Double Sloped Decay: Subjective Listening Test to Determine Perceptibility and Preference

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Double Sloped Decay: Subjective Listening Test to Determine Perceptibility and Preference

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ABSTRACT
Can music listeners, both experienced and inexperienced, distinguish a double-sloped decay from a Sabine decay? Do they prefer the double slope? A simulated space, based on an actual built coupled-volume hall, was conceived in room acoustics software to create double sloped and classic Sabine auralizations. The simulated decays were compared with in situ measurements taken in a built coupled volume concert hall for validation. The impulse responses generated were convolved with an anechoic musical recording, grouped in pairs, and played for subjects. Participants listened to the recorded pairs over headphones and were asked to determine (1) if the two recordings sounded different, (2) which recording was more likely to have a double slope or had a more dramatic double slope, and (3) which of the two recordings they prefer. The more a recording diverged from a standard Sabine decay, the more likely the respondents were to identify that recording as having a double slope. When asked to identify a preference, subjects were no more likely to select a recording with a double-sloped decay, than a Sabine decay.

1. INTRODUCTION

The *phenomenon* of double slope decay is well documented [1,2,3]. Researchers are currently exploring it as a *tool* to provide listeners in concert halls with a measure of simultaneous clarity and reverberance [4,5]. Yet little published research exists examining the double slope as a *value*.

For this study, ray-tracing software was used to model a coupled volume concert hall, with apertures that regulated the acoustic coupling between the main hall and a coupled volume. Varying the aperture size yielded varying decay patterns, many of them with an observable double-slope: a rapid decay at first, then a slower decay. Listeners were exposed to pairs of musical passages with differing double slope and Sabine decays. The subjects were tested on their perceptions of the value of the double slope decay in the music passages, and asked to identify a preference between the two passages. In this way, it was hoped that the value of the double slope decay could be defined. To further explore the role of the double slope decay, listeners were asked to illustrate the roles that stop-chords and listener location may play in the perception of the double slope.

The work of Atal, et al. [6] described the subjective running reverberation time as a function of only the first 160 ms of decay, implying that the later, slower decay in a double slope may be irrelevant to perception. Bradley and Wang [7] tested 30 human subjects and found that as either the aperture connecting the main hall and coupled volume of a computer-modelled hall increased – or the volume of the coupled volume increased – the impressions of reverberance also increased. However, no significant relationship was obtained for clarity. Bradley [8] expanded the study to include preference, and found that double-sloped decays were most preferred, though others examining Bradley's data found an inverse relationship between the degree of the double slope and preference. Two other recent (unpublished) investigations consider perceptibility of the double-sloped decay. Knight [9] found that subjects only perceived the later, slower decay when the temporal spacing between successive double-sloped pink noise bursts was between 170 ms and 420 ms. Therefore, the later decay can be perceived "between musical events, rather than simply at the ends of passages, if the spacing between notes is sufficient." Picard [10] used both pink noise and music to identify subjects' thresholds for noticing a difference between a Sabine decay and a double-sloped decay. It was found that subjects were more likely to recognize the difference between a double-sloped decay and a classic Sabine decay as divergence from a Sabine decay increased.

For the work reported in this paper, paired comparison tests were used to establish listener preferences. Fidell and Green [11] identified this method as producing more consistent data than that generated from other methods. Thurstone [12] established the Law of Comparative Judgment as a valid method of measure. Ando [13], Sato et al. [14], Hase et al. [15], Noson et al. [16], and Ando and Kurihara [17] each used paired comparison tests to establish listener preference.

CATT-Acoustic software generated the music tracks, all of which were created with the extrapolation function deactivated to better model coupling. This software uses a hybrid of ray tracing, image source modelling, and cone tracing to simulate impulse responses in computer-modelled rooms. Anderson et al. [18], using the image source model ODEON to represent coupling in St. Paul's Cathedral, found substantial disagreement between modelled and measured data. Ricol and Junker [19] found data derived from computer models to be similar to that in measured rooms with coupling. Similarly, Njis et al. [20] demonstrated agreement between measured and computer-modelled data, provided that models establish well-defined scattering coefficients. Ayr et al. [21] found agreement between a CATT model and measurements taken in a church with a coupled chapel, provided that a high number of rays per octave were emitted from the source. Though the two rooms used in Ayr's study were coupled, a double-sloped condition was not found to be present either in the model or in the actual rooms.

2. VALIDATION

Two coupled volume concert halls were modelled in CATT-Acoustic; which will be termed Old Hall and New Hall (to protect confidentiality). Built a decade apart and designed by the same acoustic consultant, these facilities are similar. The main halls of both facilities have approximately equal geometric volumes (within 1.5%), and forms (shoebox shape, three tiers). The location and quantity of aperture is the primary difference between the two halls: New Hall has nearly five times the available aperture area as Old Hall, with multiple door locations extending the height of the transverse section. Conversely, Old Hall's apertures are concentrated along the upper portions of the room. The software uses a hybrid of ray tracing, image source modeling, and cone tracing to simulate impulse responses in computer-modeled rooms.

To validate the software model used, the author recorded Old Hall stop-chords of a rehearsing organist at 16 locations throughout the hall under the following conditions: all available apertures were fully opened and the room was unoccupied. A pair of electret-condenser microphones was used for binaural recording the organist (onto a DAT). Background noise presumed to be emanating from a mechanical system was audible. Stop bars derived from receiver locations were isolated, imported into Matlab, and frequency-filtered. In all but one receiver location, the double slope was not subjectively detectable to the author either by listening, or from graphically examining the impulse response generated from the recorded stop-chords. In the one location, where it was perceptible, the effect was perceived as slight, and a visual inspection of the impulse response judged it as, "perhaps displaying a double slope."

Because the software package CATT-Acoustic would be used to create double sloped conditions for all of the listening tests presented in this paper, its fidelity in modelling a coupled volume concert hall is germane to the study. Thus the software modelled Old Hall at the same 16 receiver locations, spatially coinciding with the locations of the in situ measurements. A comparison of the measured and modelled impulse responses, at 125 Hz, 500 Hz, and 2000 Hz can be found in Figure 1. The version of the software (v.8.0b) is the first to offer users the option of deactivating the tail correction, which is used to extrapolate the later part of the decay in ray tracing software. By deactivating the tail correction in the simulations used for this study, it is believed that the software is better able to model the double-sloped decay. An unintended and unwanted side-effect of the tail correction deactivation may be evident in the echoes predicted by the software model, which can also be seen in some of the modelled decays presented in Figure 1.

The model was found to maintain better agreement with measurements in the higher frequencies, with predicted values generally higher than measurements at low frequencies. The in-situ measurements suggested a non-existent or barely-perceptible double slope decay and the modelling software suggested the same. Although this is not a full validation of the model, the software is an acceptable tool for producing carefully controlled variables with otherwise-identical conditions. The tests presented here hinge on *comparisons* between conditions rather than absolute simulations of halls. CATT-Acoustic was found to be an acceptable mode of creating auralizations for paired comparison testing measuring the value of the double slope.

New Hall was next modelled. This model also failed to produce a double sloped decay. The concrete block was replaced with smooth concrete, which, under a limited set of aperture configurations, allowed for a double slope decay to be modelled [22,23,24]. Modelling a room of this size typically requires a number of rays per octave of the order of 10,000. More rays are necessary to predict sound energy that moves through small

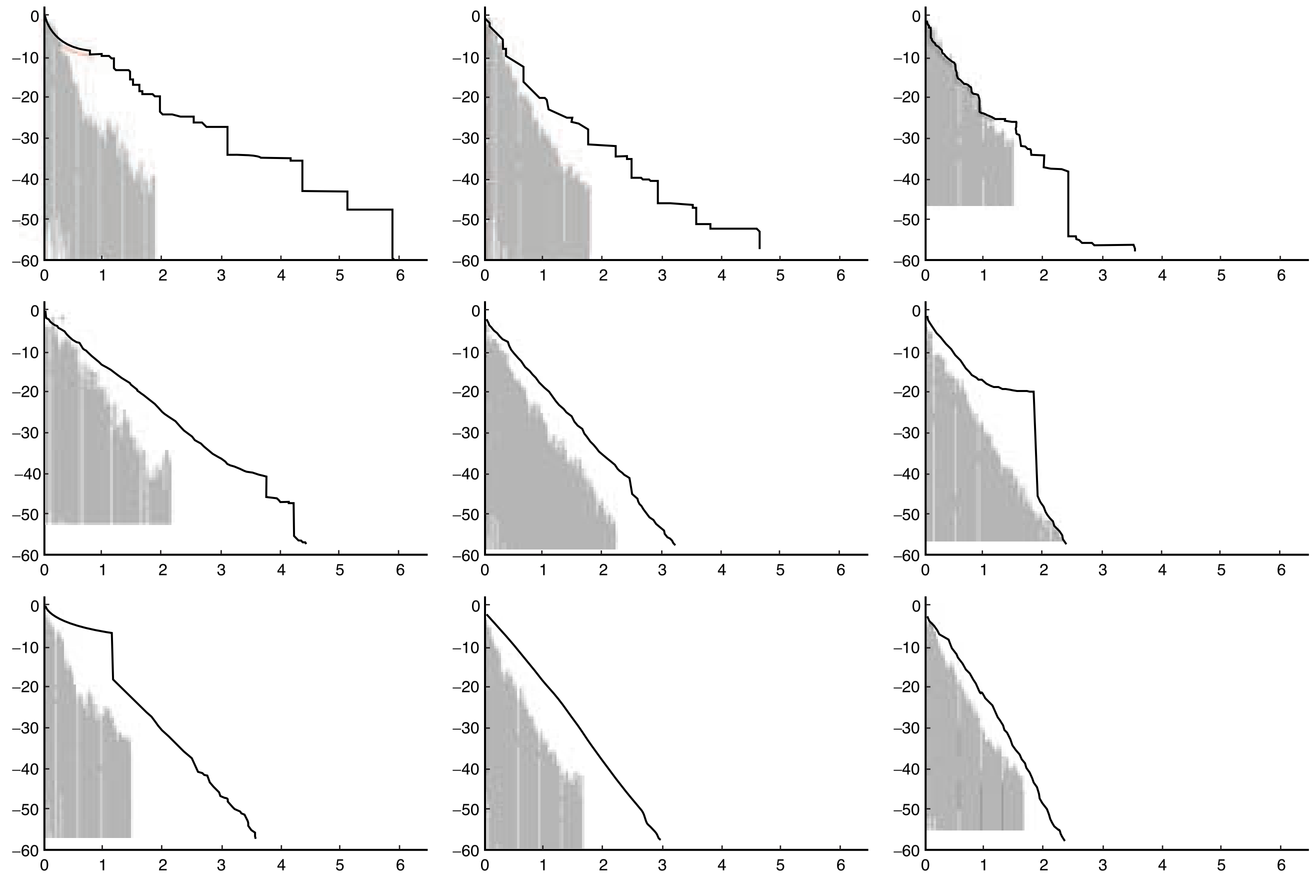

Figure 1. In-situ impulse response measurements in a coupled volume concert hall with values predicted by a ray tracing software model. Left, 125 Hz; centre, 500 Hz; right, 2000 Hz. Top row, Orchestra level; centre row, side balcony near coupled volume aperture; bottom row, top rear balcony. Measurements shown as a series of vertical lines; simulation, as a single line. Y-axis is in decibels; X-axis is in seconds. Abrupt steps in the otherwise smooth software-based predicted decay are likely echoes from strong late reflections.

apertures twice to effect a double sloped decay. To that end, a separate study was undertaken to determine the appropriate number of rays for a coupled volume simulation. A simulation using 2,000,000 rays per octave was generated using a material and compositional configuration of New Hall that produces a plainly visible double slope echogram. Successive simulations were then run with fewer and fewer rays per octave and compared to the 2,000,000 ray per octave trial. A modelling system with 200,000 rays per octave was found to be acceptable, as it produced results indistinguishable from the 2,000,000 rays per octave trial.

3. METHOD

The tests presented here used two population samples: attendees at an acoustical society conference and college students. Each test was preceded by an explanation of the double slope (the conference attendees were presented with a paper on the subject and the students were given a lecture). Beranek [25] lamented that researchers often administer subjective listening tests to students rather than to sophisticated concert-goers. Sato et al. [14], Noson et al. [16], and Farina [26] used subjects experienced in making or judging music for listening tests. Sakai et al. [27] considered intra-subject-group differences between listeners (age, time of day, etc.) and Trapenskas, et al. [28] found that a short training session prior to testing improved subjects' ability to localize what they hear.

Test 1 utilized ray tracing software to convolve the New Hall simulated decays with a brief anechoic recording. The effective aperture size in New Hall was varied, yielding five different auralizations of double-sloped and classic Sabine decays for inclusion into the subjective listening test. (The Virginia Tech Architecture Library maintains a copy of New Hall's construction drawings.) These recordings were then split into eight couplets for headphone playback as a paired comparison test to determine perceptibility and preference of the double-sloped decay (Fostex T40RP headphones connected to Samson S-phone headphone mixer/amp/bus set to two-channel playback). Test subjects were asked to report if they heard a difference between a classic Sabine decay and a double sloped decay in each pair of auralizations. Participants were then asked to distinguish between two different double slope decays and identify which one is "more" double sloped. Finally, they are asked which of the two auralizations they prefer.

The three groups, with differing levels of listening experience and acoustics knowledge were tested: (1) an opportunity-sample of 21 volunteers from an Architectural Acoustics section of the 145th meeting of the Acoustical Society of America in Nashville, (2) a group of five "proficient" listeners, selected from the first group of conference attendees, who were exceptionally good at differentiating between the two samples given for each track, correctly identifying identical tracks (see Figure 2), and (3) twenty six students with varying levels of interest and experience in acoustics and music listening. Fourteen of the students were in an advanced architectural acoustics course, eight architecture graduate students were not in an acoustics course, and four acoustics graduate students were attending the North Carolina Chapter of the Acoustical Society of America meeting in Raleigh, April 2004. It should be noted that two of the subjects complained of audible background noise during the testing of ASA conference attendees in Nashville.

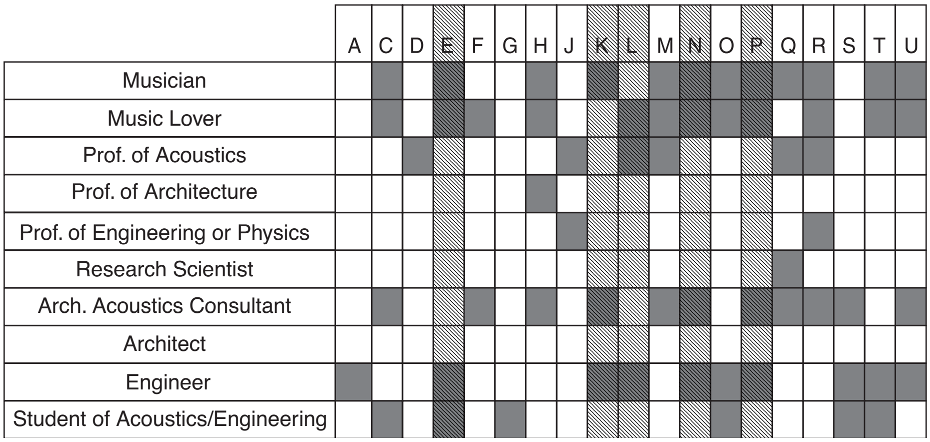

Figure 2. Backgrounds of sample listeners from attendees at the Acoustical Society of America meeting in Nashville. Proficient listeners (those that were able to correctly identify identical pairs of simulations as identical) are indicated with full-column shading.

In the first set of tests, listeners reported identifying double sloped decays based on the decay in the passages' stop-chords, so a second test was fashioned to see if respondents are able to identify, and express a preference for, double sloped decays in running music. Like the first test, the second test used paired comparisons; but some of the music passages were truncated, so that respondents were unable to hear the stop chord decay at the end of the recording. This second test was administered in a similar way as the first: ten volunteers, who attended the 148th Meeting of the Acoustical Society of America meeting in San Diego, took part in a paired comparison test headphone study (some of whom identified themselves as subjects in the original Test 1). Test 2 was also given to six students enrolled in an architectural acoustics graduate course. Subjects were again asked to identify if they heard a difference between tracks A and B, which one (if either) was "more double sloped," and which one they preferred.

4. RESULTS

Figures 3 through 6 summarize the results of the survey. For each coupled pair, a graphical representation of the 1000 Hz impulse response is shown on the left. The phrases "0% open," "1% open," "10% open," and "100% open," refer to the degree of acoustic coupling between the main hall and the coupled volume in the model that generated the impulse response. "0% open," denotes the doors fully closed position, and the resultant impulse response modelled what would be found in a concert hall without a coupled volume. The 1% open and 10% open conditions were found to be part of a narrow subset of hall composition that generates a marked double sloped decay. The 100% open condition identifies an impulse response generated from a model with all of its doors 100% open. (The totality of the door area available amounts to 10% of the available surface area of the main hall, not including the area devoted to audience seats. For example, "1% open" refers to a condition where all of the doors are 1% ajar, rather than a condition where 1% of the doors are fully open.) At the doors-fully-open condition, the hall maintains an impulse response that, while still double sloped, approaches the Sabine estimation of what would be found in a single, non-coupled hall, with a volume equal to that found in the main hall plus the space found in the coupled volume.

In Figures 3 through 6, to the right of the impulse response, answers to the three questions asked to the respondents can be found. The first is "These two recordings sound _______." And the respondent is given the choice of "Different," "Same," or, "Not sure," denoted by "Y," "N," and "?," respectively on the graphs. The bar in the graph, corresponding to the correct answer, is shaded. The second questions asked is, "If different, which one of these recordings is more likely to have a double-sloped decay or has a more dramatic double-sloped decay?" Respondents were given the choices of "A," "B," "Equal likelihood or degree of double slope," "Neither has a double slope," or "Not sure," denoted in the figure as "A," "B," "=," "-," "?," respectively. "N/A," in the figure indicates that no answer was given. Again, the correct answer (or the answer deemed more correct based on the 1000Hz impulse response graph and its depiction of a double sloped decay) is shaded. Finally, subjects were asked, "As a listener to music, which of these recordings do you prefer?" and given the choices of, "A," "B," "Both equally," and "Not Sure." Within each question response summary are three subgroups: proficient listeners, ASA conference attendees, and students. The graphs are designed to read (1) across the page from left to right to understand respondents' ability to distinguish between the two tracks, ability to perceive the double slope, and preference respectively, (2) across the page, left to right within a question, to distinguish between subgroup responses from proficient listener to conference attendee to student, or (3) from top to bottom to judge differences between pairs of impulse responses.

Test 1 involved eight pairs of recordings, and two sets were identical; Test 2 involved four pairs of recordings, and one set was identical. In each of these identical recordings, two tracks of anechoic recordings, convolved with software-generated impulse responses, were played over headphones and subjects were first asked to identify if they sounded different or the same. In each of the three identical pairings, a plurality of the conference attendees incorrectly identified the pair as "different" and a majority, between 55% and 70%, responded in each case either that the pair was different or that they didn't know if the pair was different. In two of the three pairings, students incorrectly identified the identical pair as different by similar margins, however, two-thirds of the students surveyed were correctly able to identify one of the identical pair of double-sloped simulations as "same." Therefore the test uncovered a significant number of liberal responders (see Figure 3). Those in the opportunity-sample who attended the conference and correctly identified both sets of identical samples as "same" were teased out in a subset deemed "proficient listeners." Note that responses from the proficient listeners subset were also included in the larger pool of Acoustical Society of America (ASA) subjects.

Figure 4 highlights the Test 1 results and from it one can summarize most of the findings in this line of inquiry. Moving from top to bottom, the impulse responses to be compared become more divergent in the later part of the decay, and moving down the first

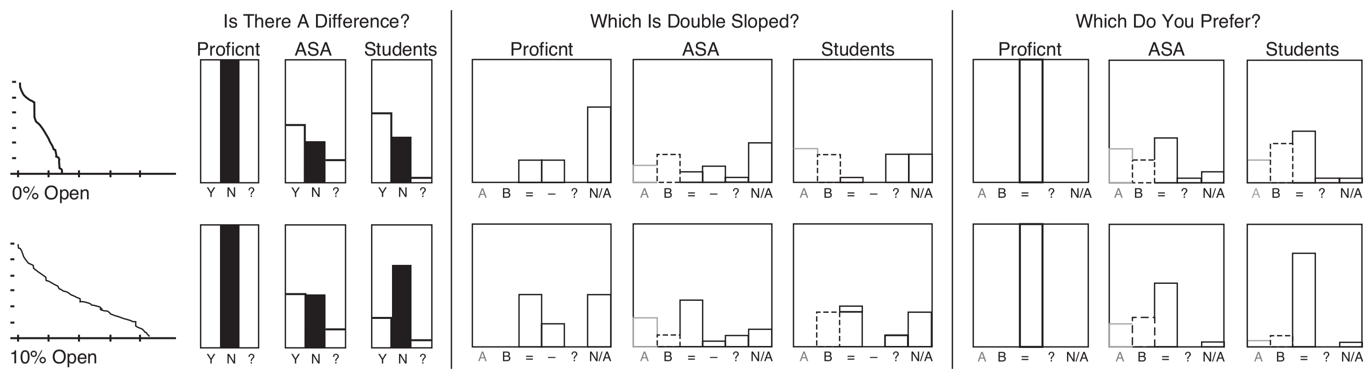

Figure 3. Two Test 1 control group pairings, one shown in each row. The relative proportion of respondent's answers can be seen in the graph, with the correct answer shaded. Note that often subjects incorrectly identified these identical recordings as sounding different.

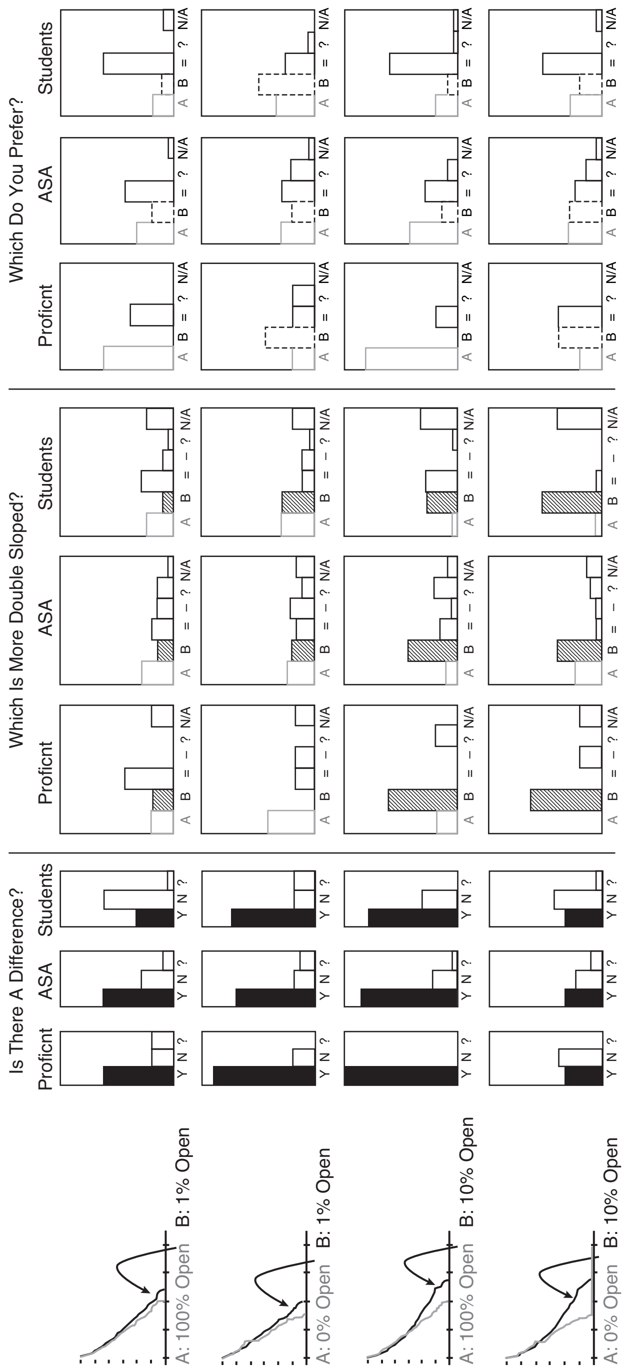

Figure 4. Four Test 1 group pairings.

six columns of bar graphs indicates that as the two late decays become more divergent, listeners are better able to distinguish between them and better able to identify which item of the pair is “more” double-sloped. In each graphic, the “more” double sloped condition is standardized, so as to be identified as “B,” while the decay more closely approximating an exponential Sabine decay is identified as “A.” This was not the case in the actual headphone listening test, where the order of the samples was randomized. The difference between the top two trials (rows) and the bottom two are significant when examining a subject’s likelihood of selecting the “correct” recording when one was asked, “If different, which one of these recordings is more likely to have a double-sloped decay or has a more dramatic double-sloped decay?” The top two sets of decays, with intra-pair similar impulse responses, saw few subjects identify the correct “more” double sloped decay, while the bottom two pairs saw a plurality of respondents able to identify the “more” double sloped decay.

In deciphering listener preference, no trend is discernable, and it is not possible to observe a preference for either the more double sloped decays or those that more closely resemble Sabine exponential decays.

When examining trends between listener groups, within a single question, it appears that the proficient listeners were best able to identify differences between decays that were in fact different and, in the bottom two trials, best able to correctly identify which decay was “more” double sloped. The ASA Nashville conference attendees appeared to be better able than the students to correctly identify the differences between these recordings, though it remains unclear as to whether they were better than the students at identifying which recordings are “more-double-sloped.” Finally, of the three groups, when asked which one of the recordings they most prefer, the students were the most likely to respond that they prefer both recordings equally.

After taking Test 1, some subjects commented that they were able to identify the double slope from the stop chord at the end of the passage, but weren’t certain that they could identify a double slope in running music. Cremer, and Müller [3] commented on this: “There is no point in attempting to increase the sensation of reverberation in a rather dry room by coupling it to a reverberant room (such as the attic) if the added reverberation appears only during the later part of the decay. This would not be noticeable in running music, but only at sudden stops. On the other hand, this effect could be quite attractive in some circumstances.” To address this question, Test 2 was created and administered to a limited set of ten conference attendees and six students in an architectural acoustics class. This second test included four pairs of recordings: two pairs of different tracks that truncated the end of the recordings so that the stop chord would not be a factor in deciphering a double slope, one pair that remained untruncated, and one pair of identical recordings, to be used as a control. The order of the tracks varied between listeners.

As discussed earlier, most of the respondents (67% of the students and 70% of the conference attendees) incorrectly identified the control group of identical tracks (doors 10% open) as sounding different. The other three pairs asked subjects to compare the 0% open condition with the 10% open position; two of the pairs were truncated and one was not. A summary of the truncated and untruncated responses, with the untruncated responses from Test 1, included for reference, can be found in Figure 5.

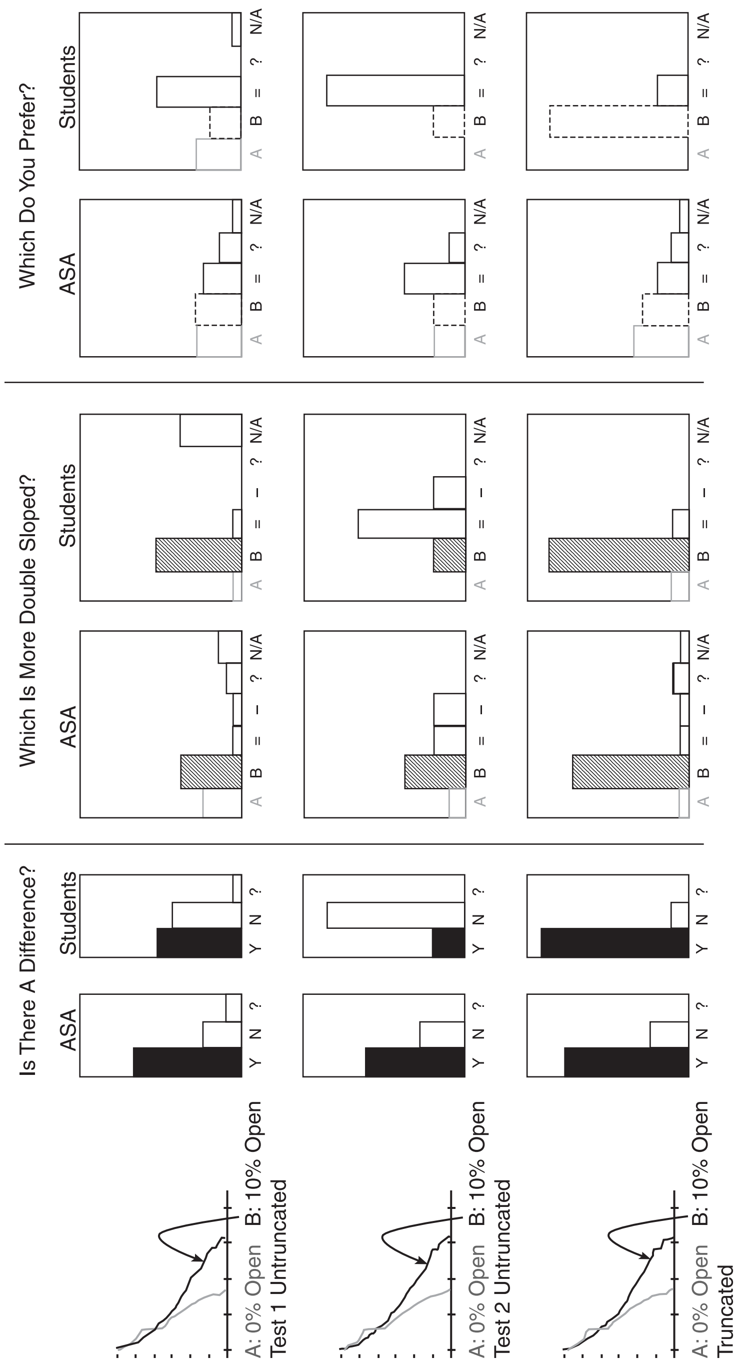

Figure 5. One Test 1 group pairing and two pairings each from Test 2.

In Test 2, conference attendee respondents were likely to correctly identify the two tracks as different, both in the truncated and untruncated conditions. For this subgroup, the differentiation responses in Test 2 to the untruncated tracks were similar to the responses that had been given in Test 1. The six students in Test 2, however, differentiated the two tracks in ways that are difficult to explain. Five out of the six members of this subgroup were unable to correctly identify the two untruncated tracks as different – a result that is fairly inconsistent with the larger group of students tested with the identical tracks in Test 1. The one student who correctly identified the two tracks as different was the only one to correctly identify the track that was “more” double sloped. However, each student was given two sets of truncated tracks taken from the same two models, and 11 out of the 12 responses correctly identified the two tracks as different.

This discrepancy could be explained by the small number of samples in the set, or the diluted significance of the differentiation question itself given respondents’ tendency to hear a difference even when both tracks in a pair are identical. Yet it is harder to dismiss when taking into account the results of the perception question asking which track is “more” double sloped. To that query, 10 of the 12 responses correctly identified the truncated 10% open auralization as “more” double sloped than the truncated 0% open auralization. This is bolstered further by the responses from the conference attendees. Half of the responses in that group correctly identified the “more” double sloped track among the two untruncated auralizations – a clear plurality and though not a significant majority. However, when given two sets of truncated tracks, 14 of the responses correctly selected the “more” double sloped track, with only one incorrect response for the other track (five other responses were spread between “both,” “neither,” “not sure,” and “no answer”). In this test, with these subjects, both the professionals at the conference and the students in the class were able to correctly identify the “more” double sloped track, even without the benefit of the end-of-passage stop-chord. This group was perhaps more effective at perception of the double slope *without* the stop-chord than they were with the stop-chord.

As was the case in Test 1, it is difficult to discern a general pattern linking the presence, absence, or degree of the double slope decay with listener preference. It is worthy of note, however, that 10 of the 12 student trials comparing the truncated double slope to the truncated Sabine exponential decay resulted in a preference of the double slope decay. None preferred the Sabine exponential decay and two felt the two were of equal merit. Thus the students tested showed a preference for the double sloped simulations when comparing truncated tracks, which were the only tracks where the students were able to successfully differentiate.

All of the simulations discussed up to this point were taken from seats modelled at orchestra level, near house-centre. It was observed that orchestra level seats near the apertures that connect the main hall with the coupled volume demonstrate a peculiar, almost triple-sloped, decay. For this reason, two pairs of tracks were included. One asked respondents to compare the double sloped 10% open condition simulated at the house-centre seat with the same hall configuration simulated at the house-left seat. The other compared the 0% open, main hall only centre seat simulation with the 10% open house left simulation. Summaries of the comparisons can be seen in Figure 6.

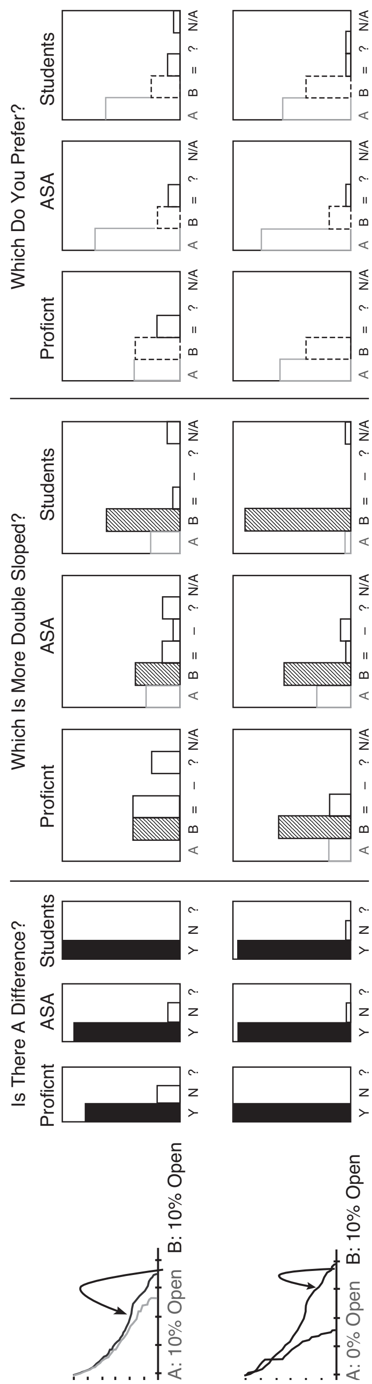

Figure 6. Test 1 group pairings.

The results, in differentiation, perception, and preference of the double slope were more apparent than that when the location remained constant and only the architectural composition of the hall was varied. When comparing the two locations, both taken with the same 10% open configuration, nearly all the respondents correctly identified the two decays as different. The percentage of subjects correctly identifying the difference between the sounds auralized at these two locations, with identical hall conditions, exceeded that which was found when comparing any of the pairs of variable hall conditions with constant location. A still-higher percentage of subjects heard a difference between house-centre 0% open and house-left 10% open. The difference was perceived by a majority of all three subgroups.

When asked to identify the “more” double sloped track where the location varied and the hall condition remained constant, some respondents were able to correctly identify the correct simulation: a small plurality of the conference attendees and a small majority of the students identified the house-left position as more double sloped. (Subjects of course were not aware of either the hall conditions or the receiver location when the test was administered to them.) When asked to compare the 0% open house-centre condition with the 10% open house-left condition, respondents more easily identified the correct answer: a small majority of the conference attendees and a large majority of students correctly selected the 10% house-left track as “more” double sloped. In each of these two cases the students were more likely to be correct than the professionals, something not seen in many of the other comparisons.

This subset of paired comparisons, which included both location and hall configuration, were the only ones where general trends of preference could be found. A majority of listeners, both in the professional subgroup and the student subgroup, both in the comparison that varied location only and the comparison that varied location and hall composition, preferred the house-centre simulation. The very fact that a majority of the subjects preferred the house-centre location even when the hall composition remained constant, while no over-arching preference trends could be established when the hall composition was allowed to vary, suggests that in these two tests, subjects were not responding to the varying decay rate of the impulse response as much as to spatial nature of the sound. Perhaps Inter-Aural Cross Correlation (IACC) or Lateral Fraction (LF) or some other binaural metric would better illuminate what is haptic perception and what is double-sloped-decay perception.

5. CONCLUSIONS

When asked to model an existing coupled volume concert hall created from published data, drawings, and a site visit, the ray tracing software CATT-Acoustic was found to be more accurate in the high frequencies than in the low frequencies. The same modelling method was used to simulate another coupled volume concert hall for the purposes of auralizing the sound field found, given different hall configurations and different receiver locations. The resulting simulated tracks varied in the presence, absence, and “severity” of the double slope decay generated. Over the course of three years tracks were played over headphones for two types of audiences: ASA conference attendees and architecture/acoustics students. Subjects were asked differentiation, perception, and preference questions with the aim of illuminating the listener's role in the coupled volume concert hall and the double slope decay impulse response.

Generally, subjects were able to correctly identify different tracks as "different," and were more likely to correctly identify tracks as "different," when the late portion of the impulse responses of the two tracks varied more from one another. (The early parts of the decays were similar, as would be expected in a coupled volume concert hall.) However a liberal-response tendency was noted as subjects often incorrectly identified control pairs of identical tracks as "different." When asked to identify which of the two tracks in a pair is "more" double sloped, listeners again were more likely to identify the correct track when the late parts of the impulse response decays vary more from one another. The author was unable to identify a strong pattern in the responses when subjects were asked to select a preference between the pair of recordings.

To explore the role of the stop-chord in differentiation, perception, and preference selection, a second test was introduced, which truncated some of the recordings upstream of the stop-chords. Listeners were perhaps *better* at differentiation and perception in these cases than in conditions where a stop-chord was available.

Finally, receiver location was added to coupled volume concert hall aperture condition as a variable. It was surmised that location may be a greater influence on paired comparison perception and preference than aperture condition. Subjects were very likely to recognize and identify the difference between pairs of recordings taken at different locations, even when the simulated architecture of the hall around the receiver remained constant. Respondents also showed a preference for the sound auralization simulated near house-centre relative to the auralization simulated near house-left.

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