Artificial enveloping reverberation for binaural auralization using reciprocal maximum-length sequences

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Binaural auralization through proper room-acoustic simulation can produce a realistic listening experience as if the listener were sitting in a room, with spatial perception, including enveloping reverberance. Based on analysis of experimentally measured binaural room-acoustic data, this paper discusses an approach to creating artificial but natural-sounding reverberation for binaural rendering that can be employed in simulating such an environment in an efficient way. Approaches to adjusting the spaciousness of enveloping reverberance within the context of artificially generated reverberation are investigated via hearing tests. This paper exploits the excellent pseudorandom properties of maximum-length sequences to generate deterministic and controllable decorrelations between binaural channels for artificial reverberation for room-acoustic simulations with high computational efficiency. To achieve natural-sounding enveloping reverberance in an enclosed space, and thereby an immersive environment, the shapes of both the reverberation energy decays and the spatial characteristics are found to be decisive. This paper discusses systematic hearing test results that support the mentioned finding.

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I. INTRODUCTION

This paper discusses an approach for creating and adjusting artificial enveloping reverberation for binaural room-acoustic simulation and auralization. Artificial reverberation processes for auralization via room simulations have been actively investigated in recent decades.1–3 Reviews of artificial reverberators using the all-pass-filter approach can be found in Refs. 4–6. More recently, some of the geometrical room-acoustic simulation techniques that are available have been summarized in Ref. 7.

The all-pass-filter-based approach was originally proposed by Schroeder and Logan,8,9 and an artificial reverberation process using convolution of artificial/simulated room impulse responses (RIRs) with anechoic signals, referred to in the present paper as the finite impulse response (FIR) filtering approach, was first proposed by Moorer in 1979.10 In the early 1990s, many room-acoustic simulations based on geometrical acoustics were proposed. One of these was a binaural artificial reverberation process, developed with the aim of reducing the computational load of the simulation.11 In this FIR filtering approach, an exponentially decaying random noise is added to the late part of a room impulse response. When convolved with anechoic sound materials, an artificial reverberation associated with a desired degree of reverberance can be created. For binaural rendering techniques, such as binaural room-acoustic simulations,12,13 an FIR-filter-based artificial reverberation is created by the tails of binaural room impulse responses (BRIRs) based on the addition of exponentially decaying random noise. The decay rates (reverberation times) are determined via the statistical room-acoustic principle or extracted from the early part of detailed room-acoustic simulations. The use of two exponentially decaying random noise samples in the late reverberation tails can create an artificial spatially enveloping reverberation for a binaural rendering without the need for geometrical room-acoustic simulations (e.g., ray-tracing)10,11 with their high computational costs.

This paper discusses a number of advantages of using reciprocal maximum-length sequence (R-MLS) pairs14 to create reverberation tails that lead to natural-sounding enveloping reverberance because the cross-correlation between each R-MLS pair is of deterministically low value. The significance of using R-MLS pairs in comparison with those used in previous work10,11 is that R-MLS pairs (and the related coded sequences) possess predictable highly decorrelated values and are easily generated using a recurrence algorithm without a large memory requirement.

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High decorrelation values correspond to a high degree of spaciousness in the perceived enveloping reverberance. Auditory spreading in response to varied degrees of incoherent noise stimuli has been the subject of previous psychoacoustic investigations. However, the classical study by Jeffress et al. involved an anechoic environment rather than a room-acoustic one and did not consider the reverberation process. An early attempt to understand perceived reverberance in a room-acoustic environment was made by Plenge and Romahn, but they did not deal with the issue of spaciousness adjustment pertaining to the reverberance. With the R-MLS pair approach, in addition to the highest achievable degrees of spaciousness, one can mix two channels of pseudorandom noise to control the decorrelation values of the mixed R-MLS pair for binaural channels so that the degree of spaciousness can also be adjusted independent from the degree of reverberance. This is just one of the practical significances of this approach, since different enclosure conditions will provide different degrees of spaciousness in addition to reverberance. In the present work, based on psychoacoustic investigations, it is demonstrated that simply shaping the decaying envelopes of random noise in the late reverberation tails is insufficient in terms of naturalness and envelopment of the artificial reverberation. Similar to previous work, the present study adjusts the decaying envelope (for controlled reverberance) in individual octave bands, in each of which the target reverberation time shapes the exponentially decaying envelope of the R-MLS pair. However, in contrast to previous work, the interaural decorrelation values of the binaural reverberation tails in the individual bands must also be adjusted to achieve the desired degree of spaciousness (spatial envelopment of reverberance).

This paper briefly describes the procedure of binaural artificial reverberation with controllable spatial envelopment and reverberance. Based on evaluations of experimentally measured BRIRs from five existing performance venues and three worship spaces, the decorrelation values of the reverberation tails are adjusted to create artificial reverberation for natural-sounding enveloping reverberance. Natural-sounding enveloping reverberance is also significant in recent investigations of speech intelligibility in a reverberant environment, as well as in studies of reverberation effects for different musical motifs, loudness, coupled volume systems, and recently developed object-based spatial sound reproduction.

The artificial reverberation approach discussed in this paper was inspired by basic ideas originating from the work of Moorer and Martin et al., but goes further to investigate the spatial cues in the late portion of the reverberation tails based on experimentally measured BRIRs. In addition, this work exploits the key cues related to the naturalness of the enveloping reverberance obtained from hearing tests on eighteen subjects. To the best of the authors’ knowledge, detailed spatial cues as discovered through experimentally measured binaural data have not previously been studied to any great depth in the context of artificial reverberation.

This paper is organized as follows. Section II presents background information on the finite-impulse-response filtering approach for auralization. Section III introduces basic properties of the reciprocal maximum-length sequences pertaining to the creation of artificial reverberation. Section IV presents investigations of experimentally measured data from a number of existing performance venues with the aim of selecting the starting time of the late reverberation tails and analyzing in detail the interaural decorrelations of these tails. Section V discusses subjective tests and results on the issues of naturalness and spaciousness of the enveloping reverberance. Section VI further discusses critical perception issues related to the auditory resolution and sensitivity of enveloping reverberance. Section VII concludes the paper.

II. BASIC PRINCIPLE OF AURALIZATION

Performance venues can be approximated by linear time-invariant systems between sound sources and receivers. RIRs in these venues describe sound transmission from sources to receivers. In the binaural listening situation in particular, BRIRs describe sound transmission through the room, arriving at the two ears of the listener. Sound signals captured in an anechoic environment, which are essentially free from any reflections, are convolved with the BRIRs, which are finite in temporal length. This process, also termed finite-impulse response (FIR) filtering of anechoic sound signals, leads to binaural samples. When these sound samples are rendered properly to the listener’s ears, the listener will experience auditory perception as if they were sitting inside the venue. The recent developments of room-acoustic auralization and virtual auditory reality/display are based on this fundamental principle.

Figure 1 conceptually illustrates an echogram in an enclosure, containing direct sound, early reflections, and a late reverberation tail.

FIG. 1. Conceptual energy impulse response in an enclosure, containing direct sound, early reflections, and a late reverberation tail.
the space. The decaying reflections are hardly perceptually distinguishable, unless there are singular strong echoic reflections significantly higher than the averaged decaying levels. This phenomenon was exploited in the early 1990s to achieve auroralization by means of binaural scale modeling,\textsuperscript{13,27} despite the limited peak-to-noise ratio in the reverberation tails due to the miniature binaural microphone systems then available. On the other hand, in order for realistic reverberance to be perceived, a certain density of late reflections has to be obtained in room-acoustic simulations. Achieving these, even with today’s computer technology, can be a time-consuming procedure. In particular, virtual reality and gaming systems often require rapid, even real-time, changes in room configurations, and any attempt to exactly simulate late reflections in the reverberation tails will become redundant. This is one of the reasons why Martin\textit{ et al.}\textsuperscript{11} proposed a straightforward omission of late reverberation tails in binaural room-acoustic simulation. Instead, they took a pair of random noise signals with decaying envelopes. The random noise pairs thus processed then replace otherwise numerically expensive simulations to complete the full BRIRs. Two random noise signals with decaying envelopes can readily provide the required density in the reverberation tails. They do need to be largely incoherent mutually, in order to achieve a given perpetual degree of spaciousness. Martin\textit{ et al.}\textsuperscript{11} also discussed a possible way to control the different degrees of spaciousness.

III. MAXIMUM-LENGTH SEQUENCES FOR BINAURAL REVERBERATION

This paper proposes a special class of pseudorandom noise, a so-called bipolar maximum-length sequence (MLS), to create artificial reverberation tails of BRIRs. This section briefly reviews a special type of MLS pair. A mixing network is employed for adjusting the degree of spatial cues in the artificial reverberation tails.

A. Reciprocal MLS pairs

An \( n \)-stage linear feedback shift-register device can generate a binary periodic sequence of maximum length \( 2^n - 1 \). Numerically, a linear recurrence can easily generate binary MLSs.\textsuperscript{28} MLSs exhibit a number of attractive random properties as found in random noise, yet they are deterministic within one sequence period. Summaries of the pseudorandom properties of the MLSs and their related sequences in the context of acoustical applications can be found in Refs. 3 and 29.

When the MLSs are bandpass-filtered, they become pseudorandom Gaussian-distributed noise. Figure 2 compares the time-domain signals and magnitude spectra of a (1 kHz) octave bandpass-filtered MLS of period length 8191 points and a Gaussian noise of length 8192 points, generated at a sampling frequency of 48 kHz. (a) Octave bandpass-filtered MLS and Gaussian noise in the time domain. (b) Probability density distribution function of the MLS as shown in (a) along with its Gaussian function. (c) Probability density distribution function of the Gaussian noise as shown in (a) along with its Gaussian function.

The artificial reverberation tails are derived from the sum of individual bandpass-filtered MLS pairs, followed by processing stages discussed below, since RIRs, partic-
Most importantly, any given MLS leads to a time-reversed copy of itself, the reciprocal MLS (R-MLS), through an appropriate decimation. This R-MLS pair possesses considerably low cross-correlation, or corresponding high decorrelation, values. This paper uses normalized decorrelation coefficients throughout, corresponding to the complementary value of the normalized cross-correlation coefficients between each pair of R-MLSs. Xiang applied this special type of MLS to different measurements of simultaneous dual and multiple acoustic source channels. Table I lists the lowest bounds on the decorrelation coefficients of R-MLSs between 2\(^{-14}\) and 2\(^{-1}\) points. Hardly any other “decorrelated” random noise pairs can reach such high decorrelation values, except for a few MLS-related sequences such as Gold sequences and Kasami sequences. For applications to artificial binaural reverberation, most R-MLS pairs are able to provide interaural decorrelation coefficients (IADCs) as high as 0.98. The IADC is positively correlated with the spatial extent of spaciousness. MLSs of degrees between 14 and 20 are sufficiently long for most room-acoustic reverberation applications, with time record lengths ranging from 0.37 to 24 s at a nominal sampling frequency of 44.1 kHz.

**TABLE I. Lowest bounds of decorrelation coefficients of reciprocal maximum-length sequence (R-MLS) pairs of degree \(n = 14 - 20\), with their length being determined by \(2^n - 1\) points. Time record lengths of the given R-MLSs at a sampling frequency of 44.1 kHz are also given.**

<table>
<thead>
<tr>
<th>Degree</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (points)</td>
<td>16383</td>
<td>32767</td>
<td>65535</td>
<td>131071</td>
<td>262143</td>
<td>524287</td>
</tr>
<tr>
<td>Decorrelation</td>
<td>0.9844</td>
<td>0.9890</td>
<td>0.9922</td>
<td>0.9945</td>
<td>0.9961</td>
<td>0.9972</td>
</tr>
<tr>
<td>Time length (s)</td>
<td>0.37</td>
<td>0.74</td>
<td>1.49</td>
<td>2.97</td>
<td>5.94</td>
<td>11.89</td>
</tr>
</tbody>
</table>

**B. Temporal and spatial attributes of reverberance**

At least two perceptual attributes of reverberance are relevant for room-acoustic simulations and auralization. First of all, there is the temporal attribute of the reverberance. Aural perception of reverberance is directly associated with acoustic reverberation due to temporally decaying processes of finite duration, particularly in an enclosed environment containing reflecting surfaces or objects. The temporal characteristics of the reverberation are largely attributable to the reverberation/decay time associated with the late reverberation tails. Arguably, both early decay time and reverberation time\(^{12}\) can be associated with perceptual reverberance. In the current context of artificial reverberation tails, direct sound, early reflections, and even the early portion of the reverberation process are of less concern. These can be accurately created either through binaural room simulations\(^{15}\) or from experimental measurements, such as by binaural scale modeling.\(^{12,27}\)

Second, the perceived reverberance also has distinct spatial attributes. In a common listening experience, a mono reverberant sound sample is rendered diotically to the ears of a listener, who will often perceive the associated reverberance as spatially confined, if not localized “in the head.” On the other hand, when a listener is sitting in a performance venue, such as a concert hall, through auralization in a binaural room simulation of such a venue, the perceived auditory reverberance appears to be spatially surrounding, significantly outside the listener’s head, with a spatial extent that depends on the type of venue and the location of the receiver. In the room-acoustics literature, this attribute is referred to as envelopment, or late envelopment in the present case, and has been extensively studied by Griesinger.\(^3\) The enveloping reverberance represents the spatial attribute of the auditory reverberance. The different spatial extents of auditory envelopment are well described as different degrees of auditory spaciousness of the reverberance and are associated with the enveloping reverberance. Both temporal sustaining characteristics and spatial envelopment are intrinsic attributes of auditory reverberance. Note that spatially localized, yet non-enveloping, reverberance may occur. An example is provided by a more absorptive space next to a door that opens into another distinctly more reverberant room, such as is often found in coupled volume systems.\(^{24}\) This non-enveloping reverberance is, however, beyond the scope of the current discussion.

The spatial extent, namely, the spaciousness of the enveloping reverberance in a binaural listening situation, in binaural room simulations is largely attributable to interaural decorrelation of the reverberation tails of the BRIRs. A high degree of spaciousness corresponds to a high interaural decorrelation coefficient (IADC). This is why IADC is used as a physical quantifier throughout this paper.

**C. Mixing network for adjusting decorrelations**

High IADCs are beneficial in creating a high degree of spaciousness of the enveloping reverberance. A classical psychoacoustic experiment using stationary broadband noises by Jeffress et al.\(^{15,34}\) is worth mentioning here before we discuss spacious enveloping reverberance in the room-acoustic context. A concise summary of this experiment and its results can be found in Blauert’s book on spatial hearing.\(^{20}\) When the coherence or degree of interaural cross-correlation of two noise signals fed into a subject’s two ears was adjusted, the auditory event of the stationary noise changed the extent of the relatively confined region, although sharply localized auditory boundaries were not identifiable. The fundamental difference between the present work and previous studies is that here the focus is on perception of room reverberance. The
A lower degree of spaciousness associated with the reverberance can be obtained in the current approach using the mixing network depicted in Fig. 3 between A and B (see also Refs. 3, 11, and 36 for a similar utilization of this network, differing significantly from that used by Jeffress\textsuperscript{15,34}). One bandpass-filtered pair of R-MLSSs is additively mixed to the opposite channel by an attenuating factor of $0 \leq \chi_k \leq 1.0$ within the $k$-th octave band. For $\chi_k \rightarrow 0$, the bandpass-filtered R-MLSS pair still possesses a high value of interaural decorrelation, as intrinsically given by the R-MLSS pair as listed in Table I. For $\chi_k \rightarrow 1$, the two channels of bandpass-filtered R-MLSSs approach an identical, zero-decorrelated, value.

After mixing of the bandpass-filtered MLS pair, the two time signals from each channel are multiplied by an exponentially decaying envelope

$$E(t) = \exp\left(-\frac{6.9}{T_k} t\right),$$

where $T_k$ is the reverberation time within the $k$-th octave band. This envelope controls the temporal attribute of the reverberance. At either the bandpass-filter stage or the exponential-decay stage, two multiplicative factors $\beta_{L,k}$ and $\beta_{R,k}$ provide the possibility of adjusting the resulting artificial reverberation tails $h_{L(k)}$ and $h_{R(k)}$ for the left and right channels. In this way, the artificial reverberation tails can be created for varied IADCs while keeping the reverberation times constant, or vs. In other word, when convolving music or other useful anechoic signals with the binaural room impulse responses featuring so created artificial reverberation tails, two separate stages in this network enable a varied degree of enveloping spaciousness while keeping the reverberance constant in the perceived space, or a varied degree of reverberance while keeping the enveloping spaciousness constant. The individual reverberation tails over all octave bands of interest are then summed together to generate the resulting binaural reverberation tails.

IV. EXPERIMENTAL EVALUATIONS OF BINAURAL DECORRELATIONS

Previous studies\textsuperscript{10,11,13} have used the reverberation/decay times to control the decaying envelopes of the reverberation tails. Martin \textit{et al.}\textsuperscript{11} proposed using the interaural cross-correlation coefficient (IACC) to dictate the mixing of the artificial reverberation tails. To date, no strategy has been presented to determine which interaural decorrelation coefficients across individual frequency bands are to be used for binaural simulation of artificial late reverberation. To deal with this issue, the present study proceeds to analyze experimentally acquired RIRs measured in a number of performance venues, including the Troy Savings Bank Music Hall, the Boston Symphony Hall, the Concert Hall in the Experimental Media and Perforating Arts Center (EMPAC) at Rensselaer polytechnic Institute (RPI), and three other middle-sized performing arts venues and two worship spaces near the RPI campus, including a number of places of worship. This section describes some representative results for the late interaural decorrelation coefficients (L-IADCs) over octave bands.

A. Time limit of late reverberation tails

The starting time for the late reverberation is critical for the present study. Classically, concert hall acoustics has adopted 80 ms as a time limit for clarity indices,\textsuperscript{32,37} although that limit has recently been revised.\textsuperscript{38} In contrast, the present approach adopts a time at which there will be no significant change in the key feature, namely, the normalized L-IADCs of the late portion of the reverberation tails in BRIRs. The normalized IADC is defined as

$$\text{IADC} = 1 - \max[\text{IACF}(\tau)],$$
where the interaural cross-correlation function\(^{32}\) (IACF) is defined as

\[
\text{IACF}(\tau) = \frac{\sum_{k=t_1}^{t_2} h_L(k) \sum_{k=t_1}^{t_2} h_R(k + \tau)}{\sqrt{\sum_{k=t_1}^{t_2} h_L^2(k) \sum_{k=t_1}^{t_2} h_R^2(k)}}, \tag{3}
\]

with \(-1 \text{ ms} \leq \tau \leq +1 \text{ ms}, t_2\) is the upper limit of the BRIIRs \(h_L\) and \(h_R\), and \(t_1\) is the time limit addressed in the following discussion.

The starting time for the reverberation tails depends on the location within the venue under consideration. The present work deals with binaural room simulation and rendering. The interaural decorrelations of the late reverberation tails in the BRIIRs are experimentally evaluated for five existing performance venues and three worship spaces. Hidaka \textit{et al.}\(^{38}\) challenged the classical time limit of 80 ms for musical performances\(^{32}\) and proposed a limit in the range 90\textendash}120 ms. In the present study, the time limit \(t_1\) is selected based on the criterion that there be no significant variations in the L-IADCs of the late reverberation tails, because the artificial reverberation tails for each frequency band must be assigned a fixed L-IADC value using the mixing network shown in Fig. 3.

Systematic evaluations of the late interaural decorrelations of experimentally measured BRIIRs in a number of performance venues are performed using the start limit \(t_1\) as one adjustable parameter. Figure 4 illustrates one group of representative results. The interaural decorrelation coefficients are calculated from the start time limit \(t_1\) until the end of the experimentally measured BRIIRs, with \(t_1\) changing from 80 to 105 ms. A time limit ranging from 90 to 100 ms has been found at a number of strategic seat locations within the halls. Note that this group of evaluations is carried out using experimentally measured binaural room impulse responses over refined (one-third octave) frequency bands as shown in Fig. 4(a), taken from one specific (representative) seat. Although the IADC curves may vary from seat to seat, the time limit \(t_1\) lies in the 90\textendash}100 ms range, beyond which the IADC will not change significantly. This is also true for bandpass analysis at octave-band resolution. This range agrees with those found in other work studying related issues associated with BRIIRs.\(^{36,39}\)

Beyond this limiting time, the reverberant reflections are conceivably coming from statistically uniform incident directions. The binaural room simulation should provide results up to this time limit, while the proposed approach to mixing and processing of the R-MLS pair provides the artificial reverberation tails after this time limit.

**B. Frequency characteristics of late interaural decorrelation**

From the time limit \(t_1 = 90\) ms until the end of the experimentally measured BRIIRs in a number of performance venues, the L-IADCs of the late reverberation tails are evaluated. A single sound source with three channels and covering a frequency range between 50 Hz and 18 kHz is used, while an artificial head (HEAD acoustics, HMS II) is used as the binaural receiver, with a sampling frequency of 48 kHz. Figure 4(b) presents some representative IADC curves over octave bands. Experimental evaluations at a number of different seat positions show different trajectories of the L-IADC curves. The curves represent averaged trends of the L-IADC as a function of frequency at measured positions. In the low-frequency range, the overall L-IADCs have low values, but increase with increasing frequency. In other words, the binaural late reverberation tails from 90 ms until the ends of the BRIIRs are less uncorrelated in the low-frequency range, while they become increasingly uncorrelated at higher frequencies.

Note that even though a one-third octave-band analysis provides a more detailed resolution of values over the audio-frequency range, the basic trends are similar. Some hearing tests have also been conducted to confirm the results in terms of spatial enveloping reverberance. The perceptual differences among filter types (octave and third-octave, as well as critical bands) are insignificant.
The reverberation tails often exhibit different lengths, depending on room-acoustic conditions. Therefore, different MLS degrees ranging from 14 to 20 can be adopted to match approximately the reverberation tails for most conceivable applications at a given sampling frequency. Since each increase in the degree of the R-MLS pair will double the total length of the sequences, it is straightforward to find a suitable length/degree of the R-MLS pairs, even though it might be slightly longer than needed, and the exponential decay of the envelope will ensure that the values of the reverberation tail envelope will be negligibly small. As in Fig. 3, the R-MLS pairs are first bandpass-filtered, but the resulting bandpass-filtered pseudorandom noise pairs are still highly decorrelated, even when the tail lengths are taken to be shorter than the MLS lengths ($2^n - 1$ points, with $n$ being the MLS degree). Taking 8kHz octave bandpass-filtered R-MLS pairs as examples [see the similar time trace illustrated in Fig. 2(a)], Table II lists the lower bounds on the values of the decorrelation functions for MLS degrees ranging from 15 to 19. For a given MLS degree, only a portion of the pseudorandom noise is taken from the entire R-MLS noise pairs. To be more precise, the lengths of the bandpass-filtered pseudorandom noise pairs are taken from 0.55 to 1.0 of the total length of the respective MLS length/degree, with a step value of 0.05. If a factor 0.50 of the total length of one R-MLS pair needs to be adjusted for the desired reverberation tails, then MLS pairs of one degree lower will be used. Note that these decorrelation values of bandpass-filtered R-MLS pairs in the 8kHz octave bands are slightly lower than those from the broadband R-MLSs, and the resulting lower bounds on the decorrelation functions vary consistently within small ranges as listed in Table II. Since the IADC values decrease toward lower frequencies (see Fig. 4), these decorrelation values are sufficiently high to allow any desired low values of IADCs to be achieved using the mixing network shown in Fig. 3.

V. HEARING TESTS FOR NATURALNESS AND SPACIOUSNESS

The experimental evaluations of the L-IADCs in the late portion of BRIRs briefly discussed in the previous section shed light on the frequency characteristics associated with the spatial attribute of enveloping reverberance. This section discusses a series of hearing tests to validate the naturalness and adjustability of the spaciousness associated with enveloping reverberance created using R-MLS pairs with the specified frequency characteristics. Altogether, eighteen subjects ranging in age from 21 to 43 years participated in the tests. Fifteen of the subjects had a background in acoustics and the other three a musical background. All subjects were pre-screened by standard audiometry to confirm their normal healthy hearing.

A solo 5s musical excerpt of piano playing (from Chopin’s Nocturnes, Op. 9) was chosen as the anechoic sound to be convolved with all BRIRs. The excerpt consisted of smoother (legato) playing, impulsive chords and notes, followed by silence. The purpose of choosing a short musical piece was to assist the participant in making comparisons—more specifically to help the participant to accurately retain their memory of the perceived spaciousness of the previous musical sample.

<table>
<thead>
<tr>
<th>Portion of MLS length</th>
<th>Degree 15</th>
<th>Degree 16</th>
<th>Degree 17</th>
<th>Degree 18</th>
<th>Degree 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55–1.0</td>
<td>0.9852–0.9888</td>
<td>0.9887–0.9914</td>
<td>0.9923–0.9952</td>
<td>0.9960–0.9971</td>
<td>0.9969–0.9981</td>
</tr>
</tbody>
</table>

For systematic hearing tests, the experimentally measured BRIRs are convolved with anechoic music signals, and these convolved sound samples are taken as the reference, while the artificially created BRIRs use the early portion of the experimentally measured BRIRs to which artificially generated reverberation tails are appended. As indicated in Fig. 4, the limit time is taken at 90ms, and the artificial reverberation tails using one
R-MLS pair of 65,355 points (degree 16) are shaped in the individual octave bands by the same frequency-dependent reverberation times and the same L-IADCs as those measured experimentally (see Fig. 5). Figure 6 illustrates the artificially generated reverberation tails appended to the experimentally measured BRIRs in the Troy Savings Bank Music Hall, with the specific L-IADC spectrum as shown in Fig. 5. The direct sound and the early portion up to 90 ms are taken to be those measured experimentally. The only difference lies in the reverberation tails, which, for all but one pair, are created using the R-MLS pair. The exception is a single reference pair, which is composed solely of experimentally measured data. When adjusting the $\beta_k$ values in Fig. 3, the resulting BRIRs are checked using Schroeder integration to the artificial reverberation tails. The only difference lies in the reverberation tails, which, for all but one pair, are created using the R-MLS pair. The exception is a single reference pair, which is composed solely of experimentally measured data. When adjusting the $\beta_k$ values in Fig. 3, the resulting BRIRs are checked using Schroeder integration to the artificial reverberation tails.

FIG. 6. (Color online) Artificially generated reverberation tails appended to the early portion of the binaural room impulse responses measured in the Troy Savings Bank Music Hall. The late portion of the reverberation tails after 90 ms are replaced by the reciprocal maximum-length sequence pair of 65,355 points (degree 16), with the appropriate decay rates and interaural decorrelation coefficients shown in Fig. 5.

A. Naturalness of the reverberance

To validate the hypothesis that the artificial reverberation tails mimic the L-IADC spectra in creating a naturally sounding enveloping reverberance, the hearing tests take the experimentally measured BRIRs convolved with music signals as reference, while the L-IADC spectra of sound samples created artificially in the reverberation tails are adjusted. The adjustment closely follows the same L-IADC spectra that is found in the late portion of the experimentally measured BRIRs.

Furthermore, if only the temporal characteristics are individually adjusted in the artificial reverberation tails as reported in previous work, and the interaural decorrelations are not individually matched to the specific characteristics, but rather mixed in a broadband manner, then the interaural decorrelations will exhibit spectra with higher L-IADC values toward lower frequencies and slightly lower values, but flat, toward higher frequencies, as shown in Fig. 5. The hearing tests also include artificial reverberation with unmatched L-IADCs. The broadband L-IADCs amount to 0.42, after mixing with $\chi = 0.3$ using the mixing network in Fig. 3, and the individual L-IADCs over the frequency range between 63 Hz and 8 kHz exhibit spectra like those indicated by dotted lines in Fig. 5 (particularly the one labeled $\chi = 0.3$).

For the hearing tests, binaural samples from convolution with the BRIRs experimentally measured at a single source–receiver location in the Troy Savings Bank Music Hall are taken as the reference. A broadband source sound system covering the frequency range between 50 Hz and 18 kHz is positioned in the middle of the stage, while the artificial head is on the main floor at Seat 5G, facing toward the sound source.

Two different artificial reverberation tails are created. One pair of artificial reverberation tails is appended to the early portion of the measured BRIRs. These artificial tails contain the matched temporal decay characteristics based on the reverberation times obtained by analyzing the experimentally measured values and the spatial characteristics based on the L-IADCs. The matching adjustment is conducted as close as possible to the analyzed values of both the reverberation times and the L-IADCs over the frequency range between 50 Hz and 12 kHz. The reference BRIRs are also bandpass-filtered between 50 Hz and 12 kHz to match the frequency range under test as closely as possible. Another set of artificial reverberation tails is derived that match the temporal characteristics only via the reverberation times. No individual L-IADCs are adjusted, but a broadband mixing with $\chi \approx 0.3$ is used for achieving an overall L-IADC of about 0.42 (see Fig. 5).

This group of hearing tests relies on preference tests via A–B comparisons. The subjects are given the task of comparing pairwise binaural hearing samples via a pair of equalized headphones between matched and unmatched samples derived from the artificial reverberation tails. One pair of samples (A–B) is randomly played across all 18 subjects. For each randomized pair, subjects can switch back and forth as many times as needed for repetitive listening between Sample A and Sample B. At the same time, the subjects also have the opportunity to click a reference button provided by the user interface to listen to a reference sample derived from convolution of the experimentally measured BRIRs. The subjects are instructed to pay attention only to the perceived reverberance and to choose which one of three options (Sample A, Sample B, and No Perceived Difference) seems to sound closest to a naturally sounding reverberance. The instruction states that the sound sample associated with the naturally sounding reverberance can be activated through the reference button. Figure 7(a) illustrates the hearing test results from the eighteen subjects, which suggest a clear preference for the matched rever-
FIG. 7. (Color online) Preference tests using (a) hearing samples of the matched and unmatched spatial characteristics and (b) hearing samples derived from measured natural and artificial reverberation tails with interaural decorrelation coefficients that increase with increasing frequency as shown in Fig. 5.

beration tails. Specifically, the binaural reverberations created artificially using the R-MLS pair appear to be more natural when the interaural decorrelation characteristics found in the measured BRIRs are realized in the artificial reverberation tails. When the temporal characteristics are shaped via the reverberation times in individual octave bands, without matching of the individual L-IADCs, the artificial reverberance is clearly less preferred, even though the temporal attributes of the reverberance might sound similar. 11.11% of subjects express no perceived difference, which is presented as uncertainties in form of standard deviations on either of two results.

The second group of hearing tests aims to establish whether or not the previously mentioned temporal and spatial adjustments to the artificial reverberation tails have succeeded in generating a naturally sounding reverberance. One sample is derived from convolution of the experimentally measured BRIRs from the Troy Savings Bank Music Hall with the artificial head at Seat 5G facing the sound source on the stage, while the other sample is derived from the early portion (up to 90 ms) of the same experimentally measured BRIRs, but with the artificial reverberation tails appended to the early BRIR portion with matched temporal and spatial characteristics as close as possible to those from the experimentally measured BRIRs. The subjects are presented binaurally with two sound samples, which can be switched back and forth as many times as needed. The subjects are instructed that one sound sample, among each pair of two samples, is definitely derived from the naturally measured BRIRs, although it appears in a random manner. One pair of these samples (A–B) is randomly played across all 18 subjects. The subjects are instructed to pay attention to the perceived reverberance and are asked to give a preference to the one that sounds more natural to them. Similarly, they have the option of choosing one of the three options (Sample A, Sample B, and No Perceived Difference). Figure 7(b) illustrates the hearing test results. The subjects’ preference for the natural reverberation tails amounts to 44.4%, whereas 33.3% of subjects prefer the artificial reverberation tails, and 22.2% express no preference for either, which is presented as uncertainties in form of standard deviations on either of two results. When adding the half of those subjects choosing ”No Perceived Difference,” as one-side standard deviation to either of two results, there is a small difference between the two groups, 55.5% versus 44.4%, indicating that the artificial reverberation tails created using the specifically matched L-IADC spectra lead to a perceptually natural-sounding reverberance.

B. Spaciousness adjustment of enveloping reverberance

The results of the hearing tests discussed above suggest that the naturalness of artificial reverberance can be improved when the L-IADC spectra replicate those found in a large number of evaluations of the experimentally measured BRIRs. The L-IADC spectra exhibit an overall increase with frequency over the audio-frequency range. In room-acoustic simulations, it is also of practical interest to adjust the degree of spaciousness of the enveloping reverberance. Inspired by previous work,11 this study also investigates the adjustability of the spaciousness of the enveloping reverberance for different values of the L-IADCs using the mixing network described in Sec. III C. In the following hearing tests, the L-IADC spectrum used for the adjustable spaciousness is taken from the experimentally measured BRIRs in the Troy Savings Bank Music Hall as shown in Fig. 5, but with a modification at high frequency (8 kHz) as shown in Fig. 8 to make the L-IADC spectra increase monotonically with frequency, similarly to the spectra shown in Fig. 4(a). In this way, any desired L-IADC values can be specified using the maximum value of the L-IADCs, in this case at 8 kHz. For example, the L-IADC spectrum labeled as Spectrum 3 in Fig. 8(a) has an L-IADC value of 0.99 at 8 kHz. The application of a single factor sets the spectrum to the L-IADC value of 0.5 at 8 kHz, labeled as Spectrum 2 in Fig. 8(a). In order to achieve high values of the L-IADCs, R-MLS pairs are proven to have the advantage of generating artificial reverberation tails for any L-IADC values lower than 0.99 using the mixing network in Fig. 3 in a well-controlled manner.
The study begins with the highest L-IADCs, which are then gradually decreased, but with the overall shape of the L-IADC spectra remaining unchanged. The hearing tests conducted here are intended to quantify the relationship between the physical measurements in the form of the L-IADCs and the perceived auditory extents of the enveloping reverberance. The hearing tests offer each subject the chance to choose the hearing sample associated with the greater extents of the perceived enveloping reverberance via an A-B comparison in a randomized manner. The subject again has to choose among three options (Sample A, Sample B, or No Difference). Three different spatial incremental groups are tested in Spatial Group I, dealing with two pairs (Spectrum 1 vs. Spectrum 2, and Spectrum 2 vs. Spectrum 3), Spatial Group II, with three pairs, and Spatial Group III, with four pairs, as illustrated in Fig. 8(a)–8(c), respectively.

For Pair 3 of Group II in Fig. 8(b) and Pair 4 of Group III in Fig. 8(c), the artificial reverberation tails are appended to the BRIRs of the first 90 ms portion experimentally measured in the Troy Savings Bank Music Hall, in similar way to those in the previous hearing tests. Since this study deals with room-acoustic simulations, the other early portions of the BRIRs are simulated using CATT Acoustic software to create “Medium” and “Small” rooms for the artificial reverberation tails to be appended. Of interest in the current context are the estimated reverberation times and the interaural decorrelation coefficients (E-IADCs) of the early portion of the BRIRs simulated for the small and medium rooms as listed in Table III and the measured values in the Troy Savings Bank Music Hall (taken as a “Large” room). The maximum values of the E-IADCs of two simulated rooms amount to 0.16 and 0.5 for small and medium rooms, respectively, while the reverberation times at 1 kHz (oct.) estimated from the early portion of the simulated BRIRs amount to 0.95 s and 1.4 s, respectively. The reverberation time at 1 kHz (oct.) and the maximum E-IADC of the Troy Savings Bank Music Hall amount to 2.0 s and 0.83, respectively.

Table III also lists three groups of hearing tests in A-B comparison pairs. Spatial Group I contains two pairs (Pair 1 and Pair 2). Each has the same early portion of the BRIRs from a simulated “Medium” hall. The artificial reverberation tails generated using R-MLS pairs are featured with the same temporal characteristics, but with two different values of L-IADC. Figure 8(a) shows their L-IADC spectra. In a similar fashion, Group II implements the L-IADC spectra for three pairs as shown in Fig. 8(b), where Pair 1 and Pair 2 employ the early-portion BRIRs of the simulated “Small” and “Medium” rooms, respectively. Pair 3 is derived from the same early portion of the experimentally measured BRIRs in the Troy Savings Bank Music Hall. Similarly, Pair 4 in Spatial Group III employs the early portion of the ex-

<table>
<thead>
<tr>
<th>Room type</th>
<th>Small room</th>
<th>Medium hall</th>
<th>Large hall</th>
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<td>Early BRIR</td>
<td>Simulated</td>
<td>Simulated</td>
<td>Measured</td>
</tr>
<tr>
<td>Decay time</td>
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<tr>
<td>Maximum E-IADC</td>
<td>0.16</td>
<td>0.5</td>
<td>0.83</td>
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**TABLE III.** Halls used for the hearing test pairs of three different spatial groups.

FIG. 8. (Color online) Spectra of late interaural decorrelation coefficients: (a)–(c) Two, three, and four pairs of L-IADC spectra for Spatial Groups I, II, and III.
Figure 9 illustrates the results of the hearing test intended to quantify the perceptual attributes of spaciousness extent with respect to the physical parameters. The horizontal axes represent L-IADC values of the artificial reverberation tails in the physical domain, while the vertical axes represent the perceptual extent of the enveloping spaciousness. If 100% of subjects associated the hearing sample with the reverberation tails of, say, Spectrum 3 to be larger than that associated with Spectrum 2, then the perceptual measure represented by the arrow would be aligned with the diagonal (solid) line, projected to the vertical axis, resulting in the greatest increase in the perceptual domain. A perceptual measure represented by an arrow aligned with the horizontal dotted line would indicate that 50% of subjects believed that the sample associated with the reverberation tails of the larger L-IADC value is of greater extent than that associated with the smaller L-IADC value. In other words, these hearing test results (around 50%) fail to associate the larger L-IADC spectrum of the reverberation tails with a greater extent of auditory spaciousness, which is manifested by the fact that the perceptual measure represented by the arrow is projected onto the vertical axis with no perceptual increase. The variation bars represent the percentage of the subjects who choose “No Difference” during the hearing tests.

Figure 9(a) illustrates the results for Spatial Group I, which contains two pairs of different L-IADCs in the reverberation tails. For example, Pair 2 compares the perceptual extent of enveloping reverberance associated with L-IADC values of 0.99 compared with 0.5, corresponding to Spectrum 3 versus Spectrum 2 in Fig. 8(a). In this spatial group illustrated in Fig. 9(a), for Pair 1, according to 78.2% of the subjects, the perceived spaciousness associated with the reverberation tail of the L-IADC Spectrum 2 is larger than that associated with Spectrum 1. For Pair 2, 73.1% of the subjects believe that the perceived spaciousness associated with the reverberation tail of the L-IADC Spectrum 3 is larger than that associated with Spectrum 2. Similarly, Fig. 9(b) illustrates the Spatial Group II results for three comparison pairs with four different L-IADC values, while the corresponding L-IADC spectra are shown in Fig. 8(b). The results are 67.6%, 64.8% and 61.1% for Pair 1, Pair 2, and Pair 3, respectively. Different spatial extents of enveloping reverberance seem to be distinguishable, with a clearly decreased degree in comparison with Spatial Group I, giving the largest spatial difference. Finally, Fig. 9(c) shows the Group III results for four comparison pairs with five different L-IADC values. The corresponding L-IADC spectra are shown in Fig. 8(c). The results are 53.7%, 52.8%, 50.0%, and 49.1% for Pair 1, Pair 2, Pair 3, and Pair 4, respectively. The subjects are unable to distinguish any increase in spaciousness among the comparison pairs.

Experimentally measured BRIRs in the Troy Savings Bank Music Hall, while Pair 1 employs that of the simulated “Small” room. Pair 2 and Pair 3 employ that of the simulated “Medium” room. The three spatial groups of hearing samples are presented to the 18 subjects in a single test session consisting of a total of 54 pairs in randomized manner. This is because a total of 18 pairs of the three spatial groups (including reversed-order pairs) are presented three times to each subject in random manner.
VI. DISCUSSION

According to a large number of experimentally measured BRIRs of existing spaces, the limiting time beyond which L-IADC values will not change significantly ranges from 90 to 100 ms. Most binaural listening samples used in the hearing tests here are based on a limiting time of 90 ms. In many room-acoustic simulations, the limiting time does not have to be exactly within the range 90–100 ms. As a general rule to guide the room simulation strategy, it can be much longer, say 110 ms, to facilitate the initial use of geometrical or wave acoustics to simulate the space under consideration, after which the artificial reverberation tails proposed in this paper can be applied. Conversely, a specific application may require less simulation accuracy, and the limiting time can then be chosen to be much shorter than 90 ms. The longer the limiting time, the higher the computational costs have to be driven.

In a room-acoustic environment, particularly with regard to the spatial attributes of enveloping reverberance, auditory sensitivity to the spatial extent of perceptual envelopment seems to be rather low. Subjects should be instructed to pay attention to a single aspect of auditory perception, namely, perceived reverberance during subjective tests. Based on a natural reference derived from measured BRIRs, sound samples using artificial reverberation tails can be compared and judged on their "naturalness." The hearing test results in Fig. 7(a) seem to reveal that the artificial reverberation tails created for matching the detailed spatial characteristics of binaural artificial reverberation using the R-MLS pair leads to a more natural-sounding envelopment of binaural reverberance in the context of room simulations. Elevated IADCs in the low-frequency range or flat IADC spectra seem to appear unnatural to the human auditory system.

On the other hand, in the A-B comparison of hearing samples with two different L-IADC values in the artificial reverberation tails, with the early portion of the BRIRs kept the same, subjects are asked to choose whether the spaciousness extent is "more spatial" or "less spatial."

The human auditory system seems to be able to resolve the degree of spaciousness of enveloping reverberance with only rather low resolution. The spaciousness of the enveloping reverberance as adjusted by changing the L-IADC from 0.05 to 0.99 for typical spectra can only be perceived as no more than 3 different degrees. Due to highly limited auditory resolution of the human hearing system pertaining to the enveloping spacious reverberance, spaciousness of enveloping reverberance is intrinsically lacking spatial boundaries in the auditory space, therefore, one choice of no difference in the above discussed hearing tests has been considered indicative and important. 'No difference' between the natural samples and the matched IADC spectra in the reverberation tails (Test II) is desirable. The test results in Fig. 7(b) also demonstrate small differences which indicate that matched L-IADC spectra in the artificial reverberation tails succeed to mimic the natural ones. On the other hand, if the L-IADC spectrum steps become sufficiently small as Fig. 8(c) show, the hearing tests clearly indicate that the human auditory system fails to distinguish small differences in enveloping spaciousness as in Fig. 9(c). This type of psychoacoustic experiments do expect no difference from the beginning of the hearing tests, until no difference cases are found. The results illustrated in Figs. 9(b) and 9(c) may also hint at just noticeable differences in the spatial extent of enveloping reverberance associated with late reverberation when the L-IADC value is altered in the range from 0.25 to 0.33. Conceivably, there may also be a dependence here on the specific nature of the sound or music. More systematic investigations are left for future research.

VII. CONCLUDING REMARKS

This work proposes the use of reciprocal maximum-length sequence (R-MLS) pairs for generating artificial reverberation tails of binaural room impulse responses (BRIRs). This approach can be applied to binaural room simulation and auralization. The R-MLS pairs possess deterministically high decorrelation values. They are easy to generate and can be used for binaural reverberation tails with any low values of interaural decorrelation coefficients (IADCs) in individual frequency bands using a simple mixing network as discussed in Sec. III. Two distinct temporal and spatial attributes are associated with enveloping reverberance. The temporal attribute is dictated by exponential decay rates. The evaluation of the reverberation tails of experimentally measured BRIRs described in Sec. IV reveals that the late BRIR portions exhibit a specific spectral shape for the interaural decorrelation coefficients (L-IADCs), with an increasing trend with frequency within the audio-frequency range. The subjective tests discussed in Sec. V confirm that this specific spectral shape is crucial for the creation of naturally sounding enveloping reverberance. By maintaining this spectral shape by suitable adjustment of overall IADC values, different spatial extents of the enveloping reverberance can be achieved. The systematic hearing tests described in Sec. V.B reveal that the human auditory system can distinguish no more than 3 degrees of spaciousness in the enveloping reverberance.

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