Optimal Acoustic Reverberation Evaluation of Byzantine Chanting in Churches

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ABSTRACT

Byzantine chants constitute a form of monophonic vocal music characterized by lengthy phrases and by musical scales with intervals smaller than the western music semitones. Byzantine churches have extremely long Reverberation Time and their acoustics is dominated by the contributions of the diffuse sound field. Thus, the sound character of Byzantine chanting is closely linked to the acoustic reverberation. In this work we examine the perceived preference for the various features of reverberation imposed on excerpts of Byzantine psalms. This is achieved by simulations of typical churches with varying internal volume, reverberation time and source / receiver distance, utilizing chants from the DAMASKINOS corpus. The simulation (auralization) results were evaluated via statistical preference method using a group of 15 listeners. The results of such controlled experiments illustrate the listener preferences and acceptability of various parameters or combinations of parameters related to reverberation, e.g. of the Reverberation Time value in relation to church dimensions and listener position inside the church.

1. INTRODUCTION

Byzantine chants represent the earliest form of Christian music that follows the tradition of the Eastern Orthodox Church. Byzantine music is purely vocal and monophonic and is performed by chanters (psaltes) [1-3]. Byzantine music scales (diatomic, enharmonic, chromatic and tetrachord) have intervals that are often smaller than the typical Western semitone and the musical result is characterized by a very distinct pronunciation and prolonged phonemes [1]. As is the case with most religious music genres, acoustic reverberation complements the sound of the human voice and plays an important role in the aesthetic and presentation of such signals [4]. Byzantine chants are thus directly associated with acoustic reverberation generated within churches adding distinct acoustic characteristics and usually associated with long Reverberation Time (RT). Furthermore, due to significant distances from the source, Byzantine chants are usually perceived or recorded in highly diffuse fields where late reverberation dominates the signal.

Via the accepted scientific principles and depending on the application, acoustic reverberation is considered either as an essential element of the overall sound quality or as harmful sound distortion. From the signal processing point of view, a reverberant signal $r(n)$ captured by the microphone or arriving at the ears of the listener is represented via the filtering effect (convolution) of the source (anechoic) signal $s(n)$ and the room impulse response (RIR) $h(n)$. It is also well known that the RIR of any reverberant space can be separated in two parts: the early reflections and the late reverberation. The early reflections produce a spectral degradation which is perceived as spectral coloration, while late reverberation relates to the diffuse field and mainly generates the distinctive reverberant tails [5]. An analysis of acoustic reverberation from the perspective of different applications, cultural disciplines and traditions is given in [4] while the properties of perceptually compliant late reverberation were investigated in [6] whereas other studies consider the perceived level of reverberation [7]. Most of these studies concluded that perceived late reverberation is strongly dependent on the source signal and the shape of the reverberation decay.

However, the effect of acoustic reverberation on Byzantine church music cannot be directly accessed via such scientific approach which is usually adopted for the evaluation of the quality and intelligibility of music or speech signals. It is likely that the aim of ritual music and specifically Byzantine music is not to preserve intelligibility, spectral integrity or temporal signal features, but instead to blur and dissolve the features and the semantic aspects of the signal into an immersive acoustic experience which transcends sound features and enhances other multisensory stimuli of vision and scent [8]. In this respect, reverberation may be considered as a mechanism for introducing an appropriate level of acoustic abstraction to the perceived spatial sound sensation in accordance to the spirituality imposed by the Byzantine icons, the architectural elements of space, the light and shadows and the scent of incenses. The intermingling of these elements may be considered to lead towards the "…representation (*eikon)* as enactment, an in-spiriting or *empsychosis* of *pneuma* (spirit) in matter…" [8].

Given the importance of reverberation (especially via such late, diffuse field effects), in the Byzantine chanting, it is likely that the evolution of the musical form of these chants has been also influenced by the acoustics of the Byzantine churches. This aspect has been discussed in [8] pointing out the construction of Hagia Sophia church with its excessive reverberation (estimated RT ≈ 10 sec), has lead to the evolution of different types of music which were incorporated into the Byzantine liturgical tradition: the *kontakion* of Romanos Melodos (around 555), a chanted sermon and the *Cheroubikon*, a special hymn performed at the offertory procession. Following such developments, the *asmatike akolouthia* emerged as a combination and sequence of solo, choir and congregation parts.

To assess the perceived effects of the Byzantine chants, an earlier paper by the authors [9] has investigated the significance of reverberation and suppression of it (dereverberation) for extreme RT conditions, such as the ones found in big churches especially on excerpts from Byzantine chants. Two subjective tests were conducted one for evaluating the perceived reverberation on excerpts of Byzantine chants and the second to assess the effect of adding artificial reverberation in already reverberant recordings as well as in dereverberating such recordings. The results had shown that reverberation discrimination is possible, especially when listeners have the option to focus in certain signal components that reveal the inherent characteristics of the reverberation processing. On the other hand, the identification of dereverberation processing was not as easy, since in most cases the addition of artificial reverberation probably masked the dereverberation effect. Furthermore, listeners were able to discriminate between different RT conditions.

To complement this study, the current work focuses on more detailed aspects of reverberation. Here, typical Byzantine church spaces have been simulated via acoustic software [10], where specific parameters (church size, reverberance, source-receiver position, etc.) were varied. Excerpts corresponding to two chants were extracted from the DAMASKINOS corpus [3, 11], reverberant signals were created and listeners were asked for their preference for each reverberation scenario. The reason for the choice of listener preference test can be deduced by the previous discussion where it was stressed that the analysis of acoustic parameters themselves via the usual methodology could not necessarily correlate with the functional role and subjective preference of reverberation characteristics for supporting Byzantine chanting.

This work is organized as follows: Section 2 discusses the methodology for simulating, auralising the church reverberation on the chants and assessing listener preference, Section 3 presents the results of the analysis of these listening tests and Section 4 presents the conclusions drawn from this work.

2. METHOD

2.1 Auralisation

For the purposes of this paper, excerpts from the DAMASKINOS database are used [3, 11] this being a corpus of Byzantine chants, developed by the University of Athens. It contains samples derived from selected representative professional chanters, recordings under controlled conditions in low-reverberation (semi-anechoic) conditions. These sample recordings were then convolved with the binaural room impulse response (BRIR) obtained via acoustic simulations of different churches and source / receiver configurations (explained in the following section). Let $s(n)$ represent the source signal (in the discrete time domain), $r_{Ax0x}(n)$ the reverberant signal received at position 0x of the virtual listener and for position Ax of the virtual source within the church (any of the 2 binaural channels) and $h_{Ax0x}(n)$ being the corresponding BRIR response evaluated by the acoustic simulation program for position 0x of the virtual listener and for position Ax of the virtual source within the church (any of the 2 binaural channels). Then:

$$r_{Ax0x}(n) = \sum_{m=1}^{M} h_{Ax0x}(n-m)s(m)$$

2.2 Simulation of church acoustics

Probably the most famous of the Byzantine cathedrals was St. Sophia (Hagia Sophia) in Constantinople, built between 532 and 537 and being considered as the epitome of the Byzantine architecture. The church has a volume larger than 260,000 m^3, with reverberation time RT around 10 sec (at 1 kHz) [8, 12] and speech intelligibility is significantly low [12]. Although, this is a unique example of Byzantine church architecture, from the acoustics point of view it presents several important and general characteristics of Christian churches: (i) extremely diffuse field with minimal early reflections, (ii) very long RT and (iii) long distances between the source and the receiver, resulting in long delays and low direct to reverberation ratios. To simulate such acoustic properties, a 3D acoustic model of a "generic" Byzantine was implemented using a commercially available, geometric acoustic-based program [10].

The program uses 3 different algorithms to derive echogramsand acoustic parameters:

(1) Standard ray-tracing with a spherical receiver which estimates sound pressure level, lateral energy fraction, and most known acoustic parameters,
(2) Image Source Model (ISM), for detailed early reflection calculations, based on first order images of the main source in all the reflecting planes and second order sources created by calculating new images in all reflecting planes (except of the previously calculated). This procedure is repeated until the specified maximum arrival-time is reached.

(3) Randomised Tail-corrected Cone-tracing (RTC) for the full response, but handling deterministically the direct sound and first order specular and diffuse reflections. With this approach, echograms (BRIRs) for auralisation were generated.

Figure 1 shows the shape of this generic church. From this shape, 3 different versions were developed having “Small”, “Medium” and “Large” acoustic features and Reverberation Time between 2.5 and 6 seconds. The geometric and acoustic properties of these models are given in Table.1.

Within each of these church models, sources were placed in positions A0 (representing the position of the priest at the altar) and positions A1 representing typical positions of the *psaltes* (chanters).

For each of these source positions, listener positions were at 01 (position at the back of the church), 02 at the vicinity of the *psaltes* (position A1x02 representing the self listening condition), 03 (a close side position) and 04 (a side medium distance position), as is shown in Figure 2. The distance of each source / receiver configuration is also given in Table 1.

2.3 Preference tests

To assess the subjective preference of reverberation on Byzantine chants, a variation of the standard MUSHRA test was conducted [13] and the listeners were asked to rate the preferred amount of reverberation (the “suitability of reverberation for the specific signal”) on a scale of 0-100. In such a preference test, no hidden anchor was included, but a separate reference-button allowed listeners to hear the unprocessed signal was available on the interface which is shown in Figure 3. This reference signal in this case was the original excerpt of the psalm from the DAMASKINOS database without any additional reverberation. Using the above experimental protocol, a score of 100 indicates that the subject considered the reverberant signal as being highly preferable than the original semi-anechoic; conversely a score of 0 indicates that the subject considered the reverberant test signal was totally inappropriate. The 48 different test samples produced from 2 Byzantine chant excerpts, 3 RT conditions and 8 positions were presented through headphones (S-Logic, Ultrasone AG) to the listeners.

In each experimental condition, the listener rated 3 samples (i.e one sound excerpt for 3 different RT conditions). The subjects were able to switch with their mouse between different stimuli, via a computer interface. A training session preceded the formal experiment, and the subjects were allowed to complete the test at their own pace without any interruptions from the experimenter. The experiments were conducted with 15 male and female (self-reported) normal-hearing experienced listeners. The collected data were subjected to an analysis of variance (ANOVA) to reveal whether the differences presented above are statistically significant.

3. RESULTS

3.1 Analysis method

The collected data from the preference test were subjected to an analysis of variance (ANOVA) to reveal whether:

(a) there was any systematic trend in the recorded preferences
(b) the recorded differences are statistically significant
(c) a significant interaction exists between different tested parameters.

Note that in order to justify statistically significant differences the result of the p-factor of the ANOVA test must be $p < 0.05$.

From this analysis, and with respect to points (b) and (c) above, it was found that:

- The Reverberation Time of the church was the most significant factor in the preference ($p<0.000$). This is somehow obvious given that this parameter was assessed by the test.
- The type of psalm was also found to affect the preference of the listeners ($p<0.001$)
- The source-receiver configuration and listener position also affects the preference of the listeners ($p<0.011$).
- There is significant interaction between the listening position and Reverberation Time ($p<0.038$).

3.2 Reverberation Time

With respect to the statistically significant preferences now, as is shown in Figure 4, all listeners had a clear preference for the reverberant signal within the medium and small sized churches, compared to the original semi-anechoic. The preference results for the large church are marginally negative, i.e. there was a marginal (statistically insignificant) preference for the original signal.

Furthermore, most listeners had a clear preference (mean value 74.087%) for the medium sized church having a Reverberation Time of 4 seconds. Next, the listeners (mean value 53.996%) had a preference for the small sized church with a Reverberation Time of 2.5 seconds. Last, , the listeners (mean value 46.296%) had a preference for the large sized church with a Reverberation Time of 6 seconds. In this and other figures, the error bars indicate the 95% confidence intervals for these results.

3.3 Type of chant

This preference was found also to depend on the type of psalm. As is shown in Figure 5, listeners appeared to have a stronger preference for the reverberation effect for Chant01 (a psalm sang by a choir) with a mean score of 60.66% than Chant 01 (sang with solo voice) which had a mean preference score of 55.592%.

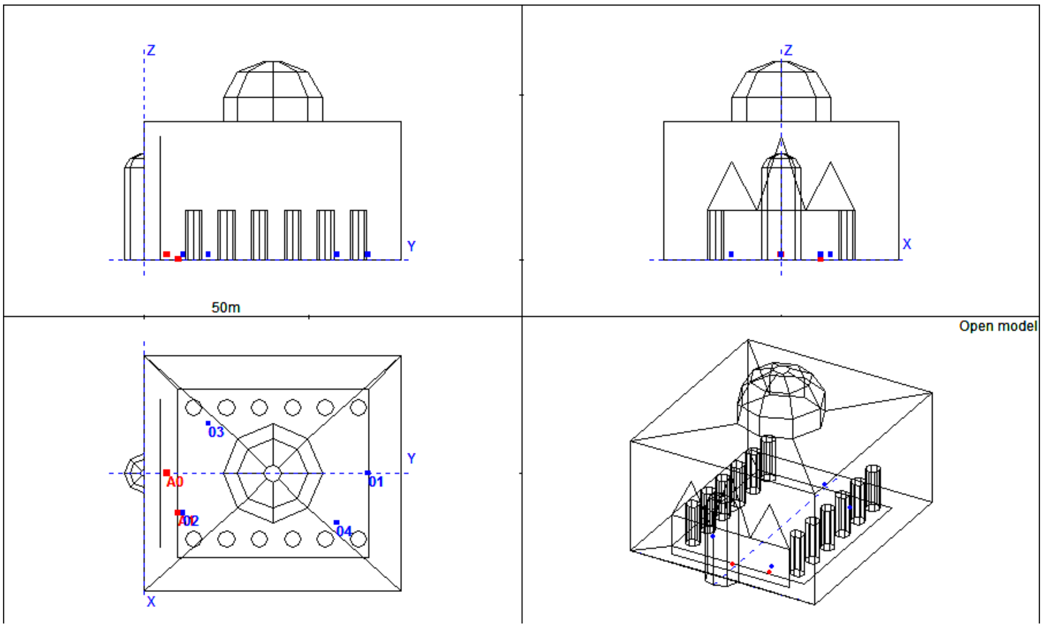

Figure 1. Side, top and 3-D views of the generic Byzantine church acoustical model.

	Small	**Medium**	**Large**
Dimensions LxWxH (m)	50x40x17	60x52x31	78x71x42
Volume (m^3)	34000	96720	232596
Reverberation Time (s)	2,5	4	6
Source (Ax) _ Receiver (0x) Distance (m)	A0_01 = 33 A0_02 = 11.6 A0_03 = 14.3 A0_04 = 31.6 A1_01 = 31.6 A1_02=self-listening A1_03 = 26 A1_04 = 24	A0_01 = 43 A0_02 = 11.6 A0_03 = 12.8 A0_04 = 39.3 A1_01 = 38.3 A1_02=self-listening A1_03 = 18 A1_04 = 32	A0_01 = 63 A0_02 = 13 A0_03 = 20 A0_04 = 55.1 A1_01=69 A1_02=self-listening A1_03 = 8.5 m A1_04 = 48 m

Table 1. Geometric, acoustic properties of different churches and simulated source / receiver distances.

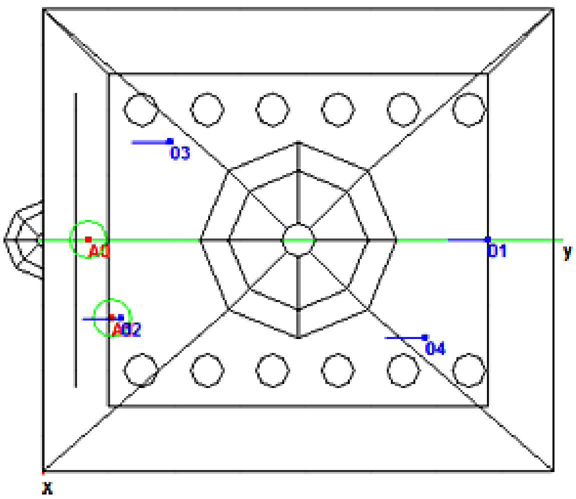

Figure 2. Top view of the generic church acoustic model indicating source (Ax) and listener (0x) positions.

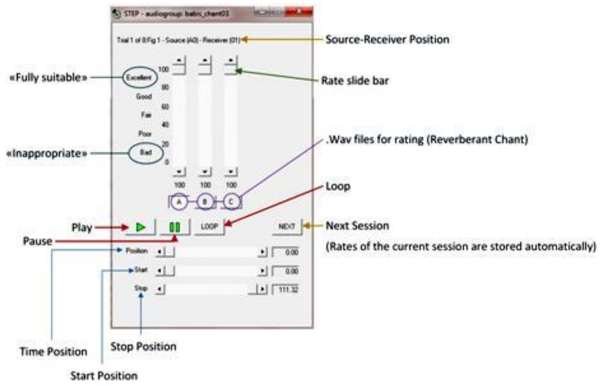

Figure 3. Listening test interface and user-controlled functions.

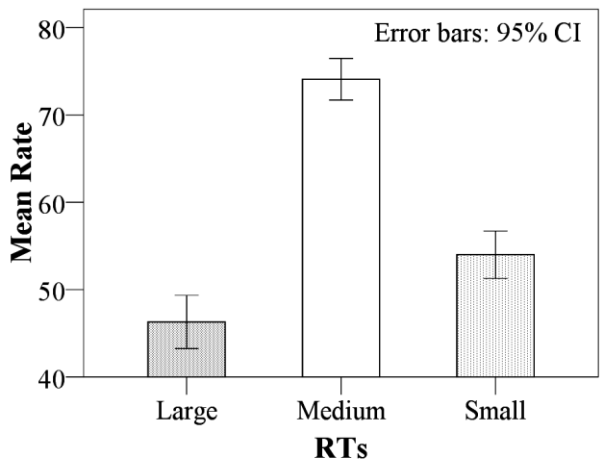

Figure 4. Mean rating of reverberation preference, as function of different church size and RT value

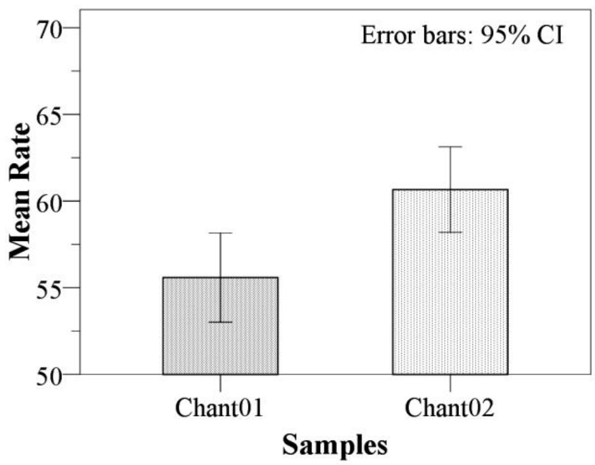

Figure 5. Mean rating of reverberation preference, as function of different chant.

3.4 Listening position

With respect to the source / receiver configuration, the mean results (over all churches) are shown in Figure 6, noting with reference to Figure 2 and Table 1, that notation A0 indicates the source being located in the entrance of the *bema*, in front of the altar i.e. the typical position for the priest and A1 indicates positions where the chanters (*psaltes*) are located, at the *analogia*. In all listening positions, the preference for the reverberant chants was significant, but it appeared that listening at positions 03, a near side position (see Figure 2), produced the stronger preferences with a mean score of 63.5%. It is also significant to note the self-listening effect for the chanters, indicated by the configuration A1_02, where there seems also to be a strong preference for the reverberation effect. Overall, distant listening positions (A0_01, A0_04, A1_01 and A1_04) did not receive favorable preference ratings.

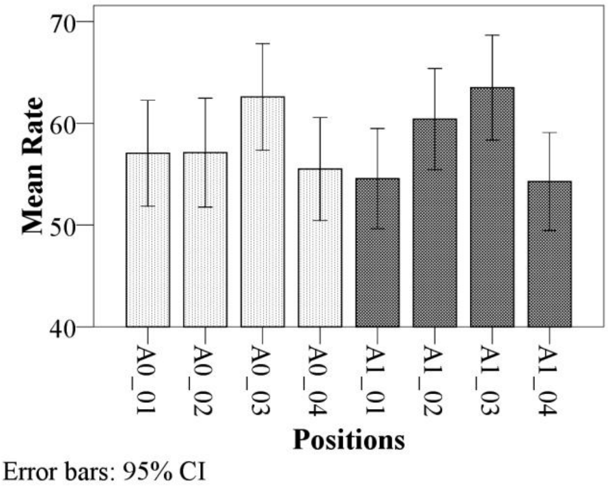

Figure 6. Mean rating of reverberation preference, as function of different source / receiver position.

From these average results, it is also useful to consider in more detail the results for listening position in each church type, shown in Figure 7. As was discussed in Section 3.2, there is a strong preference for the reverberation generated by the medium sized church and for the position 03, but also significantly for position 02, i.e. for the close positions to the priest or chanters. In general, preference for the close listening positions (02,03) appeared to be rather similar, assuming that these were in the small or large church which had lower preference. However, as was also discussed previously, the self-listening effect for the chanters can be also very positive for such church reverberation. From this figure, it is also evident that for the large and highly reverberant church, the signal arriving at the more distance positions 01 and 04, appears to be less preferred than the original signal.

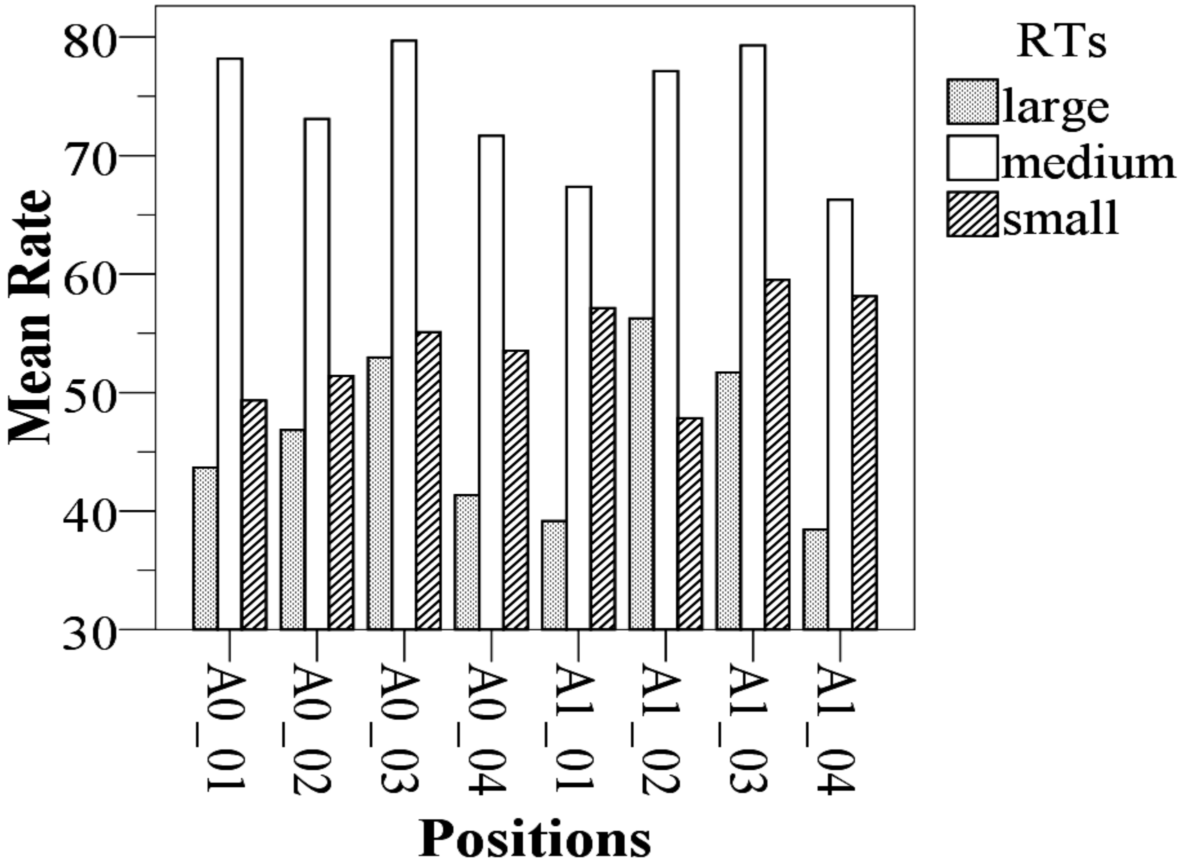

Figure 7. Rating of reverberation preference, as function of different source / receiver position and church size.

4. CONLUSIONS

The current work generated realistic 3-dimensional reverberation from exact geometric shapes representing generic Byzantine churches. In those virtual acoustic environments, excerpts of Byzantine chants were reproduced, simulating different positions for binaural listening of the generated sound. Under such controlled experimental conditions, the preference for the generated reverberance for a sufficiently large sample of listeners was assessed via standardized statistical procedure.

The results of this work have reaffirmed the significant and positive effect of reverberation on the appreciation of Byzantine chants. As was also found before, listeners were able to discriminate the different reverberation characteristics on such chants and overall had a preference for the added reverberant character in comparison to the original semi-anechoic source. Furthermore, statistically significant differences were found for their preference for the Reverberation Time and church size, where most listeners had a clear preference with a mean value 74.087% for the medium sized church having a Reverberation Time of 4 seconds. Next in their preference with a mean value of 53.996% was for the small sized church with a Reverberation Time of 2.5 seconds. Last, the listeners (with mean value 46.296%) had expressed mixed opinions for the large sized church with a Reverberation Time of 6 seconds. In such case it appears that excessive reverberation has a detrimental effect on the clarity of the reproduced chant which has been assessed as less positive by the majority of listeners.

However, the results have also shown some difference in preference ratings with respect to the musical form of each psalm, with the one based on choral chanting to be considered to be more benefited by the added reverberation.

The results have also shown a strong preference of the chanters themselves (*psaltes*) for the added reverberation which in practice would assist their performance. For such self-listening case, the preference for the added reverberation from the medium-sized church appeared to be over 77%, dropping to 55% for the reverberation of the large church and to 48% in the case of the small church. This indicates that the amount of reverberation added should be significant in order to be beneficial to the chanter when he is listening to his own voice in the church. Note that for the case of the small church, the chanter will mostly perceive amplified the spectral coloration imposed by early reflections since in this case small amount of late reverberation is generated due to the small-sized church.

Overall, for all different sized churches and reverberation values, the highest listener preferences (63.5%) were for positions close to the priest or opposite to the chanters, at distances ranging from 12.8 up to 20 m (depending on the church size).

The less favorable positions were for the more distant listening positions, at distances ranging from 31.6 up to 69 m (depending on the church size). Under such conditions late reverberation is dominating the signal and the direct to reverberant signal ratio is very poor.

For the listening position preference results for each specific church, it was found that for the most preferred medium sized church, most positions, except the very distant ones, received ratings above 70%. Even those distant positions had a sufficient clear preference with rating above 65%. In contrast, distant positions in the large church were considered to have so much excess reverberation that the chants appeared to have deteriorating quality with respect to their original condition prior to adding reverberation.

It has to be added, that the above study was by no means extensive and clearly there are further aspects related to the interaction between Christian Orthodox liturgy and church acoustics that require investigation in the future.

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5. REFERENCES

[1] D. Delviniotis, G. Kouroupetroglou, and S. Theodoridis, “Acoustic analysis of musical intervals in modern byzantine chant scales”, Journal of the Acoustical Society of America, vol. 124(4), p. 262-269, 2008.

[2] E. Wellesz, “A History of Byzantine Music and Hymnography”, Clarendon Press, 1961.

[3] D. Delviniotis, G. Kouroupetroglou, “DAMASKINOS: The prototype corpus of Greek Orthodox ecclesiastical chant voices”, Proc. of the International Conference “Crossroads Greece as an Intercultural Pole of Musical Thought and Creativity”, Tsessaloniki, Greece, June 6-10 2011, pp. 289-302.

[4] B. Blesser, “An interdisciplinary synthesis of reverberation viewpoints”, Journal of the Audio Engineering Society, vol. 49(10), p. 867-903, 2001.

[5] H. Kuttruff, “Room acoustics”, Applied Science Publishers Ltd, London, 2nd Ed., 1979.

[6] M. Karjalainen, H. Jarvelainen, “More about this reverberation science: Perceptually good late reverberation”, Audio Engineering Society Convention, vol. 111, p. 11 2001.

[7] D. Griesinger, “How loud is my reverberation?”, Audio Engineering Society Convention vol. 98, p. 2, 1995.

[8] B. Pentcheva, “Icons of Sound: Hagia Sophia and the Byzantine Choros”, Chapter 2 in “The Sensual Icon: Space, Ritual, and the Senses in Byzantium,” Penn State Press, 2010.

[9] A. Tsilfdis, Ch. Papadakos, E. Kokkinis, G. Chryssochoidis, D. Delviniotis, G. Kouroupetoglou, J. Mourjopoulos, “Reverberation and de-reverberation effect on Byzantine chants”, Audio Engineering Society Convention 135, New York, 2013.

[10] Catt-Acoustic v9., http://www.catt.se/

[11] G. Kouroupetroglou, D. Delviniotis, and G. Chrysochoidis, “DAMASKINOS: The Model Tagged Acoustic Corpus of Byzantine Ecclesiastic Chant Voices” in Proc. ACOUSTICS Conf., Heraclion, Greece, 2006, pp. 68–76.

[12] C. Weitze, J. Rindel, C. Christensen, A. Gade, “The acoustical history of Hagia Sophia revived through computer simulation”, Forum Acusticum, 2002.

[13] ITU RBS.1534-2001: Method for the subjective assessment of intermediate quality levels of coding systems. 2003.