequencies” show very little values for both parameters.

In Figure 6 is reported an example of Room Slowness and Room Inertia curves.

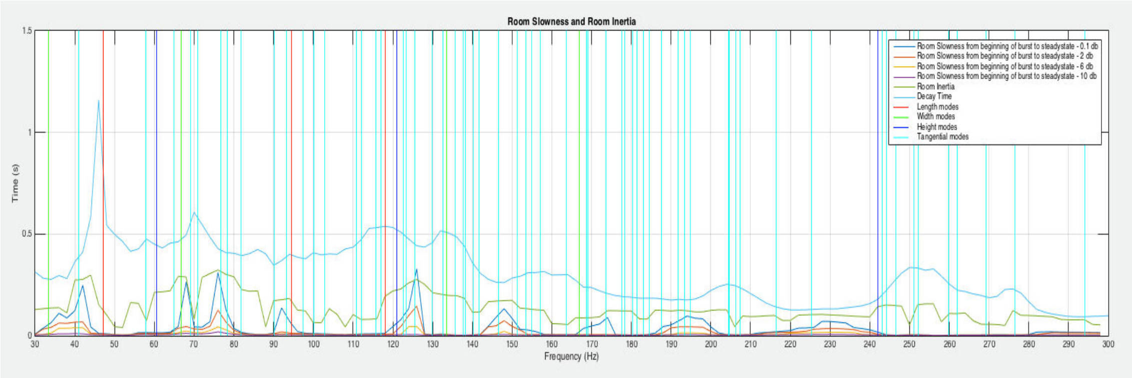

Figure 6 –Room slowness and room inertia

4. PAST RESEARCH ON HEADPHONES

4.1 Tests on headphones on musical sounds

A previous study from the authors searched similar phenomena using headphones (9). Since the aim was to find a psychoacoustic relation with the perception of music, sounds needed to be generated by musical instruments instead of being pure tones or recorded music. Synthetic kick drums and sampled bass sounds recorded with a DI box were used in order to avoid the influence of the room they would have been recorded in. The sounds were then auralized by convolution with the room IRs, and the test asked simple questions regarding the perceived volume, quality of sound, level of degradation of two or a sequence of test sounds.

4.2 Results

From the results, it is confirmed that the psychoacoustic perception of listeners is greatly affected by the presence of room modes, which can alter the sound level perception and the perceived sound quality. This is quite important in music production and in music high quality listening but it has an importance also in low frequency noise assessment.

The tests demonstrated that the effect of room modes is clear when the sound fundamental frequency actually excites one of the room’s eigenfrequencies. This demonstrates that also from a perceptual point of view it is wrong to use a generic octave or third octave reverberation time describing room decay at low frequencies.

When sounds are long enough to enter their steady state domain, the perception is closer to FFT curve. For short sounds the research set the overshoot level response in frequency as a useful instrument.

Furthermore, it is clear that listeners are able to perceive the degradation caused to a sound by the convolution with an impulse response, to a degree that is correlated with the temporal characteristics of the room (more evident for “slow” rooms), the type of sound (more evident for impulsive sounds), and the duration (more evident for short sounds). Time is clearly a critical variable both on transient evolution and its perception.

Listeners seem to be more sensible to changes in precision and resonance rather than to changes in loudness. Specifically, all rooms were correctly ranked in perceived quality according to Room Inertia, Room Slowness and Decay Time.

5. LISTENING TESTS IN THE LISTENING ROOM

The sensory test was performed as a one-sided paired test to confirm that a difference exists concerning the volume and the resonant quality between two samples. In order to prevent from wrongly concluding in favor of a difference which would not exist, the type I error (α) was fixed at 0.05, while it is acceptable a higher risk of not detecting a difference which exists thus the type II error (β) was fixed at 0.10. The percentage of assessors detecting the difference p_d was fixed at 50 %.

5.1 Participants

For the chosen parameters, ISO 5495 (10) recommended a minimum number of assessors of 33. The authors recruited 38 assessors. They were 36 males and 2 females, aged 19 to 49, the mean age being 34. None of them ever participated to sensory tests. Thirteen of them are professional musicians, eight are semi-professionals and the others are amateur musicians. Five of them have a degree at the conservatory and twenty have had previous experience in a recording studio. None of them declared to have hearing impairments.

5.2 Procedure

Musical sound stimuli were presented in the listening room (10) via loudspeakers. The fundamental frequency of each sound was tuned near a problematic frequency in the room (figure 4), spotted with the aforementioned analysis. All sounds were played at the same original volume from the playback system (Reaper on MacBook Pro, RME Interface, Dynaudio BM15 midfield monitor loudspeakers) and the test aimed at evaluating the natural effect of the room in these conditions. Sounds also had different durations and characteristics, similar to those used in (9), and will be described by the results tables. The same type of musical sounds were been as defined in 4.1, convolution was naturally added by the room.

The test was split into two phases: the first concerning the perceived volume, while the second the resonant quality of sounds caused by the presence of resonant modes in the room. In both cases, tests were made with different sounds, and different durations (single notes or repeated notes).

Preliminarily, a training session was proposed to the assessors before each phase of the test. Each training session was composed of three trials ordered by increasing difficulty. At each assessor a total amount of twenty-one couples of stimuli were proposed: thirteen for the first phase and eight for the second one. For each couple in the first part, assessors were asked: *"Which of the two sounds has a lower perceived volume?"*, while, in the second part of the test, the question was: *"Which of the two sounds is perceived as more resonant?"*. In each comparison, the playback order of the two sounds was switched in order to avoid biases. For example, in the first part of the test, calling A the stimulus with expected higher volume and B the stimulus with the lower one, questions were composed of a mixture of AB and BA couples of stimuli. The same procedure has been performed for the second part of the test.

5.3 Results

In this section, correct response corresponds to the case when the assessor declared to perceive the expected response according to (9). As a general rule of thumb, it was expected that sounds with fundamental frequency on a frequency response peak would be perceived as both louder and more resonant.

Considering each stimulus separately, the number of correct responses (among a total of 38 assessors) are shown in tables I, II, III, IV and V. The values of sounds corresponding to the "expected" answer have been highlighted according to the expected behavior seen in the past research on headphones (9), indicating that different durations and type of sounds have an impact on the perception.

5.3.1 **Results regarding perceived volume**

In the following questions, the listener was asked to state which sound in each couple was perceived as quieter.

Table I – Results of listening tests. Couples of stimuli no.1--8

Perceived volume with respect to note duration (150 and 550 ms)

Couple	Sound	Dur. (ms)	Freq (Hz)	H(f)	#correct	#required	Passed
1-2	**PureTone**	**150**	**76**	**peak**	**36**	25	yes
	PureTone	550	76	peak			
3-4	**Bass**	**150**	**76**	**peak**	**21**	25	no
	Bass	550	76	peak			
5-6	PureTone	150	52	valley	**12**	25	yes
	PureTone	**550**	**52**	**valley**			
7-8	Bass	150	52	valley	**18**	25	no
	Bass	**550**	**52**	**valley**			

On the peaks of the frequency response, the behavior is the following. Couple 1-2 confirms that, at frequencies for which the room reacts slowly, shorter sounds are perceived as quieter. As a matter of fact, at these frequencies, the room shows high values for Room Slowness (rise time) and frequencies are not able to reach their steady state for short notes. Failed test of stimuli couple 3-4 suggest that the spectral complexity of a bass note masks the previous behavior.

On the valley of the frequency response it was expected that listeners would perceive overshoot peaks and state that the longer one was quieter as it happened on headphones tests (9). Surprisingly, with pure tones more people perceived the shorter one as quieter, while with bass sounds, the results were not meaningful.

Table II – Results of listening tests. Couples of stimuli no.9-18

Perceived volume of single notes with respect to relative position of the fundamental frequency and peaks or valleys of the frequency response

Couple	Sound	Dur. (ms)	Freq (Hz)	H(f)	#correct	#required	Passed
9-10	**PureTone**	**150**	**86**	**valley**	**22**	25	no
	PureTone	150	92	peak			
11-12	**PureTone**	**550**	**86**	**valley**	**33**	25	yes
	PureTone	550	92	peak			
13-14	**Kick**		**86**	**valley**	**16**	25	no
	Kick		92	peak			
15-16	**Bass**	**150**	**86**	**valley**	**7**	25	no
	Bass	150	92	peak			
17-18	**Bass**	**550**	**86**	**valley**	**21**	25	no
	Bass	550	92	peak			

These couples compared nearby frequencies with a different FFT, or steady state, level. With short pure tones, as expected, listeners tend to perceive the same volume because of the perception of peaks which are really close. With longer tones, the steady state is exposed and most listeners correctly state that the sound with the lowest steady state value is quieter, in accordance to (9).

The test of stimuli in couple 13-14 failed. As a matter of fact, percussive sounds like Kick hits do not reach a steady state because of their nature. Since the opening peak has a similar value on both frequencies, this could explain why results are not meaningful.

In couple 15-16, the results are the opposite when the fundamental note is centered on the same frequencies, as seen before complex sounds have a different perception than pure tones.

In sounds 19 to 24, each sound was repeated 8 times with a short interval between sounds. In couple 25-26, two musical excerpts were prepared with kick hits and bass lines. The "Slow" excerpt featured all notes with fundamental frequency placed on a peak of the frequency response, where the room reacts slowly (see fig. 5 first and second subplot). The "Fast" excerpt had notes with fundamental frequency on valleys, in which the room reacts fastly.

Table III – Results of listening tests. Couples of stimuli no.19--26

Perceived volume of repeated notes and musical excerpt with respect to relative position of the fundamental frequency and peaks or valleys of the frequency response

Couple	Sound	Dur. (ms)	Freq (Hz)	H(f)	#correct	#required	Passed
19-20	**PureTones**	**150**	**88**	**valley**	**36**	25	yes
	PureTones	150	76	peak			
21-22	**Bass Notes**	**150**	**88**	**valley**	**35**	25	yes
	Bass Notes	150	76	peak			
23-24	**Kick Hits**		**88**	**valley**	**32**	25	yes
	Kick Hits		76	peak			
25-26	Excerpt	21000		"Slow"	**27**	25	yes
	Excerpt	21000		**"Fast"**			

Results suggest that when the sound is closely repeated, the perception of listeners regarding volume is always in accordance with the frequency response, even for sounds with a complex spectrum. In particular, two musical sections can be perceived at different volumes just by exciting different frequencies in the listening environment. This demonstrates the importance of accurate FFT analysis: correlation between the room resonance pattern and the fundamental frequency of the sound is very important and this cannot be understood using a simple band analysis as requested by most international norms nowadays.

5.3.2 **Results regarding perceived resonant quality**

In the following questions, the listener was asked to state which sound in each couple was perceived as more resonant.

Table IV – Results of listening tests. Couples of stimuli no.27--34

Perceived resonance of single notes with respect to relative position of the fundamental frequency and peaks or valleys of the frequency response

Couple	Sound	Dur. (ms)	Freq (Hz)	H(f)	#correct	#required	Passed
27-28	PureTone	150	52	valley	**26**	25	yes
	PureTone	**150**	**42**	**peak**			
29-30	Kick		52	valley	**35**	25	yes
	Kick		**42**	**peak**			
31-32	Bass	150	52	valley	**32**	25	yes
	Bass	**150**	**42**	**peak**			
33-34	Bass	550	52	valley	**28**	25	yes
	Bass	**550**	**42**	**peak**			

Regarding the perceived resonant quality of the sound, most listeners are able to identify as most resonant, the sound whose fundamental frequency is placed on a peak in the frequency response. Results become more defined for complex sounds rather than on pure tones, suggesting that spectral complexity could increase the sensation of resonance. For long bass notes, results are slightly less defined. As found in the headphone tests (9) resonant quality of a note seem to be more evident on short notes and percussive sounds.

Sounds 35 to 40 featured sounds repeated in the same way as sounds 19 to 24, while the musical excerpts of couple 41-42 were the same of couple 25-26.

Table V – Results of listening tests. Couples of stimuli no.35--42

Perceived resonance of repeated notes and musical excerpt with respect to relative position of the fundamental frequency and peaks or valleys of the frequency response

Couple	Sound	Dur. (ms)	Freq (Hz)	H(f)	#correct	#required	Passed
35-36	PureTones	150	88	valley	**35**	25	yes
	PureTones	**150**	**76**	**peak**			
37-38	Bass Notes	150	88	valley	**31**	25	yes
	Bass Notes	**150**	**76**	**peak**			
39-40	Kick Hits		88	valley	**38**	25	yes
	Kick Hits		**76**	**peak**			
41-42	**Excerpt**	**21000**		**"Slow"**	**38**	25	yes
	Excerpt	21000		"Fast"			

Results suggests that the repetition of sounds can also help identify the most resonant one in each couple. Furthermore, all listeners clearly perceived the effect of room modes on the resonant quality of a complex musical excerpt.

6. Conclusions

Regarding the term “resonant” there was initially some uncertainty in listeners. The training phase helped them understanding the correlation between the term and the perceptual effect, confirming the importance of a training phase in psychoacoustic tests.

From the outcome of the test, it appears that listeners are more capable of perceiving changes in the resonant quality of sounds if compared to changes in volume introduced by a room at different frequencies for single low frequency complex tones, the opposite appears for pure tones.

The perception of loudness on longer notes or for repeated notes appears to be very closely related to the Frequency Response Amplitude; longer sounds seem to reduce the perceived resonance.

Results suggest that the perception of loudness levels and resonant quality improves when sounds are rapidly repeated. In this case, the perception of loudness seems to be in accordance with the frequency response, however the same questions should be repeated also with single longer notes to study the dependence with the Overshoot Response that was seen in a previous study on headphones.

Interestingly, two musical excerpts performed in the same room can have a very different perceived level and resonant quality depending on the notes played in each sequence, further confirming the effects of resonance modes when matched on the sound frequency content on the perceived level and quality of sound. This opens to the importance of accurate amplitude and decay analysis in frequency in the acoustics for audio field but also in the noise assessment measurements in small rooms.

7. Future studies

Similar tests should be conducted in other rooms with worse problems due to resonance modes in order to confirm these results. Further studying is needed about the influence of the Overshoot Response over the Frequency Response on the perception of short sounds.

More tests with more listeners, a protocol of questions on different rooms could help explaining the few non-expected results as well as confirming the obtained ones.

These tests should aim to find perceptual thresholds regarding the difference of amplitude and duration between sounds with similar peak amplitude and different steady state levels, below which the perceived volume is the same for most listeners. A perceptual threshold curve for decay perception in real rooms is needed and it should consider the importance of frequency matching between the sound content and the resonance response.

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