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ACOUSTIC CHARACTERIZATION OF THE ANCIENT THEATRE OF TYNDARIS: EVALUATION AND PROPOSALS FOR ITS REUSE

Elena Bo, Eirini Kostara-Konstantinou, Federica Lepore, Louena Shtrepi, Giuseppina Emma Puglisi, and Arianna Astolfi

Politecnico di Torino, Department of Energy – DENERG, Corso Duca degli Abruzzi 29, 10124, Turin, Italy
email: elena.bo@polito.it

Nikolas Barkas

Democritus University of Thrace, Department of Architectural Engineering, University Campus
67100 Xanthe, Greece

Ancient theatres are one of the most representative signs of civilization belonging to Greek culture. The origin of these structures dates back to the 5th century BC: designed for the perfect acoustics, they were used at different purposes – religious ceremonies, political assembly, theatrical and musical performances – with progressive developments and diffusion outside Greece. Theatres were object of architectural modifications already in ancient epoch, during Hellenistic and Roman periods. Today, the damages due by time, atmospheric agents and invasive restorations are responsible for critic conditions of conservation of ancient theatres and, consequently, of their remarkable acoustics. Moreover, the revival of the ancient drama leaded to the reuse of ancient theatres nowadays, practice that is commonly accepted in many countries, but barely reasoned on the effective properties of their complex acoustical apparatus. A deep historical study on theatre's architectural developments, meant from the acoustical viewpoint, is at the base of the evaluation of the chosen case study: the theatre of *Tyndaris*, in Sicily, Italy. In this article, the results of an extended measuring campaign are reported, with objective data. Thus, the subsequent analysis of the theatre as geometrical model allowed the comprehension of its original acoustical characteristics and the design of a scenic proposal, specifically developed to enhance the natural acoustics. Furthermore, this scenery was evaluated by means of an acoustic simulation tool, Odeon v. 13.1. The calibration of the virtual models referred to the objective acoustic parameters, to the arrival time of the only strong early reflection (Δt) and to the direct-to-reflective energy ratio (DRR). Listening tests were finally performed using auralizations.

1. Introduction

During centuries, ancient open-air theatres underwent a process that defined their architectural and acoustical components. They were composed by a reduced number of distinctive elements, which had each one a specific acoustic role. A semicircular inclined amphitheater (form of a truncated cone) guaranteed the correct visual and listening angle. The plane of the *orchestra* allowed enforcing the first reflection coming from the speaker. The *proscenium* had the function to raise the speaker from the *orchestra* floor. The absence of the roof allowed the faster dispersion in the open-air field of annoying late reflections. Finally, the background wall (or *skené*) was a reflecting mirror for the direct sound in direction of the audience, and also an efficient diffuser with its several niches. This particular element saw the most consisting improvements in terms of dimensions and complexity during the evolution of the ancient theatre types, starting from Greek (distinguished in Minoan, Pre-Aeschylean, Classic), passing through Hellenistic and reaching the summit with the Roman theatre; but nowadays only the ruins of its footings still survive in most of the cases.

Not only time and lack of conservation are responsible of the decay of these structures. In fact, after the Roman Empire fall, theatres were abandoned; suddenly, the design procedure of a theatre changed and, throughout this process, the original sense of the architectural design of ancient theatres was lost. Thus, for the first acoustical investigations on open-air theatres it is necessary to wait until 1967, when François Canac published his book about twenty-years-long research on Greek and Roman theatres [1]. He defined the geometric functions that govern the acoustic behavior of the functional elements of the theater. His geometrical study reproduced the ancient scenery layouts in order to give form and brought to light the figure of the invisible soundscape of open-air theatres.

Assumed that ancient theatres are non-standard acoustic spaces and that the specific sound field of the open-air theatre makes unsuitable the usage of the room acoustic parameters defined in [2], such as Reverberation Time (T_{30}), Early Decay Time (EDT), Clarity (C_{80}) or Sound Strength (G), which are referred to in-door environments, a combination of the two different scientific approaches is recommended: the geometrical study on the existing consistencies and the parametrical analysis through the simulation software. A generic scenery proposal, defined with Canac's geometrical method, is tested through mathematical calculations, computer simulations (software Odeon v. 13.1) and listening tests. The chosen case study is the Greek theatre of Tyndaris. This paper, focused on the evaluation of the effectiveness of the scenery design focalized on speech requirements, aims to examine the acoustic importance of the theatrical elements (*cavea*, *orchestra* and in particular the scenic element: *skené*) for the completion of the scenic design enabling the reproduction of a passive acoustic function. In account of this, useful guidelines for scenic designers are provided.

2. Case study

The ancient theatre of Tyndaris is chosen as object of research: Hellenistic on its origins, the theatre consists of three parts, each one originated in a different period [3]. Firstly the *cavea* was built, and then the *skené* was added later. Suddenly, in Roman times (around 22-21 B.C.) the theatre was transformed into an *arena*: the level of the Greek *orchestra* (a semicircle with a diameter of 20.10 m) was lowered of 0.90 m; the *proscenium* and the four first rows of the theater were destroyed and used to build a 2.50 m height *podium*. Only the Greek-Hellenistic scene was not modified during the Roman period, but it collapsed in late-medieval age. Thus, the parts that last until today (Fig. 1) belong to various interventions and restorations. Only the footings of the monumental stage building survived. The *cavea* mostly damaged is now covered by protective panels in wooden, which allow people seating. From left to right, the parts that still present the original rows are the *cunei* 3, 4, 5, 6 and 9. Around the *cavea*, the *podium* with three openings is well preserved.

3. *In situ* measurements

A measurement campaign was conducted in the theatre of Tyndaris by the Department of Energy of Politecnico di Torino, 5th - 7th September 2015. According to [2], measurements were performed in unoccupied conditions with omnidirectional source and receiver. Previous considerations on ancient theatres measurements, defined during ERATO European project [4], were taken into account.

Two different types of impulse sources were used: firecrackers (types "Raudo Manna New Ma1b" and "Perfetto C00015 Raudo New"), and a dodecahedron (Bruel & Kjaer Omnipower Sound Source, mod. 4296) powered by an amplifier (Lab. Gruppen, mod. LAB 300), then connected to the laptop through soundcard (Tascam, mod. US-144). The microphone (Shoeps, mod. CMC 5-U) was connected to the laptop as well. The source positions investigated were S1, almost in the center of the *orchestra*, shifted horizontally of 1 m from the actual center to avoid acoustical focus [5], and S2, behind the first source position, distant 6.6 m from S1. Source height was 1.5 m and a custom-made tripod was used to keep firecrackers in fixed position. Nine receiver positions were disposed on three radial axes of the *cavea* at the height of 1.2 m, as shown in Fig. 2.

Figure 1: Greek theatre of Tyndaris, in its actual conditions of conservation.

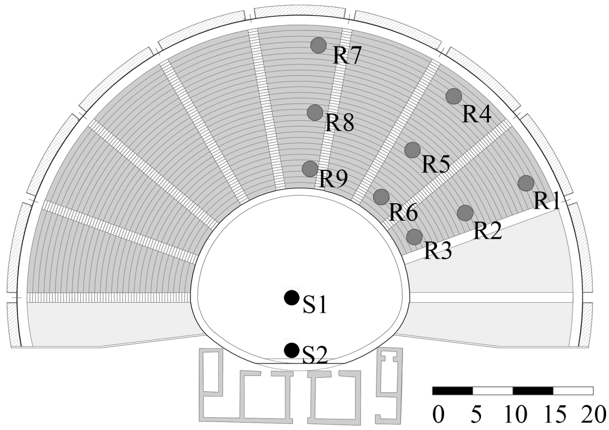

Figure 2: Greek theatre of Tyndaris plan; sources and receivers measurements set up.

Two source types had different characterizations: the reproducibility of firecrackers needs to be strictly checked; but they could maximize the Signal-to-Background noise Ratio (SNR), obtaining sharp Impulse Responses (IRs), while dodecahedral source could have a limited sound power for open-air conditions. Thus, Background Noise Level (BNL) measurements were carried out as well (NTi Audio, mod. XL2 Audio and Acoustic Analyzer): BNL measured was 34 dB(A) in unoccupied conditions; this allowed using both sources. A deeper analysis on the uncertainties of these measurements was conducted in [6, 7]. Environmental conditions were monitored during the measurement sessions: wind speed (anemometer Testo, mod. 450-V1), Relative Humidity (RH) and temperature (hygrometer/ thermometer Testo, mod. 608-H1). IRs obtained with firecrackers were recorded during day-time (wind speed = 1.30 m/s, HR = 70%, temperature = 29°C), while with dodecahedral source during nigh-time (wind speed = 0.30 m/s, HR = 77%, temperature = 26°C).

4. Geometrical analysis and scenic proposal

The so-called "canonical equation of the ancient theatre" defined by Canac was the basis for the understanding of the geometrical acoustics of the theatre of Tyndaris. Angle ε (formed by the line connecting the steps of the auditorium and the radius of the sound that reach the ear of a spectator) is considered responsible of the acoustical quality of the theatre: its solid cone, whose minimum is quantified equal to 4° to each viewer, provides visual and acoustic comfort preventing the absorption by the spectators. Equation (1) shows the relationships between audition angle ε, the inclination of the *cavea* (α), the diameter of the *orchestra* (D_0), the size of the *proscenium* (h = height of the *proscenium* level plus the height of the mouth of the actor), and the position of the viewer (H = height from the level of the *orchestra*). Figure 3 shows graphically these elements.

$$D_0 - h\frac{\cot g\alpha}{\sin\varepsilon} = D_0 + H\,\frac{\cot g\alpha}{\cos(\alpha-\varepsilon)\sin\alpha} \tag{1}$$

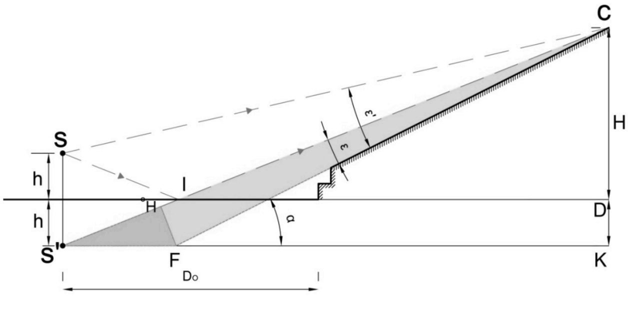

Figure 3: Greek theatre of Tyndaris, section with canonical equation elements explained.

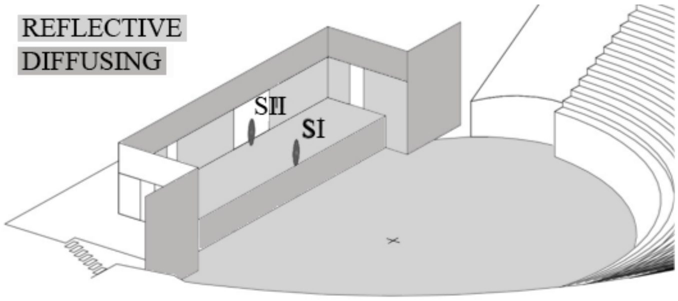

Figure 4: Greek theatre of Tyndaris, acoustical scenery: final proposal.

Two other geometric functions are introduced: Eq. (2) aims to eliminate the echo by relating *orchestra* and *cavea* (β is the angle from which depends the delay between direct and reflected ray), convolving the energy contribution made by the reflections in a specific point of the auditorium:

$$d = (S'C - SC) = 2hsen\beta \qquad (2)$$

$$\frac{D_0}{H} = \cot g\beta$$

Finally, Eq. (3) defines the geometric space of displacements of the actor (in front of the *skené*), with t equal to the distance of the actor mouth from the *proscenium* floor (1.60 m). The positive reflections coming respectively from the *orchestra* (SS1) and from the *proscenium* floor (SS2) is determined as follows:

$$SS1 \geq \frac{tH \cot g\alpha}{H + h_0} \qquad (3)$$

$$SS2 \geq \frac{t(D_0 + H \cot g\alpha)}{H - h_0}$$

These geometric functions may be useful to designers by proposing contemporary scenic elements historically and acoustically coherent to the existing architectural context. In this study case the chosen main function is the speech (tragedies and comedies). Firstly the calculations are based on boundary elements, in particular: i) the height of the *proscenium*, which must not be too high for the risk of losing all the contributions of the reflections (absorbed from the spectators), ii) the role of the *orchestra* (capable of increasing the sound of 3 dB) that has be free and reflective, iii) the geometric space of the actors movements, and finally iv) the depth of the *proscenium*. Based on these thresholds, an acoustic scenic proposal was developed (Fig. 4). More details on the definition of the scenery are available in [8].

5. Acoustic simulations

Simulations were performed through a geometrical acoustic software: Odeon v. 13.1. IRs from sources are computed using an hybrid calculation method, considering for early reflections a mixture of the Image Source Method (ISM) and Ray-Tracing Method (RTM), and for late reflections a special RTM generating secondary sources that radiates energy locally from the surfaces [9].

5.1 General Settings

For the creation of the theatre geometry, MATLAB v. R2015b was used: a script was created containing the main characteristics of the theatre (i.e. number of rows, height of the *cavea*, blocks division, and stairs' height). The other elements were added from Autocad v. 2013: the ruins of the ancient *skené*, two lateral blocks (*cunei)* with the corresponding parts of *podium* of the *cavea,* and the *orchestra*'s floor. Since different contemporary elements were present during the *in situ* measurements (a vibrating wooden panel placed on the *orchestra* and new wood staircases partially covering the *cavea*), they were modeled too. The final output was then inserted in a closed box, in order to simulated the propagation of the sound in out-door conditions (absorption coefficient α equal to 1). Omnidirectional sources were defined as in the measurements, considering the theatre unoccupied. For what concerns set up related to software algorithm, 1500 ms of impulse response length and 4 millions of rays were considered. Transition Order (TO) was set to 1 for the calibration, as only a strong reflection coming from the *orchestra* floor was considered; in the following simulations with also the scenery the TO was increased to 2. Weather conditions were set according to data measured *in situ*. The measuring position S1 was analysed for the model calibration. For guarantying the efficiency of the prediction model for sound prevision, this operation was made carefully, experimenting a new methodology reported in the following subsection.

5.2 Virtual model calibration

5.2.1 Calibration on objective acoustic parameters

The considered acoustic parameters [2] were T_{30}, EDT, C_{80} and G. They were calculated by analyzing measured and simulated IRs with Dirac v. 5 and Aurora v. 44. The calibration was performed by comparing the variation of parametric results in frequency octave bands. For measured data set, firecrackers IRs were considered, reporting on bars standard deviation with respect to repetitions in same position. As example, measured vs. simulated results for R9 are shown (Figs 5a, 5b, 5c, 5d).

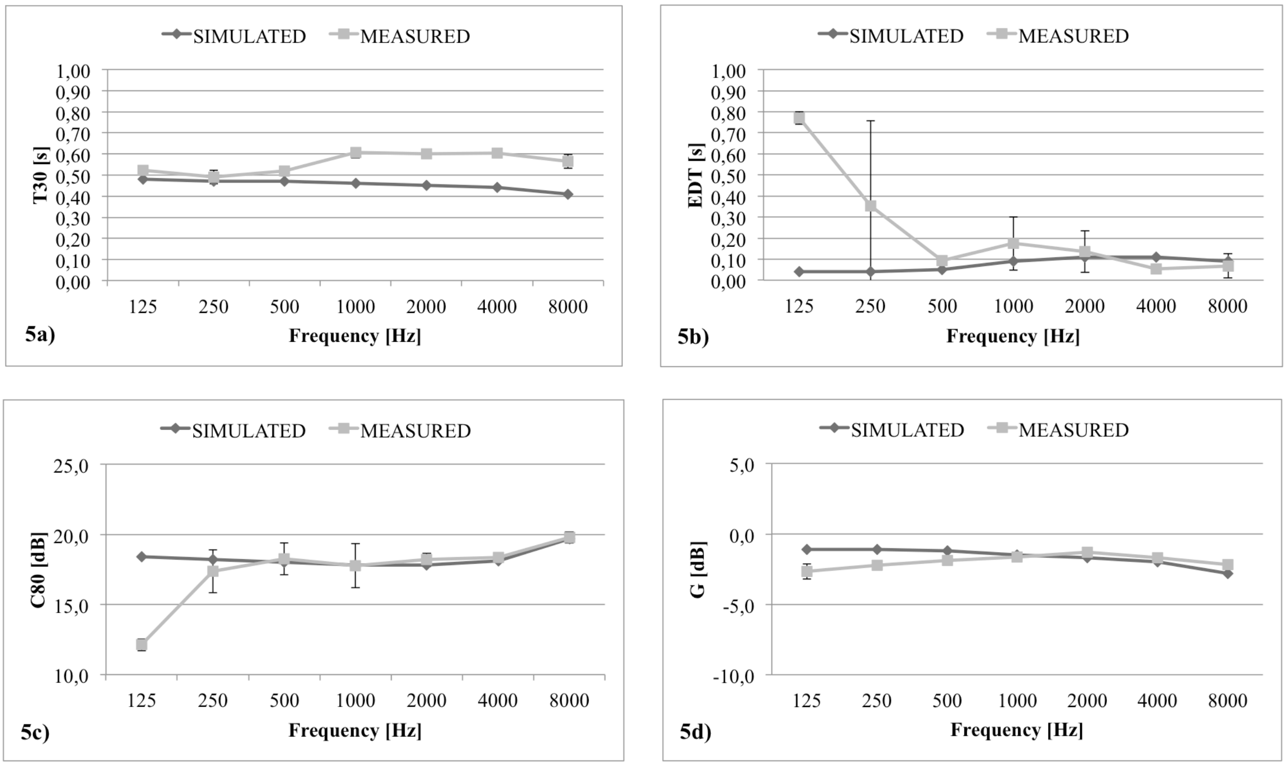

Figure 5: Standard calibration methodology applied on receiver R9. Measured vs. simulated values reported in frequency octave band for a) T_{30}, b) EDT, c) C_{80}, and d) G parameter.

As noticeable, energy parameters, such as the G or the C_{80} (respectively, Figs. 5c and 5d), shown a really good fit with real measurement, unlike the parameters related to time as T_{30} and EDT (Figs. 5a and 5b). Recently [10] sustained that conventional T_{30} is not applicable for definition of acoustical quality of unroofed auditoriums, and it demonstrated that the spatial assets affects the temporal quality of the reverberation is affected. Thus, conventional time parameters, based only on sound energy decay, could be not proper for the acoustic evaluation of unroofed spaces. Moreover, also energy parameters are affected by recurring results: C_{80} is usually higher compared to enclosed conditions range, while G decay strongly depends on the source-receiver distance.

5.2.2 Calibration on energetic and temporal components of the IRs

While standard values used to calibrate the model only slightly vary by modifying the characteristic material coefficients during calibration (absorption coefficient α, scattering coefficient s), the trend of the IRs seemed to be more sensitive. Thus, the following attempt of optimization of the usual calibration method was made, comparing measured and simulated IRs by considering two main aspects. Figure 6 resumes the concepts of Δt and DRR on a measured IR of example.

- Δt (early reflection arrival time): verification of consistency of different arrival times at the receiver of the direct sound and the first reflection (temporal component of the IR);
- DRR (Direct-to-Reflective energy Ratio) [11]: comparison between the ratio of the energy between the direct peak and the first reflection peak (energetic component of the IR). Just Noticeable Difference (JND) considered 2 – 3 dB as stated in [12].

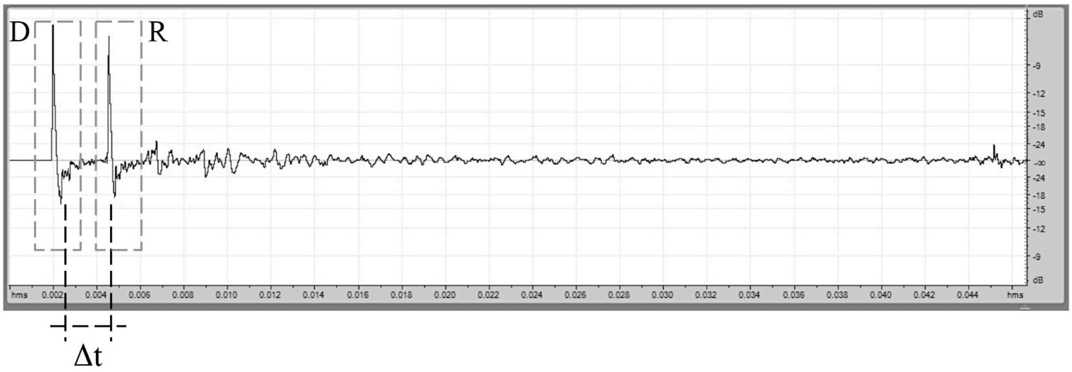

Figure 6: Graphic definition of Δt and DRR on a measured IR (firecracker, measurement path: S1-R6).

In Table 2 are reported the results of the analysis conducted through MATLAB on all measured (M) and simulated (S) IRs. Both firecrackers (M_F) and dodecahedral source (M_D) IRs were considered.

Table 1: Δt and DRR calibration results

Receiver	Δt M_D [ms]	Δt M_F [ms]	Δt S [ms]	DRR S/M_D [dB]	DRR S/M_F [dB]
R1	3.15	3.23	3.38	0.37	2.01
R2	2.83	2.88	2.99	0.52	0.51
R3	2.40	2.46	2.34	1.29	1.99
R4	3.22	3.15	3.40	1.92	0.13
R5	2.99	2.98	3.04	1.19	1.80
R6	2.61	2.58	2.38	0.28	2.15
R7	3.24	3.21	3.45	1.46	1.57
R8	2.86	3.00	3.08	2.40	2.92
R9	2.49	2.60	2.45	1.96	2.89

5.3 Objective Results

After the calibration of the model, the scenery proposed was added to the theatrical apparatus, and several simulations were carried out, considering source positions SI and SII shown in Fig. 4. The main parameters considered were G and DRR, plotted as a function of source-receivers distance. Figures 7a and 7b show respectively the results; for sake of easier comparison, logarithmic regression curves are added.

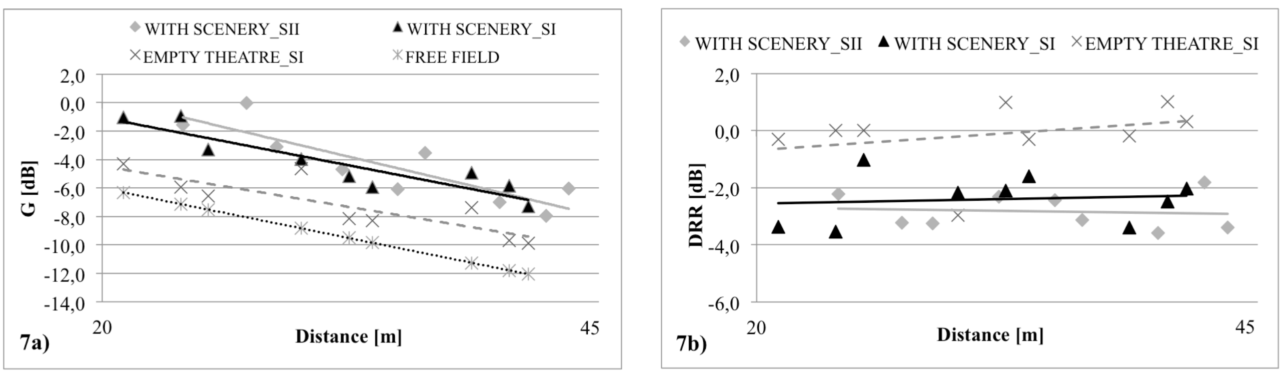

Figure 7: Simulated values averaged at 500 Hz -1kHz and corresponding logarithmic regression curves for a) G, and b) DRR parameter. Source in positions SI and SII, all receivers, with and without scenery.

Simulated G values follow quite well the free field trend, with a gain of 2 dB in empty condition. Values obtained with the source SI, on the edge of the scene, are lower than those obtained with the source SII, rearward of about 3 m respect SI and closer to the wall scene: about 2 dB are gained at shorter distances, coinciding with the first rows of the auditorium. The trend line of G in presence of scenery testifies an increase of 4-5 dB compared to the empty theatre simulated condition.

For DRR calculation, another MATLAB script was used: instead of identifying only the two main peaks, this considered the whole IR as reverberant after the first 2 ms (namely, the direct sound). This was necessary since the insertion of the scenery in the theatre added other important reflections in addition to *orchestra* floor image source. Thus, it is evident that in presence of the scenery DRR is reduced respect the bare condition of the theatre, as noticeable from Fig. 7b. SII involves a further increase in the reverberant component, especially in the backward positions, where the DRR is reduced of about 1 dB respect SI values, but with the considered JND this should be not perceptible. The trend line of DRR is almost constant along the axis of the distances: this means that the influence of scenery is homogeneous in all the positions of the auditorium.

6. Listening tests

To identify the perceptible alterations between different acoustical conditions in the *cavea,* a listening test was carried out on auralized soundtracks prepared with Odeon IRs. Two different simulated scenarios were compared: empty theater and with scenic proposal conditions.

6.1.1 Auralized soundtracks

The tests consisted in three different types of *stimuli*: speech, music (bowed string instrument, a viola), and chorus. The original tracks were anechoic recordings, then virtually convolved using Aurora, with duration of 7-8 s for each signal. All the auralizations refer to two listening positions: R1 (external axis, last row) and R6 (diagonal axis, first steps) shown in Fig. 2. For speech and music listening test the sound source was located in SII with the scenery, and in the SIII (corresponding to measured position S2 in the *orchestra*) for the empty theatre; instead, for chorus listening test the source was located in SIII (according to historical chorus position) with and without the scenery.

6.1.2 Test organization

The test was developed through software IND-LisTEn [13]. The two sets (empty theatre and with the scenery, both without audience) were compared following the methodology of the simple AB comparison test, for a total of 6 pairs, randomized and repeated three times to avoid bias, for a total of 18 pairs and 15-20 min per test. The task requested was to rate each AB couple on the base of a subjective preference; the question was: “Which sample sounds better?” with the possibility to chose the sample A, B or to express any choice. At the end of the task, the listener was also asked to describe the main differences perceived listening each couple A and B. About 16 normal hearing subjects were chosen. The listening tests were realized in one days, in a quiet office in Politecnico di Torino with BNL equal to 26.7 dB(A). The conditions were common for each listener: they used professional headphones (Sennheiser, mod. HD 600) and same laptop configurations.

6.1.3 Results

The analysis was conducted separately on the three *stimuli*, by the average of the repetitions of each pair proposed to the listeners. Fig. 8 shows the preferences with or without scenery in percentage, referring to positions R1 and R6.

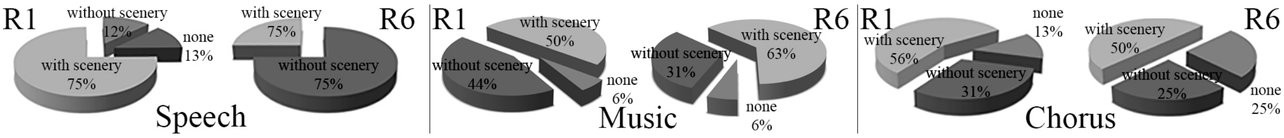

Figure 8: Resulting percentages in R1 and R6 referred to Speech, Music, and Chorus Listening test.

For speech listening test, the most significant result was the almost total preference expressed for with scenery configuration for position R1, placed in the last rows where the scenic elements led to a sharp increase in sound intensity. Hence for the participants the goal of strengthening the audability inside the theater was achieved. Instead for R6, in the first rows, the situation without the scenery was preferred, as these tiers reach optimum levels of intensity already through direct sound and *orchestra* reflection. So in this case a loss of clarity was perceived. In the case of music signal, despite the scenery was not specifically designed for music listening, the results shown a slight preference for the configuration with the scenery, both in R1 and R6. The preference was based, as told by the listeners, on the perception of higher sound envelopment, feeling of spaciousness, fullness, and brilliance of the musical signal. Finally, in chorus listening test the sound source placed in the *orchestra* resulted more difficult to rate. As reported by listeners, the configuration with the scenery was characterized by a thicker sound effect in both receivers (slightly higher in position R1).

7. Conclusions

This article deals with a scenic proposal for the reuse of the ancient theatre of Tyndaris nowadays as performance space. Firstly, a measuring campaign was carried out in order to define the actual acoustical condition of the theatre: two different types of sound source were used (firecrackers and dodecahedral source). The acoustic temporary scenery was developed with speech function: a historical analysis was conducted in order to define the requirements allowing a proper revival of the ancient drama. Canac's trigonometric equations for the ancient theatre audability were applied to define the boundary limits for the scenery. Once defined, prediction tool Odeon v.13.1 was used to perform simulations on a virtual model of the theatre calibrated on real measurements. The calibration of the model was accomplished following two methodologies: a traditional one, based on standard parameters (T_{30}, EDT, C_{80} and G); an optimized one, based on the temporal and energetic components of theatre's IRs, corresponding to two new parameters, namely Δt and DRR. Thus, the acoustic model calibrated was simulated with and without the scenic proposal. The parametric analysis of G and DRR revealed optimal values in presence of the scenery, due to benefits at the reflections path. Finally, a simple AB comparison listening test was performed on auralized soundtracks, on the scenarios with and without scenery. The request was to express a preference and three stimuli were chosen: speech, music and chorus. The results confirmed the predisposition of the scenery for the speech function. Future works will include the estimation of audience's absorption effect.

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