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Exploring perceptual annoyance and colouration assessment in active acoustic environments

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ABSTRACT

In active acoustics, signals from microphones within a room are processed and fed to loudspeakers in the same room, creating an extended reverberation time and modified room perception. The system's performance is limited by the audibility and acceptability of colouration at gains close to instability. Some listening tests have been presented in the literature to assess perceptual colouration, but thresholds for when the colouration becomes annoying or unacceptable have not previously been established. In this paper, we revisit the prediction of the gain before instability and show how this can be used to equalize an active acoustics system. Then, we present new listening tests where listeners were asked to rate the audibility and annoyance of changes introduced by 8 channel active acoustics systems in two rooms at various simulated gains. We show that the annoyance depends on the initial room acoustics as well as the loop gain; perceptual thresholds for *slightly annoying* degradation varied from -5.4 dB to -8.5 dB, relative to instability. These thresholds are discussed in the context of objective measurements calculated from the impulse responses. The resonance perception is linked to the gain where the reverberation time starts to grow much more quickly in some frequency bands than others. It is also shown to be well predicted by the standard deviation of the magnitude response, with a value of 0.62 corresponding to *slightly annoying* degradation.

1 Introduction

Reverberation enhancement systems aim to manipulate a room's natural acoustics in order to make the room suitable for an intended use [1]. For example, a performing arts centre may be treated with absorbing materials to provide good sound for cinema or rock music, but would require a longer reverberation time to host a string quartet or orchestra. *Active acoustics* systems achieve changes to the room's acoustic properties by placing microphones and loudspeakers within the room, and using electronic processing to create the desired sound. Changes to the acoustics with active systems can be deployed instantaneously, even during a show, and can potentially utilize the sound reinforcement system present in the venue [2].

In [3, Ch. 10], active acoustics systems are divided into *in-line* systems that process the sound through an external reverberator, and *regenerative* systems that process microphones in the room through acoustic feedback. In-line systems [4, 5] typically require microphones close to the sources, while regenerative systems generally place microphones throughout the audience area and feed the signal back through the loudspeakers via gains/filters [6, 7, 8] or reverberators [9]. Conceptually, in-line systems afford significant algorithmic freedom to shape the enhanced reverberation, while regenerative systems allow to extend the overall late reverberation time in the venue. However, in-line systems focused on a stage area may not provide the audience with the sensation of being in the same room as the musicians. In practice, many active acoustics systems employ a hybrid approach [1], where the exact processing applied depends on the position of the microphones with respect to the stage and the audience.

It is important in regenerative systems to set the *loop gain* (electronic gain in the feedback loop) at an appropriate level. If the loop gain is too low, any reverberation enhancement will be barely perceptible; if it is too high, the system may exhibit colouration or even become unstable. Thresholds of loop gain before instability (GBI) have been investigated extensively in the active acoustics literature [10, 11]. Although much of the work frames the probability of instability in a statistical sense, it is also possible to calculate the threshold of instability for a given system measured in situ, as we shall discuss below. Various technical solutions have been proposed to increase the GBI, including time-variation [12, 13, 14], frequency shifting [15], and feedback cancellation [16, 17]. Even so, there are generally a relatively small range of gains that are sufficient to achieve a strong reverberation enhancement effect, while staying far enough from instability to avoid objectionable colouration.

To avoid colouration, adding 5–17 dB of headroom to a marginally stable system is typical in the literature, although this varies depending on the number of channels [18] and the equalization employed. Due to this variability, it is important to understand the perception of colouration in relation to measurable physical parameters. In [19], colouration was linked to decays being longer in some sub-bands than others, and eventually the modulation transfer function was shown to become inconsistent when the system is close to feedback. In [18], a number of objective colouration metrics computed from room impulse responses (RIRs) were investigated, aiming to compare the resonant RIRs to ideal values drawn from a statistical perspective on classical room acoustics. One promising metric was based on the standard deviation of the RIR's frequency response; this was also shown to correlate with listening tests, where 10 non-expert listeners rated the colouration on a scale of 0—100. Later use of the same metric in [20] also showed a good correlation with perceptual ratings in active acoustics, and in [21] was also noted to be of use to predict colouration in general room-in-room reproduction. More recently, a method to estimate colouration based on recorded signals was proposed, and shown to be effective to identify the emergence of colouration and ringing [22]. However, while the colouration metrics discussed can indicate the increase of colouration, the perceptual thresholds where the colouration becomes annoying, or unusable, have not yet been established.

In this paper, we present new listening tests and analysis of the resonances produced when driving two equalized 8-channel pure regenerative systems at different loop gains. Where previous work has used a scale of 0–100 with no labelled mid-points, we use a degradation scale to understand further the perceptual audibility and annoyance of the resonances introduced by the feedback system. We have two main aims: (1) determine perceptual thresholds based on this rating scale, (2) investigate objective physical correlates to these ratings, including the colouration metric from [18].

In Sec. 2, we review the feedback system problem statement and numerical prediction of the threshold of instability based on eigenvalue analysis. In Sec. 3, we briefly introduce the active acoustics system case-studies used in this paper. In Sec. 4, we describe the listening test stimulus preparation and design, and in Sec. 5 we present the perceptual results. In Sec. 6, we discuss the listening test findings in the context of objective measurements, and in Sec. 7 we summarize.

2 Background

An active acoustics system comprises a number of microphones and loudspeakers placed in a room. The sound from the acoustic source travels directly to the receiver and is also received at the microphones. The microphone signals are electronically processed through a reverberator and reproduced by the loudspeakers, being heard at the receiver and sensed at the microphones creating a feedback loop.

In this paper, we use the loudspeakers and microphones installed in two venues to investigate the perception of resonances arising due to gains close to instability. A block diagram of the system studied is shown in

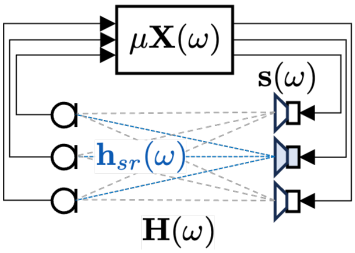

Fig. 1: Feedback system, showing the electronic processing $\mathbf{X}(\omega)$ with loop gain μ, and the acoustic matrix $\mathbf{H}(\omega)$. The loudspeaker outputs are $\mathbf{s}(\omega)$. One source in the loudspeaker array (illustrated with shading), with transfer paths to the microphones $\mathbf{h}_{sr}(\omega)$, is used to excite the feedback system in our simulations.

Fig. 1. As the stability of the whole active acoustics system is governed by the stability of the feedback loop, excitation with any loudspeaker is sufficient to excite the resonances of interest.

The source weights of the L loudspeakers are composed of contributions from the initial excitation and the feedback system, written in the frequency domain in vector form as

$$\mathbf{s}(\omega) = \mu\mathbf{X}(\omega)\mathbf{h}_{sr}(\omega) + \mu\mathbf{X}(\omega)\mathbf{H}(\omega)\mathbf{s}(\omega), \qquad (1)$$

where each element of $\mathbf{s}(\omega)$ (dimensions $L \times 1$) is the complex source weight at a certain loudspeaker, $\mathbf{h}_{sr}$ is the $M \times 1$ vector of acoustic transfer paths between the exciting source and the M microphones, μ is a scalar feedback gain constant over all channels, $\mathbf{X}(\omega)$ ($L \times M$) is the electronic reverberator and $\mathbf{H}(\omega)$ ($M \times L$) is the matrix of acoustic transfer paths between the loudspeakers and microphones in the system. The electronic reverberator $\mathbf{X}(\omega)$ may represent a regenerative system with gains and delays, or any kind of algorithmic reverberator.

The stability of the system is governed by the *open loop matrix* $\mu\mathbf{X}(\omega)\mathbf{H}(\omega)$. By performing eigenvalue decomposition of this matrix at each frequency, a set of N eigenfunctions can be acquired, having the form [23]

$$Y_n(\omega) = \frac{1}{1 - \mu\lambda_n(\omega)}, \qquad (2)$$

where $\lambda_n(\omega)$ is the nth complex eigenvalue at the frequency ω, and N is the rank of $\mathbf{X}(\omega)\mathbf{H}(\omega)$ (the lower of L and M). Thus, when any $|\mu\lambda_n(\omega)|$ is close to unity and $\angle\lambda_n(\omega) = 2\pi$, the whole system is unstable. At the threshold of instability, a certain resonant frequency has an infinite decay time. As μ is reduced, the decay becomes finite but the resonances still cause problematic colouration for high loop gains.

3 Active acoustics systems

We use two case study active acoustics systems, *Showroom* and *Theatre*. Both systems use 8 microphones and 8 loudspeakers for the simple regenerative processing studied in this paper. Showroom has approximate dimensions 7.2 × 11.4 × 3.8 m, is heavily treated with absorbing material and has an average reverberation time (RT) of 0.31 s (500—2000 Hz octave bands). The active acoustics system uses L-Acoustics SYVA loudspeakers. Theatre is a theatre with approximately 1700 seats and average RT of 1.36 s. The active acoustics system uses L-Acoustics X8 loudspeakers.

In the context of this paper, the two systems are deployed with a simple regenerative processing, that is, the reverberation matrix $\mathbf{X}(\omega)$ is diagonal, with frequency-dependent attenuation acting as a band pass filter. There is a global pre-delay, and a broadband overall gain μ that shall be varied for our experiments. Both systems use L-Acoustics P1 processors for microphone pre-amplifiers and bus equalization, and use the AVB protocol for networked audio communication.

To calibrate the systems, an acoustic measurement of the system is first taken. Our approach is to directly measure the open loop matrix $\mathbf{X}(\omega)\mathbf{H}(\omega)$, which minimizes the measurement time on-site and the volume of data acquired. The Showroom data was acquired with a sweep length of 3 s and 4 repeats; the Theatre data was acquired with a sweep length of 6 s and 2 repeats. The sweep lengths differ due to the baseline reverberation times of the rooms, and fewer repeats were used for Theatre due to time constraints on site.

Equalization is first applied at each microphone input to flatten the magnitude response of each connected microphone-loudspeaker path, and additional equalization is applied to all microphone channels to optimize the headroom before instability across the frequency range. For the latter part, numerical eigenvalue analysis following Eq. 2 is used to ensure stability.

The magnitudes of the maximum eigenvalues of the open loop matrices after all equalization (i.e., those that give the highest risk of instability among the N

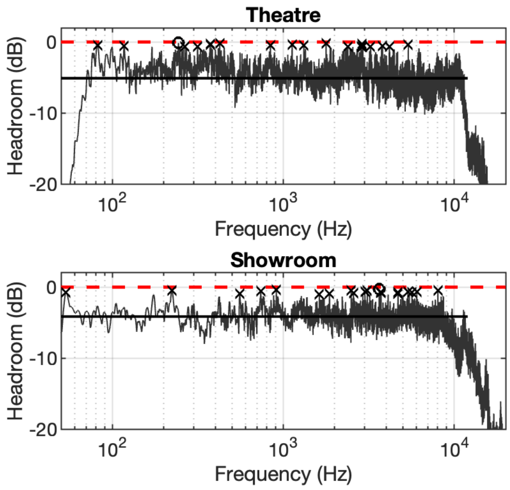

Fig. 2: Predicted headroom for the equalized active acoustics systems. The horizontal lines show the mean headroom to feedback across frequency; the 20 highest peaks are marked (×; highest peak ○).

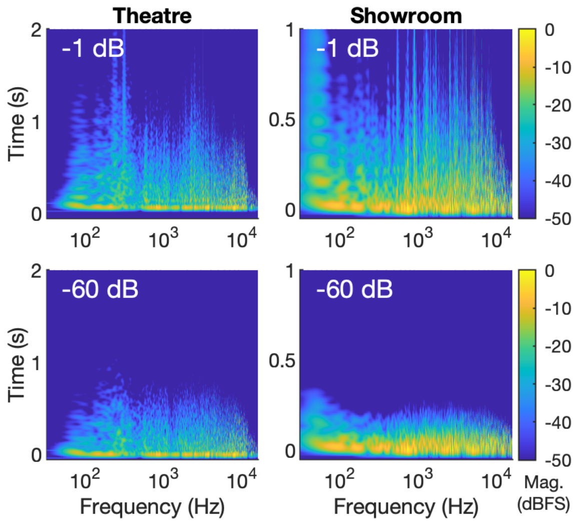

Fig. 3: Spectrogram of the simulated resonant systems at gains of −1 dB (upper) and −60 dB (lower) relative to instability. Note the different time scales for the two rooms.

eigenvalues at a given frequency) are shown in Fig. 2. An initial normalizing gain is applied such that the GBI is 0 dB for both systems. In Fig. 2, it can be seen that the eigenfunction peaks (○, ×) all have approximately the same headroom to instability. It should be noted that it is unlikely for all of these peaks to be simultaneously excited, due to the phase criterion for instability. Nevertheless, equalizing based on eigenvalue magnitude allows the pre-delay to be freely modified in the installation without risk of feedback. The black line shows the mean distance to feedback across frequency; on average, any frequency in the Showroom is 1 dB closer to feedback than in the Theatre.

4 Listening test methodology

In this section, the creation of listening test stimuli is first described, then, the listening test protocol is explained.

4.1 Stimulus creation

Stimuli for the listening test were created by synthesising resonant impulse responses based on the open loop measurements of $\mathbf{X}(\omega)\mathbf{H}(\omega)$ made in situ at 48 kHz sample rate. The initial excitation signal $\mathbf{h}_{sr}$ was the impulse response from a single loudspeaker to all microphones, as depicted in Fig. 1, with a coarse equalization to flatten the magnitude response. Then, the feedback system was simulated by recursion of Eq. 1 in the frequency domain with 50 iterations. The loop gain μ was set with reference to the predicted eigenfunction peaks (Eq. 2), such that $\mu = 0$ dB would be on the threshold of instability as shown in Fig. 2. Then, loop gains from −60 dB to −1 dB relative to instability were used for the computation. The FFT size was 2^{16} (1.37 s) for Showroom and 2^{17} (2.73 s) for Theatre, such that the slowly decaying resonances at high loop gains were suitably captured. The response was simulated at all microphones, and one representative microphone IR was chosen as the test stimulus.

The resulting IRs were used directly for the physical analysis, and convolved with anechoic recordings to create the stimuli for the listening tests. Two recordings were used: a balloon burst[1] and English male speech [24, Track 5]. For the speech, a 17 s clip was taken, and for both stimuli sufficient post-silence was added to allow the simulated resonant system to decay fully.

To illustrate the starting room acoustics and the effects of increasing loop gain close to instability, spectrograms of the simulated RIRs at −60 dB and −1 dB

[1] https://freesound.org/s/210767/

Gain (dB)	-60	-20	-18	-16	-14	-12	-10	-8	-6	-3	-1
Theatre	1.36	1.37	1.38	1.38	1.39	1.40	1.43	1.47	1.54	1.75	2.17
Showroom	0.31	0.33	0.34	0.36	0.38	0.42	0.47	0.54	0.66	0.96	1.64

Table 1: Estimated reverberation time (T20) in s, averaged across 500—2000 Hz octave bands, for the gains relative to instability in each room.

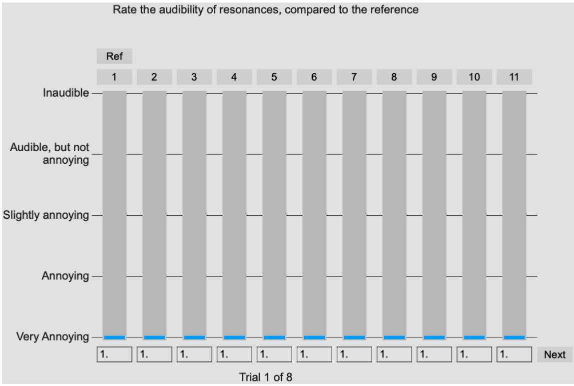

Fig. 4: Listening test interface.

loop gain relative to instability are shown in Fig. 3. In the upper plots, resonances are clearly visible. The reverberation times (T20) for increasing gain, are shown in Table 1.

4.2 Listening test protocol

Listening tests were designed to investigate the emergence of resonances with the increase in loop gain. Listeners were asked to *rate the audibility of resonances, compared to the reference*. In order to assess the usability of the active acoustics systems with a certain loop gain, a scale with clear labels at each rating was used. In addition, in order to study only the introduction of (additional) resonances by the active acoustics system, a reference-based method was chosen.

The nature of increasing the loop gain in active acoustics means that it is difficult to describe the whole range of changes using a single perceptual attribute. For example, when the effect of the active acoustics system first becomes audible, the *reverberance* changes. With increased gain, the system undergoes further timbral changes resulting in *colouration* and finally *ringing* of one or two frequencies when the system is very close to feedback.

As such, the ITU P.800 degradation scale was employed [25], with participants making ratings on the discrete scale: *inaudible* (5); *audible but not annoying* (4); *slightly annoying* (3); *annoying* (2); *very annoying* (1). Thresholds for the higher quality ratings in the scale are of most interest: a rating of *inaudible* implies that the active acoustics system is not making an audible change; *audible but not annoying* implies that the listener perceives a change and finds it acceptable, while *slightly annoying* suggests an increase in the audibility of the resonances that may no longer be acceptable in a professional audio context.

Based on a pilot test, the factor Gain was set at 11 levels: -60 dB (reference); 2 dB increments between -20 dB and -6 dB; -3 dB, and -1 dB. In addition, factors of Room (Theatre and Showroom) and Stimulus (Speech and Balloon), as discussed above, were included. A multiple stimulus presentation was used, in order to group the ratings for each combination of Room and Stimulus and simplify the task. On each page, listeners were presented with the 11 gains in a random order. There were a total of eight randomized pages: 2 rooms, 2 stimuli, and 2 repeats of each judgement. The test was implemented in Max/MSP using HULTI-GEN v2[2]; the interface is shown in Fig. 4.

Tests were conducted in a quiet room with stimuli reproduced on Beyerdynamic DT770 Pro 80 Ohm headphones. Before starting the test, listeners were presented with information about the test and informed consent was obtained. Participants were also played familiarisation examples comprising all stimuli to be used in the test. During the familiarisation phase, participants were able to set the headphone volume to a comfortable level, which was then fixed for the test.

4.3 Participants and post-screening

17 listeners participated in the experiment (15 male, 2 female). Participants ranged from 22–66 years old (median 37). All participants work in professional audio and 14 of the 17 listeners reported being musicians and/or experienced in critical listening.

[2]https://github.com/APL-Huddersfield/HULTI-GENv2

Post-screening of tests was conducted. The ratings given to the −60 dB reference were first checked. It was found that three participants had incorrectly rated the reference more than twice out of the eight pages in the test. The ratings from these participants were considered unreliable and removed from further analysis. The ratings given to repeat stimuli were also checked; no listeners rated repeat stimuli more than 2 points apart, more than once. In total, the ratings from 14 participants, including repeats, were used for analysis.

5 Results

The listening tests were first analyzed to assess the influence of the factors Gain, Room and Stimulus. A non-parametric multinomial logistic regression found Gain ($p < 0.0001$) and Room ($p < 0.0001$) to be significant, while Stimulus was not significant ($p = 0.4387$). Further analysis of the perceptual results therefore grouped the responses for both program items together, while the other factors are studied individually.

A box plot split by the factors Gain and Room is shown in Fig. 5. It can be seen that at low gains, the interquartile range for both rooms spans the range *audible but not annoying* to *inaudible*. As the gain increases, the Showroom ratings begin to fall at a lower gain compared to the Theatre.

To further characterize the ratings, a regression analysis was performed. Given that the rating scale is bounded by a rating of *inaudible* for low loop gains (including the system off), and *very annoying* even for unstable systems, a sigmoid function was chosen. The minimum and maximum values were fixed to 1 and 5 (denoting *very annoying* and *inaudible*, respectively), and the Matlab function `fitnlm` was used to obtain best-fit parameters a and b according to

$$f(x) = 1 + \frac{5-1}{1+e^{b(a-x)}}. \tag{3}$$

The parameters a and b can be interpreted as the shift from $x = 0$ of the mid-point $f(x) = 3$, and the gradient of the sigmoid, respectively. For each room, all ratings including repeats were included in the regression analysis.

The curves can be seen to overall represent the ratings well. The obtained parameters and goodness-of-fit metrics are shown in Table 2. The curve fit parameters of −8.5 dB and −5.4 dB for Showroom and Theatre, respectively, directly summarize the gains with

	RMSE	Adj. R^2	a	b
Theatre	0.806	0.614	-5.36	-0.333
Showroom	0.692	0.763	-8.47	-0.290

Table 2: Goodness-of-fit measures and model parameters for the sigmoid fit to the perceptual ratings (Eq. 3).

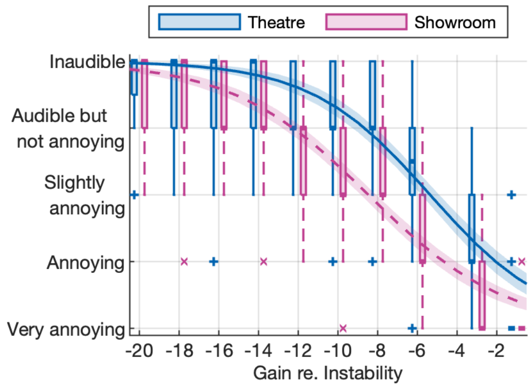

Fig. 5: Box plots with fitted sigmoid curve of the ratings for Theatre (blue, solid line, outliers +) and Showroom (magenta, dashed line, outliers ×). Shading denotes the confidence intervals of the curve estimation.

an overall rating of *slightly annoying*. The thresholds of −12.3 dB and −8.7 dB for the rating *audible but not annoying* are slightly further apart. These two sets of gains effectively define the useful operating range of the regenerative systems studied; a higher quality rating towards *inaudible* implies that there is no difference between the natural room response and the active acoustics response, and a rating lower than *slightly annoying* implies that the system gain cannot be increased further and remain at an acceptable quality.

6 Discussion

In this section we discuss the perceptual thresholds in the context of objective measurements of the RT and statistical properties of the resonant system.

6.1 Decay analysis

The overall time-frequency characteristics of the resonant systems for gains near to the threshold values from the regression model are illustrated as spectrograms

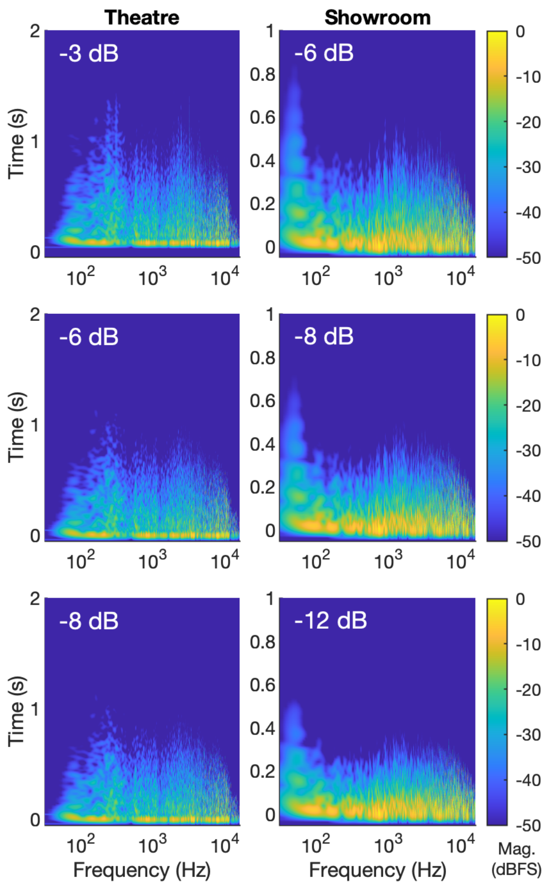

Fig. 6: Spectrograms of the simulated resonant systems at the gains closest to the perceptual thresholds of *annoying* (upper), *slightly annoying* (middle), and *audible but not annoying* (lower). Note the different time scales for the two rooms.

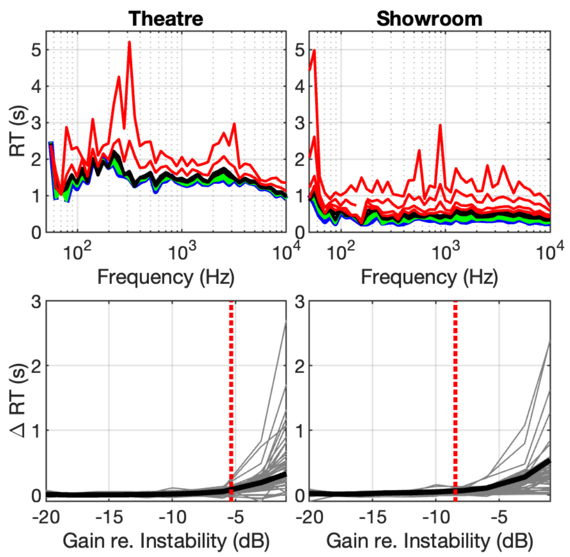

Fig. 7: RT analysis with 1/6 octave frequency resolution. Top row shows the absolute RT (see text for description of colours); bottom row shows the change in RT compared to the previous gain (each grey line is a certain frequency band; black line is the average RT 500–2000 Hz).

in Fig. 6. Gradual changes can be observed in the overall shape of the reverberation as well as the emergence of visibly longer decays for some frequencies at higher gains. In the lower row, changes compared to the −60 dB reference are *audible but not annoying*, which implies that the reverberation time is audibly extended without objectionable resonances. Comparing the bottom row to Fig. 3, the overall shape of the reverberation is similar, but with slower decay. In the middle row, corresponding to a perceptual rating of *slightly annoying*, the spectral shape of the late tail begins to change, with the decays becoming less uniform across frequency in both rooms. Finally, in the top row, corresponding to a perceptual rating of *slightly annoying*, some stronger resonant frequencies with longer decay are visible, for example around 400 Hz for Theatre and 50 Hz for Showroom.

To quantify this further, the RT in 1/6 octave bands is shown in Fig 7. The top row shows the absolute RTs, which can be seen to increase quite evenly with frequency for low loop gains (green), while for high loop gains (red) the RT becomes uneven with frequency as the resonant decays lengthen. The black curves show, for each room, the RT for the gains between the thresholds of *audible but not annoying* and *slightly annoying*. These curves exhibit increased RT compared to the baseline room, but with a similar profile across the frequency bands. Conversely, the red curves show rapid growth of the RT in certain frequency bands.

This is illustrated further in the lower plots of Fig 7. The plot shows the change in RT compared to the previous gain; for example, the data point for −8 dB shows the change in RT compared to −10 dB. With this perspective, it can be observed that at some gain around the *slightly annoying* threshold, marked with the vertical dotted line, the RT starts to grow much more quickly in some frequency bands than others.

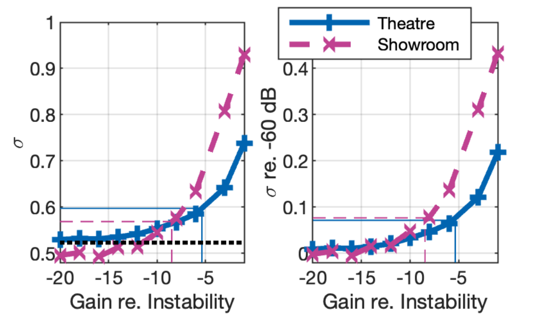

Fig. 8: Absolute (left) and relative (right) colouration metric values by room. The black horizontal dotted line in the left figure shows the theoretical σ value of 0.523, and the thin vertical and horizontal lines show the values corresponding to the intersection of the modelled perceptual thresholds for *slightly annoying*.

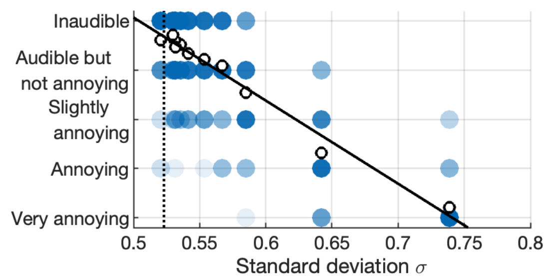

Fig. 9: Relationship between colouration metric (standard deviation) and perceptual ratings for Theatre. Each perceptual rating is shown as a semi-transparent circle (darker circles indicate higher frequency of ratings); mean ratings are shown as black circles. Vertical dotted line marks the theoretical ideal σ value of 0.523.

6.2 Colouration prediction

Given the increase in variance of RT with the loop gain, a statistical measure can be interesting to quantify the colouration. The late energy of an ideal colourless RIR is distributed according to a Rayleigh law [3], such that the ratio of the standard deviation to the mean of the magnitude of the RIR's frequency response is:

$$\frac{\sigma}{m} = \sqrt{\frac{4}{\pi} - 1} \approx 0.523. \tag{4}$$

In [18], a procedure is outlined to measure σ/m by pre-processing the frequency response to achieve a mean value m of unity then directly calculating the standard deviation σ.

Following the method and parameter choices of [18], the RIR is first windowed to include only samples corresponding to the late reverberation, defined as the decay from -15 to -35 dB. RIRs were verified to have a noise margin of 10 dB beyond this range. The RT is estimated by linear regression of the reverse integrated log decay in the same range, then the windowed signal is weighted by the factor $e^{6.91t/RT}$ to counteract the exponential decay of the RIR. The magnitude response $|H(\omega)|$ of the weighted, windowed signal is obtained with an FFT size of 2^{14}. It is assumed to be the combination of a slowly varying mean $M(\omega)$ and rapidly varying part $G(\omega)$; $|H(\omega)| = |M(\omega)||G(\omega)|$. The component $|M(\omega)|$ is estimated by 1/3 octave smoothing of $|H(\omega)|$; and $|G(\omega)|$ is then calculated, having unity mean by design. The colouration metric is the standard deviation σ of $|G(\omega)|$ calculated using frequency bins from 50—4000 Hz.

The colouration metric values are shown in Fig. 8. In the left plot, the absolute values are shown. These are broadly comparable with other values found in the literature, although when testing we found that the values were sensitive to a) the FFT size and b) random fluctuations between repeated RIR measurements. Nevertheless, there is a clear relationship with the proximity to feedback. The σ value for a gain of -60 dB was measured at 0.521 for Theatre and 0.497 for Showroom. This gives an indication that the statistical behaviour of the former is closer to the expected value without an active acoustics system installed, and may help explain why the perceptual thresholds are different for the two rooms. In addition, the colouration values grow more rapidly with increasing gain for Showroom than for Theatre.

The colouration metric values corresponding to the perceptual thresholds are quite different between the two rooms. In the right plot of Fig. 8, the values are plotted relative to the -60 dB values. For both rooms, the *increases* in σ at the marked perceptual thresholds for *slightly annoying* are comparable, being 0.0712 and 0.0765 for Theatre and Showroom, respectively.

The relationship between the perceptual ratings and the colouration metric was explored further by directly comparing the two measures. The Pearson correlation was computed, to give an indication of the rank ordering of the perceptual means compared to the colouration metric values. The correlation coefficients were -0.97 for Theatre and -0.94 for Showroom, giving further evidence that the metric is useful for predicting a change in colouration. A linear regression (RMSE: 0.162; adjusted R^2: 0.979) was further conducted on the mean Theatre ratings, as this room represents a typical use-case for active acoustics and exhibits the expected Rayleigh frequency response distribution for the dry room. The regression line is shown in Fig. 9. A colouration value of around 0.62 corresponds to *slightly annoying* resonance, which is similar to the value of 0.63 proposed in [20]. However, this result cannot be generalised from the limited data analysed here.

7 Summary

In this paper, we presented new listening test results and objective analyses of two active acoustics systems. We obtained thresholds based on perceptual degradation ratings, indicating that the allowable gain for a *slightly annoying* degradation varied from -5.4 dB to -8.5 dB relative to instability. Although it is known in the literature that the acceptable gain varies with the number of channels, such a significant variation with the same number of channels in two different rooms was unexpected.

To give the opportunity to generalize our findings to other systems, we first investigated the physical changes around the thresholds, focusing on the RT in 1/6 octave bands. The threshold for *slightly annoying* seems to be related to the gain where reverberation time starts to grow much more quickly in some frequency bands than others.

We also investigated the standard-deviation-based colouration metric first proposed in [18]. The resonance perception is well predicted by this metric, with values of 0.6–0.62, or an average increase of 0.074 with respect to the initial values of the two rooms we studied, being potentially useful values for future work to predict *slightly annoying* degradation.

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References

[1] Poletti, M. A., “Active acoustic systems for the control of room acoustics,” *Building acoustics*, 18(3-4), pp. 237–258, 2011.

[2] Roskam, F., Laval, J., Corteel, E., and Willsallen, S., “ABBA Voyage: Object-based mixing meets acoustic enhancement,” 2022, presented at IOA Reproduced Sound, Bristol, 17 November.

[3] Kuttruff, H., *Room acoustics*, CRC Press, Boca Raton, FL, 6th edition, 2016.

[4] Berkhout, A., de Vries, D., Hemingway, J., and Griffioen, A., “Experience with the acoustical control system ACS,” in *6th AES International Conference on Sound Reinforcement*, Audio Engineering Society, 1988.

[5] Walter, F. and Melchior, F., “On the measurement of electro acoustic enhanced sound fields,” in *124th Audio Engineering Society Convention*, Audio Engineering Society, 2008.

[6] De Koning, S., “The MCR system-multiple-channel amplification of reverberation,” *Philips Tech. Rev*, 41(1), pp. 12–23, 1983.

[7] Mulder, C., “Variable acoustics using multiple channel amplification of reverberation (MCR),” in *International Congress of Acoustics (ICA) Rome*, volume 5, pp. 384–385, 2001.

[8] Mulder, C., “New parameters for acoustic absorption,” in *35th German Annual Conference on Acoustics (DAGA)*, 2009.

[9] Poletti, M., “A unitary reverberator for reduced colouration in assisted reverberation systems,” in *Proc. INTER-NOISE and NOISE-CON*, pp. 1223–1232, Institute of Noise Control Engineering, 1995.

[10] Poletti, M., “The analysis of a general assisted reverberation system,” *Acta Acustica united with Acustica*, 84(4), pp. 766–775, 1998.

[11] Poletti, M., “The stability of single and multichannel sound systems,” *Acta Acustica united with Acustica*, 86(1), pp. 163–178, 2000.

[12] Lokki, T. and Hiipakka, J., "A time-variant reverberation algorithm for reverberation enhancement systems," in *Proceedings of COST G-6 Conference on Digital Audio Effects (DAFX-01), Limerick, Ireland*, pp. 28–32, 2001.

[13] Schlecht, S. and Habets, E. A., "Reverberation enhancement systems with time-varying mixing matrices," in *59th AES International Conference on Sound Reinforcement Engineering and Technology*, Audio Engineering Society, 2015.

[14] Schlecht, S. J. and Habets, E. A., "The stability of multichannel sound systems with time-varying mixing matrices," *The Journal of the Acoustical Society of America*, 140(1), pp. 601–609, 2016.

[15] Poletti, M. A., "The stability of multichannel sound systems with frequency shifting," *The Journal of the Acoustical Society of America*, 116(2), pp. 853–871, 2004.

[16] Doire, C. S., Brookes, M., Naylor, P. A., De Sena, E., van Waterschoot, T., and Jensen, S. H., "Acoustic environment control: Implementation of a reverberation enhancement system," in *60th AES International Conference on DREAMS (Dereverberation and Reverberation of Audio, Music, and Speech)*, Audio Engineering Society, 2016.

[17] Abel, J. S., Callery, E. F., and Canfield-Dafilou, E. K., "A Feedback Canceling Reverberator," in *Proceedings of the Digital Audio Effects Conference*, 2018.

[18] Meynial, X. and Vuichard, O., "Objective measure of sound colouration in rooms," *Acta Acustica united with Acustica*, 85(1), pp. 101–107, 1999.

[19] Nielsen, J. L., "Detection of coloration in reverberation enhancement systems," in *Proc. INTER-NOISE and NOISE-CON*, pp. 1213–1222, Institute of Noise Control Engineering, 1995.

[20] Watanabe, M., Takayuki; Ikeda, "Objective detection method of sound coloration in electroacoustic enhancement system," in *International Congress on Acoustics*, Buenos Aires, 2016.

[21] Haeussler, A. and van de Par, S., "Crispness, speech intelligibility, and coloration of reverberant recordings played back in another reverberant room (Room-In-Room)," *The Journal of the Acoustical Society of America*, 145(2), pp. 931–944, 2019.

[22] Mohlin, P. and Höstmad, P., "Blind estimation of sound coloration in rooms using chi-square distributions of damping constants," *The Journal of the Acoustical Society of America*, 152(1), pp. 456–469, 2022.

[23] Poletti, M. A., "An assisted reverberation system for controlling apparent room absorption and volume," in *101st Audio Engineering Society Convention*, Audio Engineering Society, 1996.

[24] Bang & Olufsen, "Music for Archimedes," *CD 101*, 1992.

[25] "Methods for subjective determination of transmission quality," *Rec. ITU-T P.800, International Telecommunication Union, Geneva*, 1996.