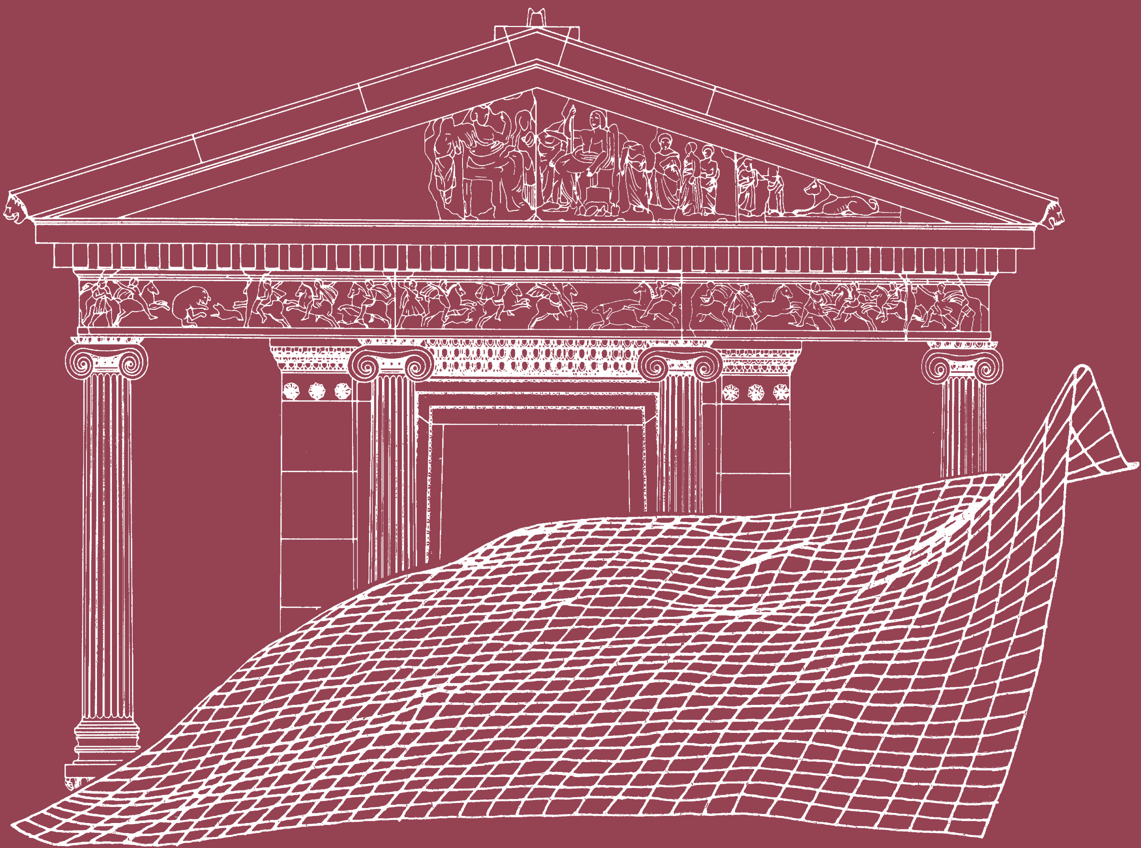

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From digitalisation and virtual reconstruction of ancient musical instruments to sound heritage simulation and preservation, edited by Angela Bellia

Note e Recensioni:

FROM DIGITALISATION AND VIRTUAL RECONSTRUCTION OF ANCIENT MUSICAL INSTRUMENTS TO SOUND HERITAGE SIMULATION AND PRESERVATION

edited by
Angela Bellia

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INTRODUCTION: AN OVERVIEW OF HOW VIRTUAL RECONSTRUCTIONS AND SOUND SIMULATIONS CAN IMPROVE OUR KNOWLEDGE ON ANCIENT MUSICAL INSTRUMENTS AND SOUND HERITAGE

This special issue aims to discuss how digital technologies based on 3D modelling and sound simulation can expand our knowledge of ancient musical instruments and sound heritage. Computational methods for processing the 3D models allow for a more accurate analysis of surfaces, volumes, internal structures, and density of materials of ancient instruments. Being non-invasive, these methods enable the study of the instruments' measurements and morphology, overcoming the limitations posed by their fragility. Although reconstructions cannot tell us unequivocally how ancient musicians played these instruments and how audiences perceived their sounds – given that we cannot replicate the experience of ancient listeners – they offer the chance to not only break through the time barrier by reviving sound emissions, but also to explore the types of sound experiences that ancient peoples were exposed to, taking in consideration that they would be operating within different cultural, social and musical contexts (Betts 2017, 23-25).

Whilst the consequences for our interpretations are still to be defined, the application of technology to the study of instruments allows for different kinds of approaches and studies that aim to acquire a better understanding of ancient sounds, such as those produced by string instruments, but also wind and percussion instruments, including examples from the Greek, Roman, and Etruscan periods as well as ancient instruments found in Northern Europe and South America (De Angeli *et al.* 2018). By combining optical metrology with computational analysis, some of the subjective observations on ancient instruments can be substituted by measurable parameters, opening up new perspectives for the study of ancient music and sound heritage as well as the organological and technological development of instruments in order to understand the artisan production manufacturing process of these special artefacts (Safa *et al.* 2016). Studying how these material objects have undergone transformations and forms of handling, the survey on the evolution of these instruments could help us in defining a novel approach and methodology to the 'active preservation' of instruments and sound tools in order to develop new research fields in both humanities and technological research areas also involving the study of sound heritage (Avanzini *et al.* 2015, 2016; Pretto *et al.* 2020). For this reason, novel methodologies related to virtual reconstructions and sound simulations of instruments and sound heritage are a work in progress (Bressan, Canazza 2013) and are needed to confirm or, where necessary, modify the hypotheses as well as to enhance and improve new ones (Farina, Tronchin 2013).

Moreover, 3D-printed models can enable the exploration of their musical potential (Both 2008; Bellia 2019a). Indeed, the virtual reconstruction of ancient musical instruments allows us to implement our knowledge of the main processes of their production thanks to the 3D scanning phase (Angela Bellia), the post-processing phase, and the reconstruction phase in a virtual environment (Antonio Rodà, Sergio Canazza, Giovanni De Poli, and Zezhou Sun, Emily Whiting). Digital technologies based on 3D models can overcome further limits related to ancient instruments (Stefan Hagel): given that their reconstruction is virtual, many different hypotheses can be tested despite the fact that these instruments are often damaged and cannot be played anymore (Sun *et al.* 2020). Indeed, it is possible to produce a basis for assessing different reconstructions.

It is worth noting that virtual models can be easily shared, making possible global access to this form of heritage; they can also be printed, thereby providing the opportunity to produce physical copies at a relatively low cost (Zoran 2011; Fangbemi, Zhang 2018; Damodaran *et al.* 2021).

Keeping in mind that virtual instruments can be used in subjective listening tests to compare the 'sound quality' of different instruments for the evaluation of (real or simulated) restoration of ancient instruments, and for preliminary listening tests with newly designed ones before they are actually built, sound features of musical instruments, as well as their vibrational behaviour, represent one of the most important and fascinating fields of acoustics, or even of applied physics (Tronchin 2020). This aspect is sometimes neglected (or at least not investigated enough) during the restoration of ancient masterpieces, even though it is well known that the instruments' sound production is something of inestimable value.

It is worth noting that a significant number of archaeological finds of ancient musical instruments are exhibited at archaeological museums (Georgios Th. Kouroupetroglou, Spyros Polychronopoulos, Konstantinos Bakogiannis). Some scholars are exploring user friendly, adaptable and expandable digital tools in order to create virtual instruments, which can reproduce their sounds within exhibitions (Swift *et al.* 2021) devoted to a lay public and students – and, in some cases, also useful to scholars and researchers – in order to disseminate the knowledge of ancient music not only among specialists, but also to a larger community (Micheloni *et al.* 2016; Bakogiannis *et al.* 2020).

In this regards, it is essential to emphasise that modern studies on ancient music's technical history (Eichmann, Fang, Koch 2012, 2016) should be always seriously considered in order to avoid that digital application might misguide archaeologists and conservators if documented ancient sound – grounded on attested playing techniques and tunings – remains disregarded.

Moreover, in sound simulation of ancient instruments (Terzēs 2020) should be avoid arbitrary sorting into classes, especially if an appropriate modelling description that simulates the basic sound mechanisms and factors is the aim of the reconstruction of instruments.

Digital technologies based on 3D modelling and sound simulation provide new insights in sound studies, as the data can be applied to sound simulators and soundscape reconstructions in ancient architectural structures and ancient spaces (Till 2019). With the aid of new technologies in geo-referenced sound mapping and multimedia applications, it is possible to recreate, play, and test musical instruments and their sounds both under laboratory conditions and on-site in different architectural settings.

In this regard, this special issue aims also to explore the sonic interactions and the spatial configuration of sanctuaries and theatres in their respective landscapes and environment in order to investigate the use of auralisation technology in the archaeological field, as well as experimental interpretative 3D reconstructions integrating acoustic models. Indeed, in the last few years many scholars have devoted their studies and research to these themes with different methods and results, all with the aim of exploring how digital technologies based on 3D modelling and sound simulations can expand our knowledge on sounds and open new perspectives on the study and preservation of sound heritage and audio files (Sergio Canazza, Giovanni De Poli, Alvise Vidolin).

This is an ambitious way of approaching and analysing archaeological sites, and involves speculating on the soundscape of performative spaces of ancient cultures as well as reconstructing how they were experienced. Combining binaural recording technology, psychoacoustic analyses, and site-mapping techniques, research methodology enables researchers to re-create the original conditions with high fidelity along with the precise orientation and directionality of sounds. Since the data points can be generated from digital recordings, this capability can be used to further explore the human sonic experience of the acoustic environment (Jordan 2020; Bellia 2021).

In this regard, it cannot be discounted that the sonic aspects of theatral structures that existed in connection with the origin and significance of their public character might have played an integral and important role in increasing the functionality of these buildings as places of interaction and communication on multiple sensory levels, involving highly visual imagery and dramatic sounds, as well as other sensorial experiences (Cristina Manzetti, Nikos Papadopoulos). Thanks to the analysis of some acoustics parameters and the listening of sounds in a 3D environment, it is possible to explore the creation process of performative structures. Moreover, the study of the sound features and sonic environment of these structures provides us with new insights on their acoustic reasoning and function (Manzetti 2019). In this respect, in recent years the study on sound has attracted enormous interest and yielded substantial insights, yet there are still many aspects of sound heritage to be explored in order to consider sound as a form of cultural heritage to be understood, preserved and disseminated. For this reason, these topics should be addressed through the contributions of scholars working in various fields, not only including archaeology and archaeomusicology (Both 2009), but also information engineering, interactive museums, sound heritage, acoustics, physics, virtual heritage, ecoacoustics, and craftsmanship.

It should be noted that, although a generation of European researchers has been excluded from the research system of their country of birth due to the stagnating research funding landscape of the past decade and the rigid, conservative, and anachronistic hierarchy of academia in some countries (especially in Southern and Eastern Europe), collaborations and interdisciplinary research involving humanities and technological fields have been enhanced thanks to the hard efforts of researchers and the investment of European resources (Bellia 2019b). Formulating theoretical foundations, principles and processes to be followed (traceable, transparent, reproducible and verifiable), these collaborative and multidisciplinary works can provide not only a better integration and a growing 'ibridation' among humanities with technological fields, but also an unmatched contribution to the workings of innovation in the present and in the future of studies related to music and sound, which can be spread widely among researchers and the general public.

By trying and trying again, we will be able to not only produce significant insights on sound heritage and new lines of research in the fields of digital heritage and of digital approaches to historical acoustemology (Geoffroy-Schwinden 2018), but also present a novel analytical framework that models the acoustics of archaeological spaces. As Marie Skłodowska-Curie said: «Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less».

Preliminary versions of some of the themes contained in this special issue were presented at the webinar *From the Digitalisation to the Virtual Reconstruction and Sound Simulation of Ancient Musical Instruments* held on February 25th 2021 at the Institute of Heritage Science of the National Research Council of Italy. I would like to thank all the speakers for their interesting papers, as well as everyone who attended and participated in creating a positive environment. Special thanks must go to Costanza Miliani, Director at the Institute of Heritage Science, for encouraging me to organise the event. I am also very grateful to Paolo Romano and Nella Pagano as well as to Danilo Pavone, Silvia Iachello, and Fabio Viscuso for their valuable collaboration and support.

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3D VIRTUAL RECONSTRUCTION AND SOUND SIMULATION OF OLD MUSICAL INSTRUMENTS

1. Introduction

For millennia, music culture has been handed down orally since the earliest detailed written music documents are relatively recent (Tomlinson 2012). Therefore, what we know about the music of the past is due to indirect documents, such as literature, music theory treatises, and iconography. In this context, archaeological finds of musical instruments such as ancient flutes or harps coming from ancient Egypt or Greek-Roman areas are a very important direct source of information. Unfortunately, these instruments are often seriously damaged and can no longer be played. Therefore, by observing these artifacts we can get an idea of the global shape and analyze the materials they are built from, but we can not listen to their sound and have experience of the performing practice.

Traditionally, playable copies of ancient instruments were built by craftsmen. This approach has several limits: a) the manufacturing process is usually slow and expensive; b) often one or few copies only can be built, limiting access to the instrument; c) when the reconstruction is uncertain, due to the poor state of conservation of the artifact, it is difficult to test and evaluate different possibilities.

Digital technologies based on 3D models overcome these limits. The reconstruction is virtual, therefore many different hypotheses can be tested; finite elements methods (Umetani *et al.* 2016) and physically informed algorithms allow to simulate the sounds produced by the artifacts, also giving a basis for evaluating the different reconstructions; virtual models can be easily shared, making possible global access to the heritage; finally, additive printing technologies offer the opportunity to have physical copies at relatively low costs. Nevertheless, methods and algorithms to obtain a virtual reconstruction of musical instruments in an automatic or semi-automatic way are still missing. Several algorithms were developed in the past years for simulating the sound of known instruments, but these algorithms need to be modified and improved to meet the requirements of these ancient and almost unknown instruments. 3D printing processes need to be tuned to consider the influence of materials and textures on sound generation.

2. Related work

The importance of music in particular, is a topic discussed broadly in literature (Sacks 2006; Bergh 2007; Storr 2015). Music, as a cultural activity that can express and evoke emotions (Cooke 1959), is believed to be able to bind people and bring them together. «No culture so far discovered lacks music. Making music appears to be one of the fundamental activities of mankind» not only in present days but also in ancient times (Storr 2015). Thanks to the written music compositions handed down over the years and the specific details of the construction of the musical instruments, we can still nowadays arguably "hear" not only Bach's music but also, for instance, Mozart's and Beethoven's music the same way as the audience of their time. Furthermore, most of the places where they performed, along with some well-preserved musical instruments, dated back to their time, still exist today (Greilsamer, Freeman, Baker 1927). However, the same cannot be said about ancient music.

Although a good amount of ancient Roman and Greek musical artifacts have survived from antiquity, most of them are fragmentary and, for the most part, in no condition of being played. However, in order to better understand a musical instrument, it is very useful to listen to the sounds it produces (Pretto *et al.* 2020). The archaeology of music field focuses on excavating, identifying, classifying and ultimately reconstructing these ancient musical instruments (Van Keer 2010). Usually the first reconstruction is digital where a 3D model of the artifact is created. Making a 3D model opens many possibilities when it comes to analysing, simulating and recreating the lost sounds of the instrument, as well as creating a material copy of the instrument (Koumartzis *et al.* 2015). Afterwards, all efforts are aimed at further investigating the difference between the simulated sounds of the 3D model and the sounds produced by the physical replica. It is important to note that the materials constituting the instrument (including their provenance, treatment and workmanship), the playing posture and techniques, textual information as well as the location are all elements that need to be considered when simulating the sounds of the instrument (Both 2009). Therefore all the musical discoveries need to be evaluated in their archaeological and historical context, rather than in isolation (Bellia 2019). For example when reconstructing the Greek lyre of Hermes a tortoise-shell was used as a soundbox (Koumartzis *et al.* 2015).

There are several other reconstructions and sound simulations of ancient musical instrument. A fascinating case is the discovery in Sanzeno (Italy) of the remains of ancient Celtic musical artifacts known as *karnykes* (Roncador *et al.* 2014). These musical instruments were war trumpets that were used by the Celtic population to psychologically terrorize their enemies. Thanks to multiple international collaborations the historical and chronological context as well as the chemical and metallurgical properties of these musical artifacts have been studied. In 2011, to better understand the unique sounds produced by this instrument, a first prototype, made in brass, has been created. In addition to the case of the *karnykes* from Sanzeno, musical artifacts belonging to the same family have been excavated in Tintignac (France). Because the *karnykes* from Tintignac were recovered in better conditions than the ones from Sanzeno, experts were able to put some of the parts together to make an almost complete authentic *karnyx*. Afterwards the virtual copy of the instrument was analyzed from an acoustic point of view to obtain data regarding its sounding characteristics. More specifically, several measurements concerning input impedance, resonance and playing frequencies have been made and the possible influence of the artifact's structure on the radiated sound was taken into consideration (Gilbert *et al.* 2012).

Another interesting example is the virtual and physical reconstruction (using polymer as the main material) of the *aulos* wind instrument found under Temple R at Selinunte and dated to 570 BCE (Bellia 2019). This important discovery can help researchers better understand and investigate the ancient Greek music.

In general, not only small but also bigger organizations and museum institutions have been involved. The museum of Louvre-Lens has presented the first big exhibition *Musiques! Échos de l'Antiquité* dedicated to ancient musical instruments belonging to Greek, Roman and Egyptian ancient civilizations. Among these instruments, it is worth mentioning the case of the *cornua* of Pompeii. Five of these ancient wind instruments, belonging to the brass family, have been excavated and recovered in Pompeii, Naples. A virtual reconstruction of artifacts has been created and the sounds have been all modelled and synthesized with the help of the Naples National Archaeological Museum (Emerit *et al.* 2017).

Another project that is important to mention is the European Music Archaeology Project (EMAP)[1], which has already reconstructed high-quality physical reproductions of more than 60 ancient musical instruments. Several exhibitions have been arranged where the public was able to touch and play some of these ancient instruments and experience past sound worlds and environments (De Angeli *et al.* 2018).

It is however important to note that, except for a few projects such as EMAP or Museo Interactivo de la Mùsica in Malaga (MIMMA)[2], not much has been done to promote and enhance these ancient musical instruments on the web. As we have seen, a certain number of research on sound simulation and virtual/physical reconstruction of ancient instruments exists, however, apart from the individuals involved in the research, most people do not have the possibility to listen to the fascinating music these musical artifacts can create. It is true that some of these researches have promoted these instruments through museum installations (Bellia 2019; Pretto *et al.* 2020); however,

[1] http://www.emaproject.eu/ (retrieved May 5, 2021).

[2] http://www.musicaenaccion.com/mimma (retrieved May 5, 2021).

as discussed in the previous section, museums do not have the same appeal and the same potential to reach as many people as online websites can.

2.1 *Tuning and timbre*

Digital models are interesting because they allow us to have accurate measurements to simulate sounds, which is important to have evidence on the music of the time and to support hypotheses on the playing technique. Being able to listen to their sound and understand the methods of production allow us to have information on their use and role in society (Fritz *et al.* 2021).

Among the many characteristics of a sound, the pitch is often considered the most important, at least from a musical point of view. Indeed, by knowing the set of pitches that can be generated by an ancient instrument, we can infer which structures of pitches (scales, modes, tetrachords, etc.) were used at that time. This is a very important aspect for many musical traditions, in particular for the ancient Greek-Roman music, where the analysis of coeval musical instruments can give evidences for a deeper understanding of the various historical theoretical treatises (see e.g. Barker 2007) and support hypotheses related to the fine-tuning of those pitch structures (Hagel 2009).

However, other aspects of the sound different from pitch are also interesting, such as intensity and timbre. To study these aspects, digital synthesis techniques offer many useful approaches. The sound produced by acoustic musical instruments is caused by the physical vibration of a resonating structure excited by a suitable action. It can be represented by a mathematical model and can be computed by synthesis algorithms (De Poli 1983; Borin *et al.* 1992).

If an existing reference instrument is available, it is possible to store in wavetables a large quantity of sound examples and during synthesis we just need to play one sound from the stored repertoire. Pitch transposition can be obtained by varying the speed when reproducing the sound. This technique (*sampling*) is characterized by high computational efficiency and high imitation quality, but by low flexibility for sounds not initially included in the repertoire or not easily obtainable with simple transformations.

Granular synthesis constructs complex acoustic events starting from a large quantity of elementary acoustic elements called grains. When the grains are irregularly distributed, we can obtain "clouds" of micro-sounds, or sonic textures, where the general statistical properties are more important than the exact sound evolution. In general, we can expect these types of sounds to occur in the real world when they are the result of multiple realizations of the same event or the same phenomenon. For example, among unpitched percussion, we find micro-sounds in the angled rainstick, (shaken) small bells, (grinding) ratchet, (scraped) guiro, (jingling) tambourine, and the many varieties of rattles.

Various instruments can be modelled as exciters, characterized by a rich spectrum, and a resonator (called filter) that transforms its spectrum. The *source-filter model* allows to control and modify the fine (pitched or noisy) structure of the source separately from the spectral envelope of the filter. It is very effective for voice and resonating percussion instruments synthesis.

Physical modeling synthesis refers to sound modeling techniques in which the synthesis algorithms are designed based on a description of the physical phenomena involved in sound generation, in particular the physical objects and interactions that generate the sound. Among the different techniques, the *digital waveguide model* is particularly efficient for simulating flexible structures such as strings, cylindrical or conical tubes. This technique is based on the analytic solution of the equation that describes the propagation of waves in a medium and is realized with delay lines, junction elements, and filters. The structure and the parameters of the model can be derived from measurements of an actual artifact, but it is possible experiment the acoustic effects of structure and parameter variations, in correspondence of different reconstruction hypothesis.

3. Methodology

To build a digital model of a musical instrument, we can start from different sources: pictures, textual descriptions, technical drawings, and, of course, archaeological finds (Fig. 1). In the latter case, we need to measure these finds, by hand or, better, using recent techniques such as structured light scanners or computational tomography. From these techniques we can directly obtain a first rough 3D model of the instrument or the parts/fragments of it. By means of digital processing techniques, the instrument can be virtually restored. Interesting, we can obtain many different versions of the restored

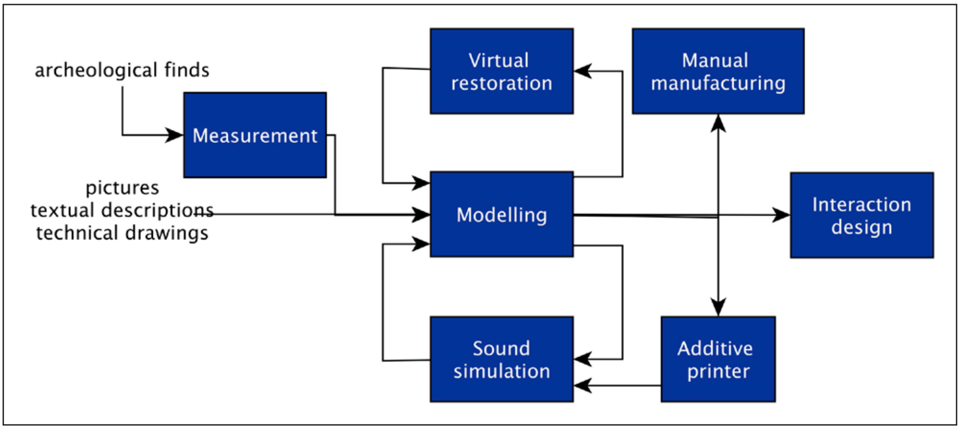

Fig. 1 – An iterative approach to the model of ancient musical instruments.

instrument, starting from different sets of hypotheses (about geometry, materials, missing parts, etc.) or addressing different objectives (e.g., to show the instrument as it is now or as it was originally).

From the restored model, we can then obtain a simulation of the sounds that could be produced by a musical instrument with such geometrical and functional properties. The generated sounds can also be used as a validation of the assumptions taken to build the model and can sometimes suggest further improvements to it.

The 3D model can also be used as a guide for a craftsman to construct physical copies of the instrument. Or, more easily, a physical version of the model can be directly obtained by an additive printer. In turn, following an iterative process, the physical copy can be used to estimate the parameters of the sound simulation algorithms more precisely.

Finally, the large amount of data and knowledge coming from this process, can be used to design novel approaches for enhancing the access to these instruments by scholars and the general public.

4. Case studies

The approach presented in Section 3 is exemplified through three case studies, differing in many aspects, the most relevant one is the state of conservation: the first study is a Pan flute in a good state, with 14 pipes mostly intact; the second is a brass musical instrument, quite damaged and broken in 8 more or less incomplete pieces; the last one is instead a lost instrument, of which we have only some technical drawings.

4.1 *Padova's Pan flute*

The first case presented in this paper is a well preserved ancient Pan flute, recovered in Egypt in the 1930s and currently exhibited in the Museum of Archaeological Sciences and Art (MSA) at the University of Padova (Fig. 2). Before being included in the permanent exhibit, the flute underwent a major restoration program for consolidation and (passive) preservation. Details about the history of the artifact, the place and circumstances of its recovery, as well as related literary and iconographic references in the Greek-Roman world, are provided in previous publications (Avanzini *et al.* 2015, 2016).

In comparison to similar findings, see e.g. the Pan flutes hosted at the Petri (Swift *et al.* 2021) and Louvre (Emerit *et al.* 2017) museums, this musical instrument is in a quite good state of conservation, with almost intact 14 pipes. The results of a radio-carbon analysis support the hypothesis that the flute dates back to the 7th c. CE.

From an acoustic point of view, the sounds of a Pan flute are generated by blowing inside the cavities of the pipes from the opened side of them. The

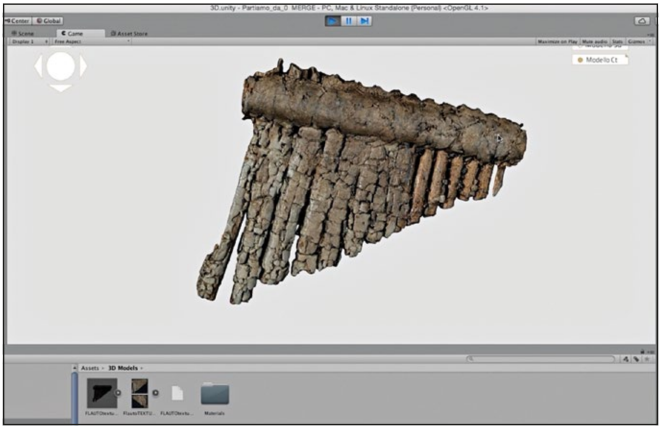

Fig. 2 – A view of the rendered 3D model of the Pan flute of Padova.

other end of the pipes is closed: in our case, the closures are obtained by means of the natural knots of the lake reeds that make up the instrument. Since the shape of the cavities of the reeds is well approximated by a cylinder with the length much greater than the diameter, the analytical solution of the wave equation is well known and allows to calculate the fundamental frequency of the sound produced by each pipe by means of the Eq 1:

$$f = \frac{4c}{l_{int} + \Delta l} Hz \qquad (1)$$

where c is the sound velocity, l_{int} is the internal pipe length, and $\Delta l=0.305 d_{int}$ is the length correction at the open end, proportional to the internal pipe diameter d_{int} (Fletcher, Rossing 1991).

As shown by this equation, the estimation of the fundamental frequency requires the internal dimensions of each pipe. Since many pipes were full of residual dirt, which could not be removed to not compromise stability, a series of non-invasive analyses, based on 3D scanning using computed tomography (CT), have been performed (Avanzini *et al.* 2016). Taking into account the inevitable measure errors, we estimated the possible range of the fundamental frequencies produced by each pipe (Table 1).

As previously stated, digital models of a musical instrument also allow us to simulate the sounds that such an instrument can produce. However, when we want to return the sounds from a so distant past, we must address the issues that we know very little about the way (e.g., the position and shape of the mouth in relation to the opened end of the pipe) those instruments were played, and which kind of music (i.e., sequences of pitches and rhythms)

pipe	f_{min} [Hz]	f_{max} [Hz]
1	638.7	649.7
2	677.2	700.7
3	753.6	773.5
4	843.1	874.4
5	928.3	974.7
6	1010.1	1041.3
7	1142.2	1184.3
8	1283.2	1346.4
9	1389.6	1438.2
10	1538.3	1602.0
11	1721.8	1758.1
12	1901.4	1957.3
13	2128.4	2205.1
14	2292.9	2499.7

Table 1 – Fundamental frequencies (min and max) estimated for each pipe starting from the measurements taken from the CT scan.

was used to be played, because no audio recordings exist and only very few fragments of written music (in some form of notation) arrived to us[3].

To get around these issues, we developed an interactive digital instrument that allows a user (musician, scholar, general public) to choose which notes to play and to control interactively some performance parameters such as the amplitude envelope (i.e., how the loudness of a sound varies in time). The user can play the instrument by using its blow, similar to an acoustic Pan flute: the flow of the blow is estimated by a sensor and its amplitude envelope is translated in messages of the MIDI protocol, namely *NoteOn* (attack), *ControlChange* (decay, sustain), and *NoteOff* (release), which control respectively the start, the time evolution, and the stop of the sound reproduction; then, these messages were sent to a sound synthesizer, specially developed on the base of a sampling approach (see Section 2.1).

The choice of this synthesis method for the Padova's Pan flute was guided by the following considerations: in comparison to other synthesis techniques it has a low computational cost, suitable for an interactive application; the Pan flute is a well-known instrument and it is easy to record or find audio samples of good quality; the main interest of this project was in rendering and studying the pitch patterns (musical scales, tetra-chords) generated by the instrument and the fine tuning of the tones, therefore a more refined simulation of the timbre was beyond its scope.

[3] The study of musical practice also includes the agogic and dynamic aspects of the music performance (Canazza *et al.* 2015).

An interactive museum installation[4] for the instrument has also been designed and built. Thanks to this installation the visitors can hear the sounds of the Pan flute by physically blowing on specific holes, each having a microphone, located on a panel. This multimedia installation also provides the possibility of discovering the instrument's background and history as well as inspecting its 3D models (Avanzini *et al.* 2015, 2016). The creation of the installation was based on a carefully tuned multidisciplinary design approach centered on *Design Thinking* (Pretto *et al.* 2020).

4.2 *Voghenza's Roman brass*

The second case study is related to several pieces of metal, unequivocally recognized as a brass musical instrument, found in the context of the excavation of a Roman building in Voghenza, close to Ferrara (Italy), dated to the 2nd c. CE, and now hosted in the archaeological section of the Civic Museum of Belriguardo. This instrument is the subject of an ongoing multidisciplinary project[5], that aims to analyze, reconstruct, and valorize this important musical heritage.

The instrument, made of a metal alloy, is broken into 8 pieces, and each piece further suffers from large holes and damages. The 3D model of each piece was acquired by means of a structured light system that uses light patterns (or codes) and is based on digital cameras and projector. Models of the different pieces were subjected to two kinds of numerical elaboration. The first one aims to repair small holes and deformations by means of filters and numerical interpolation and is particularly suited for pieces with less severe damages. The second one aims to estimate the geometry of the entire instrument, by virtually reconnecting the pieces, also in case of very corrupted parts. In particular, an original algorithm was developed to estimate the central axis of the curved tube of the instrument and its increasing diameter (see Sun *et al.* 2020 for more details). Fig. 3 shows the estimated geometry (blue) of the entire instrument superposed to the original damaged pieces.

After the estimation of the geometry of the recomposed instrument, it is possible to simulate the set of tones that a musical instrument with that dimensions can produce. The mouthpiece, very similar to that of modern trumpets, trombones, and horns, reveals that the Voghenza's instrument certainly belongs to the brass family. The modalities of sound generation of these instruments are widely described in literature (e.g. Fletcher, Rossing 2012). The acoustic waves produced by the vibrating lips propagates through

[4] Here you can see a video of the installation: https://youtu.be/P4yjw5R5qqY?t=165.

[5] The project currently involves the University of Padova (Dept. of Information Engineering and Cultural Heritage), the University of Bologna (Dept. of Cultural Heritage), the University of Salento (Dept. of Cultural Heritage), the Boston University (Dept. of Computer Science).

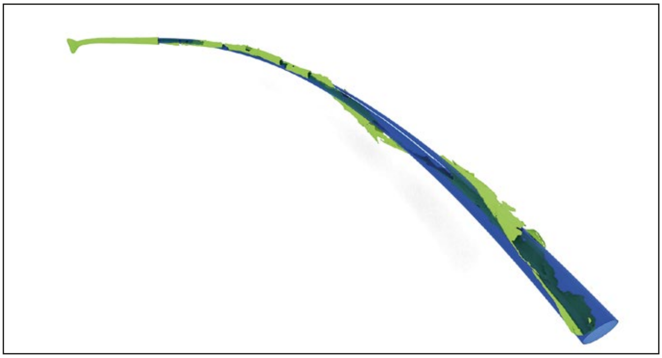

Fig. 3 – Aligned pieces from 3D scanning (green) and restored/rebuilt instrument (blue).

the cylindrical part of the instrument, the length of which can be modified in many brass instruments by means of holes (as in the cornetto), valves (as in the trumpet) or a sliding mechanism (as in the trombone). Then, the waves reach the ending flared section, where part of the acoustic energy is radiated to the outside of the instrument, and the rest part is reflected inside the bore.

From what we can observe from the remains, the Voghenza instrument has no holes, valves, or sliding parts. Therefore, the fundamental frequency of the tones depends largely on the peaks of the acoustic impedance of the bore. This impedance can be estimated analytically, starting from the well-known wave equation and solving it in the case of a wave propagating in a bore with increasing diameter. The solution lets to the following equation (Chaigne, Kergomard 2016) that allows the estimation of the frequencies f_n corresponding to a local maximum of the acoustic impedance:

$$f_n = \frac{c}{2(l + X_i)}\left[n - \frac{1-\nu}{2}\right] Hz \qquad (2)$$

where c is the sound speed propagation, l is the length of the cylindrical part, X_i is the length of the flared part, ν is a coefficient related to the shape of the flared part, and n is an integer number.

The unknown parameters of Eq. 2 were estimated by fitting the geometry of the reconstructed instrument (Fig. 3). Table 2 reports the frequencies of the natural resonances of the instrument estimated from Eq. 2. Finally, a sample of these sounds[6] were generated by a physically-informed algorithm based on a waveguide model (Cook 1991).

[6] Examples of the sounds can be listen at: http://www.dei.unipd.it/~roda/brass/.

n	f_n [Hz]
1	123
2	266
3	409
4	553
5	696
6	839
7	982
8	1126
9	1269
10	1412

Table 2 – Natural resonant frequencies estimated from the geometry of the re-constructed 3D model of the instrument.

4.3 *Milan's* Studio di Fonologia Musicale

The last case study is a quite particular musical instrument, or better a set of instruments that were part of the *Studio di Fonologia Musicale* of Milan. Some of these instruments are no more existing, at least in their earliest form, but they are well documented by means of original technical drawings and pictures. During the 1950s and 1960s, this studio was one of the leading places in Europe to produce electro-acoustic music, together with Paris and Cologne. Although not ancient in a strict sense, these instruments can be considered as remarkable examples of industrial archaeology, due to its uniqueness and to the rapid evolution of the electronic technologies. Moreover, they represent the first steps towards the diffusion of musical electronic and digital devices that, in the following decades, radically changed the way of producing music and listening to it. The Studio (Novati 2009) was founded in 1955 at the Milan offices of the Italian Radio-Television (RAI), under the initiative of the Italian composers Luciano Berio and Bruno Maderna. In a few years, the Studio became one of the European centers of reference for the production of electroacoustic music, by deploying cutting-edge devices for the generation and processing of sound. These devices were especially designed and crafted by Alfredo Lietti: oscillators, filters, modulators, and other unique pieces, created with great care to meet the needs of the composers who attended the Studio. In 1967 the Studio underwent a partial renovation; as a consequence, much of the older equipment was dismantled and has been lost (Rodà 2012). However, many photographs, diagrams, drawings, and audio recordings[7] were found in the archive of the Studio and thanks to these

[7] Magnetic tapes containing the music works produced by using the electronic devices of the Studio. See Bressan *et al.* 2013 for aspects concerning the preservation of this type of documents.

Fig. 4 – The replica of the control panel of one of the original oscillators of the Studio.

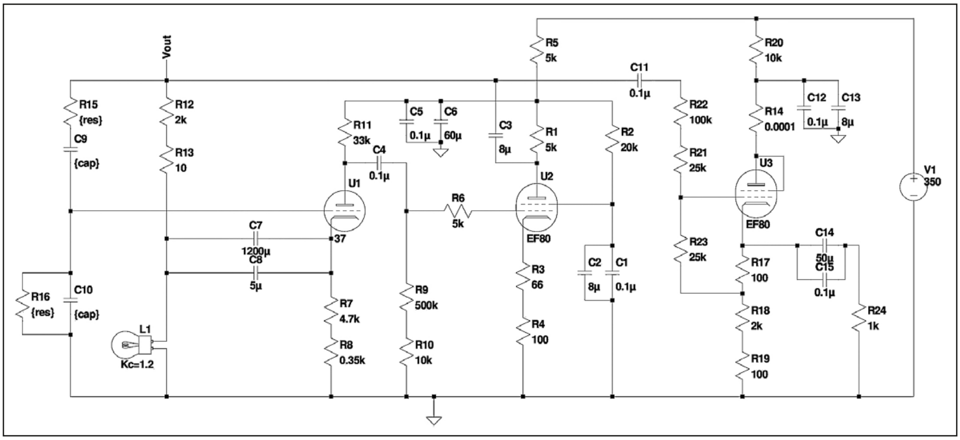

Fig. 5 – A transcription of the technical drawing of the oscillators designed by Alfredo Lietti for the Studio di Fonologia of Milan.

documents it is possible to know the characteristics and the functionality of most equipment that no longer exist. Electronic music instruments differ from traditional ones in many respects: the use of electric energy as the main sound producing mechanism, rapid obsolescence, the dependence on scientific research and available technology.

In 2011, the EU-funded DREAM project (Novati, Dack 2015) defined an approach to an active preservation of the electrophone instruments of the Studio, by following a multidisciplinary perspective that involved engineering, interaction design, and musicological competences. The project main outcome was to build a tangible copy of some of the electronic devices of the Studio, by using digital simulation of the internal analog components and by replicating the physical appearance (Fig. 4).

The digital simulation of the sound generated by the devices was obtained by starting from their technical drawings. For example, Fig. 5 shows a transcription of the technical drawing of the oscillators designed by Alfredo Lietti for the Studio. Each electric and electronic component of this schema can be characterized by well known (because the single components were produced industrially) input-output functions, that was simulate numerically. By combining the function of the different components it is possible to simulate the output signal of the entire device (Avanzini, Canazza 2012). This approach is very similar to the physical modeling techniques (see Section 2.1) used to simulate the sound produced by acoustic instruments, with the difference that in this case we deal with electrical signals rather acoustic waves. Finally, a public installation was built and temporarily exhibited at the Music Instrument Museum in Milan; in this way visitors could feel the original experience of playing and producing electronic music (Canazza *et al.* 2011), by acting on switches and knobs[8].

5. Conclusions

Digital modeling techniques offer great opportunities for the study of musical instruments of antiquity, or even just no longer playable due to a precarious state of conservation or a rapid technological obsolescence. Of particular interest is the numerical simulation of the sounds those instruments could generate when they were in use: digital models allow us to generate and listen to those sounds, even if we have only a few fragmentary pieces of the instrument or just some descriptions or pictures. Although many sound modeling and simulation techniques are described in the literature, the choice of which one to use strongly depends on a) the state of conservation of the artifact (almost intact, strongly incomplete, no longer existing); b) its acoustic properties and the manner in which it is played (for example, percussion instruments are generally modeled differently from flutes or brass instruments); c) the aspects to be studied (musical structures, intonation, timbre); d) the access modalities that we want guarantee (e.g., only for scholars or accessible and playable by the general public). The case studies presented in this article offer three concrete examples of how and why these choices can be made.

What these projects showed us is that returning the sounds of instruments that are now silent is of great importance to support knowledge on the development of music and its function within the societies of the past. At the same time, specially from the point of view of museum curators, it represents

[8] See https://youtu.be/7dxjJrmUMxA?t=260 for a demonstration of the digital simulation of some electronic devices of the Studio.

a great opportunity to bring this knowledge to the general public through a means (the sound) that is always very engaging, thanks to the emotional response that music and sound usually induce in the listener.

During the past decade, museums have embraced digital technology to enhance visitors' experiences. The use of digital technologies encourages museum visitors to actively engage with the artifacts. While respecting the original culture, technologies enable the development of new languages and experimentation by multiplying the narrations of the work. In this way, the visit to a museum becomes both educational and entertaining. Presenting artifacts to the general public is a complex task for their multifaceted nature, and digital technology must not sacrifice accuracy or depth of information for the sake of entertainment. Deploying digital technology is a multidisciplinary effort that requires interplay among different fields, from history and archaeology to information engineering and craftsmanship. A proper design methodology is necessary to draw the role of the artifacts of museums and galleries in the visitor experience.

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ABSTRACT

Digital technologies and 3D models, nowadays largely used to document archaeological remains and to obtain hypothetical reconstructions when these remains are more or less heavily damaged, can also be powerful tools to simulate and render the acoustic response of an environment, such as the interior of a building, or an artifact, such as sounding objects or musical instruments. This work addresses the cases of three musical instruments of the past – namely a Pan flute, a brass instrument, and an electrophone instrument – coming from different periods and in different states of preservation, which voices can now be heard thanks to as many multidisciplinary projects. Possible approaches to the simulation of the sounds that these instruments could generate are discussed in relation to different aims and contexts.

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COMPUTED TOMOGRAPHY AND HANDCRAFTING PROCESSES OF AN ANCIENT MUSICAL INSTRUMENT: THE *AULOS* FROM POSEIDONIA[1]

1. Introduction

Among non-invasive investigation methods applied to cultural heritage, the role of radiology is well known. For several years, the definition of diagnostic imaging has mostly been used in medicine in order to highlight the numberless series of available investigative methods in radiology (e.g. computed tomography, magnetic resonance imaging, ultrasound, etc.). Whilst this technological enhancement has improved the work of radiologists, these innovations are still not fully considered or exploited in some fields of research applied to art and cultural heritage, and especially to musical heritage (Pretto *et al.* 2020). In this field of research, only a few museums and institutes for the preservation and restoration of musical instruments have autonomous radiological sections (Swift *et al.* 2021). This could explain the gap between medical radiology and radiology applied to musical heritage, particularly regarding ancient instruments (along with the lack of presence of specialised figures in these institutions) (Bär *et al.* 2018).

Indeed, until recently, although its methods have great potential in the diagnostics and conservation of ancient musical instruments, radiology has been underused in this field of application. Thanks to digital imaging and computed tomography (CT), diagnostic imaging can give us significant results in the study of ancient instruments, providing scholars with valuable information that would be otherwise unavailable. Indeed, CT also enables the study of the instruments' measurements and morphology, quickly generating information and overcoming the limitations presented due to their fragility without jeopardising the integrity of specimens; this method can also measure the thickness of the internal structures (Fuchs *et al.* 2019). Moreover, the CT allows two and three-dimensional reconstructions on coronal, axial and sagittal planes, revealing details of the constructive characteristics of instruments as well as the state of their conservation, allowing for their digital storage and making possible a non-contact re-investigation at any time. CT also ensures the data is collected in a less error-prone form, so that the figures obtained

[1] This article is – in all its parts – the product of a joint effort of both authors. Only for academic purposes, we attribute here the textual part to Angela Bellia and the graphic part to Danilo Paolo Pavone.

from the object can be checked later. Optimally, this amounts to preparing a three-dimensional (3D) digital image: CT serves this purpose extremely well because it also exhibits internal structures of instruments, and allows for a useful evaluation of the instruments' working processes as well as the visualisation of invisible fracture lines and lesions in their structures, showing possible modifications, damage and repairs.

2. Background

Considering the changing framework in ancient instruments studies from one that treats them as images to another that considers them exclusively for their organological characteristics, the aim of our study is to analyse how the application of computational imaging to ancient instruments can provide a new means of understanding, interpreting and disseminating results, and, most importantly, to enable us to study these artefacts as multidimensional entities and three-dimensional material objects that have undergone transformations and forms of handling (Zoran 2011).

That is particularly important given that musical instruments, until recently, have been treated as images, as artistic depictions and objects whose meanings and functionality needs to be surveyed through iconological and organological methods. As such, they have been rendered and represented as two-dimensional, finished and static entities. Their formal qualities, e.g. size, features and proportions, took priority over, say, material processes, technologies of making, postproduction modification, circulation, deposition and discard. Yet, as many studies have shown, musical instruments were continuously modified. Sometimes, they were intentionally fragmented, reshaped and re-introduced into circulation. Moreover, these artefacts were special three-dimensional objects meant to be engaged with in a multi-sensory way: they were handled, interfered with, interacted with by human bodies and with other entities, such as architectural features and spaces as well as other objects and materials.

Despite the image-based discourse on musical instruments being challenged by several studies in the last decade, it has largely shaped the way they are depicted in archaeological and music archaeological publications: it is this corpus of images that has in turn shaped further thinking and discussion on ancient instruments, especially since it has always been the case that very few people have been able to handle the original, three-dimensional, physical objects. Using 3D digital models combined with cutting-edge digital methods, some of the subjective observations typically made by scholars on ancient instruments on the basis of traditional measurements can be substituted by measurable parameters, which also opens up new perspectives for the study of the production processes of instruments. Taking into consideration the *aulos* found at Poseidonia in southern Italy, which dates from the end of the 6th to the beginning of the 5th c. BCE, this article focuses on the process of the creation of ancient instruments through 3D scanning and printing technology, which can be used not only as a methodological case study, but also as a research tool.

3. The *aulos* from Poseidonia

The *aulos* from Poseidonia was found in 1969 in tomb 21 at the necropolis of Tempa del Prete, a few kilometres South of the town outside the ancient city walls, where musical instruments were also discovered in two other graves and in the best-known 'Tomb of the Diver' (Bellia 2016). In the same tomb 21, most likely belonging to an adult man on the basis of the grave goods, a small turtle shell was also found, which most likely was the sound-box of a *barbitos*. The *aulos*, a pair of pipes – with vibrating reeds in their mouthpieces – held out in front of the player, was the omnipresent musical instrument in Greek cults, festivals and funerary rituals (Fig. 1). The different types of *auloi* were classified on the basis of their range, pitch, and origin as well as their material and occasion of musical performance. As in the so-called 'early type' *auloi* – which are defined by the absence of mechanisms for sound production – the wind instrument found in tomb 21 (held today at the National Archaeological Museum of Poseidonia-Paestum, modern Capaccio, Salerno, inv. 23068), was played by covering the holes in the upper part of the two tubes with fingers and by covering the thumbholes placed at the back of the pipes, which form a pair (Fig. 2a-b) (Bellia 2012, 98-99; Psaroudakês 2014).

A peculiarity of the tubes belonging to the instrument from Poseidonia is the presence of two similar small holes (Hagel 2010-2011) (Fig. 3a-b), which would have had expressive purposes given that a musician could use these little holes for modifying resonance and, as a side-effect, the timbre of the instrument or the "colour" of its sound (Barker 2002, 67-70). Moreover, eight sections form the tubes; each section suffers from damage, but on the whole the instrument is well preserved. Understandably, the parts receiving the reeds and the reeds are missing: being made from cane, they are forever lost to us.

According to written sources, deer bones were used to form *auloi* (Pollux, IV, 71): in particular, the tibia of a deer was the most common material used for making *auloi* in ancient times, at least until the Hellenistic age (West 1992, 81-82). Given the texture of material, particularly the adult deer bone could be handled easily, and it required tools and processing techniques similar to those used for working ivory and wood. Moreover, deer bone is usually white or ivory: it could be smoothed, acquiring a lustre tending towards bright white or a golden colour. Being similar to the rare and precious ivory, the deer bone

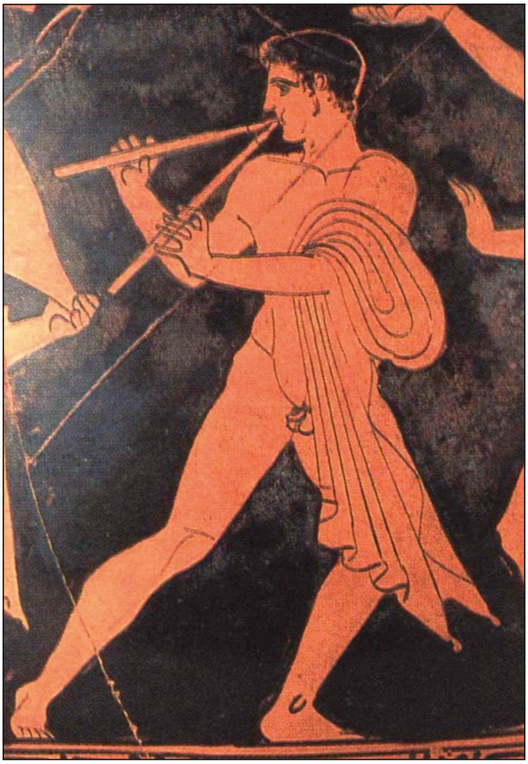

Fig. 1 – Regional Archaeological Museum of Agrigento. Inv. AG. 22797. *Aulos* player. Particular of the Attic red-figured bell krater from the necropolis of Contrada Pezzino in Akragas. 5th c. BCE.

Fig. 2a-b – National Archaeological Museum of Poseidonia-Paestum, inv. 23068. The *aulos* found in the tomb 21 of Tempa del Prete. 6th -5th c. BCE. From Psaroudakês 2014, 129, figs. 13-14.

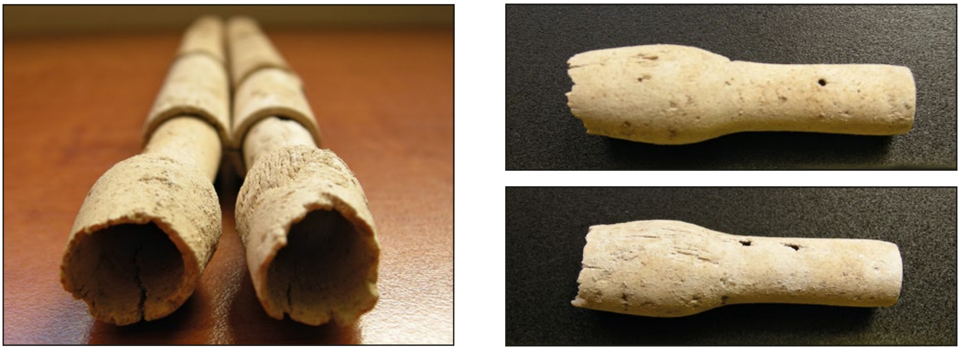

Fig. 3a-c – Small holes in the mouthpieces and outhpieces end of the tubes. From Psaroudakês 2014, 127, figs. 4-5a-b.

Fig. 4a-b – A deer tibia bone and a hypothesis of how the craftsman could transformed deer bones into musical instruments sections. Photo: Marco Sciascia. Illustrator: Danilo Paolo Pavone.

was not only aesthetically pleasant, but it was also easily available and very low cost, given that it was a form of food waste. For this reason, bone-processing shops were often placed near slaughterhouses or sanctuaries, where deer sacrifices and banquets of meat were held (Angliker 2016).

Some ancient texts focus on the materials used for the handling of the *auloi* in the Greek-Roman ages, highlighting how there were several of them and a variety of uses on the basis of sonic demands and needs, as well as of scales and of the "regionality" of Greek musical practice. Athenaeus (IV, 182d, *FGrHist* 275 F 82) and Pollux (IV, 75-76) mention how the use of deer bone for making *auloi* was a Theban innovation, and Plutarch (*Moralia*, 150e) recalls how Greek (and Roman) craftsmen used medium to large sized animal bones for creating wind instruments. For its shape, the tibia bone is one of the most suitable to be worked not only because of its long bone flaring towards the two epiphyses, but also for its cylindrical inner part, or diaphysis, especially of the sheep, goat and deer bones (Berlinzani 2014). On the basis of their porosity and/or compactness, the tibia bones had a great influence on the instruments' sounds both due to their specific weight and for the allowed speed of sound propagation (Fig. 4a-b).

It is worth noting that bone wind instruments were generally composed of tubes joined together (given the presence of spigots and sockets) so as to be able to create mainly cylindrical tubes, as the preserved instruments found in tombs and sacred areas in Greece and Magna Graecia display. Moreover, as in the case of the *aulos* from Poseidonia, the pipes' workmanship seems to reveal the use of an arched or rope drill used by craftsmen to pierce the surfaces of the tubes. Thanks to 3D CT, we are able to explore the production process of this instrument and how its craftsman transformed deer bones into a precious musical instrument which has been passed down to us.

4. Computational methods for processing the 3D models of the *aulos* from Poseidonia

CT could be used as the primary tool in identifying and cataloguing ancient musical instruments. There is no need to invest huge sums of money in purchasing and developing expensive testing equipment. Medical CT equipment is almost universally available. There is no need to ship instruments to distant laboratories, an expensive and risky business at best. Musical instruments can be also scanned locally or *in situ*, avoiding risky transportation (Albertin *et al.* 2019). The process takes little time, is non-invasive and non-destructive, and produces digital data. This data is unique and can serve as a fool proof "fingerprint" of the instrument. Moreover, this data can also be used not only as a tool in the restoration and conservation of damaged instruments, but also to consider their affordances – the properties of instruments that enabled tubes to be handled and their capacity to produce sound of a particular volume and pitch – and to create replicas of these artefacts. This method could also provide new insights on how craftsmen handled the bones on the basis of their shape and inner structure, as well as on the development of instruments most likely linked to cultural, social and musical changes, especially in the theatrical context.

Information can be retrieved thanks to 2D cross-section images or 3D full-volume images, which allow for the inspection and the exploration of the inner part of the instrument; moreover, by processing tomographic data, a 3D model of the sample can be obtained for virtual reality applications or digital archives storage.

It is worth noting that the use of medical CT scanners gives good results only in the case of analysis of samples with a size and density similar to those of the human body, as in the case of the deer bone. In order to fulfil all these

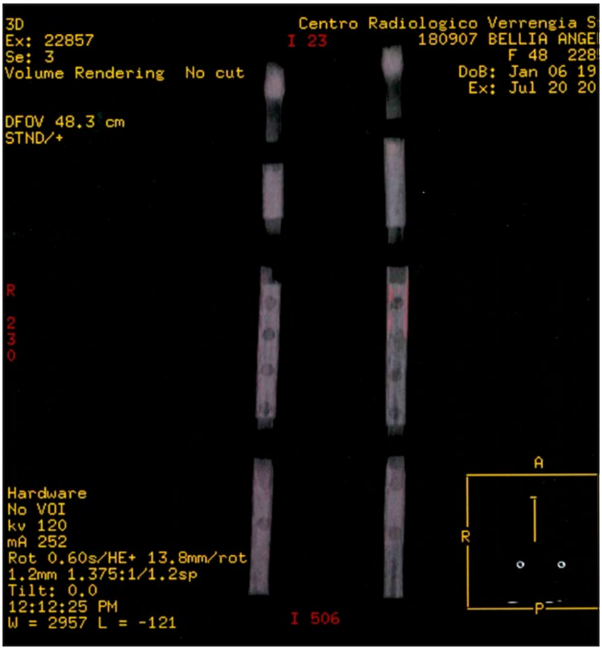

Fig. 5 – CT scan of the bone *aulos* from Poseidonia realised at the Verrengia Radiological Centre in Salerno.

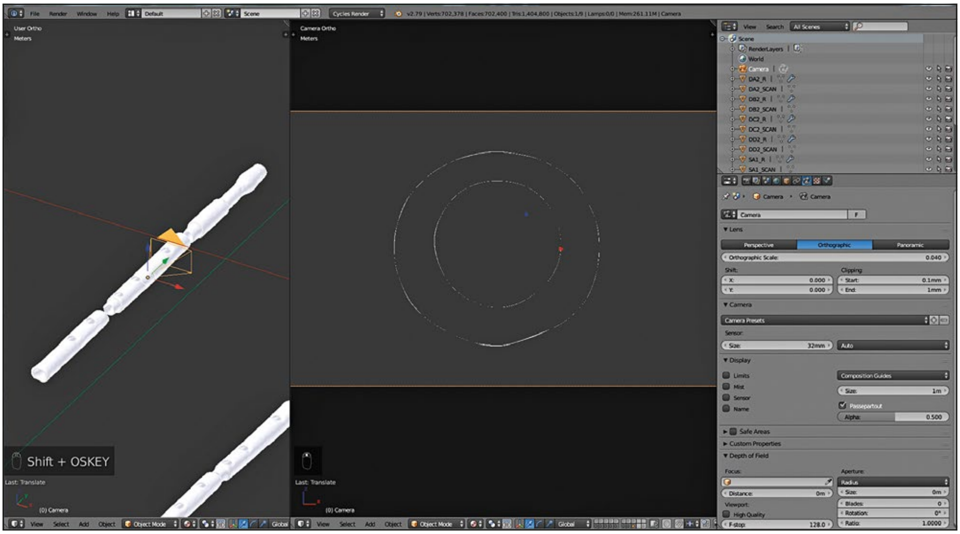

Fig. 6 – Details of the internal structure of the *aulos* from Poseidonia.

needs, after acquiring permission to use the instrument and the pick up of the instrument from the National Archaeological Museum of Poseidonia-Paestum, the CT scan of the bone *aulos* from Poseidonia (Fig. 5) was realised at the Verrengia Radiological Centre in Salerno, under the supervision of our team and of the museum team. Given that for ancient musical instruments, the inner structure contributes significantly to the colouration and amplification of their sound, it was requested that the medical staff – which was formed of radiographers and radiology technologists – focus their attentions on the scanning phase of the inner structure of the musical instrument in order to provide as much visibility as possible (Fig. 6). Moreover, given that inner structure is either hidden to the eye or inaccessible from the outside by conventional methods, we aimed to obtain information about constructional details that pointed to specific construction methods of certain instrument makers, as well as accurate measurements of the internal structure of the *aulos*. Up until that moment it was difficult (if not impossible) to access the internal sections, given that scholars who have previously studied this instrument (Bakogiannis *et al.* 2020, 53189-53192) used only traditional methods to avoid the high risk of damaging the object, providing us with hypothetical and questionable reconstructions of acoustics on the basis of available measurements.

In order to scan the wind instrument, the staff at the Verrengia Radiological Centre used a CT scanner equipped with a rotating X-ray tube. The multiple X-ray measurements of the *aulos* taken from different angles were then processed on a computer using reconstruction algorithms to produce tomographic (cross-sectional) images (virtual "slices") of the instrument sections. The files (pixel resolution: 0.625mm) were saved in DICOM (Digital Imaging and Communications in Medicine) format, a standard method to transfer images and associated information between different vendor devices, which produces a variety of digital image formats, enabling the integration of imaging devices as well as the exchange and transmission of images to multiple users. Using the Osiris software, the data generated was processed in order to obtain a three-dimensional mesh. The model was exported in STL (Standard Triangulation Language) format.

In the alignment phase, several scans from different views were mosaicked to obtain a model that could be studied in a virtual space, also producing metric measurements. Within this framework, information from the undamaged parts of the objects was utilised in combination with literary and iconographic sources in an attempt to re-create the appearance of the complete instrument.

4.1 *From the three-dimensional model to the two-dimensional drawing*

The post-processing phase focused on the reorganization of the meshes in order to obtain a correct topology of the 3D models by the separation and cleaning of the parts and a subsequent retopology of the surfaces of the models. This method allowed us to obtain a high-resolution model. Moreover, we obtained 3D renderings images of this instrument. The tools we used d are divided into those involving the use of computational methods for processing the 3D models, and those involving the development of interactive tools aimed at engaging users in the exploration of instruments.

2D graphic reference images have been imported into an orthographic camera view as image planes: from the three-dimensional model, imported and composed in the Blender 3D rendering software virtual photo set, we considered each element in the following order: front view, front view section, side view, side view section. They were subsequently composed in a single layout, allowing us to obtain an overall view of the inner thicknesses of the two pipes and of the holes of the instrument. The rendered images (scaled 1:1) have been displayed in two graphic tables (external view/section view) in order to obtain an overall and scaled view of the digitised object.

Having established the 2D viewing space in a graphic table form, the instrument was subjected to an interpretative analysis of its elements. Despite the *aulos* being well preserved, there were some gaps or missing parts as well as some structural deformations of the deer bones, which interfered with the reconstructive prototyping of the instrument. In the graphic tables created, the features of the object, such as the natural curvature of the bone tubes (DC2), were considered, taking into account their uniqueness against the prototyping of a "generic" access model (Fig. 7a-i).

4.2 *Web-based viewer for shared access to the musical instrument*

The *aulos* sections have been also implemented thanks to the 3DHOP viewer (3D Heritage Online Presenter by Visual Computing Laboratory - ISTI - CNR). This open-source framework for the creation of interactive Web presentations of high-resolution 3D models, oriented to the Cultural Heritage field, allows dynamic access to the 3D model, which is usable and measurable on a computer and/or tablet via a web browser, such as Firefox, Safari or Chrome. Moreover, the 3DHOP viewer allows users to virtually interact with the instrument in the rotation movement, activating section planes in the X/Y/Z-axes and in the measurements of the instrument's surfaces (Fig. 8a-b).

4.3 *From the reconstructive prototype to the access model*

The inner and external measurements extracted from the digitized model were essential for the creation of the reconstructive prototype. These measurements were also essential for the process of discretization and simplification of the sections of the *aulos*. Therefore, a discretized reconstruction of the actual instrument was obtained, keeping the main features of the object and modifying some deformations of single elements.

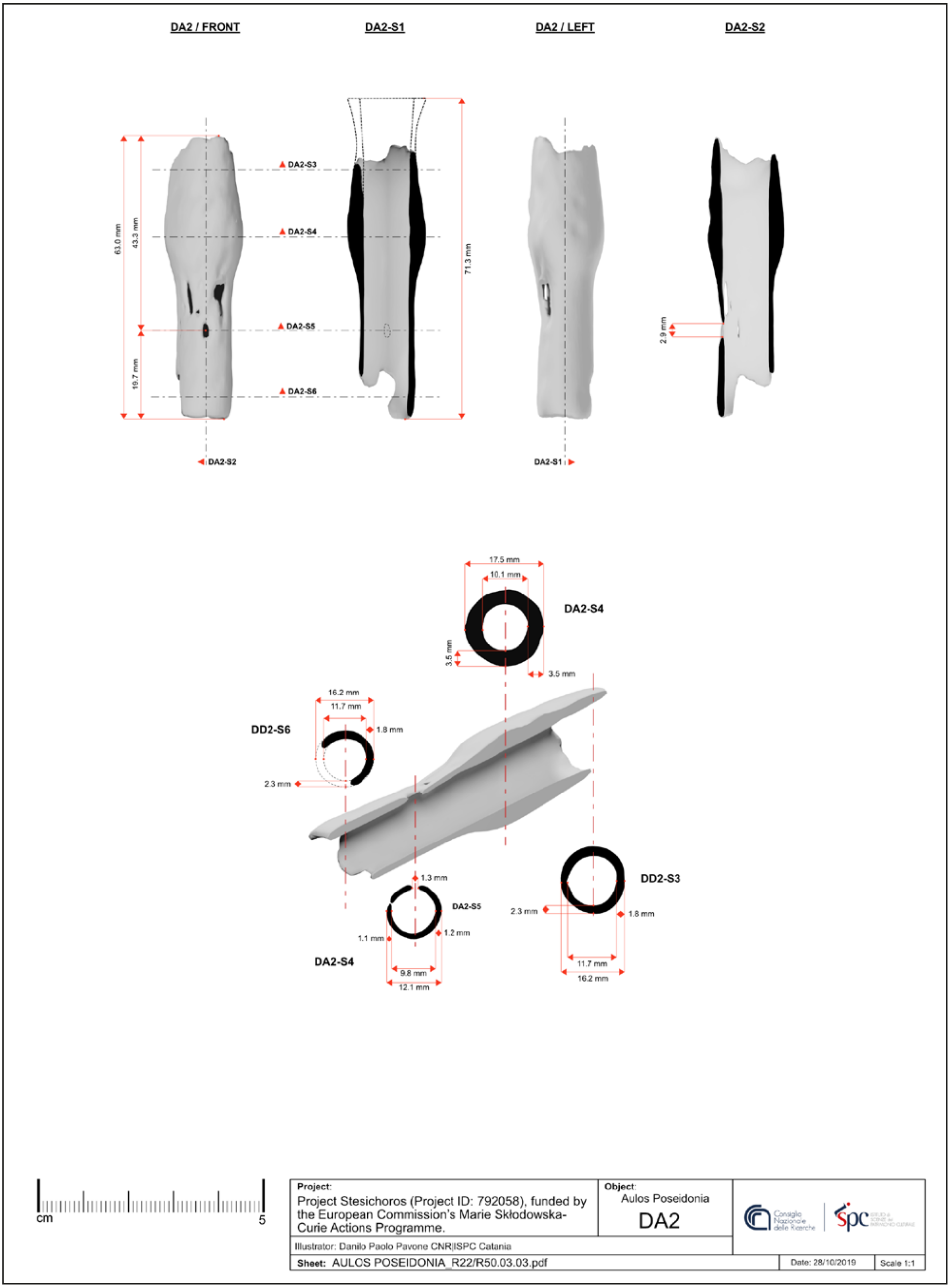

Fig. 7a – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

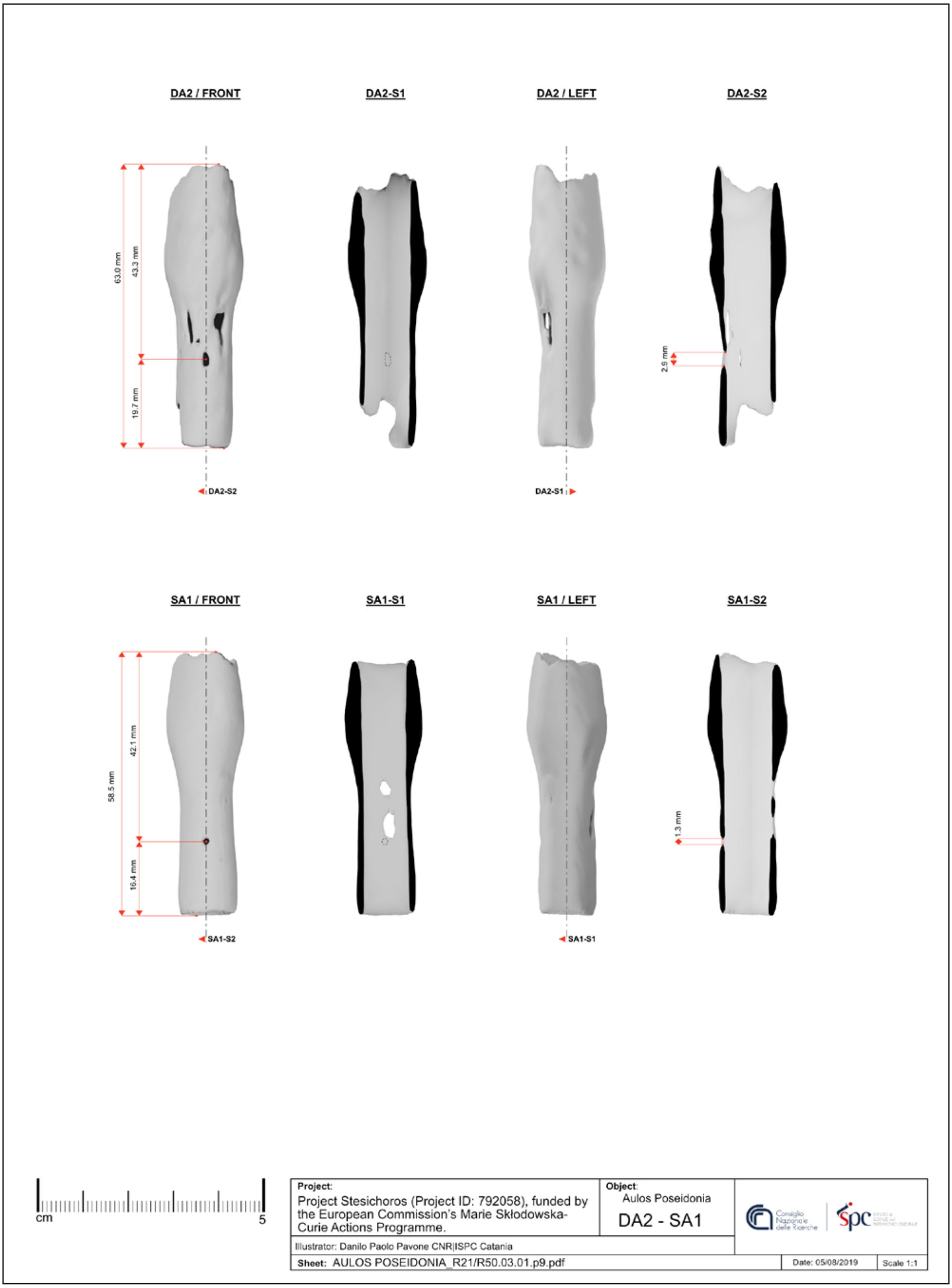

Fig. 7b – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

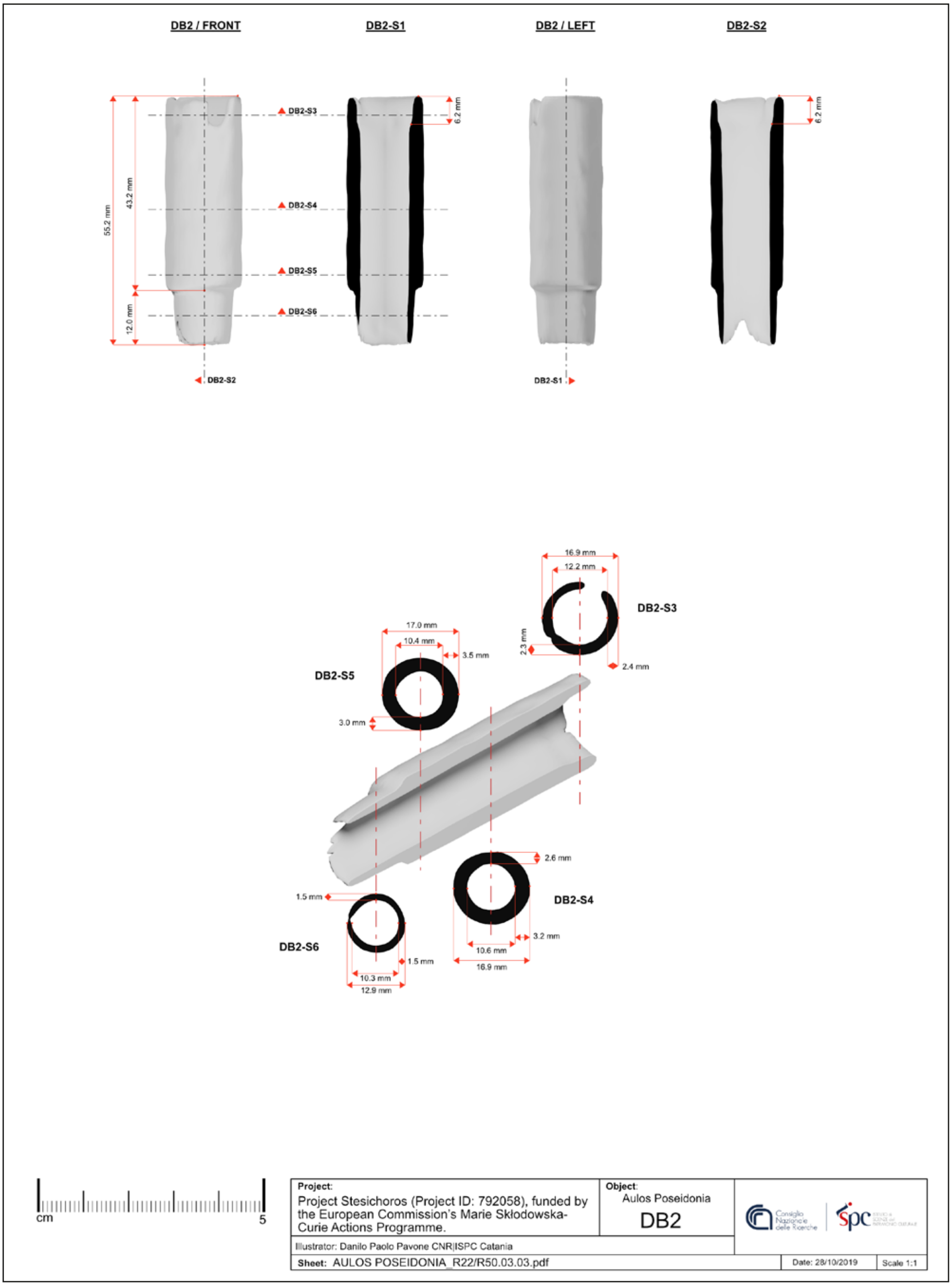

Fig. 7c – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

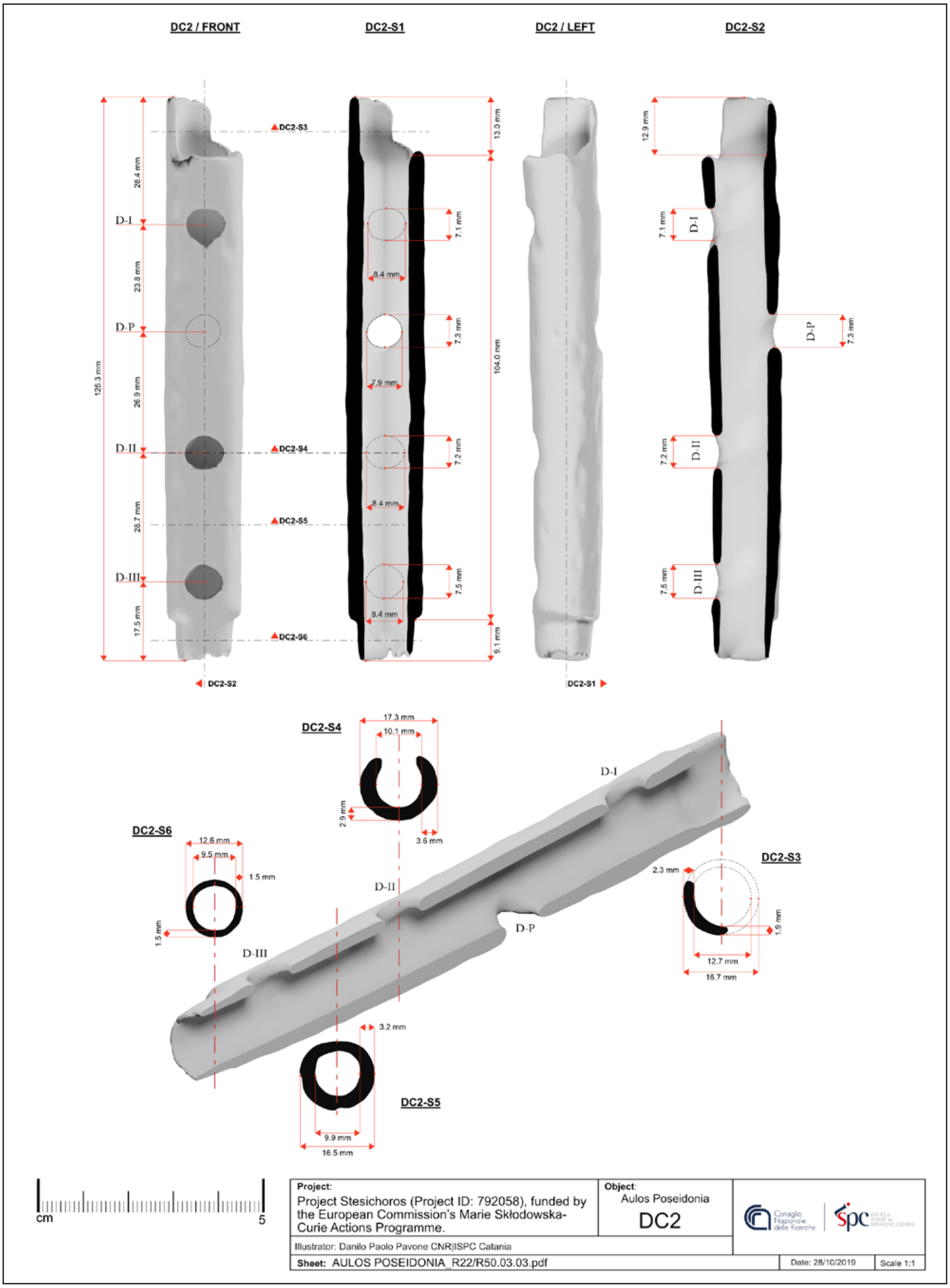

Fig. 7d – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

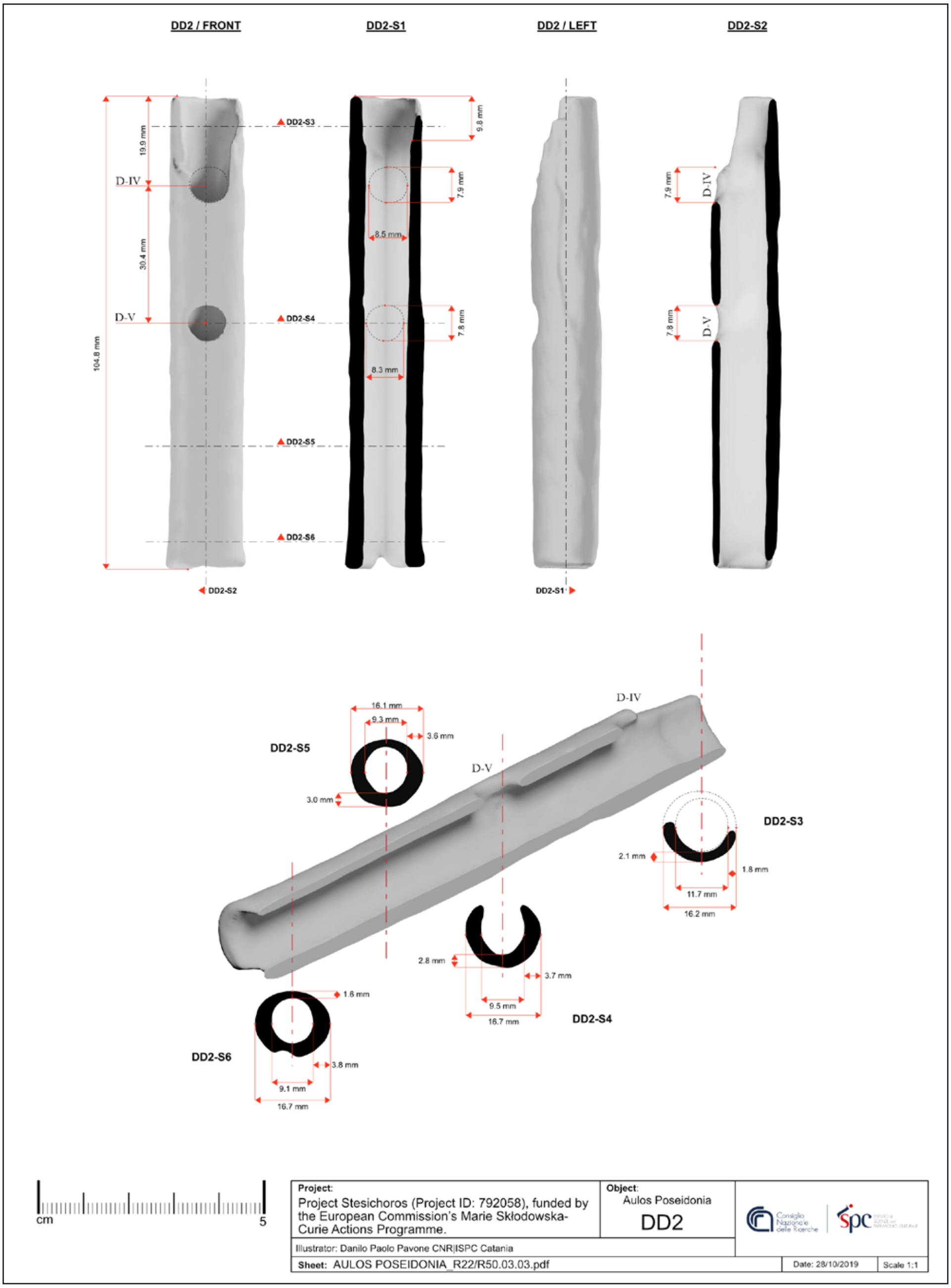

Fig. 7e – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

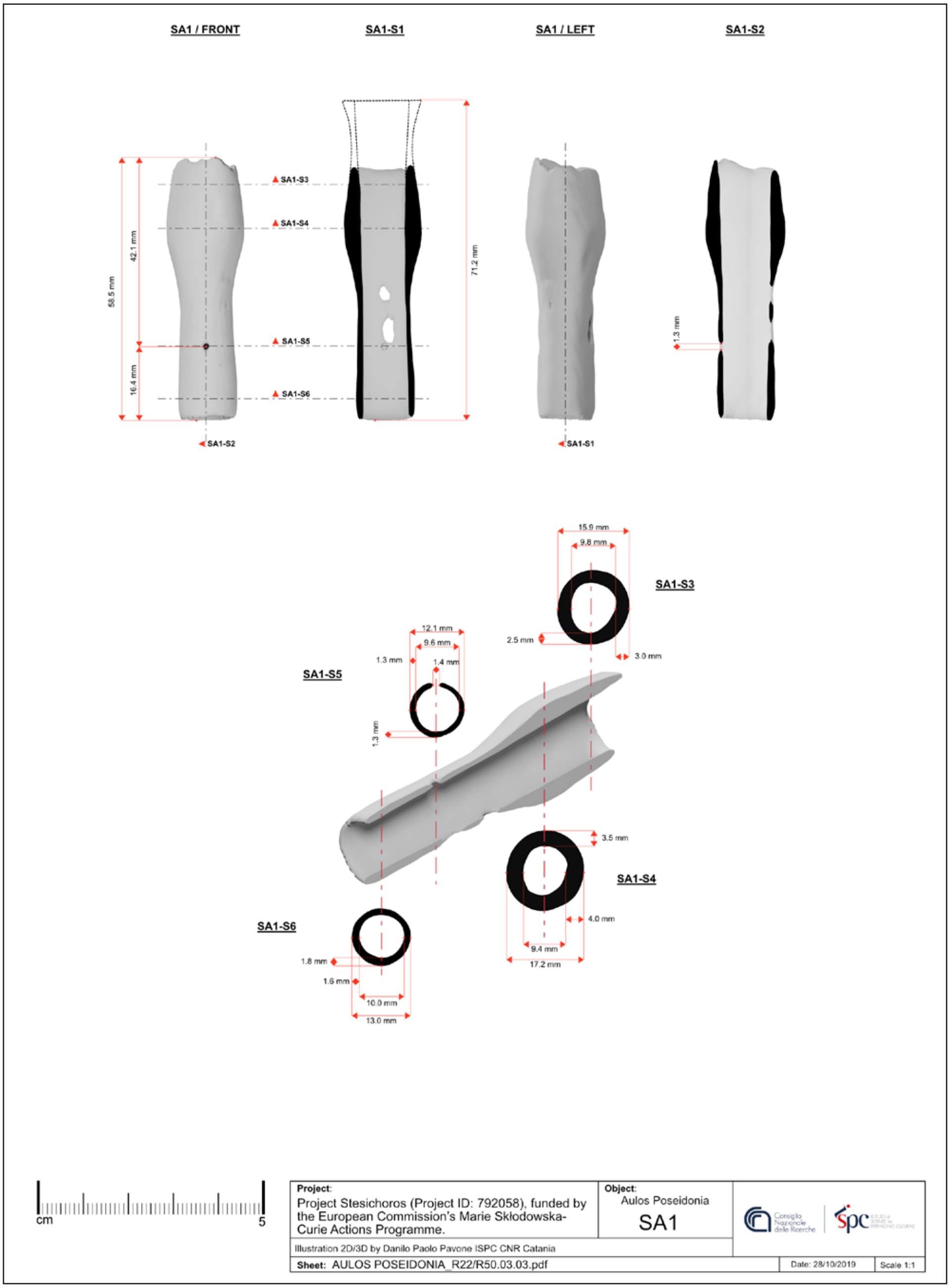

Fig. 7f – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

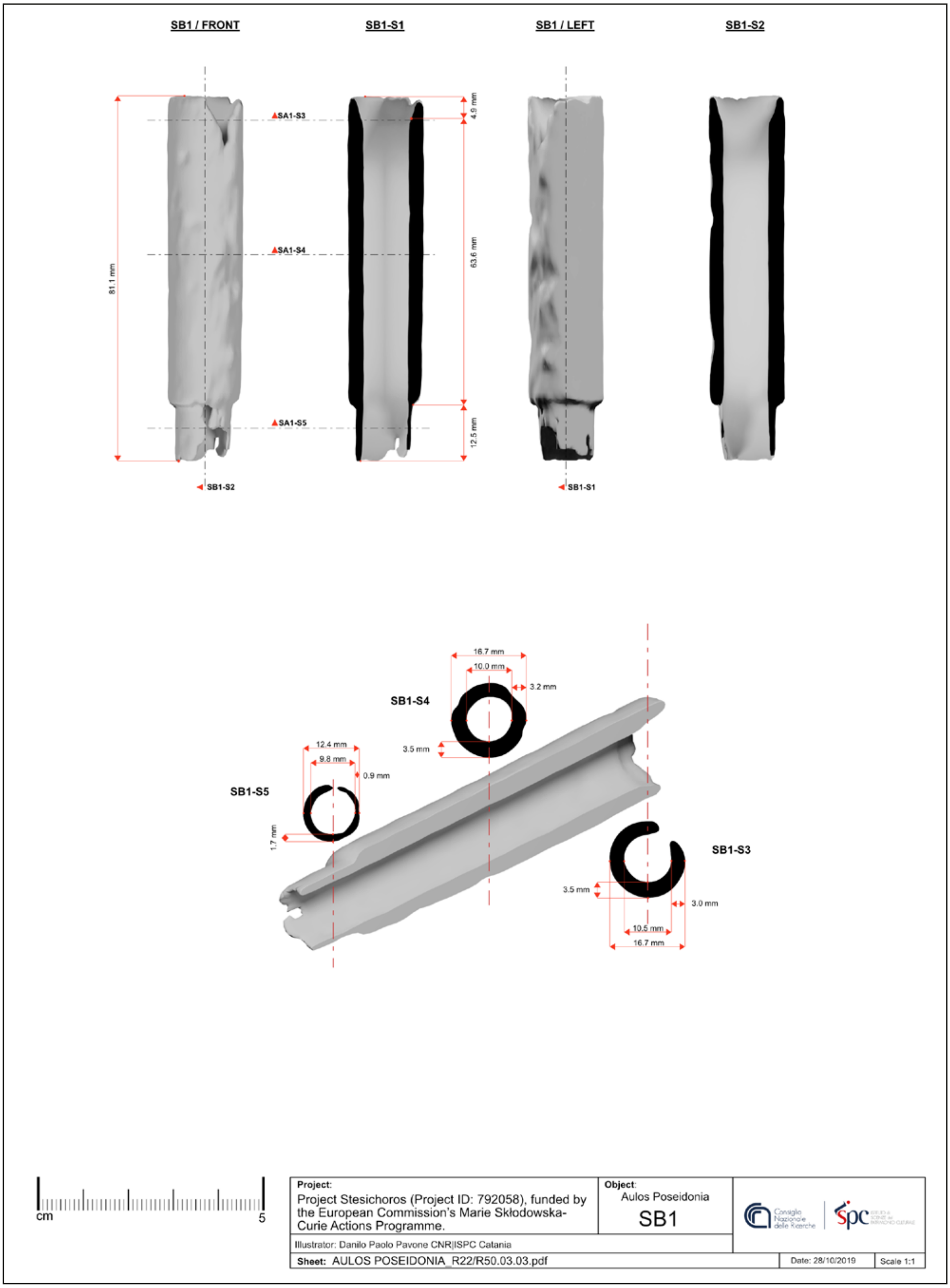

Fig. 7g – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

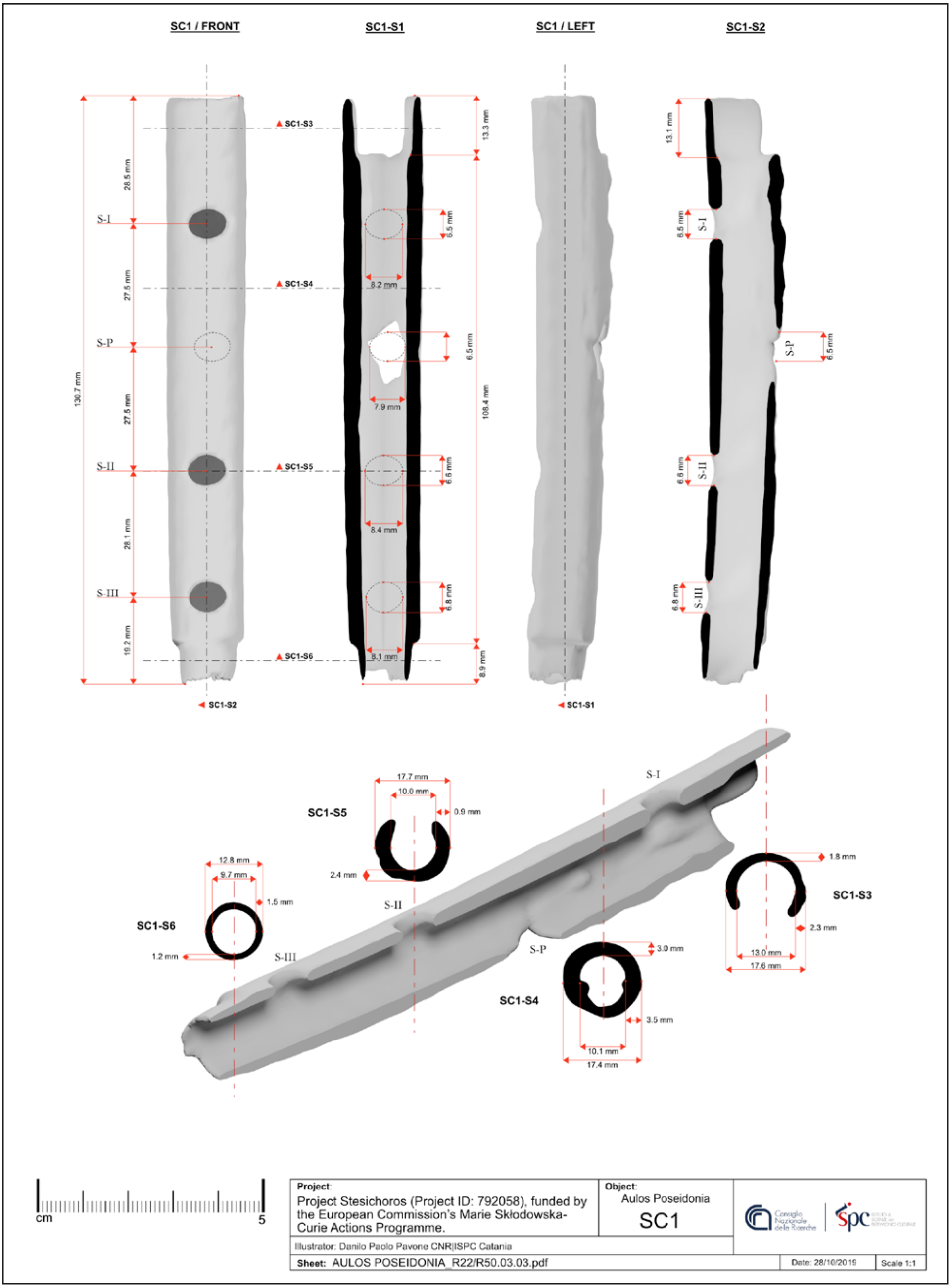

Fig. 7h – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

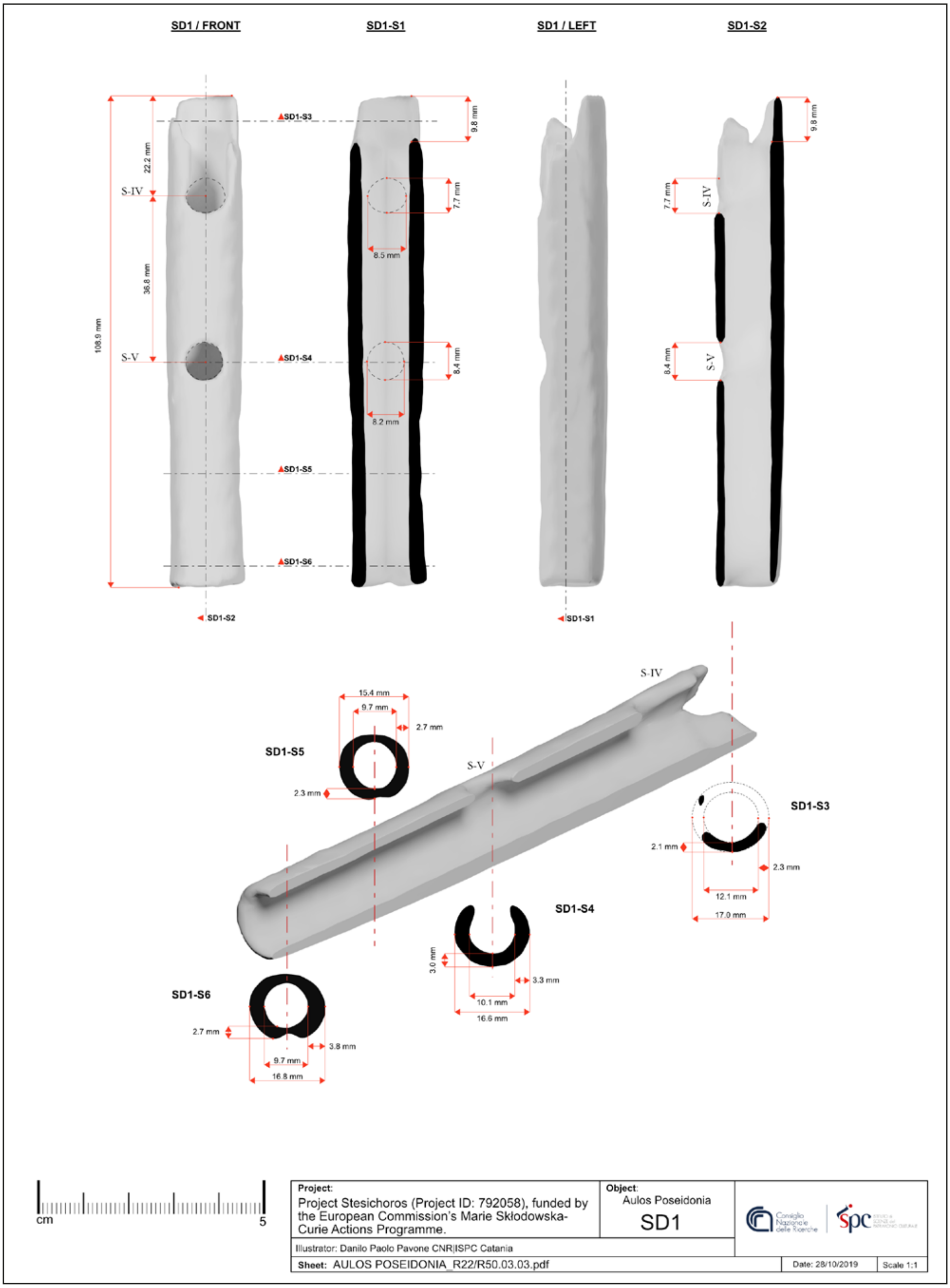

Fig. 7i – Graphic tables of the two tubes of the *aulos* from Poseidonia. Illustrator: Danilo Paolo Pavone.

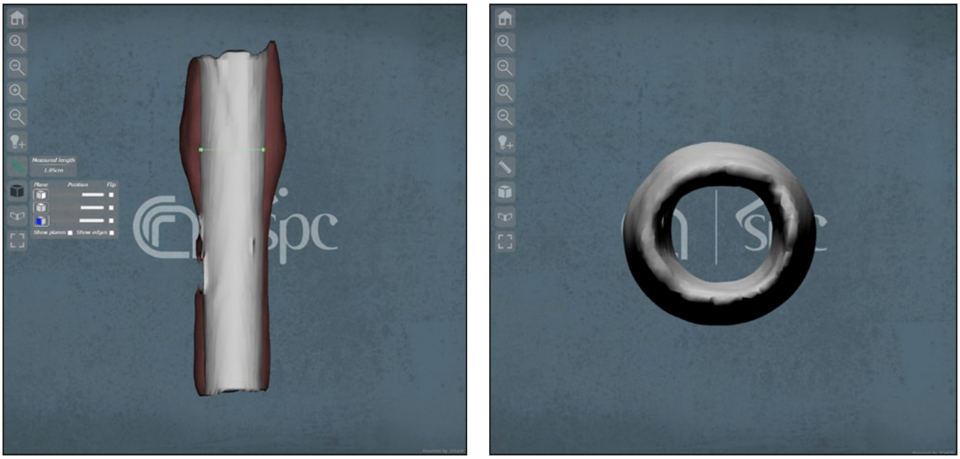

Fig. 8a-b – The 3DHOP viewer allows users to virtually interact with the instrument in the rotation movement, activating section planes in the X/Y/Z-axes and in the measurements of the instrument's surfaces. Illustrator: Danilo Paolo Pavone.

After that, the completed model was considered finished. The digital model was translated into original and restored copies, and two printed copies of the original and of the restored instrument were created in polymer material (Fig. 9a-c). Moreover, on the basis of measurements of the 3D model, an instrument maker specialised in the reconstructions of ancient musical instruments (Marco Sciascia), reconstructed the *aulos* from Poseidonia. The measurements of the 3D model of this instrument were compared with other similar instruments, especially the "early type" *auloi* dated to the 6^{th}-5^{th} c. BCE found in the *Persephoneion* in Locri (Bellia 2018, 91-92) under Temple R (Bellia 2019) at the sanctuary of *Malophoros* in Selinunte (Bellia 2017): these fragmented instruments have been subjected to CT scanning and previous research. These surveys provided us new insights within a larger music-historical picture of the development of ancient instruments, including the evolution of wind instruments' shape and the related craftsmanship.

5. Discovering the handcrafting processes of the musical instrument from Poseidonia

Whilst the interdependence between musical practice, composers, performers, teachers and instrument makers in antiquity has been understudied, these various activities were part of a complex network of interaction, as written sources remind us and archaeological specimens of musical instruments suggest, which highlight how the development and the evolution of

Fig. 9a-c – Discretized reconstruction of the actual instrument and printed copies of the original and of the restored instrument created in polymer material. Illustrator: Danilo Paolo Pavone.

these special objects was in a strong relationship with cultural, social and performative contexts. The methods for processing 3D models of musical instruments provide us with useful information on the techniques used by craftsmen engaged in designing and handling instruments (Safa *et al.* 2016). In some cases, it is not only possible to discover the procedures useful to the craftsmen for shaping a musical instrument from raw bones, but also to investigate the technique and type of tools used during the working phases: this is useful in reconstructing the chain of the technical progress of instruments. Concerning the *aulos* from Poseidonia, the study seems reveal that for the construction of this instrument, the craftsman proceeded through at least three main phases of workmanship: the preparation of the bone, the shaping of the bones and the finishing of the sections of the instrument.

5.1 *Preparation of the deer bone*

As regards to the tools used by craftsmen, on the basis of the handling traces left on the bones visible on the 3D scans, they could be bow or rope drills. Given that the spigots and sockets were very well defined and processed – and for this reason very fragile – it is most likely that the first phase of the processing consisted of the preparation of the bone for creating the sections of the instrument's pipes, which could be refined both internally and externally through the next step. As in Fig. 10a-b, the ends of some sections of the *aulos* are shaped with straight grooves: a metal blade for sawing could have been used by artisans for cutting these sections perpendicularly to the bone. Using the metal blade, therefore, a cylindrical support in the form of a tube

Fig. 10a-b – Section of the *aulos* from Poseidonia shaped with straight groove and internal parts of the section. Illustrator: Danilo Paolo Pavone.

could have been obtained from along the bone by removing the two porous ends. Furthermore, the metal saw could also have been effectively used to cut the bone into smaller pieces (Ravani, Thun Hohenstein 2010) to obtain a *holmos* and the other shorter sections.

It is worth noting that the metal saw was used by artisans who worked hard materials of animal origin since the Metal Age, however, we are not able to establish when it was used in the crafting of bone musical instruments. In workshops dated to the Archaic and Classical Ages, where processing waste has been found, this technique is documented by the presence of sawn off and discarded proximal and distal epiphyses, and diaphyses prepared for subsequent processing (De Grossi Mazzorin, Epifani 2012). Traces of this type of processing can be found on some fragments of wind instruments found in workshops in Sicily (Bellia 2012, 96-97) and Delos (Angliker 2016, 30).

5.2 *Making and shaping pipes*

To shape the sections of the deer bone instrument, tools almost identical to those still in use today by modern craftsmen working with bone or ivory were used. The chisel, as with the preparation of the support, could be useful for shaping operations because it allowed the instrument to be put into a precise shape through a series of successive notches, deepening recesses or eliminating the discontinuous surface layer of the material whilst keeping the original shape of the bone.

The final shape of the instrument sections could also have been modelled by abrasion, that is, by rubbing the object on an abrasive surface, with a circular "to and fro" movement, most likely with a metal file. Abrasion should not be confused with sanding (or polishing) since, if the first is done in the phase of shaping the object, removing a large amount of material, the second is carried out as a final finishing operation and does not transform the object's form (De Grossi Mazzorin, Epifani 2012). Given that the flat surface allowed the *aulos* player to gain a better grip on the tube, by facilitating their alternation on the holes, the abrasion technique seems to have been used by the craftsman to obtain the flatter surfaces on the upper part of the tubes sections of the.

Given the accuracy of the crafting handling of the inner and external sections of the musical instrument, it cannot be excluded that, especially for the longer sections, the craftsman used a lathe to work on the sections of the bone, making it rotate by means of a belt or a strap wrapped around the object. It is worth noting that the deer bones could have been subjected to a softening technique. As in the case of this procedure applied to horn, mentioned by written sources, softening was practiced in order to modify the shape of the bones (or parts of musical instruments made in bone), which were then moulded to the desired shape (Barker 2002, 77-81). To achieve this, bones were immersed in water. This preliminary operation made bones easier to work, without causing irreversible alterations in the composition of the bone fabric. Alternatively, it was possible to boil the bones briefly, for about fifteen minutes, so as not to alter the quality of the bone tissue itself. These procedures could be useful for working the holes of the wind instrument, which required great precision by the craftsman, as the 3D images highlight.

One of the interventions on the *aulos* sections in the shaping phase could be the perforation of the internal part: this was a delicate operation that was also essential for drilling the holes in the pipe sections. The basic principle was to drill the inside of the bone so it could be emptied in several places. Taking into account that, as it is evident in the 3D images, the internal walls of the instrument have vertical streaks, it is very likely that the craftsman pierced the bone through a rotary movement of an arched bow or of a rope drill consisting of a cylindrical stick with a sharp tip, making rotate it on the inside the bone by rubbing between the palms of the hands or by turning the spindle on the workpiece. As it is possible to observe on the 3D model, working traces of a tip correspond to the holes in the internal parts of the sections (Fig. 10b).

5.3 *Refining and polishing the instrument*

Through the final polishing of the tubes, the craftsman may have eliminated all traces of processing left on the surface of the instrument sections. This may have been done with an abrasive material. According to written sources (Pliny, *Naturalis Historia*, IX, 40), the bone objects were smoothed with the rough skin of a shark (shagreen) or of a ray fish. Alternatively, other materials of an organic nature could have been used, such as bone ash, coal dust and skins covered with sand. It cannot be excluded that this procedure was also used by the craftsman to ensure the surface of the bones used to make the Poseidonia *aulos* were perfectly smooth: given that the surface of the object is on the whole compact, it is possible that the traces left by the earlier production procedures were erased, strengthening the object and enhancing it aesthetically. However, some parts of the sections, especially those close to the holes and to the spigots and sockets, are very fragile: in these areas cracks and fractures in the bone are evident and concentrated.

6. Conclusion

As a non-destructive method that facilitates new insights into ancient musical instruments, CT allows us to obtain useful data that could not be gained by other means without disassembling the object or the risk of damaging it. The variety of sizes, shapes and materials of ancient instruments pose various challenges for CT scans. These issues have to be addressed by selecting appropriate CT parameters, scan procedures and data and image processing algorithms to obtain not only a high quality in the reconstructed volume images, but also useful information related to the craftsmanship of musical instruments. The processes of 3D scanning, 3D model creation, 3D printing, and craft reconstruction of the *aulos* from Poseidonia can facilitate the parameterisation and further processing of future scans of similar instruments and can be used to create a set of replica instruments to be considered as reasonably veracious 'functional replicas' (Swift *et al.* 2021). Thanks to these 'functional replicas', we will also be able to evaluate (to a certain extent) how far the craftsmen tailored their work to the needs of individual musicians and how they designed instruments on the basis of models or instruments transported in the ancient Mediterranean.

From a research perspective, the exploration of production processes can facilitate an enhanced understanding of the development of musical instruments used and requested in a particular social and musical context, allowing us to evaluate how shapes, craftsmanship, and evolution of instruments can be related to the development of spaces of performances, theatres, and architectural structures in antiquity.

It is worth noting that small variations in the measurements of instruments could significantly affect pitch (Avanzini *et al.* 2015; Avanzini *et al.* 2016). For this reason, the manufacturing process should be evaluated from different points of view using 3D scanning data for future use in ancient sound simulations (Sun *et al.* 2020); the data could possibly be made available for public engagement (Micheloni *et al.* 2016), and for scholars working in different disciplines, given that musical instruments research is undoubtedly an interdisciplinary field of survey which involves physics of instruments, material science, manufacturing methods and acoustics (Damodaran *et al.* 2021). In this regard, the re-creation of a plausible acoustic environment, for example, an ancient theatrical space contemporary to the instruments in which *auloi* were most likely played, could provide an insight into the acoustics of the space (Tronchin 2020), and the effect of the sounds of these instruments in a virtual environment (Farina, Tronchin 2013): this challenge could enable us to consider wider aspects of the experience of soundscapes in antiquity (Geoffroy-Schwinden 2018).

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ABSTRACT

This paper aims to explore how digital imaging and computed tomography (CT) can provide us with significant results and valuable information otherwise unavailable in the study of ancient instruments. Whilst its methods provide great potential in terms of the diagnostics and preservation of ancient musical instruments, radiology has been underused in this field of application. As an improved method for the visualisation and analysis of the material density of instruments and of their surfaces and volumes, CT allows for a useful evaluation of the handcrafting process of instruments as well as the visualisation of invisible fracture lines and lesions in their structures, showing possible modifications, damages and repairs.

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ASSESSING UNKNOWN PARAMETERS OF INSTRUMENT FINDS BY WRITING SOFTWARE

1. Introduction

The computer world has evolved considerably since I began using the computer to explore ancient music. Nevertheless, the reader, should he/she not abandon this contribution right now, will find that the author has been sticking to old-fashioned approaches wherever possible. The following is therefore partly a defence against the expectations inevitably raised by a world of shinier software, which however, I will argue, fosters a tendency towards mustering astounding resources for very limited or indeed questionable goals. Under the pretext of sharing some of my general experiences it will briefly develop into a rant, which I justify beforehand with what is at stake, politically: the waste of considerable public resources, made possible by a deficient reviewing system. I do not claim that ill intention necessarily forms the core of what I feel might (and perhaps should) develop into a major crisis of public trust in our science. As with so much that goes wrong, initial basic misapprehensions may simply propagate themselves up to a point when it is too late to pull the breaks without considerable self-sacrifice.

As researchers we may be accustomed to observe such mechanisms in enthusiasts from outside academia, whose lack of connection with the bibliography and with methodologies that keep us alert to potential fallacies have led them to fantastic conclusions heralded in social as well as conventional media. All the more it may escape us how little we are ourselves protected from similar errors whenever we venture outside our expertise. The ensuing problems expose themselves with exceptional clarity in a field like music archaeology that is still novel and lacks a solid tradition handed down in university courses. Music archaeologists turning to computer people will normally not know what the available algorithms can do – and will habitually overestimate their potential.

Experts for sound-related software engaging with archaeologists, on the other hand, will habitually overestimate the input to expect both in terms of quality and comprehensiveness. This state of mistaken confidence unavoidably makes itself heard in grandiose grant applications, in a scientific environment that has learnt to counter the shockwaves of Thatcherism with the abolition of humility. Reviewers will not normally be equally at home at both sides of the conceptual abyss, consequently share the misapprehension of the other side's potential, and therefore overlook potentially disastrous implications of those limits with which they are familiar. If a project is finally implemented, however, and if project communication works as it should, the truth may sooner or later dawn on its members[1]. In a worst-case scenario, this leads to the publication of what, for all practical aspects, would need to be termed fake results: valid products of computational modelling, while everybody involved is aware, on some level of bad consciousness, that these heavily depend on parameters way beyond any evidence and are perhaps produced by algorithms that do not really apply to the investigated material.

As I said, this is the worst case, and there are many grey shades of more or less compromised results and different portions of researcher souls sold to the promises of career and recognition. But how to avoid the allure? Of course, at least when we find ourselves in the role of a reviewer, keeping aware of the mechanisms outlined above may already help. When planning a project, on the other hand, I am afraid this will not suffice. Here a solid foundation can only be laid when a profound knowledge of the potentials and limits of all involved methodologies, archaeological, iconographical, philological, ethnological, you name it, is assembled within the single brain of at least one person. Nota bene, the potentials and limits, not all the technical details and procedures.

This may of course be achieved during intense exchange in the planning phase, where a potential PI from the music-archaeological side must not recoil from investigating what existing or planned software (which for him/her, as such, may remain a black box) needs to be fed and what it can produce with which degree of reliability as well as, crucially, how uncertainties in various parameters would affect the results. On the other hand, a PI who is primarily software expert would need to press his/her colleagues about the reliability and comprehensiveness of their data, familiarising himself/herself with all the uncertainties in the interpretation of the archaeological record, with iconographical and literary conventions and invention, knowns and unknowns about ancient aesthetics, or also pronunciation and vocal styles. He/she might also be well advised not to rely on a random colleague from a particular field just because this colleague happens to sit next door: comparatively few philologists, for instance, would be all too well informed about the sound of the ancient living voice.

Sadly, not a few projects might die at this stage, for instance when an archaeologist finds he/she needs to abandon the idea of reconstructing the soundscape of a building where we do not know if its walls might not have

[1] While I recommend the described model as an interpretational framework because it reduces the assumption of ill intent to a minimum, I must confess it may fail in some cases. One particularly infamous in music-archaeological circles was the 'virtual reconstruction' of a harp (wrongly termed 'epigoneion') by a project named ASTRA about a dozen years ago, which seems to have been flawed on many levels from the outset.

been covered in tapestries. There is an undeniable unfairness in this approach – the most honest and committed researchers stand the least chance ever to apply for funding – for which to compensate is once more the responsibility of reviewers.

From these preliminaries it may have become clear why I recommend the closest possible proximity between programmers and music archaeologists. In the following it remains to explain the advantages of the extreme case: personal unity. As everything, these come at a cost: making software work, and more, making it work in an intuitive way that integrates as seamlessly as possible within one's scientific workflow, can consume a lot of time. On the other hand, it can also be a lot of fun. Exploring uncharted territory, facing towering obstacles, iterated frustration with futile attempts, finally the joy of an elegant solution behind which the hideous shadows of subsequent challenges lurk, all this may make your working hours the rewarding experience in the quest for which others need to waste their free time gaming in front of just the same kind of screen.

2. The example of the *aulos*: what to model

In order to describe the more scientific gains, we need to settle on a particular case study. Among my attempts at computational research on ancient instruments, my experience with doublepipes is by far the most extensive. Back in 1997, starting from Martin L. West's interpretations of the *aulos* measurements available to him (West 1992, 97-101), I undertook refining his rough calculations that were based solely on hole distances by employing precise formulas that take into account bore and hole diameters as well as wall thickness, and potentially the effects of cross fingering or 'open' versus 'closed' playing (playing styles in which all holes beneath the one principally sounding the actual note are left open or closed respectively). Even the nature of the formulas evidently requires the use of a computer; the need for some proper software emerged from the fact that one crucial parameter was always unknown, namely the extension of the vibrating air column at the upper end, next to the player's mouth. Sometimes only the reed itself was missing, often including the frail top part of the pipe into which it fitted, and in other cases the entire upper part of a pipe was lost. In any case, this would require numerical experimenting with a large number of possible lengths.

In this endeavour, I have been primarily interested in the reconstruction of instrumental pitches that would hopefully emerge meaningful in terms of ancient music-theoretical writings and in turn elucidate the practical background of these. This is very different from virtually reconstructing the actual sound of an instrument. This would have required very different technology, incomparably more computing time and processor power without promising meaningful results.

In a reed-driven instrument, the quality of the sound depends to a large degree on the properties of the reed, and therefore on a factor which was almost entirely unknown when I started my research. Moreover, the sound of each *aulos* pipe is also influenced significantly by the coupling of the oscillatory regime of reed plus tube to the secondary resonator of the mouth cavity and, via this and the player's lips, to the other pipe, which drastically encumbers physical modelling. Meanwhile, with much experimental work, we have learned to produce reeds that match the ancient iconography; but this has only reduced the potential variability of the unknown parameters.

Even today, it therefore seems to make little sense to compound uncertainties in the input data with inaccuracies in physical modelling when more accurate results can easily be gained by actually sounding a replica or working model. Contrarily, a similar replica-based approach is not viable when it comes to assess the pitches of a reed instrument (though it may work quite well for flutes, see Terzēs 2020). Firstly, since at least one important variable is always unknown, a series of practical experiments would need a large number of different reeds, which is unfeasible.

More importantly, reeds are flexible and lend themselves to bending the intonation that is 'built into' an instrument. This is an advantage whenever the instrument is poorly tuned or for some other reason cannot produce all required notes straightforwardly, for instance when a musically precise positioning of finger holes conflicts with the physiology of the human hand (Hagel 2010, 71). When exploring a sound tool from another culture, however, it turns into an insuperable obstacle, because every modern experimenter who is sufficiently versed in playing reedpipes will unconsciously bend the notes emitted by each fingering in a way to fit his/her musical expectation. The computer, in turn, will render unbiased sets of pitches that rely solely on the physics of the pipe. Whenever we are dealing with an expertly made instrument – which is *a priori* to be assumed for all the expensive pipes with mechanisms, and has *a posteriori* emerged for others as well – the computer can thus be expected to help assessing the musical intentions of the original makers and consequently the musical expectations of performers and audience within the relevant cultural horizon.

3. Developing an integrated research environment

While it might have been feasible to reuse some pre-existing software for predicting woodwind pitches, this would have put tight limits on my research. Almost all modern music software is conceptually tied to the idea of an equally tempered scale, often also to a concert pitch of A440, which entails

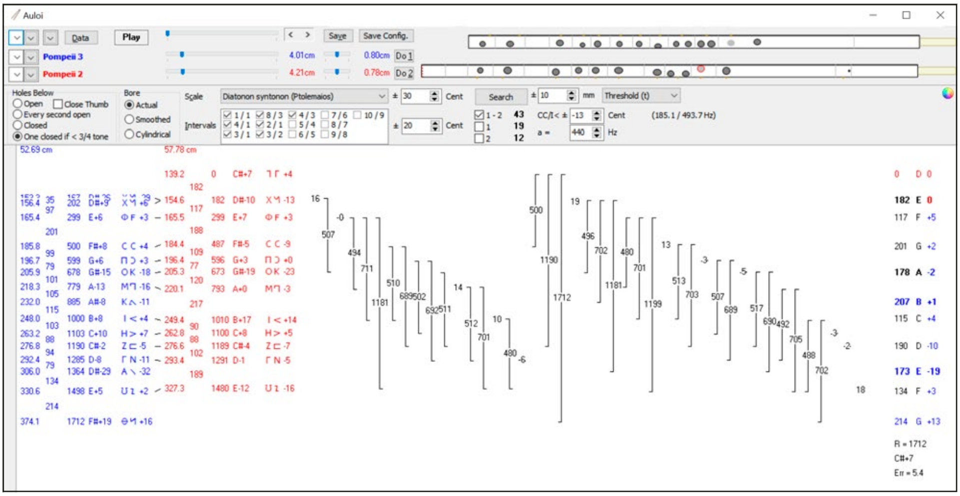

Fig. 1 – Software calculating pitches for a given instrument design with reeds of specific effective lengths. Example from Naples Archaeological Museum inv. 76892 and 76893, two pipes retrieved from Pompeii. Image Stefan Hagel.

not only considerable inconvenience but also a built-in methodological bias that is hard to eliminate. Every single output – bearing in mind the necessity of innumerable calculations while experimenting with missing parameters – would thus require to be transformed, in a secondary step, in order to display its relation with the musical structures of the ancient world, a world of a different, probably more flexible pitch standard, and of a whole flurry of fine tunings recorded by ancient authors, only two of which come reasonably close to a grid of equal semitones. Having my software purpose-made thus meant integrating meaningful output values from the start (Fig. 1).

In addition to opaque frequencies in Hertz and slightly more approachable intervallic steps in cents, as well as the deviations from roughly equivalent modern notes, it was thus possible to print each resulting pitch as its equivalent ancient note as well, of course again including the deviation from an abstract ancient semitone grid[2], using the most recent assessment of the ancient pitch standard, which has long been agreed within a range of less than a tone (West 1992, 273-76; Hagel 2009, 68-95). In addition, it becomes possible to match any calculated set of pitches with interval sequences described by ancient authors, either in terms of fractions of tones in the harmonicist tradition, most prominently represented by Aristoxenus, or in terms

[2] For mapping out ancient pitch space in this way, see Aristides Quintilianus 1.11, 24-27 Winnington-Ingram. Note that these pitches do not as such form practical scales.

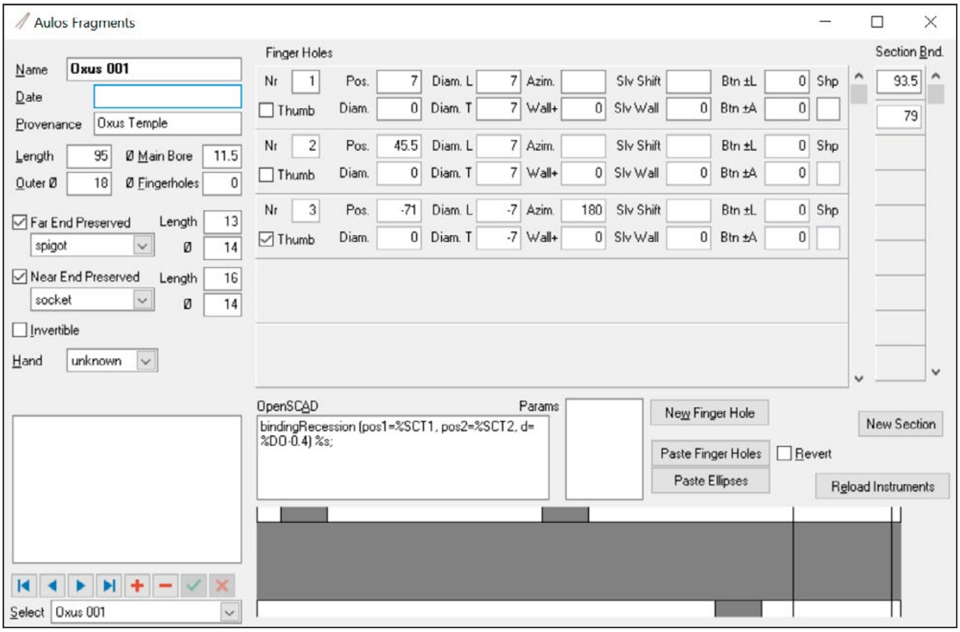

Fig. 2 – A data form describing the physical properties of an *aulos* section. Example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska. Image Stefan Hagel.

of the ratios both transmitted and newly derived by Ptolemy – or also scales suggested in modern scholarship or found in the ethnological record. In this way, what would otherwise involve tedious procedures of data transfer and separate evaluation is achieved in the blink of an eye, all integrated within a tailored graphical interface.

Behind the scenes, of course, the relevant data need to be stored. Originally I designed a Microsoft Access relational database, to which my software connected via ODBC, with separate tables describing fragments, sections and tone holes on fragments, including the position of buttons operating a potential sleeve mechanism, joining capabilities between fragments, possible (or certain) arrangements of fragments to pipes, and finally, where feasible, of pipes to instruments (Fig. 2). Such a local database comes with the considerable advantage of permitting all kinds of work without Internet connection, which was prerequisite in the 90ies but can still be useful when working in Museum basements or while travelling. With this combination of relational database and graphical user interface it has since been possible to obtain consistent musical interpretations of numerous *aulos* finds, whose predicted pitches were always closely matched by the replicas (Hagel 2004, 2008, 2010, 2012, 2014, 2020).

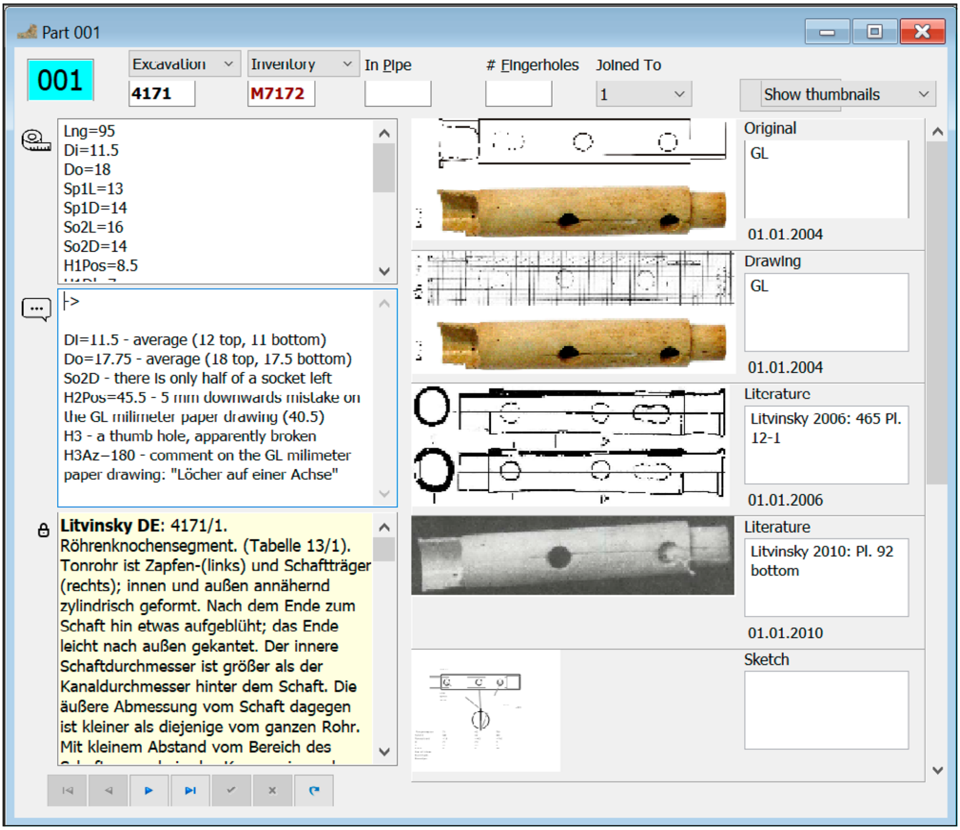

Fig. 3 – A data form collecting the evidence for an *aulos* section. Example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska, Boris A. Litvinsky. Image Stefan Hagel.

In a more modern world, and with increasing interest in the field and the establishment of collaborative projects, I have devised a complementary online database, coming with a desktop front end that connects to a mySQL server (Fig. 3). Here we store and link to image data such as photographs and drawings as well as modern literature, include competing identification systems such as find and inventory numbers, but also information about the viability of physical joints and the placement of individual fragments within tentatively assembled instruments. Together with Olga Sutkowska we have also devised a comprehensive system of sigla for all kinds of relevant measurements, enabling collaborators to include whatever technical information is available. The data can then be transferred directly to the evaluation software, whenever required.

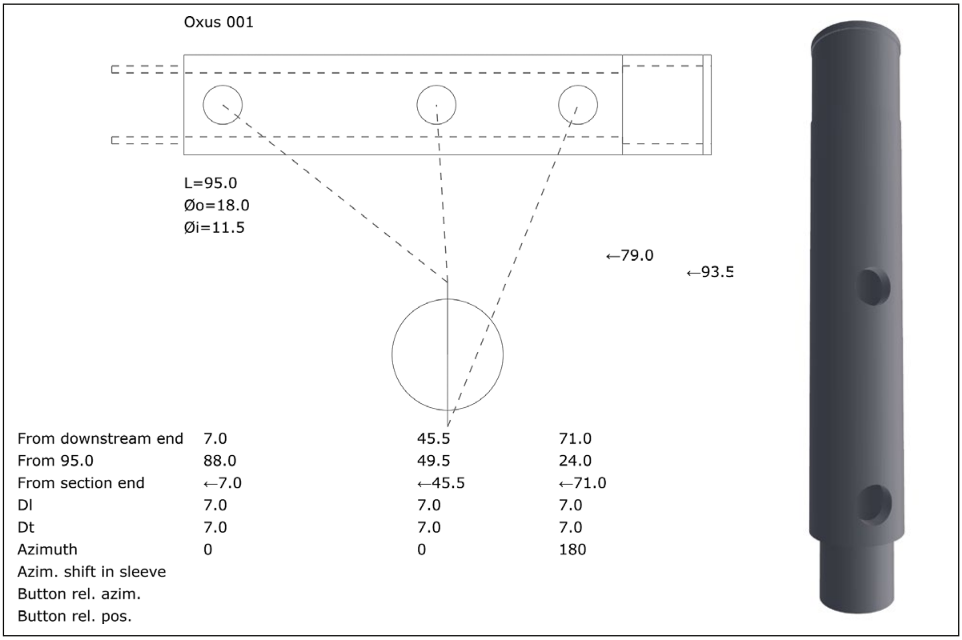

Fig. 4 – SVG sketch of an *aulos* section and printable *aulos* part. Example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska. Image Stefan Hagel.

From the same data, it is furthermore possible to create schematic SVG sketches as well as printable 3D models in OpenSCAD descriptive language (for concision using functions from an *aulos*-specific module I have written) (Fig. 4). With proper printing technology, such as selective laser sintering (SLS), the latter may yield fully working models, even up to imitating the rotating-sleeve mechanism of Roman-period instruments.

These interfaces are crucial for the quality management in our projects (Fig. 5). Firstly, errors inevitably creep in during the process of taking measurements – often hundreds on a single day – and transferring these to the computer. With an automatically generated transparent sketch, with which photographs of the objects can easily be overlaid, errors down to a millimetre or even less are readily discerned and can consequently be corrected. The fully integrated approach, on the other hand, ensures that no further transmission errors are to be expected in the course of most of the workflow. The working models, for instance, will follow the specifications up to the precision of the used printing technique. In this way, they are reliable tools for testing the acoustic predictions of the software in practice, and may even serve as performers' instruments.

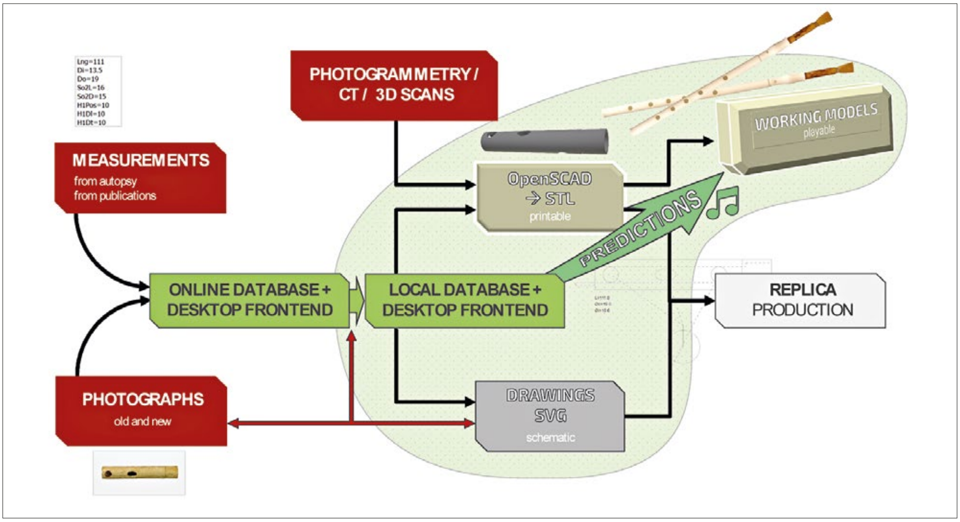

Fig. 5 – Workflow from artefact to interpretation and replication. Within the green area, copying errors should be excluded. Image Stefan Hagel.

Fig. 6 – Manufacturing part of an *aulos* bulb+insert assemblage on the CNC lathe at Middlesex University, London. Image Neil Melton, Peter Holmes.

Equally importantly, sketches and printed models are of invaluable help in the process of manufacturing actual replicas by traditional means. Not only are copying errors once more excluded; even more importantly, many communicational hurdles regarding the conceptualisation of relative positions and, above all, azimuths are easily avoided by providing a three-dimensional

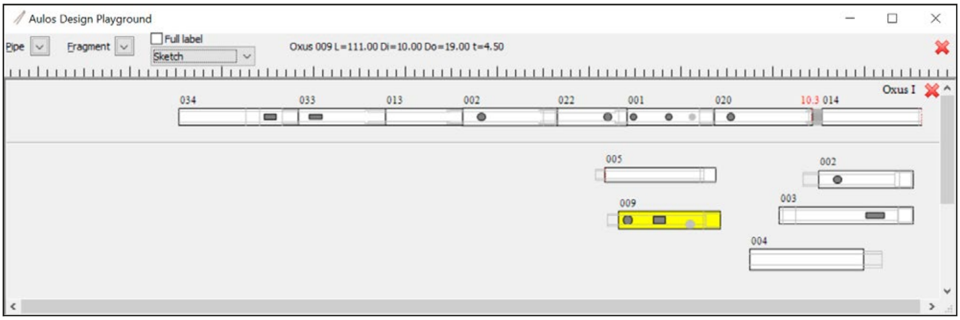

Fig. 7 – Module for experimental assemblage of *aulos* parts. Random example from the Oxus temple find. Data Gunvor Lindström, Olga Sutkowska. Image Stefan Hagel.

model of the final product. If parts of the production process involve computer numerical control (CNC), the respective input may also be derived from available formats (Fig. 6).

For the scholar, a useful by-product is the export of any data regarding either physical dimensions or the relation of predicted pitches in numerical and graphical formats, facilitating the production of diagrams and illustrations for publication. Since their dimensions thus reflect the numerical data precisely, they can easily be juxtaposed with data from other sources.

More recently, when we started to work on the highly fragmented instrument finds from Queen Amanishakheto's pyramid tomb at Meroë (Bodley 1946; Gänsicke, Hagel 2017; Hagel 2019), on the one hand, and from the Oxus temple in present-day Tajikistan (Litvinsky 1999, 2010, 424-53), on the other, it became evident that the search for physically possible as well as musically meaningful configurations of fragments required manipulating such configurations on the computer quickly and efficiently, while maintaining a live view on the ensuing pitch predictions. At this stage, a reliance on pre-existing software would once more have been detrimental. Instead, it was not all to difficult to augment our software with a new module, where the fragments can be assembled graphically using the mouse, dropping them into experimental instrument designs, or flipping them around by double-clicking (Fig. 7).

4. Robust optimisation of unknown reed lengths

As much as an extensive use of the possibilities that modern computing offers may advance music-archaeological research, its value can never be greater than that of the methodologies which are written into the software. However, as has been argued in the outset, the combination of the very different worlds of an ultimately humanities-rooted subject, on the one hand, and computer sciences, on the other, both coming with mutually intimidating languages, lends itself much more readily to the temptation of obfuscating than is possible when staying within a single well-ploughed field of expertise. It will be useful to analyse a specific *aulos*-related example, which bears on the question of what computer-assisted ‘optimisation’ may meaningfully represent.

In the foregoing I have described the universal problem of establishing the ‘correct’ effective reed length, often including a missing upper pipe end. If the intended scale of an instrument were known beforehand, this problem might be rephrased to finding the total length which produces the smallest deviation from that scale. However one might define ‘smallest deviation’ for that purpose, with an ancient instrument we will hardly ever find us in the lucky position of knowing the makers’ musical objectives in advance. For that reason, a more general approach is needed. Since ancient harmonic analysis had been centred on pitch structures bounded by pure fourths, fifths and octaves, intervals that are found to be of primary importance also in ancient Near Eastern musical sources, it appears reasonable to maximise the number of such intervals, in addition to unisons.

Of course, no material interval is ever ‘pure’ in the mathematical sense of the word, with its implication of infinite precision. The optimal configuration might therefore be defined as containing the greatest number of near-pure intervals, with a smallest total deviation. However, finding a meaningful formulaic expression for that idea is less straightforward: how would the number of intervals and the respective deviations be weighted against each other? I have found it practical to first introduce a threshold value for the inclusion of intervals, then establishing the largest possible number of these, and only in a final step use the deviations to find the precise optimal configuration for the pre-established maximal number of intervals. This has the advantage of yielding intuitive results, which can also be displayed graphically in the form of the ‘admitted’ intervals (Fig. 1). A more refined algorithm would weight each applicable interval (most practically, for instance, each interval that lies within a quartertone of the ideal) according to its deviation from the ideal, counting it fully only when it is precise. Modelling human perception requires that intervals that are only a few cents off are still assigned relatively high values, which then need to drop rather quickly to near-zero for greater deviations. The corresponding bell shaped curve is conveniently modelled as a Gaussian function of the deviation d (expressed in logarithmic units such as cents) with a maximum of 1 and a standard deviation σ (expressed in the same units) that reflects the tolerance level:

$$f(d) = e^{-\frac{d^2}{2\sigma^2}}$$

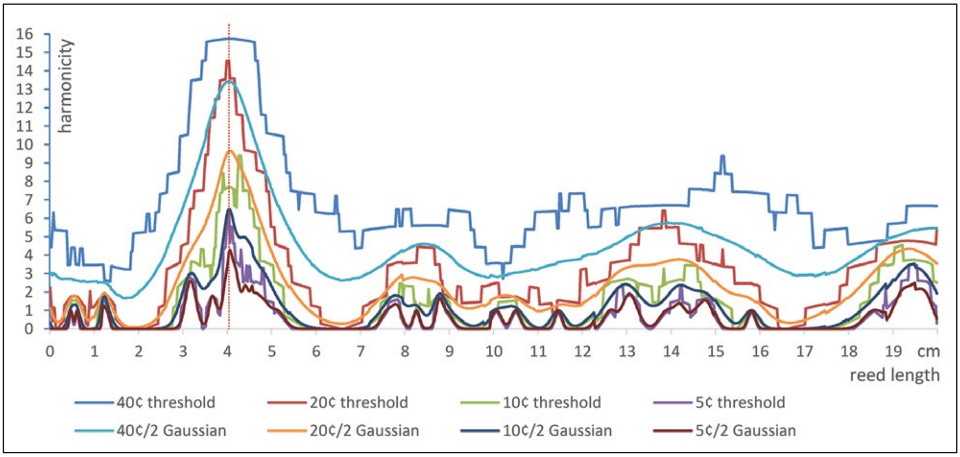

Fig. 8 – Robustness of reed length optimisation: Louvre E10962, high pipe. Red dotted line: predicted optimal reed length.

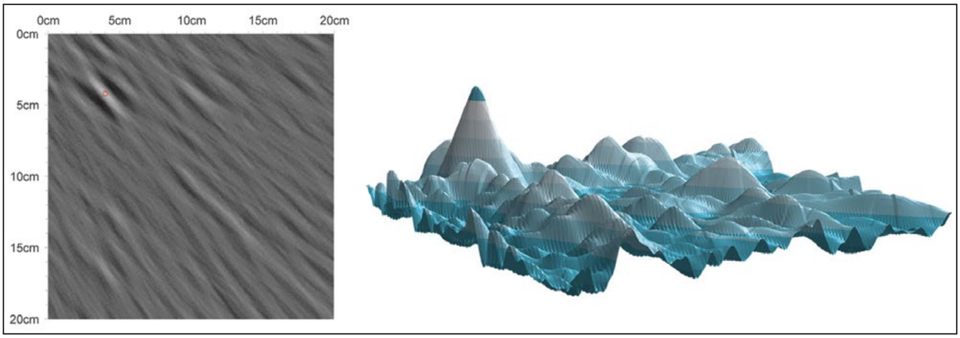

Fig. 9 – 'Harmonicity map' for various effective reed lengths configurations as colour map (threshold, 20¢) and surface plot (Gaussian, σ=20¢/2). Lighter areas (left) and higher elevations (right) indicate a larger number and higher quality of near-pure unisons, octaves, fifths and fourths. The optimum occurs at (4.01 cm; 4.21 cm); cfr. Fig. 1. Example from Naples Archaeological Museum inv. 76892 and 76893, two pipes retrieved from Pompeii. Image Stefan Hagel.

Fig. 8 shows the robustness of both approaches over a wide range of tolerance levels, using the example of intervals within a single pipe. The ragged lines reflect the threshold approach; the smooth contours, Gaussian weighting. The thresholds are varied over a factor of eight, ranging from 5 to 40 cents for the simple algorithm, and the respective half values for the standard deviation in the weighted approach (in this way, the inflection points of the bell curves coincide with the respective thresholds). Nevertheless, in spite of the fundamental differences in the algorithms as well as the extreme variation in the tolerance parameters, the predicted optimal reed length remains identical within less than a millimetre.

For a most intuitively useful threshold value, I have in practice settled on 20 cents, the tenth part of a tone, which easily accounts for small measuring errors as well. It falls just short of the so-called syntonic comma, an interval that Ptolemy described as negligible for certain practical purposes (*Harm.* 1.16, p. 39.19-22; 40.1-6; Hagel 2009, 184-85).

On the basis of either of the described algorithms, the computer can readily establish optimal extensions for either a single pipe or a pair simply by comparing the results for various values that are separated by small steps (e.g., 0.1 mm), throughout the conceivable overall range. For a pair, the results are conveniently visualised as a coloured Cartesian plane, where different shades indicate different numbers of near-pure intervals, or also as a 3D surface, where the optimum stands out as the tallest peak (Fig. 9). Where the upper ends of both instruments survive, meaningful results are expected to include similar lengths for both reeds and therefore an optimum close to the diagonal $x=y$ in the diagram.

Optimisation in this sense thus establishes a maximum by varying one specific parameter on which all members of the result set (the predicted pitches) depend.

5. Misapplying the concepts

It might go without saying that the success of the method relies on varying the right parameter across a meaningful spectrum. A reed of 30 cm length would make no sense – but the computer would not know that. Neither would it make sense to tamper with the evidence, for instance, by varying the positions of fingerholes (unless, perhaps, in order to produce an educated guess when a hole position is unknown due to damage). Producing a higher number of nice intervals is therefore not necessarily a token of better methodology; it may be quite the contrary.

An obvious example would be increasing the threshold value for admitting intervals. This would spawn new ‘near-pure’ intervals quite liberally, none of which would carry any real meaning. For instance, if the threshold is set to a semitone, i.e. five times the value I have generally been using, then a pair of notes spanning the obviously dissonant interval of a tritone would pass as a pure fourth. Even more absurdly, it might at the same time count as a pure fifth as well. When spelt out in a clear-cut way, the preposterousness of such an approach stands out so evidently that the reader may wonder why I would waste their precious time discussing the theoretical possibility of such outlandish fabrications. But what if these, instead of laying bare their misrepresentation of reality and common sense, came clad in smug technical language? Such as, «by increasing Hagel's unrealistically small admittance threshold, which in reality even falls short of the ranges associated with experimentally ascertained embouchure variation in double-reed instruments, our enhanced approach to virtually modelling the harmonicity of *aulos* finds was able to discover no less than 11 hitherto undetected potential pure intervals, taking our understanding of ancient music to a new level».

How many readers and even reviewers would not swallow this without raising an eyebrow? Note that all the facts are correct: embouchure variation can indeed change the pitch of a fingerhole significantly (though much less so for bass notes), and this consideration might well be technically implemented as an increased threshold, which would correctly increase the resulting numbers. Even so, a sum of truisms does not necessarily make a conclusive argument. In fact, the fictitious «enhanced approach» above basically abandons researching the properties of the actual instrument under scrutiny. Instead, it models the options of playing that instrument *against* its built-in musical properties. Undeniably, it is indeed possible to elicit the «undetected pure intervals» by adjusting the reeds in various different ways. Ultimately, it may well be possible even to play, from the same pair of fingerholes between the two pipes, once a fourth and once a fifth. However, this is trivial. The same could be argued for reed instruments of the modern Western orchestra. Nonetheless, we know that these modern instruments are carefully manufactured to play particular pitches, and there is good reason to assume that the same was true for many ancient instruments.

Unfortunately, the preceding is no mere fiction. The same logical error forms the basis of a recent publication (Bakogiannis *et al.* 2020), in which the authors sent the computer through five million iterations each of various algorithms only to establish what anybody equipped with a sketch of the Louvre *aulos* scale (Louvre inv. E10962; Bélis 1984; Hagel 2004, 2014) can work out: if all the notes would come close enough to a 'Pythagorean' tuning, one would count precisely 56 pure intervals. That is just the way a diatonic scale works; all one needs to know is that one pipe ranges from *A* to *a*, and the other from *A* to *d'* but lacks *B*.

The cited study also presents methodological issues in other respects. Its software (ENTROTUNER) relies on two types of input, fundamental frequencies and instrumental sound spectra. Instead of physically modelling the former, the authors use published values (53190), apparently without noticing that these do not represent the required fundamental frequencies but already take the predicted inharmonicity of higher partials into account (Hagel 2004, 380).

A sound spectrum, on the other hand, can only be obtained from a replica, with all the uncertainties associated with the reed and not least the playing technique. The authors multiply the problem by recording not a replica of the narrow wooden instrument with a small reed under scrutiny (which would have been available to them through their cooperation with renowned music archaeologist Chrēstos Terzēs), but a bone instrument with a wide bore and huge reed blades that produces a fairly different sound, and do not even compare the resulting data with the available published spectrum of a Louvre replica (Hagel 2004, 387 Diagram 1). Finally, the bone instrument is also used in a final experiment that shows how a musician can reproduce 'optimised' pitches on a replica.

I have deemed it necessary to dwell on a particularly flawed example because all this has huge bearings on our understanding of ancient music. Bakogiannis *et al.* claim to have achieved «the re-determination of the musical scales and a more in-depth understanding of the musicological aspects of an era» (53194). Actually, they have but enforced their preconceptions of how a scale must work upon an ancient artefact. All ancient authors, in contrast, agree that the true scales of antiquity by no means followed the principle of maximal 'harmonicity' at all costs. Not some but all of the contemporary lyre tunings so meticulously reported by none less than Claudius Ptolemy (*Harm.* 2.15-16) stand in stark opposition to the 'Pythagorean' scale implied by Bakogiannis *et al.*

Those ancient scales feature different kinds of (mostly smaller) semitones, which disrupt tuning sequences that rely exclusively on pure fourths and fifths. If an ancient *aulos* were built to play in tune with a cithara of Ptolemy's cultural environment, it would likely reflect such different fine tunings. There might be a reasonable chance to detect these using the method I have employed in previous studies, even though it relies on a *general* importance of pure fifths and fourths (see e.g. Hagel 2009, 353 on potential links between such a 'deviant' note and the musical documents of the period). Contrarily, a procedure that instates harmonicity where the instrument design does not bear it out would *a priori* override the intentions of ancient makers and musicians.

To be sure, it is perfectly possible that some non-pure intervals in the calculations depend on shortcomings in the formulae (less likely), measurements errors (more likely), or original design flaws rather than genuine musical intention. Also, ancient performers would certainly have tried to compensate for such shortcomings. It is absolutely reasonable to point out that this might have been the case, and to which extent each pitch would need to be bent. Only, one needs to keep in mind that such speculations cannot possibly bring us any closer to deciphering the intentions of ancient musicians than does the study of the physical properties of the artefacts in combination with literary testimonies and the evidence from the remains of ancient tunes.

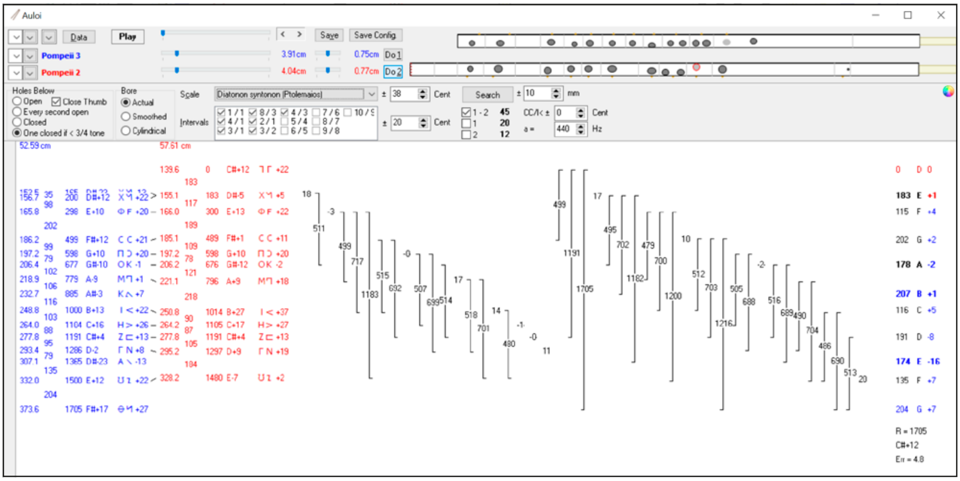

Fig. 10 – The data from Fig. 1 optimised for closed thumb holes. Image Stefan Hagel.

6. A small step forward

All this is by no means to say that the method I have followed cannot be improved upon. On the contrary, I would like to conclude by addressing an inaccuracy I had previously been sluggish enough to accept, but which I take this opportunity to eliminate. Above, we have come across the difference between 'open' and 'closed' playing: when the finger holes below the 'sounded' hole are closed, the note becomes just a tiny little bit lower (the effect is much more pronounced on most modern instruments, whose fingerholes are smaller in respect to the bore). Generally I have found that the open variant produces better results and therefore published these (with required modifications on instruments with a more chromatic design, where part of the holes was mechanically closed in any performance setup).

However, this misrepresents the physiology in the case of the thumbhole. When 'sounding' its note, the thumbhole is of course opened, by rolling the thumb on its tip, which then supports the instrument. However, whenever the index finger hole above it is released, it would be entirely unpractical to keep the thumb hole open as well; instead, the thumb naturally ensures a securer grip on the pipe by rolling back over its hole (where the makers sometimes carved an extra recess for it to rest in). As a consequence, an open-holes-below approach must be expected to misrepresent the pitch of the index finger hole, for which we need to reckon with at least one closed hole below. Apart from the index hole, no other hole is of course affected (unless in the case of *auloi* with more than one thumbhole, none of which are yet published).

After adjusting the software accordingly, the computer-optimised configuration changes from that shown in Fig. 1 to that of Fig. 10. The differences are minute, but it may be significant that they point in the direction of better tuning. In terms of near-pure intervals up to 20 cents deviation, we now obtain 45+20+12 instead of 43+19+12. Most strikingly, the top interval on the higher pipe has shrunk from 217 cents to 204 cents, precisely the whole tone ancient theory requires here (in the Lydian *tónos*, which is the central key of the ancient system and one of the keys the instrument could play, this interval marks the distance between *nḗtē synēmménōn* and *nḗtē diezeugménōn*, respectively a fourth and a fifth above *mésē*). One might also note that the difference in effective reed lengths has shrunk from 2 mm to 1.3 mm; but this is hardly of practical relevance.

What about the other published many-holed instruments? On the Louvre *aulos*, the adjustment for closed thumbholes produces one additional near-pure interval between the pipes, though this comes at the comparatively lower cost of losing one within the higher pipe; here, as well, the top interval shrinks from predicted 213 to 206 cents, almost precisely a whole tone. The Berlin *aulos* also gains one near-pure interval, from 18+9+3 (with reeds of 24.0 mm and 36 mm, which already contains an improvement over the originally published 16+7+4) to 19+8+4 (reeds: 24.5 mm; 35.5 mm).

Such a general tendency towards 'better' harmonicity when correcting measurements (Hagel 2012, 105 and 110, fig. 1) or refining the modelling of instrument physics and practicalities of playing raises confidence in the scientific method and indeed substantiates the validity of the approach. The prerequisite for this is that none of the adjustments are made precisely in order to fit the hypothesis. It is a pity that modern technology has not only given us unprecedented tools to advance all fields of enquiry in revolutionary ways, but makes it increasingly difficult to tell their proper and fruitful application from biased and redundant misuse. A relatively young and notoriously interdisciplinary field like music-archaeology is perhaps especially vulnerable in this respect – but the promise of recovering even a distant ringing of humanity's musical past is certainly worth the effort of keeping an alert eye on the technological demons that so easily subvert the intentions of their masters.

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ABSTRACT

Music-archaeology can show exemplarily the potential as well as the dangers of digital approaches. Both are here illustrated using case studies from the field of virtual modelling the intended scales of ancient reed instruments, with a focus on the requirement of the closest possible collaboration between music-archaeologists and programmers from the planning stages of a project and throughout its development. On the one hand, the potential robustness of predictive algorithms is shown, on the other, methodological fallacies are exposed that have led to redundant results and consequently misguided interpretations, which however, due to the ubiquitous partition of expertise, have slipped through reviewing processes. Finally, the author amends a problematic detail in the approach underlying previous publications of his own, showing how reflecting the physiology of *aulos* playing more accurately may enhance the harmonicity of modelled pitch sets, which in turn lends further credibility to the general method.

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AUGMENTATION AND ENRICHMENT OF CULTURAL EXHIBITS VIA DIGITAL INTERACTIVE SOUND RECONSTRUCTION OF ANCIENT GREEK MUSICAL INSTRUMENTS

1. Introduction

A significant number of Ancient Musical Instruments (AMIs) findings, which date from the 5th c. BCE to the 1st c. BCE, are kept in various archaeological museums in Greece and all over the world. Some of them are in good condition. Some of the most important AMIs are exhibited at the Archaeological Museum of Piraeus (Psaroudakēs 2013a): from the classical era a flute (Psaroudakēs 2013b), a chelys (a type of lyre), and a *trigonon* (a type of harp) (Terzēs 2013), and at the Archaeological Museums of Megara (Terzēs 2020): from the Hellenistic period two pairs of *aulos* with metal sliding keys. Some of the excavated AMIs have been studied by expert archaeomusicologists who emphasized their functional restoration and reconstruction (Bellia 2015; Safa *et al.* 2016). Indirect but valuable information about the musical instruments of Greek antiquity can be found in ancient Greek literature (the surviving texts of ancient Greek authors) and the musical iconography (representations of musical instruments on vases, painted or embossed works). The research results on ancient Greek music have increased exponentially in the last twenty years (Pöhlmann, West 2001; Hagel 2009a), and that is mainly due to the development of archaeomusicology and the recently excavated AMIs (Psaroudakēs 2000, 2002, 2008, 2010, 2013a; Hagel 2004, 2008; Terzēs 2013, 2020).

According to recent studies (Kurke 2000; Murray, Wilson 2004), organized sound (music and song) was the main factor that formed the ancient Greek intellectual and artistic product (epic, choral/lyric poetry, drama, comedy). However, even nowadays, there are not enough studies regarding the sonification of the AMIs to cover the majority of the excavated instruments, and therefore, the museum visitor cannot hear the actual sound of an exhibited instrument. On the other hand, their visual representation is widespread (a large volume of digitized illustrations is available). Despite the fact that recent technology is put in practice and remarkable progress has been done (i.e., digitization of the cultural apparatus, development of on line museum tours and digital guides based on mobile devices, such as tablets or smartphones), the reconstruction of the AMIs sound is still not available, except Avanzini's individual project (Avanzini *et al.* 2015).

The reconstruction of AMIs via physical apparatus (replicas), through interdisciplinary study and research (musicology and archaeology), provides satisfactory results. Nevertheless, as it is usually approached by trial and error techniques, it requires disproportional effort, which increases the construction cost (Hagel 2009b; Psaroudakēs 2013a; Koumartzis *et al.* 2015). A similar problem is present in the construction of traditional instruments, especially in the process of standardization and optimization. The introduction of playable reconstructed musical instruments in the museums (as is the case with any object that contains elements of ancient technology) is not considered appropriate, and it is not adopted because: a) of aesthetic arrangement issues of the exhibition space, b) of noise disturbance issues when used by a visitor, c) the generated sound is not representative especially in the case of AMIs made of animal bones (Safa *et al.* 2016), and d) of provided grounds for anachronistic interpretations that may hurt the exhibited instrument. We here propose an enriched museum experience where the visitor sees the original AMI and at the same time interacts with its digital simulation through a tablet, a digital kiosk, or a mobile device (either by altering some of its features or by playing notes) and hears the generated sound (on headphones) in real-time. Moreover, this application will help the scientists (i.e., archaeomusicologists) to study the AMIs as it provides flexibility in modifying the instruments' parameters (e.g., geometrical features) and swiftly obtaining the relevant sound. This is a powerful tool that will speed up the musicological study of the AMIs, by enabling a fast and accurate scale estimation. Furthermore: a) our method can be combined with recent methods that take into account the musician's interaction with the instrument to optimally tune the set of generated fundamentals (Bakogiannis *et al.* 2020), b) our method's output signals can then be filtered with a digital filter which simulates the acoustics of various ancient theatres to obtain their sound in their natural auditory space (Vassilantonopoulos, Mourjopoulos 2003; Polychronopoulos *et al.* 2013), and c) the instrument's introduced geometry can be treated as an acoustic metamaterial (Polychronopoulos, Memoli 2020) enabling the 3D printing of a functional (in some instrument classes) musical instrument (Noreland *et al.* 2013).

In the last two decades, the synthesis of the sound of musical instruments using the method of physical modeling (Eckel 1995) has received increasing attention in the field of music technology. This method is based on the description of the production and propagation mechanisms of sound using mathematical models that describe the acoustics of sound production. It embodies the Newtonian ideal of an exact mathematical model of a mechanical-acoustic process (Roads, Strawn 1996). Unlike the rest of the simulation methods, it does not require instrument recordings in order to build a model, which is a rather significant advantage in some cases (i.e., in the case of an excavated ancient musical instrument where it is fragile or/and not in one piece).

For the creation of the virtual musical instruments and their use during the performance, the physical modeling method is going to be used as it provides not only more realistic but also more expressive synthetic sound (Välimäki, Takala 1996; Aramaki *et al.* 2001; Rabenstein, Trautmann 2001). The usual methods of sound synthesis (FM, additive, subtractive, AM, PD, Granular: Miranda 2002) try to reproduce the spectral content of the acoustic signal produced by a musical instrument, but their parameters are not related to the instrument's physical parameters. Moreover, all the other methods, for example, the widely used and computationally cheap method of sampling (reproduction of recorded samples from the physical instrument), require the existence of the instrument. This is a major constrain when the instruments in question are excavated, thus, fragile and usually not in one piece. On the contrary, the physical modeling method does not produce the sound directly but produces and controls the process that creates the sound (Serafin, Smith 2000). The main approaches of this methodology include the digital waveguide (Välimäki, Savioja 2000), the transfer function model (Borin, De Poli, Sarti 1992), the modal synthesis (Bisnovatyi 2000), and the finite differences using resonant filters (Bilbao 2009). Furthermore, approaches for the physical modeling of double-reed musical instruments have been presented in the literature (Erkut, Karjalainen 2002; Bilbao, Smith 2003; Karjalainen, Erkut 2004; Bensa *et al.* 2005).

The Virtual Musical Instrument (VMI) is a credible (as much as possible) digital representation of the corresponding real one and consists of two distinct parts (Tzevelekos, Georgaki, Kouroupetroglou 2008). The first is responsible for the audio reconstitution of the produced sound in real-time, and we call it Acoustic Virtual Musical Instrument (AVMI) and the second one is the Visual Representation, which is usually a realistic three-dimensional representation. The most promising simulation method of AMIs is based on physical modeling algorithms that solve the system of equations that corresponds to the acoustics of the real musical instrument (Välimäki V, Takala 1996). A digitally simulated AMI has to produce a sound as similar as possible to the sound that the corresponding musical instrument makes and, moreover, to enable the ability to interact with it through an external physical apparatus. Nevertheless, there are no strict directions and autonomous frameworks for the development of AVMIs. Most of the relevant applications are limited (closed and non-scalable systems) and do not combine their visual representation as the user interacts with them (i.e., playing music). They are not easy to use and not suitable for non-specialists (e.g., museologists, archaeologists) as they cannot modify them or develop their own digital AMI based on specific requirements (e.g., to accurately reproduce the sound of a specific exhibited AMI). In this work we show the simulation method of the AMIs and propose a flexible and scalable digital tool through which: i) the museum's scientific staff will be able to create an AVMI that will accurately reproduce the sound of a specific AMI and ii) the experience of each *in situ* or online visitor of the museums will be enriched and enhanced with the digitally generated sound (by every single digital AMI) along with its three-dimensional representation, but will also enable the real-time interaction to produce music.

2. Methods

In this section, we discuss the simulation of wind AMIs (classes: *Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) and the simulation of string AMIs (classes: *Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*).

Digital waveguides were used to simulate the wind AMIs. Due to the complex shape of their body and material properties, the string AMIs are simulated using a hybrid method. We used Digital Signal Processing (DSP) and, more precisely, digital waveguides to simulate the vibrating string (Askenfelt, Jansson 1993; Fletcher, Rossing 1998; Giordano, Gould, Tobochnik 1998; Rossing 2010; Perov, Johnson, Perova-Mello 2016) and Finite Element Method (FEM) to simulate the vibrating body of the instrument (Richardson, Roberts 1985; Karjalainen, Smith 1996; Carlson 1996; Stanciu, Vlase, Marin 2019). Through this hybrid (DSP-FEM) method, the overall sound production mechanism is modeled, and the sound produced by the musical instrument is approximated.

2.1 *Wind instruments*

Not all wind instruments share the same type of excitation mechanism (sound generator). The classes of wind AMIs this project is taking into account have three different types. The first one is the reed instruments, where the exciter includes the dynamics of reed vibration and air flowing through a reed aperture. Initially, the reed is at rest, where the pressure difference (between the mouth pressure and the pressure inside the reed) equals zero, and the reed's opening area is at its maximum level. While they slowly increase the pressure, the blades are closing progressively. When the pressure difference exceeds a certain value, the reed is forced to shut rapidly (Almeida, Vergez, Caussé 2004). The second is the air-jet-driven instruments, where the excitation mechanism is described by the air jet deflected. The acoustic oscillation inside the resonator creates an oscillating transversal flow through the embouchure hole, which perturbs the jet's trajectory (Carpenter 2012; Fabre, Gilbert, Hirschberg 2018) at the flow separation point. Because of the unstable nature of air jets, this perturbation travels and gets instinctively amplified along with the jet. The required acoustic energy to sustain the air particles' oscillation inside the resonator is provided by the interaction of the perturbed flow with the labium (De La Cuadra 2006). The perturbed flow

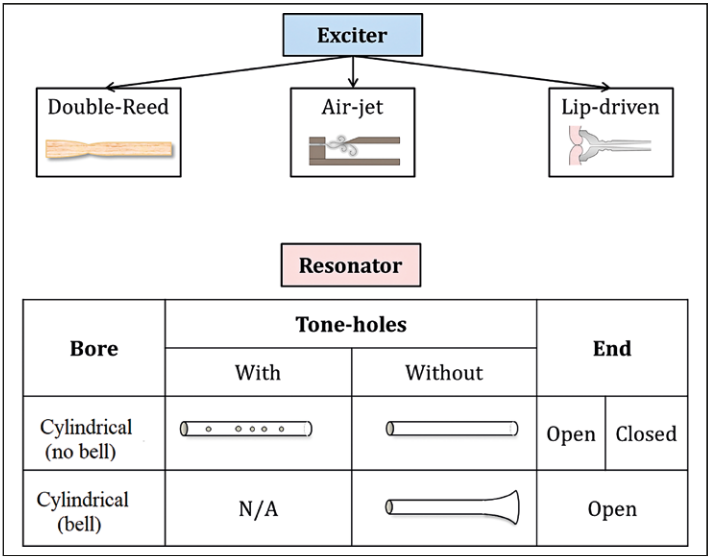

Fig. 1 – Three types of excitation mechanisms: Double-reed (*Aulos*), Air-jet instrument (*Plagiaulos* and *Syrinx*), and Lip-driven (*Salpinx*). Resonator types with various geometries, with (*Aulos* and *Plagiaulos*) and without tone-holes (*Syrinx* and *Salpinx*), with open (*Aulos*, *Plagiaulos*, and *Salpinx*) or closed (*Syrinx*) end for and the cylindrical bore without a conical bell (*Aulos*, *Plagiaulos*, and *Syrinx*) and with a conical bell (*Salpinx*).

is amplified until it reaches a side displacement which prevents its form from being cohesive and results in the reformation of the air jet. The behavior of the air jet inside a flue instrument is a non-linear phenomenon. This non-linearity is due to the fact that, even though the jet grows linearly at first, when it interacts with the perturbed flow, it breaks into vortices that conclude into turbulence (Carpenter 2012).

The third one is the lip-driven generator mechanism. There is an important difference between this type of excitation mechanism and the aforementioned two types, which mainly arises from the fact that the blowing pressure tends to force the player's lips open, while in woodwinds, it tends to force the reed closed. It should be noted here that, in this mechanism, the lips are the equivalent to the vibrating reed.

Fig. 1 shows the exciter types that will be discussed here as they are relevant to the exciter mechanisms of the instruments this work is focusing on. More precisely the exciter types of the AMIs we simulated are: Double reed (*Aulos*) (Almeida, Vergez, Caussé 2004, 2007), Air-jet (*Plagiaulos* and *Syrinx*) (Chanaud 1970; Fletcher, Rossing 1998; Auvray, Fabre 2016; Fabre, Gilbert, Hirschberg 2018), and Lip-driven (*Salpinx*)

(Benade 1990). The various resonator types are also shown in Fig. 1; with (*Aulos* and *Plagiaulos*) and without tone-holes (*Syrinx* and *Salpinx*), with open (*Aulos*, *Plagiaulos*, and *Salpinx*) or closed (*Syrinx*) end and the cylindrical bore without a conical bell (*Aulos*, *Plagiaulos*, and *Syrinx*) and with a conical bell (*Salpinx*). The cylindrical bore of the *Aulos*, *Plagiaulos*, and *Syrinx* was modeled as a one-dimensional digital waveguide, i.e., as two delay lines, one for the left and one for the right going wave, as the theory of digital waveguides describes (Scavone 1997; Czyżewski, Jaroszuk, Kostek 2002; Smith 2002; Scavone 2018). Concerning the excitation mechanism, in the case of *Aulos*, a reflection coefficient factor is used (due to the reed mechanism) (Smith 2002, Polychronopoulos et al. 2021), while in the case of *Plagiaulos* and *Syrinx*, the sigmoid function is used to simulate the air-jet excitation mechanism (Cook 1992), and in the case of *Salpinx* the lip oscillation is simulated as a mass-spring-damper oscillator (Cook 1991). The open and close ends were simulated by digital filters according to the frequency-dependent transmittance and reflectance happening in each type of ending. The reflection and transmission characteristics of the *Salpinx* bell are implemented by using lumped filters (Berners 1999) in combination with the waveguide model of the instrument. According to Smith 2004a, the reflectance of the travelling waves due to the bell of a woodwind instrument is commonly modeled as a low-pass filter, while the transmittance is implemented as a complementary high-pass filter. The modeling methods described above simulate the basic mechanisms and factors of the wind instruments' sound generation, in particular, the bore's geometry (length, inner and outer diameters), the bore's ending type (open/closed), the bore's shape (cylindrical/ conical), the tone-holes (number, position, and dimensions/ geometry), and the excitation mechanisms (reed driven, air jet, and lip driven). Our models can be further expanded to enable additional simulation parameters, such as the player's subtle control of the sound quality (e.g., vibrato and transients), type of flaring, and the mouthpiece effect, and can be further tuned to produce more realistic outcomes (Bakogiannis *et al.* 2021).

The fundamental note (frequency) created in the resonator depends on the length of the resonator and whether the end of it is closed or open. As a simplified practice, one can assume that, by opening a tone-hole, the effective length of the resonator reduces and, therefore, the fundamental frequency generated is higher. For an open-end, the wavelength of the fundamental frequency is approximately twice the length of the pipe, and for a closed-end the wavelength is approximately four times the length of the pipe (Wolfe 2018). In the final application the user sets the parameters' values for each AVMI (see Figs. 3 and 4) and both wind or string instrument physical models run in the time domain to synthesize the relevant audio signal and plot its spectrum in the frequency domain through the Fast Fourier Transform.

2.2 *String instruments*

DSP using Digital Wave Guides (DWG) and FEM solving in Time Domain are the two most commonly used physical modeling techniques. The DSP method is more commonly used than the FEM mainly because it is less computationally demanding. Therefore, in order for the algorithm to be able to respond and play the sound of an instrument in real-time, the DSP method is more suitable. The vibration of string musical instruments can be simulated as 1D DWG. However, the vibrating body of the instrument, which is the main sound source due to its complicated geometry, cannot be simulated with the same computationally cheap method. Julius Smith published an article comparing the effectiveness of DWG and Finite Difference Time Domain (FDTD)

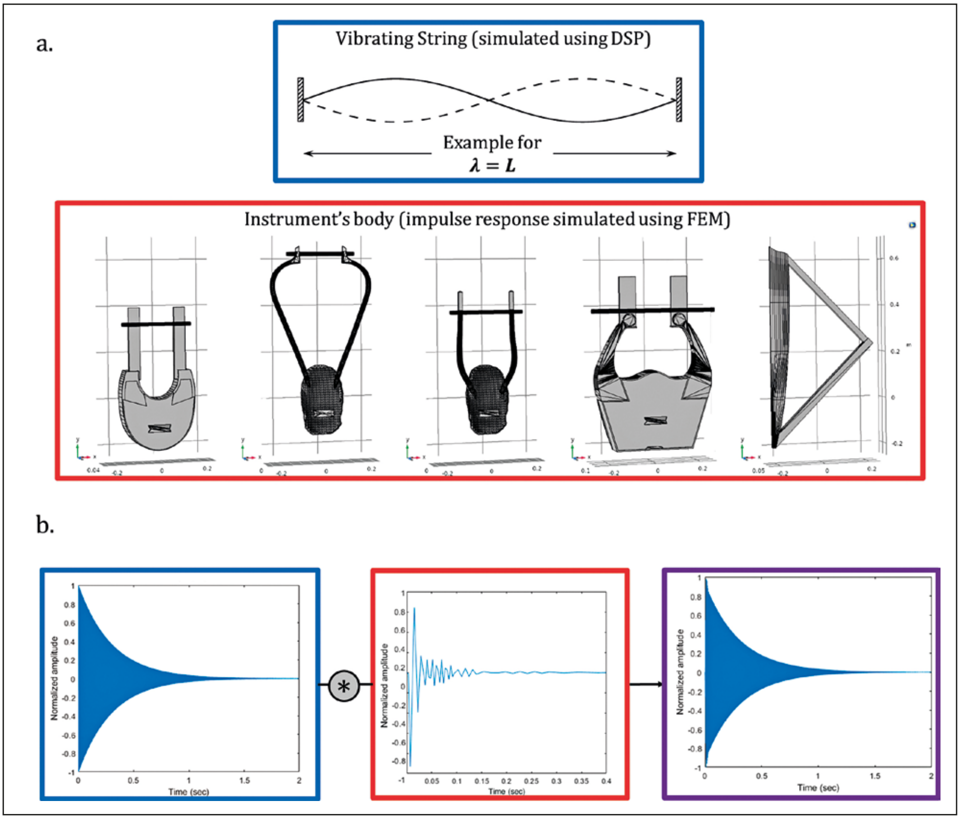

Fig. 2 – a) blue frame: the vibrating string; red frame: the 3D of the body of the instruments (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) in COMSOL Multiphysics 5.5. b) blue frame: the signal from a vibrating string (string's length = 0.36 m, Tension = 32.85 N, Linear Density = 0.0005832 kg/m) simulated using DPS (digital waveguides); red frame: the impulse response of the body of the instrument (*Trigonon*) using FEM; purple frame: their convolution.

(Smith 2004b). Our FEM model used to simulate the body's vibrations through the calculation of its impulse response shares common principles with FDTD as it runs in the Time Domain in order to calculate the impulse response of the system. After Smith's work, more works followed (Erkut, Karjalainen 2002; Bilbao, Smith 2003; Bensa *et al.* 2005). Cumhur Erkut and Matti Karjalainen came up with an approach combining the two models for the simulation of string instruments (Erkut, Karjalainen 2002). Additional work was published 2 years later by the same authors with a more generalized approach proposing a renewed hybrid model (Karjalainen, Erkut 2004).

In this work, in order to encounter the complicated geometry of the body of the string instruments, a hybrid method was used. The signal from the vibrating string (DSP-DWGs) is convoluted with the impulse response of the body of the instrument (FEM – solving in Time Domain) for our hybrid model to output the final audio signal of the wind AMI (Karjalainen, Välimäki, Jánosy 1993; Karjalainen, Smith 1996) (Fig. 2). The complete study of the sound produced must include, in addition to the distinct study of the string and the body, the role of the bridge. The frequency response of the body is obtained by exciting the bridge at different frequencies (Rossing 2010). In low frequencies, there is a better agreement between the produced sound and the excitation than in high frequencies. This is due to the fact that the directionality can vary as a function of eigenfrequency, as well as the fact that a small movement of the bridge does not automatically imply a high level of sound production. More precisely, the body of the string musical instrument functions as a linear mechanical-acoustical system, which transforms the forces imposed by the vibration of the string into sound pressure waves propagating in the air.

As the calculation of the impulse response in FEM requires some time, we here propose two application types: a) the impulse response of all the AMIs exhibited in the museum is pre-calculated in order for the visitor to be able to interact with the digital instrument in real-time altering only the strings' parameters and b) the user is able to upload the 3D geometry of the body of the instrument and parameterize the strings as well. The first application type runs in real-time, and it is better for commercial use, while the second one provides more freedom in the design and it is more research-oriented. In case the string AMI, found in the excavation, is in one piece, its geometry can be easily obtained by using a 3D scanner. If there are missing parts, the archaeologist can digitally design various possible versions of the instrument's body and study each version's results. Moreover, the digital calculation of the impulse response does not require a physical measurement (which is not possible since AMIs are fragile and the impact could destroy them), enabling the researchers to test their assumptions regarding unknown parameters of the soundboxes, even when there are no actual remains of the instruments (for instance, in the case of *kitharas* or *phorminx*).

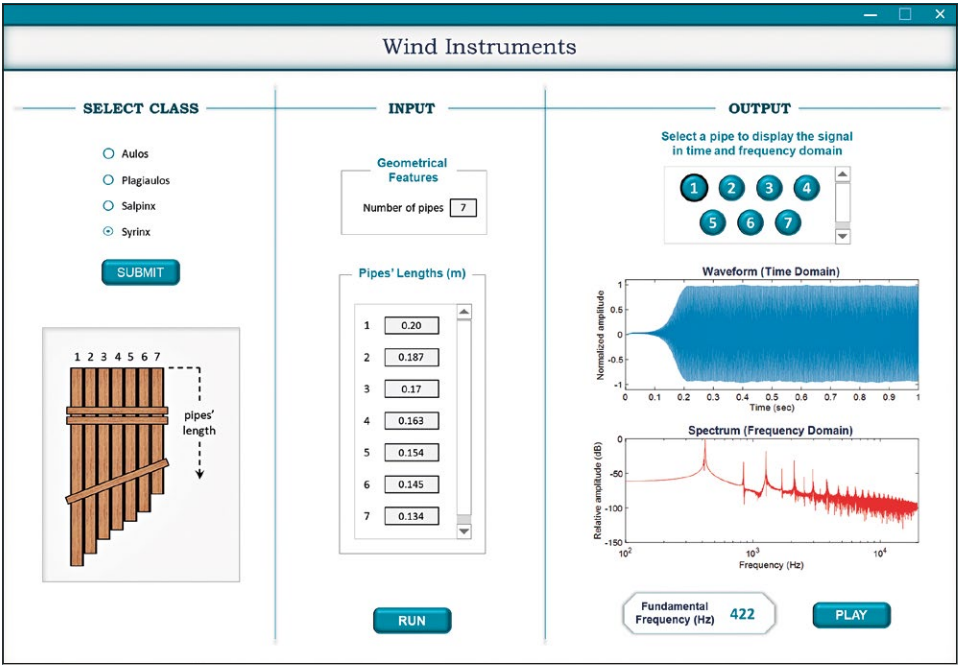

Fig. 3 – The Graphical User Interface of the wind instruments. The user can select between instrument classes (*Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) and the relevant parameters. In the example shown here, the *Syrinx* class is selected and the parameters are shown. The generated signal in time and frequency domain as well as the fundamental frequency, are calculated right after the user hits the run button. After the calculation is completed, the user selects the desirable pipe and the relevant plots are illustrated on the right part of the GUI. The audible stimulus occurs by hitting the play button.

3. Application

We here demonstrate the Graphical User Interface for the project's wind (Fig. 3) and string (Fig. 4) instruments. The user can select between the instrument classes of a wind (*Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) or a string (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) instrument. We would like to note here that due to the way we are simulating the body of the string instruments we provide the option for the user to add a 3D geometry, which is giving extra flexibility considering that small differences in the body of the instrument will significantly affect the generated signal. Then, a set of parameters show up as illustrated in Fig. 3 and Fig. 4 in the input section. We narrowed down the allowed parameters' values to be between low and high extreme values (within logical limits, e.g., two tone-holes cannot be at the same position). This is mandatory firstly for the algorithm to be able to

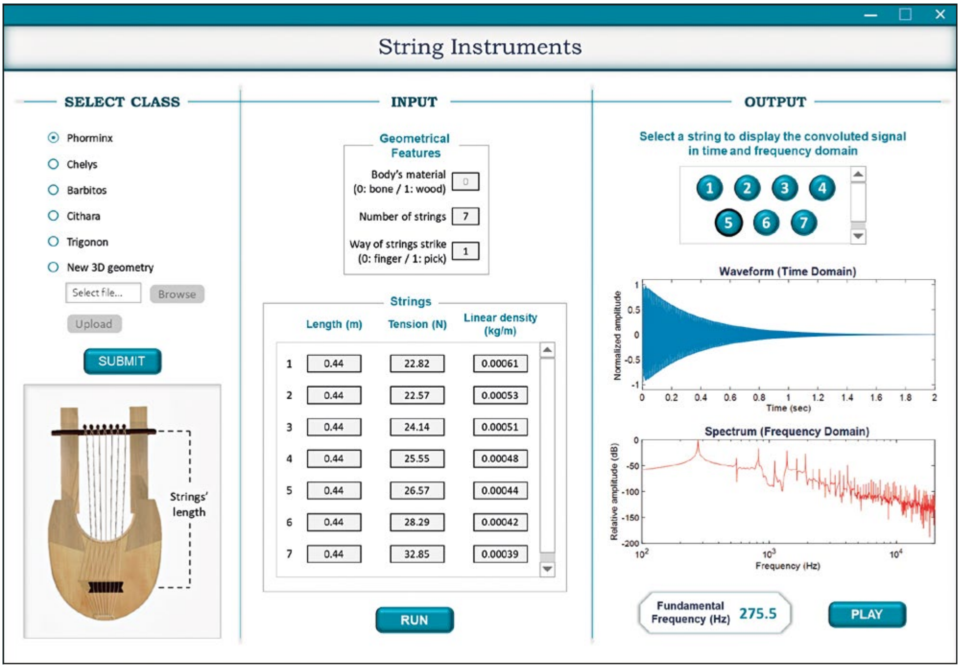

Fig. 4 – The Graphical User Interface of the string instruments. The user can select between instrument classes (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) and the relevant parameters. In the example shown here, *Phorminx* class is selected and the parameters are shown. The generated signal in time and frequency domain, as well as the fundamental frequency, are calculated right after the user hits the run button. After the calculation is completed, the user selects the desirable string and the relevant plots are illustrated on the right part of the GUI. The audible stimulus occurs by hitting the play button.

run the calculations (e.g., not acceptable parameter number of strings = 0) and secondly for the results to make sense (e.g., not acceptable 50 m long string as it does not make sense for an AMI). In the examples shown in Fig. 3 and Fig. 4, *Syrinx* and *Phorminx* classes are selected, and the relative parameters are shown. The generated signal in the time and the frequency domain, as well as the fundamental frequency, are calculated right after the user hits the run button. After the calculation is completed, the user selects the desirable option (e.g., pipe in the case of the syrinx in the example of Fig. 3 or string in the case of any string instrument), and the relevant plots are illustrated on the right part of the GUI. The audible stimulus occurs by hitting the play button.

This application will be useful not only to scientists but to a broader audience as well. The first category is mainly the scientific staff of museums (e.g., archaeologists, museologists) and archaeomusicologists. The scientists who have found a Greek AMI (even if it is not in one piece) or even a visual representation of it (for example, on a vessel) will be able – most probably by assuming some geometrical features and materials – to hear how it sounds. They will be able to experiment further with all the parameters side by side with the relevant generated musical scales. The second category is comprised of museum visitors, musicians, or even students. The museum visitors will be able to interact via a touch screen interface (tablet) or a midi controller with the digitally simulated instrument and hear the result in real-time. This enables its use by musicians who want to experiment with the sounds of AMI. The application will also help students familiarize themselves with a variety of instruments that generate different musical scales than modern instruments.

4. Conclusion

In this work, an interactive digital tool of simulated wind and string AMIs is illustrated. This application will not only be a useful tool for scientists (anthropologists, archaeologists, and archaeomusicologists) to study the instrument's sound without the need of building pricey replicas but also for non-specialists such as the museum visitors' where such an application will enrich their experience. The user is able to alter the geometrical features of the instrument and hear the generated sound without the need of building replicas which is a time consuming and pricy procedure. We highlight the simulated techniques for four classes of wind instruments (*Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) using the DSP (DWGs) method and five classes of string instruments (*Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) using a hybrid method based on DSP (DWGs) and FEM (solving in the Time Domain). The application allows the real-time interaction with the selected class of the digital instrument, the alteration of its parameters (i.e., geometrical features), and its 3D visual representation.

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ABSTRACT

A significant number of Ancient Musical Instruments (AMIs) are exhibited in archaeological museums all over the world. Organized sound (music and songs) was the prominent factor in the process of both formulating and addressing intellectual activity and artistic creation. Thus, the way AMIs sound is a key element of study for many scientific fields such as anthropology, archaeology, and archaeomusicology. Most of the time, the excavated instruments are not in good condition and rather fragile to move around (in order to perform studio recordings or exhibit them). Building replicas was the only way to study their performance. Unfortunately, replicas are not trivial to build and, once built, not modifiable. On the other hand, digitally simulated instruments are easier to build and modify (e.g., in terms of geometry, material, etc.), which is a rather important feature in order to study them. Moreover, the

audio stimulus and the digital interaction with an AMI through a Graphical User Interface would give more engagement and knowledge to the museum's visitor. In this work, we show the simulation methods of wind (classes: *Aulos*, *Plagiaulos*, *Syrinx*, and *Salpinx*) and string (classes: *Phorminx*, *Chelys*, *Barbitos*, *Kithara*, and *Trigonon*) Greek AMIs and the relevant built-applications useful to scientists and broader audience. We here propose a user-friendly, adaptable, and expandable digital tool which reproduces the sound of the above classes of AMIs and will: a) allow the museum scientists to create specific Auditory Virtual Musical Instruments and b) enrich the experience of a museum visitor (either in situ or on line) through a digital sound reconstruction and a 3D visual representation of AMIs, allowing real-time interaction and even music creation.

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SEARCHING FOR ANCIENT SONIC EXPERIENCE IN PRESENT-DAY LANDSCAPES

1. Introduction

The mountaintop sanctuary to Zeus on Mount Lykaion in Arcadia, Greece hosted cult practice for centuries. An ash altar at the peak of the mountain evidences Neolithic origins and Mycenaean formalization, while a series of Hellenistic structures were built to support public, ritualized athletic competitions in a lower sanctuary (Romano 2014, 2015, 2019). Unusually, the buildings appear to have been built in one building campaign rather than appearing organically over time, suggesting a premeditated site plan. Little is known about the daily practices and rituals carried out in antiquity; the written record contains sparse references to the sanctuary and its famous games in honor of Zeus, with the most complete account of the physical environment made by Pausanias hundreds of years after it had fallen out of use (Pausanias, 8.30.2-3, 8.36.3, 8.38.5-6; Pindar, *Nemean Odes*, 10.45ff). The most significant source of evidence of ancient site use is the site itself. While the structures of the lower sanctuary sit in extensive ruin above ground level today, the hippodrome is still intact and visible, and the geological forms of the leeward mountainsides encircling the lower sanctuary have remained stable since ancient times (Davis 2017, 2018). One's imagination is necessary to envision the original architecture, but the greater landscape forms likely bear strong resemblance to past conditions.

This consistency is important to the greater sensory landscape. When traversing the lower sanctuary, startling acoustics are evident in the landscape. Communication over long distances (what will be referred to as soundlines) is possible in some positions, while moments of sonic isolation can be present in plain sight. Many of these dynamics coincide with structure footprints or prominent landscape features and are likely indicative of ancient conditions as well. Critically, the greater mountainous region surrounding the archaeological site holds promises of continuity as well. The area maintains a rural character, with low-density villages isolated from developments and major road systems. Shepherding and scattered chestnut farming continue to be the primary activities in the landscape, introducing few modern elements that might impact the archaeological area. Combined, these aspects render the landscape setting as a critical surviving site component and an experiential buffer between industry-heavy activities in the valley; the archaeological site's relative isolation affords the unusual opportunity to study the acoustic dynamics without significant outside sonic interference. What remains to be found, and which is the focus of the research described in what follows, is whether and how the acoustics could have determined the form and function of the lower sanctuary's Hellenistic layout.

2. Existing approaches to studying sound in an ancient landscape

Sound-based approaches to ancient experience have been an increasingly frequent contribution to historic site investigations. The sonic study of ancient architecture has been established through a variety of practices, including work from archaeoacoustics, sensory archaeology, affective heritage, and architectural phenomenology (Cavanaugh 1980; Mylonopoulos 2006; Scarre, Lawson 2006; Fahlander, Kjellström 2010; Skeates 2010; McMahon 2013; McBride 2014; Till 2014, 2017; Díaz-Andreu, Mattioli 2015; Hamilakis 2015; Suárez *et al.* 2016; Tronchin, Knight 2016; Sikora *et al.* 2018; Skeates, Day 2019).

Measurement-based studies often apply the tools and lessons of modern acoustic design to map the acoustics of an interior space or specific structures, for instance to recreate ancient theaters (Chourmouziadou, Kang 2008; Economou, Charalampous 2013; Witt, Primeau 2018; Barkas 2019). The focus of these studies is the architecture as designed vessels in which certain acoustical properties may have been designed. A less common perspective is to pursue measurement campaigns at larger exterior scales, such as ancient cultural landscapes or cityscapes, to understand their sonic contributions to ancient experience (Mlekuz 2004; Hamilton *et al.* 2006; Crow, Turner, Vionis 2011; King, Santiago 2011; Díaz-Andreu, García Benito 2012; Scullin, Boyd 2014; Contreras 2015; Kolar, Covey, Cruzado Coronel 2018; Primeau, Witt 2018; Rainio *et al.* 2018; Scullin 2018). Despite apparent changes to the landscapes during the intervening years, these studies demonstrate the potential and the diversity of approaches at larger scales.

One of the most recent introductions to the methodological toolkit of ancient sound study is psychoacoustic analysis (Jordan 2020; Valenzuela, Diaz-Andreu, Escera 2020). The field of psychoacoustics studies the human perception of sound in addition to the objective properties of sound energy in a space (Fastl, Zwicker 2007). Its application can effectively center human experience in sensory considerations rather than simply the affordances surrounding the human actor. When applied in historic or ancient settings, psychoacoustic analyses offer a more direct avenue for considering the daily experience of ancient users. Valenzuela, Diaz-Andreu, Escera (2020) present many of the challenges posed by this new approach and include various approaches being explored in different projects, including the introduction of predictive site modeling and lab-based sound quality assessment to determine possible ancient conditions. The investigation at Mount Lykaion is based

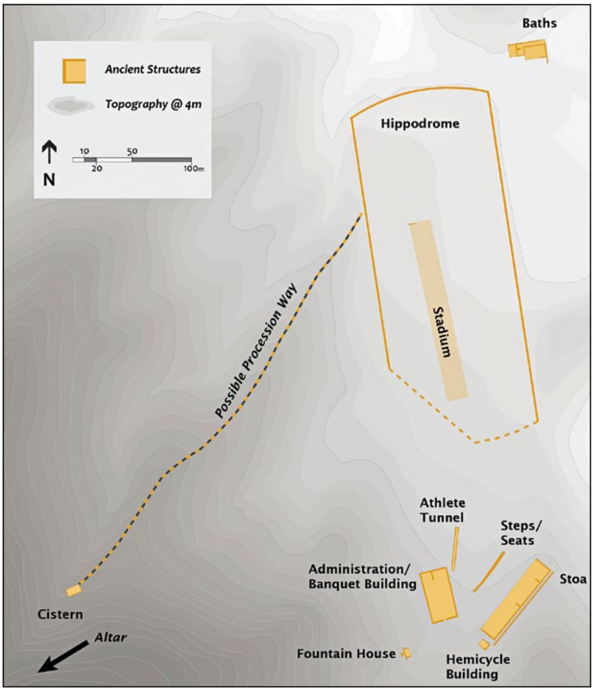

Fig. 1 – Site plan of Mount Lykaion's lower sanctuary with building remains outlined.

on observable field data gathered *in-situ* through binaural field recordings. These are then analyzed according to various psychoacoustic parameters and mapped for anomalous results, site alignments, and other patterns.

3. Site investigation approach on Mount Lykaion

Before any recordings are made, the site and its history – particularly elements related to sonic relationships and likely activities – must be understood. Details have been published previously on archaeological findings from the Mount Lykaion Excavation and Survey Project (Romano, Voyatzis 2014, 2015), as well as on the author's architectural and sound-based historical reviews (Jordan 2020, 2021). Fig. 1 depicts the visible building remains. In addition to an historical overview, direct experience of the sonic dynamics is of course essential; the author gathered this level of information over many years conducting architectural documentation, conversations with archaeological team members, observing usage dynamics during the regional Lykaion Games held on the site in 2017, and more recent field surveys (Jordan 2016, 2020).

Making binaural recordings of current conditions at Mount Lykaion fulfills three major aims. The first is to document the most accurate recorded representation of the soundscape in human experiential terms for archival purposes. A second is to enable true-to-life playback (audio fidelity), including the precise replication of sound directionality, for both analytical purposes and future archaeological interpretive potential. This includes gathering an acoustic signature to enable future convolution processing and playback should conditions on the mountain change. The third aim is to enable data analysis of the resulting recordings according to the particularities of human hearing and signal processing, which will be elaborated upon in Section 4.

3.1 *Choosing study positions*

With the above references in hand, positions and areas of research interest were identified for sonic study. Connectivity is a major theme for point selection, such as identifying whether two structures are connected by an unusual soundline or whether a structure or area surrounding the hippodrome is sonically isolated from the rest of the site. For instance, spectating was a major factor in the public ritual games held in honor of Zeus, yet no formal seating arrangements have survived – testing sought to determine what hillsides provided clear soundlines to activities taking place on the hippodrome. In a similar vein, a ridgeline running parallel to the stoa's long axis has been posited as a possible processional way between the baths and the Agno fountain (and possibly the altar). Given the sonic contributions of typical processions at the time in other sanctuaries (Pedley 2005; Mylonopoulos 2006; Connelly 2011), testing sought to identify the borders of sonic accessibility between the ridgeline and lower sanctuary. This would help identify the scope of inclusion from sonic practices along the processional way – whether the procession could be experienced throughout the lower sanctuary or only in certain nearby locales. Of particular interest were building entrances and unexplained features, such as a prominent but unexplained indentation positioned within the top tread of the ceremonial seats. Equally, sonic isolation can also determine what activities a building could host, either as co-participants in the ritual atmosphere of the games or as sonic environments unto themselves. So testing was conducted across the site at close-range and long-distance to determine site connectivity between structures as close as the stoa and adjacent semi-circular building, or as far apart as the Agno fountain and the baths.

Reciprocal recordings were made whenever possible between source and receiver positions. For example, if the speaker (source) was placed on the hippodrome and the microphones (receiver) on an adjacent hill for a cycle of recordings, the speaker and microphone positions were reversed and the recordings repeated so as to identify any directional differences in sonic experience between two points. So far, such pairings have only been recorded once; future field recording seasons will focus on repeating measurements to control for differences in weather and faunal activity and to determine baseline conditions.

3.2 *Sounds used for site testing*

In order to produce results from a wide range of possible physical conditions, communicative dynamics, and selected analysis methods, five control sounds have been employed so far: a popped balloon functioning as an impulse response for possible convolution processing; a sinusoidal sweep between 20 Hz and 20,000 Hz (the human hearing range) to observe any outlier or common characteristics at particular frequencies, and as a secondary recording for convolution processing; a series of pure tones within the human hearing range (at 498, 996, 1992, 4008, 7992 and 15360 Hz) randomized in terms of rising frequency and duration, in order to explore an abstracted version of pattern recognition inherent in music; and a series of ten sentences used in the Göttinger Sentence Test for audiometry to enable future explorations of pattern recognition, time-dependent adaptation, and speech clarity in open field conditions. The Göttinger Satztest, "Sentence Test", is a standardized series of 200 sentences that reflect the average phoneme distribution of German language speakers (Kollmeier 1990).

3.3 *Field equipment and calibration*

The equipment used for field testing was selected for stability in outdoor exposures and for extended use without a power source. Sounds had to be consistently replicable in varying conditions and at a distance, and equipment needed to be portable, long-lived, and easy to handle in rugged terrain. Recordings were made using the handheld SQobold II recording system (HEAD Acoustics, GmbH) paired with binaural headset (binaural microphones worn as headphones) with an attached GPS receiver that linked each recording with geo-locational data. The researcher wearing the binaural recording device always directed the speaker towards the receiver position. A portable, battery-powered Samson XP360 Expedition Express speaker projected the recorded sounds and was mounted at its base on a standard tripod at human height (the base was positioned at approximately 152 cm/5 feet from ground level).

The test sounds were loaded onto an iPhone SE with the iOS11.4 operating system and then played at maximum phone volume via the Google Drive app, which relayed them to the speaker via Bluetooth. The master volume on the speaker was set to a particular value for the recorded speech (resulting in an SPL of 65.4 dBA at one meter from the speaker's face), and at a higher value preset for the sweep and tones files. Two different balloons were chosen for impulse tests based on their consistency and capabilities at different frequency ranges (Pätynen, Katz, Lokki 2011): a standard G95 balloon with a 30 cm diameter was employed for short and medium-range tests (up to about 250 m/820 feet) and a larger G180 balloon with a 50 cm diameter for medium and long-range tests (from 200 up to 712 m/2337 feet). Balloons of each size were filled using a manual air pump in the field adjusted to a set pressure. Subsequently, these were held above the researcher's head directly adjacent to the speaker installation and popped with a small knife.

Meteorological data was noted at each point of signal recording using a TACKLife Anemometer (Model DA02) and a TACKLife Humidity Meter (Model HM01). As weather conditions may affect sound propagation and perception (Bohn 1988; Attenborough 2008), average value readings were taken during the period of time spent recording all five sounds at each location – a period of approximately five-to-ten minutes per placement. Any momentary sonic interference from the spinning mechanism of the wind velocity meter was found to be negligible. Generally, recordings are made when wind is at low or consistent levels – files with sudden audible gusts are rerecorded whenever possible.

Recording results were calibrated via a set of control tests that were conducted in the large anechoic chamber at the Technische Universität Berlin. Recording and speaker equipment were set up identically to field conditions and readings were taken with one meter and five meters (3.3 and 16.4 feet respectively) separating source and receiver. These measurements established a baseline for the sound propagation capabilities of the speaker.

4. Psychoacoustic analysis of field recordings

As mentioned, the goal of recording is both to gather acoustic signatures of the space through various test sounds and to create data for psychoacoustic analysis away from the field. Different analyses can be run with the same collected binaural files, homing in on key elements to human sound perception that are less frequently incorporated into other historical sound studies. These include filtering mechanisms (e.g. the ability to tune out wind interference), time-based perceptive shifts (e.g., one's immediate reaction versus one's perceptual adjustments after a few seconds), pattern recognition (e.g. language identification, birdsong identification, or merely the sorting of foreground or background sound sources), and the role of aspects such as perceived loudness, roughness, and sharpness of component sounds (Sottek, Genuit 2005; Genuit, Fiebig 2017). On Mount Lykaion, a few analyses have proven particularly useful so far that are detailed below.

4.1 *Software and file preparation*

ArtemiS Suite (HEAD Acoustics, GmbH) has been used to analyze the recorded data from Mount Lykaion by producing interactive spectrograms from which data points can be collected as needed. These images visualize each recording according to the analysis being run, providing a quick visual impression of the recording. The software package comes pre-loaded with customizable analysis functions to investigate objective and subjective components to sound perception. On Mount Lykaion, baseline sound pressure levels (dB SPL and A-weighted) provide conditions baselines. Accentuation of particular frequencies can be noted in the balloon or sweep recordings, which might hinder or favor human speech communication among many possibilities.

Other analysis functions enable the detailed comparison of contributing psychoacoustic elements; on Mount Lykaion, perceived loudness has proven a fruitful starting point for each sound source recording. Metrics such as speech clarity or intelligibility are also applicable when considering the spoken control sounds, though these were designed for and continue to be tested in interior space analysis or sonic environments prone to noisy conditions, such as busy streets and along airplane flight paths (Traer, McDermott 2016). As a result, their indicative bearing within the Mount Lykaion context is still to be determined.

Unique to ArtemiS Suite is the "Relative Approach" analysis (cp/cPa), which combines psychoacoustic elements with time and frequency pattern recognition, filter mechanisms, and adaptation over time into a single analytic of human perception of sound quality (Genuit 1996; Bray 2004). Though designed for sound quality assessments typically found in soundscape studies (Axelsson 2015; *ISO* 2018), it is a powerful tool for comparing overall impressions of sonic events on Mount Lykaion and has helped to convert anecdotal observations into consultable data. The time-based spectrograms that result have been found to be legible by a wide audience of acoustics specialists and non-specialists.

Prior to analysis, each sound recording is trimmed so that one-to-one comparisons can be made (for instance, the recordings of the pure tones are all trimmed to be seven seconds long). Averaged single values can then be derived as needed, such as the average A-weighted dB levels or average loudness of a speech file, though they are subject to significant interference when the recording includes faunal activity or wind gusts. These kinds of measurements are also useful for overall impressions before investigating certain frequency bands or other details.

4.2 *Sample analysis. Hippodrome and adjacent hills*

To illustrate how the psychoacoustic analyses described above can be applied to field observations, a few simple examples will be described. The first example is the use of the 'Relative Approach' analysis to compare the sonic experience of a sound played from two different positions. The basis of this example was anecdotal information from conversations with archaeologists and the author's site experience, which relayed that sounds from two different

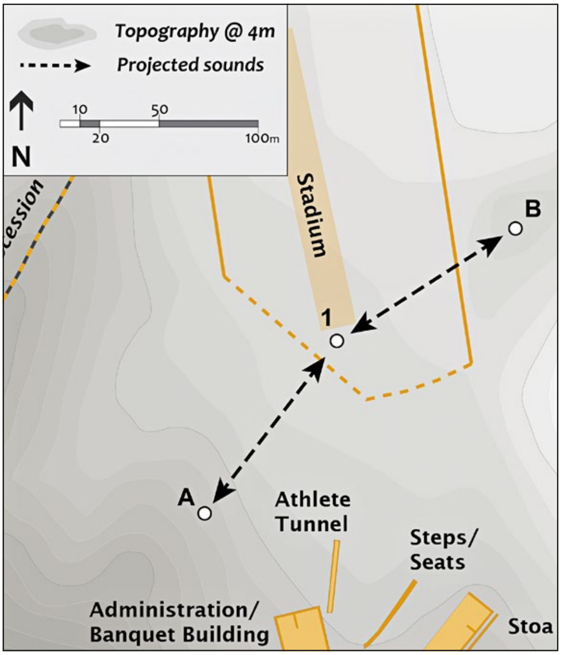

Fig. 2 – Partial site plan depicting the positions of sound sources (A and B) and microphone (1) used to compare sound quality impressions from the two hills.

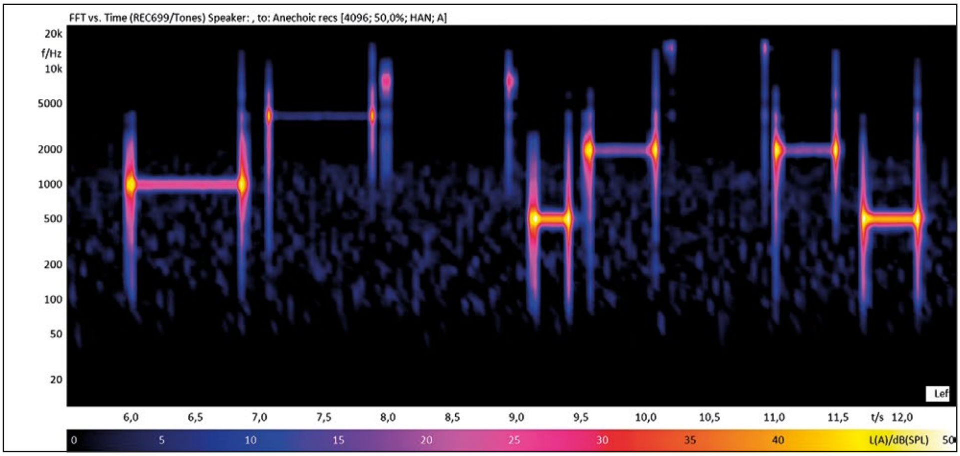

Fig. 3 – FFT vs Time analysis of tones file recorded in an anechoic chamber (A-weighted dB SPL); eight tones are visible at 996, 4008, 7992, 498, 1992, 15360, 1992, and 498 Hz, with the beginning and end of each tone particularly prominent.

hills could be heard clearly from the hippodrome surface. The intent was to determine from which hill the sound could be heard more strongly (Fig. 2).

A position was chosen on the hippodrome surface with clear sightlines to both hills and approximately equidistant from each (position 1 in Fig. 2). The leeward side of Mount Lykaion that overlooks the entire hippodrome was the first hillside for comparison (position A); a small outcrop on the eastern side of the hippodrome was the second hillside (position B). The elevation of position A is around 4 m higher than position B. The tones file described above was used to compare impressions; a baseline spectrogram of this tones file (produced in an anechoic chamber) is depicted in Fig. 3.

The recordings made on the hippodrome of the tones file projected from each hill were then compared to each other using the Relative Approach analysis with identical settings, as depicted in Fig. 4.

Comparing the two recordings, the tones under 1000 Hz can be distinguished from background noise by observing how clearly their duration stands out against background noise (straight blue and pink bars against a dark background). The analysis shows that the perception of sound from each hill seems to be very similar (repeated recordings will be needed to confirm the observation). Noting this, a new query was introduced that compared the inverse: what does the tones file played at point 1 sound like from position A and B? Fig. 5 depicts the corresponding spectrograms.

What is immediately apparent from Fig. 5 is how much stronger and clearer the tones file is perceived on the hills when played on the hippodrome surface (note that the color range for cp/cPa is identical between Figs. 4 and 5). Seven of the eight tones are clearly distinguishable against all background sound. Spot measurements taken at the points indicated in Figs. 4 and 5 give a more specific indication of the perceptual difference: the beginning of the 5th tone is heard at 40 cPa on the hippodrome but is heard at 95 cPa at point B.

In this example, field observations highlighted two different hills that were known as good places to speak from; archaeologists have used them to help communicate across the site when their walkie-talkie batteries have run low. Before employing psychoacoustic analyses, there was no way to compare how well one could be heard from each hill compared to the other; furthermore, it was not possible to conclude that sound could be better heard on the hills than on the hippodrome because too much time would elapse between listening in one position and moving to the other to repeat the experiment. Average human hearing is comparative but only within a short timeframe; we do not possess an absolute scale against which we calibrate our impressions (Genuit 1996), and the specific impression from one hill would be lost while walking to the other. The Relative Approach analysis factors these inherent functional dynamics into its calculations to depict an aurally-accurate representation of perceived acoustic quality.

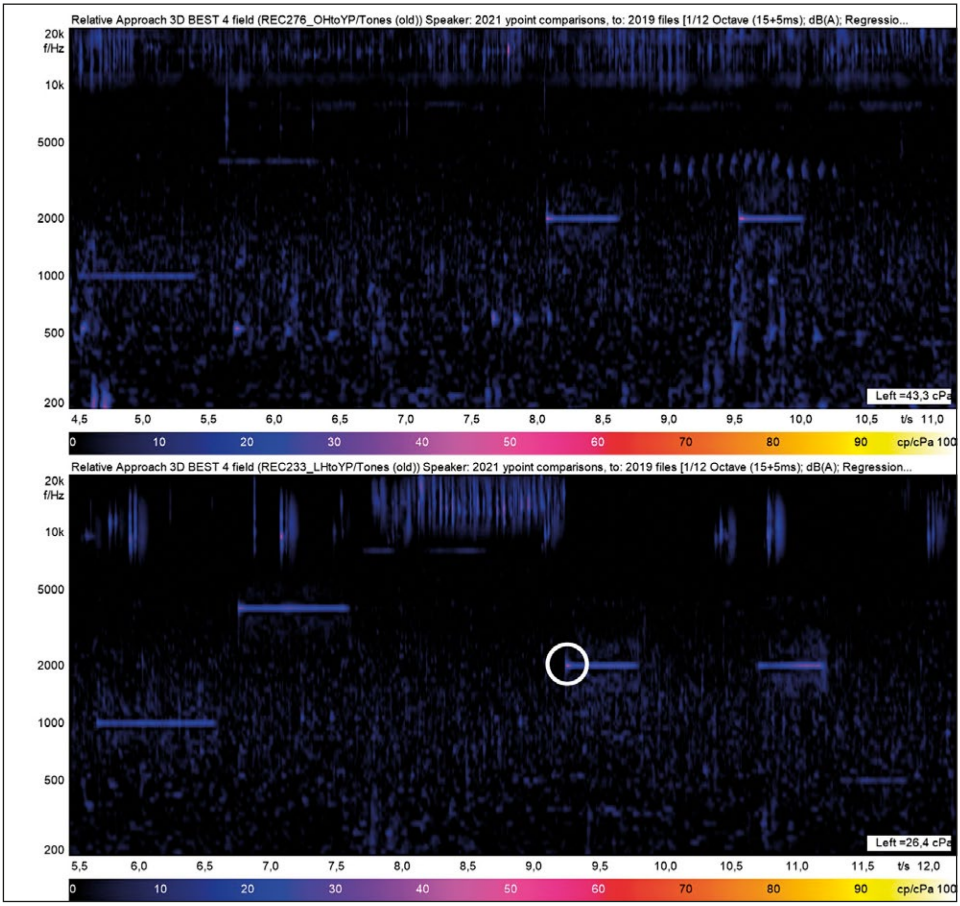

Fig. 4 – Relative Approach analyses of 1A (above) and 1B (below) recordings of the tones file projected from A and B respectively. The white circle indicates where a spot measurement was taken.

As a result, the data collected so far indicate that both hills (in the areas studied) would have made good positions from which to hear *and* see activities on the hippodrome, while those on the hippodrome might only perceive the louder activities taking place on the hillsides. This observation begins to give form to possible ancient site organization according to sound by demonstrating where the 'best' positions for spectating could have been and offering that sounds within lower frequency ranges could be better heard on the hippodrome. Does this offer insight into what sounds a crowd might have directed towards athletes or each other? Further study could identify where the relationship of hippodrome to surrounding hillsides are more evenly

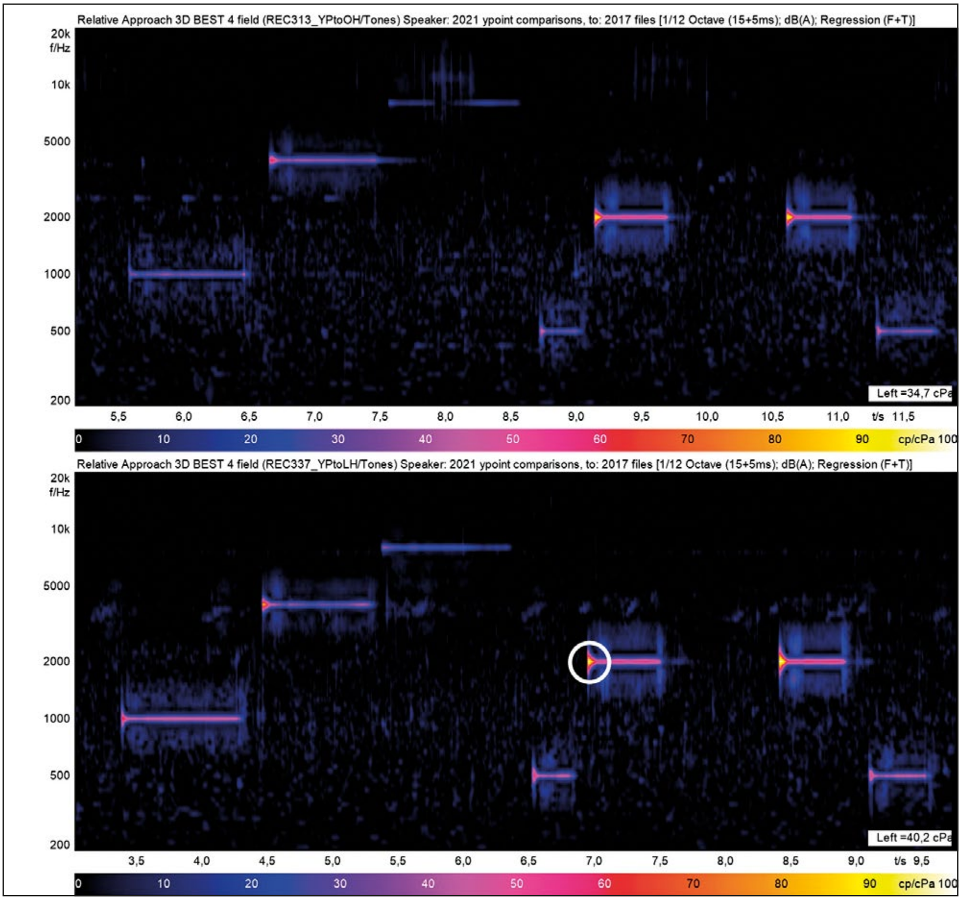

Fig. 5 – Relative Approach analyses of 1A (above) and 1B (below) recordings of the tones file projected from point 1. The white circle indicates where a spot measurement was taken.

mirrored acoustically, allowing for a dynamic exchange and participation in ritual activity between athletes and spectators.

4.3 *Sample analysis. Connectivity between a central point and two site features*

Another example can demonstrate the power of comparing specific measurements from analyses that might be more familiar. In this example, a central position within the lower sanctuary had been previously identified as a possible area for wrestling competitions, given its adjacency to the only structure thought to be for seating (see point 2 in Fig. 6 near the "Seats").

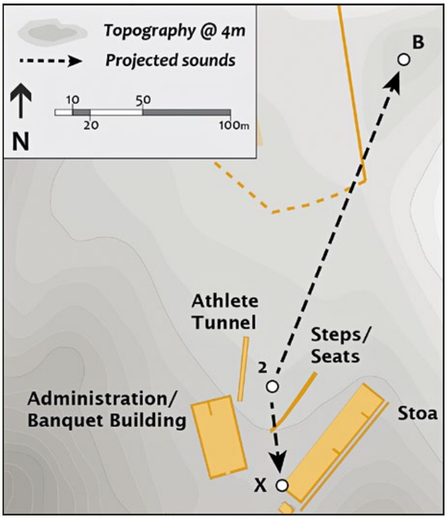

Fig. 6 – Partial site plan showing the central study position (2) and the recording positions on a hill (B) and the front of the stoa (X) used to determine inter-feature sonic connectivity. Point B is the same hill position depicted in Fig. 2.

A larger recording campaign was carried out to understand where sound projected from point 2 could be discerned throughout the lower sanctuary. Vast sonic connectivity would have rendered point 2 a potentially important component to overall sensory experience; limited connectivity would indicate that its role might have been more localized to immediate structures such as the Seats. Analyses examined the A-weighted dB SPL readings, perceived loudness (sone), and Relative Approach measurements (cp/cPa). The tones file from the previous example was examined; spot measurements were taken at the same instant across recordings for precise comparisons at the maximum reading of the individual tone and the mid-point of the tone (to account for variability and, in the case of the Relative Approach analysis, to account for adaptation over time). From the results, two positions stood out against what would be expected in an open field condition. For ease of discussion, results from the 996 Hz tone only are depicted in Tab. 1.

Noting the difference in distance between B and X to point 2, it is first surprising to note that the maximum and middle values of A-weighted dB SPL are relatively similar. On its own, this would suggest the unusual situation that sound is heard on the small hill almost as intensively as on the much closer western edge of the stoa. The perceived loudness calculation, which accounts much more specifically for human perception of loudness, shows

Projected from/to	Distance	Analysis	Tones Frequency Measurements (996 Hz)	
2 to B	160 m	FFT v Time (A-weighted dB SPL)	Max	8.98
			Mid	7.22
		Specific Loudness (soneGF/Bark)	Max	0.2651
			Mid	.2491
		Relative Approach (cp/cPa)	Max	42.18
			Mid	32.7
2 to X	56 m	FFT v Time (A-weighted dB SPL)	Max	12.76
			Mid	11.29
		Specific Loudness (soneGF/Bark)	Max	0.2124
			Mid	0.1931
		Relative Approach (cp/cPa)	Max	20.72
			Mid	19.98

Tab. 1 – Measurements and analysis of 996 Hz tones from field recordings, with dB and Relative Approach results highlighted at the small hill and western edge of the stoa.

that the sound reaching the small hill is actually louder than that reaching the western stoa, raising the possibility of an aspect of sonic accentuation at work on the way to the small hill. The Relative Approach analysis makes the difference even more apparent and depicts an entirely different experiential reality: the 996 Hz tones are heard with far more intensity on the small hill than the western stoa. The hill is three times farther away than the stoa and is hidden from view by a mature grove of walnut trees, while the western edge of the stoa is easily visible from point 2.

This example demonstrates that sightlines do not necessarily coincide with soundlines. There could be many contributing factors for why physical and acoustical proximity do not coincide in this case, but such a decisive divergence calls for repeated measurements. So far, it suggests that portions of the landscape may be more sonically present within the lower sanctuary core than between adjacent buildings. The zones of sonic participation, which could have enabled certain activities, provided privileged access, or demarcated private versus public activity, may not have been determined by the built structures or visual pathways alone. In fact, psychoacoustic study may be the best way to identify such zones.

This type of discovery underscores just how valuable psychoacoustic investigations can be in a complex outdoor environment. The measured dB level alone, even though A-weighted for human sensitivities, cannot describe emplaced human experience. Adding psychoacoustic investigation to studies of Mount Lykaion provides comparative evidence to substantiate the perceptive similarities and relationship potentials between landscape and architectural feature. These spaces are remarkably experientially connected and could have been in antiquity as well; activities at these locations could have been coordinated, directed, presided over and otherwise bound by sound, even without corresponding visual links or large architectural constructions providing hard surfaces for sound reflection. The findings can serve as the starting point for more detailed sound explorations and archaeological fieldwork in and between these areas.

5. Discussion

A number of challenges are encountered by the study of an ancient soundscape via a present one. Perhaps the biggest challenge on Mount Lykaion is that the landscape is the only artifact left to study directly – the architecture is mostly gone, plant growth patterns have changed, and the typical ancient practices and sonic participants are unknown. Yet enough of the landscape and historical references remain to act as entry-points into the experience of the ancient past. Together they provide a unique opportunity both to investigate what the site could have sounded like before the stone buildings were built and to determine if the buildings were purposefully placed to take advantage of latent acoustics in the landscape. The acoustic sophistication of contemporaneous theaters (designed for 20,000 spectators in the case of the Megalopolis theater in the adjacent valley) suggests that local builders knew how to harness acoustic properties towards public gathering. And without any evident construction for the approximately 200 years of games practices before monumental architecture was introduced, sonic study on Mount Lykaion may be the most direct way to research the early phase of the lower sanctuary and its use (Jordan 2020). Ongoing psychoacoustic analysis akin to the examples presented above are currently underway to examine connections between site and architecture in this manner.

Site-based research is an important first step to uncover what dynamics are present and what sound-facilitated relationships are possible. It does not factor in the influence of crowds, specific sound-based activities, or the influence of cultural or personal expectations; these are interpretive layers that must be added later to understand the full human experience. For this reason, effort has been made to make recordings that are robust in the information they gather and the research uses they can be put towards in the future. Yet despite the sophistication of the recording equipment and analysis software at this moment, the technologies are still under development. Debate between psychoacoustians continues as to how to apply them and what their results signify, and the field of psychoacoustics has a history derived from military development that should not be forgotten (Yost 2015; Ouzounian 2020). Psychoacoustic data can only offer conclusions based on the present moment in time in terms of understanding, especially in an outdoor context that attempts to transcend such a distant past. This is particularly true for newer metrics such as the Relative Approach analysis, but also for applications such as impulse response tests and speech clarity analyses that were developed and standardized for indoor applications.

6. Conclusion

Mount Lykaion presents a unique set of circumstances: few details about the ritual or daily practices that developed over many hundreds of years of use; evidence of a unified site plan implemented in antiquity; deteriorated architectural remains with still identifiable footprints; landforms that are greatly intact since before monumental architecture was introduced; sonic isolation from modern sound sources; and noticeably unusual acoustic properties. The application of psychoacoustics enables a comparative study of the current acoustic environment according to how people perceive it.

Psychoacoustics comes to archaeological investigation via more contemporary soundscape studies. Its introduction to historic investigations helps to bridge observations of sound behavior in a space with the way humans have found these behaviors to be meaningful through time. Between these two realms of understanding lies the consistent way humans receive and process sound, and tracing the dynamics of human sound experience can help to investigate what conditions in the past could facilitate sound-dependent activities – as they do today. Sonically meaningful spaces were not limited to theaters or public squares – Mount Lykaion was a place of such ritual interactions and meanings. It is emblematic of the need to find new ways of approaching archaeological sites as forms made to facilitate dynamic, sounded, meaningful activities.

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ABSTRACT

Research on ancient sensory experience has questioned ocular-centric research as the primary form of knowledge production in archaeological investigations. With enough information about the material composition of an ancient building, the acoustic properties of the interior spaces can be modeled for greater understanding of the daily experience of past users. Acoustics can reveal what people heard in the past, an experiential starting point to begin asking how someone heard in the past. Thus, acoustic study of place offers the potential to deepen understanding of the emplaced past experience as well as limitations to what conclusions can be drawn directly from gathered data. One area that remains underdeveloped is the research of sounded experience in ancient outdoor settings. This paper presents ongoing acoustic research at the ancient Greek sanctuary to Zeus on Mount Lykaion, applying psychoacoustic analysis to comprehensive recording efforts. Moments of sonic connectivity and isolation in this mountainous site align with past building outlines and prominent landscape features, suggesting that the sanctuary landscape likely played a key role in ritual experiences. The sonic dynamics of the landscape can still be experienced – and measured – today. The paper details the current approach to data collection and analysis on the mountain and includes some of the challenges afforded by applying acoustic study in the ancient built landscape.

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BEING A SPECTATOR IN A ROMAN THEATRE: A VR APP

1. Archaeology, auralisation, and digital applications

In the last years, studies and digital applications involving both archaeology and auralisation have increased but they are still uncommon, above all in the archaeological field. Here, our interest is to summarize a few of these works to discuss the success of such a combination, but also to highlight what can be done more to fully take advantage of this interdisciplinary approach.

The auralisation consists of the convolution of an anechoic file with an impulse response recorded in a specific position of a given space by a receiver. The result of the auralisation is an audio file that sounds as if it would be physically recorded in the specific space at the specific spot where the receiver recorded the impulse response. Thanks to 3D modelling and virtual acoustics, it is possible to obtain auralised files also of not preserved, or partially preserved, sites. In addition, the recreated sounds can be integrated with visual reconstructions and other information through virtual reality and augmented reality.

The project Archeoechi has been carried out by a team of scholars specialised in several disciplines (archaeologists, acousticians, actors and 3D experts), by the collaboration of the Department of Humanities of the University of Foggia and the AudioLab of the University of York. The project sees the development of a virtual reality application that offers an immersive experience within a Medieval cathedral in Southern Italy (Montecorvino, Puglia). The result is a fascinating educational instrument through which users, employing the head-mounted display Oculus Go, can explore the 3D reconstruction (which is based on information obtained from archaeological excavations and by analogies) of the cathedral not fully preserved. Users can interact with it, read descriptive panels and listening to a couple of auralised files as if they were at the centre of the church, back in the Middle Ages. One of the authors of the project stresses as the educational impact is higher when immersive applications take into account audio as well (Grazioli 2020).

A different digital application, for touristic promotion, has been developed by the University of Split (Croatia). It consists of a mobile audio augmented reality tool for soundscape auralisation of ancient archaeological sites, called Soundscaper. Different kind of auralised audios have been tested along Split's promenade to realize the correct audio augmented system by the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (Sikora, Đana, Russo 2016). Subsequently, the developed system has been used and tested within an archaeological site whose soundscape was recreated.

A group of students visited the archaeological site of Crkvina (9th c. basilica dedicated to St. Mary and St. Stephen), accompanied by the audio augmented reality equipment that simulates sounds that, hypothetically, populated the site at Medieval times. Through a qualitative and subjective questionnaire, the scholars have demonstrated that it is preferable an augmented audio experience while visiting archaeological sites (Sikora *et al.* 2018). Despite the tool developed is probably a very good and user-friendly instrument to attract visitors, the archaeological aspect is a bit neglected. The experience of the visitors would be culturally enriched if there would be a historical study of the many possible medieval sounds of the specific landscape. Moreover, to deliver something realistic, the auralised sound should be listened to in a reconstructed environment, as similar as possible to the original aspect of the site. This audio augmented reality tool would be much more valuable if it would not limit itself only to a walk with pleasant background sound. Hopefully, archaeologists will take the best from it.

Another project which involves sounds related to a religious archaeological site is the Virtual Paul's Cross Project. The multidisciplinary team aimed to produce a digital re-creation of John Donne's gunpowder day sermon, that occurred on 5th November 1622, to investigate the acoustic phenomena and the communicative power in the area of St. Paul's Cathedral in London, in the early modern age. This work is very well structured and has produced fascinating results. The area surrounding the cathedral has been virtually reconstructed with great accuracy, on the base of several old images as paintings and drawings. At the same time, the speech of John Donne and the entire soundfield (crowd murmur, church's bells, dog barking, birds twitters, horses) has been auralised (Azevedo, Markham, Wall 2013). On the website where the full project is presented (https://vpcp.chass.ncsu.edu/), the user can choose 8 different positions within the churchyard from which to see the reconstructed surrounding area of the church and listen to the sermon accompanied by different soundscapes.

One of the archaeological sites that is quite intriguing from an acoustics perspective is Stonehenge. Many scholars still wonder which was the function of such site: the most widespread hypothesis is that it would have been employed for ritual and ceremonial purposes, therefore the interest to study and reconstruct the soundfield a Neolithic man used to listen to (Fazenda 2013; Fazenda, Drumm 2013). The last acoustic researches about Stonehenge took advantage of 3D modelling and the real reconstruction of the site at Maryhill (Washington, USA) since it is not completely preserved nowadays. The approach to the study of the acoustics of Stonehenge and its auralisation is more advanced than simply knowing the acoustics characteristic of the place or experiencing a ceremony at Neolithic time. In this case, scholars think to acoustics and auralisation as instruments for archaeological interpretations and to raise new questions: was the circles of stones build to valorise the acoustic aspect of the rituals? What kind of knowledge the Neolithic man had about acoustic phenomena?

The auralised files are contained in the interactive Soundgate app (http://www.emaproject.eu/content/soundgate-app.html). It shows the hypothetical reconstructions of the site at different times and it allows to listen to the auralised sound of an ancient bird bone flute which was found nearby. The night visualization of the reconstruction of Stonehenge is accompanied by the sound produced by different birds, owl, nightingale and corncrake.

This is only a short list of digital applications related to both auralisation and archaeology, but there are not many more, unfortunately.

Even by this short list, a couple of characteristics are evident: the auralisation in archaeology is chiefly used to offer experiences; the most popular sites for auralisation are churches (among the cited ones, we can mention also Agia Sophia in Istanbul (Pentcheva, Abel 2017) and San Vitale in Ravenna (Knight, Tronchin 2020), in the context of the contemporary pandemic known as the plague of Justinian. The ordered sequence of reverberant aural encounters at San Vitale is posited as a method of spiritual and physical cleansing. The original metrical verse in the atrium of San Vitale refers to the church as an arcem (stronghold, for instance). The case study of Stonehenge is interesting since it differs from the majority, not only because of the typology of the site but because the aim is to investigate through auralisation the Neolithic society which used to have activities in that space. Archaeology could benefit from the implementation of the auralisation if we start considering the latter as an interpretative instrument. We can inspect the results of the auralisation from a different point of view: was the acoustics of that space good according to subjective perception? Was the people who built it aware of the architectural rules for good acoustics? Did the sound there evoke specific emotions or feelings? Did the acoustics have a particular meaning, or role, at a specific time or place?

The importance of the role of auralisation in archaeological contexts may be strengthened if more archaeologists would be involved and interested in such researches. As we can see from the short literature review presented, the majority of the studies about this topic have been published by journals of acoustics scope and none by archaeological journals.

2. VR app "Roman Theatres"

Ancient theatres have been quite well investigated from an acoustic perspective but, mainly, such kind of studies focus on the acoustic characteristics of these ancient buildings and less on the recreation of typical sounds of those spaces. Moreover, such kind of researches remains in the academic field, available and comprehensible only to specialists, without any involvement of or communication to the general public. An exception is the investigation of the acoustics of the ancient theatre of Paphos (Cyprus), which has combined acoustic measurements, auralisation and digital application (Till 2019). Through Soundgate application (already mentioned before) the user can visualize the 3D reconstruction of the Roman phase of the theatre and listen to several auralised files: waves, local birds and two Roman musical instruments played directly by the user.

The research presented in this paper is the final step of a wider PhD study finished in 2018 (Manzetti 2018). It sees the development of a virtual application for Oculus Rift, which enables the user to explore the 3D reconstruction of six Roman theatres located in Crete and, at the same time, to listen the auralisation of an ancient performance from different seats. The VR application can be downloaded at http://romantheatres.ims.forth.gr (created by Aris Kidonakis). The main aim of this VR application, developed through Unity, is to virtually bring back to life these ancient theatres and to experience the feeling of being a spectator in the past Roman times.

The VR application has been created through four main steps:

1. 3D modelling and texturing of six of the Roman theatres of Crete (the theatre of Aptera, the theatre of Hersonissos, the theatre on the acropolis of Gortyna, the theatre of the Pythion at Gortyna, the theatre at Kazinedes at Gortyna and the theatre of Koufonissi);
2. Auralisation of an anechoic file from several seats spread in the cavea of the 3D models of the six theatres;
3. Creation of icons and informative panels for each theatre;
4. Development of the VR application through Unity3D, a cross-platform game engine.

2.1 *Step 1*

The 3D models have been created after having collected and studied the available documents about their architectural structure. The virtual reconstructions of these theatres are the result of several analyses and interpretations of the data acquired: comparisons with other Roman theatres in Rome and all the Empire, description of the architecture of the Roman theatres by Vitruvius, overlapping of aerial pictures with ancient plans and geophysical maps, 3D visibility analysis and virtual acoustics analysis (Manzetti, Parthenios 2018).

3D Studio Max 2016 is the software used to realize and texturize the 3D models. The materials applied to the surfaces of the objects composing the 3D models are Mental Ray materials and consequently, the renderer has been set on NVIDIA mental ray. Mental Ray materials have been preferred to others because they offer sets of materials specific for architectural rendering (as Arch&Design Material) and a kit with pre-set characteristics for some materials, like stone and hardwood, which are present in the reconstructions of ancient theatres. Furthermore, the Mental Ray renderer eases the procedure of lightening of the scene, generating "correct simulation of lightening effects". Being an outdoor scene, the daylight system has been used in all the 3D reconstructions of the theatres, setting the real latitude, longitude and northern direction of the position of each theatre. To create a more faithful reconstruction, the terrain in its real shape has been used along with the 3D models of the theatres. Unity is a real-time engine and to maintain the characteristics set through the choice of the materials plus lightening and shadows in 3D Studio Max, the baking texture option has been chosen. Thanks to a texture procedure, it is possible to record in one image all the characteristics of the procedural texture applied to the object, which means it records the effects of the light on the object, the reflections coming from other objects and all the characteristics of the material set for that texture. After having mapped again the new images on the 3D models, they have been exported as .fbx, to easily import them in Unity.

2.2 *Step 2*

The auralisation was performed through the software Odeon Room Acoustics. For each theatre few audio files, from five to eight (depending on the size of the building), have been auralised for different positions of the cavea.

The anechoic file has been recorded in the laboratory of the Institute of Acoustics and Sensors "Mario Corbino" at the CNR of Rome Tor Vergata, with the collaboration of Dr Paola Calicchia, Dr Cristina Pace and Martina Giovanetti. The latter is a student of Classical Philology at the University of Rome Tor Vergata and she played a monologue in ancient Greek from the work "The Trojan Women" by Euripides, which has been recorded in the anechoic room of the above-mentioned laboratory. The recorded file, which is about four minutes long, has been imported in the project of each theatre in Odeon Room Acoustics and it has been automatically convolved with the impulse response recorded by the receivers placed in the cavea. Simplifying, the impulse response contains the information about the acoustic characteristics of the building (which depend on its architecture) and this is the reason why through the auralisation it is possible to create an audio file that corresponds to the real sound in a specific position of a building.

The auralised files of each theatre have been imported in Unity, so that the user can better experience the feeling of presence and, thanks to the possibility to compare various theatres, the user can also understand the influence that the architecture has on the sound. The VR application enables the user to select one of the seats of the cavea from the centre of the orchestra. He/she will automatically move to the chosen position and will start listening to the auralised file. Then the user can select another seat to move again and listen to the audio file from another position.

2.3 *Step 3*

In order to create a more instructive and educational application, some informative panels have been added for each theatre. Information includes the history and the characteristics of the theatre, its location, pictures, drawings, and details. Each category of panels is represented by an icon and when it is selected it shows the corresponding panels. The book icon is related to the panels about the history and the characteristics of the theatre. They are text panels and they contain very brief information about the state of the art of the monument (who discovered it, when and who documented it, etc.), its architectural structures (the number of sectors in the cavea, the number of seats, etc.), its state of preservation and other typical features. The images icon is connected to panels showing pictures of the theatre, ancient and new plans plus sections, and aerial images. The icon representing the top view of a theatre is related to the drawings panels, which means the plan, the section and the representation of the hypothetical reconstruction of the theatre. The location icon is connected to a panel embedding a video realized through the tool Movie Maker in Google Earth Pro, which shows the full island of Crete from above and then zooms in till the exact area where the remains of the theatre are placed.

The details icon shows a panel about the reliability and accuracy of the 3D reconstruction of the theatre. Three images in the central part of the panel indicate three different sectors of the theatre: cavea, scene and *parodoi*. On the left side of the images, the instruments used to study the theatre and helpful for the formulation of the hypothesis about its architectural structure are listed: archaeological excavations, written sources, ancient plans, aerial pictures, geophysical maps, 3D visibility analysis, and virtual acoustics analysis. On the right side of the panel, the words "reliable, possible and hypothetical" suggest the accuracy of the 3D reconstruction for each sector of the theatre. Accuracy is one of the principles listed in the Seville Charter (Lopez-Menchero Bendicho 2013) and it is fundamental to explain that the presented reconstruction is not the only possible. When we are dealing with destroyed buildings we can never be sure about their original structure, but some clues (as archaeological remains) bring us closer to reality and some others can be useful only to assume the real aspect of a building. It must be explicitly clear if the 3D reconstruction is based on reliable data and if it is an exact reconstruction rather than a conjecture based on information but without material evidence. This is fundamental if we want to have a scientific approach and if we want to disseminate culture rather than only attractive 3D models.

2.4 *Step 4*

The VR application of the Roman theatres of Crete has been developed through the cross-platform game engine Unity3D (its programming language is based on C#) for Oculus device.

The reasons to opt for Unity instead of other game engines are several. First of all, it is an open-source software that has many functionalities and often does not need any external plug-in since it has numerous libraries embedded. The second main advantage is that it can export to many platforms, more than 25 across mobile, desktop, console, TV, VR, AR and Web. In addition, Unity3D has an asset store from where many packages can be downloaded for free too; it is constantly updated with the latest techniques and tools developed; it allows you to distribute your applications for non-commercial reasons without any fee. Being a VR application, the best device to use is a head-mounted display that allows you to have a 360° view, which enhances the feeling of presence in the virtual world and the sensation to physically live the virtual experience. In addition, some of the head-mounted displays enable the user to easily interact with the objects in the virtual world.

Oculus Rift is the device that has been chosen to be used for the VR application of the Roman theatres in Crete. Oculus Rift has been preferred to the cheaper Google Cardboard for two main reasons: the better quality (the screen resolutions and the quality of the lenses) and its functionalities (the orientation tracking, the gyroscope, the accelerometer and the magnetometer).

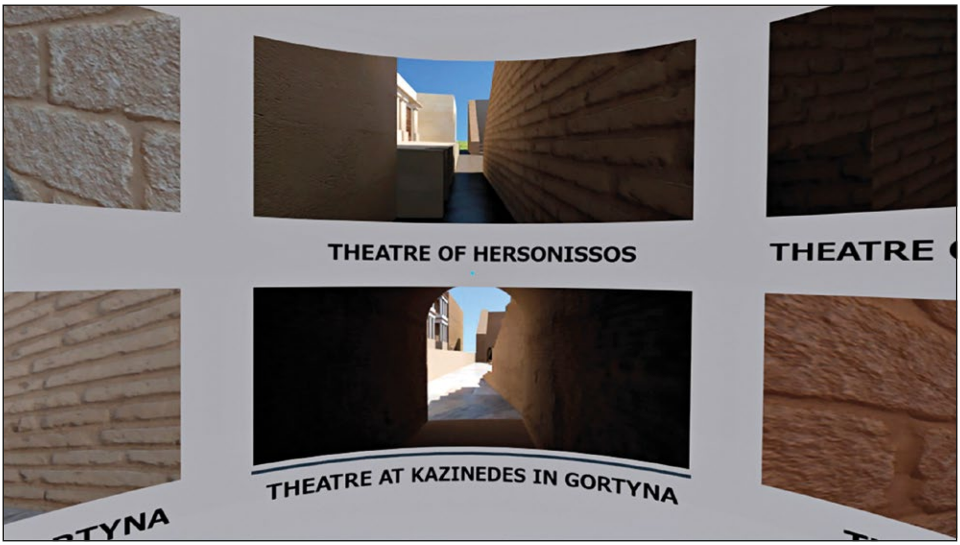

Fig. 1 – Main menu of the VR application of the Roman theatres of Crete.

Fig. 2 – Icons in the theatre of Kazinedes, at Gortyna, in the VR application.

Fig. 3 – Seat selection in the theatre of Kazinedes at Gortyna through the VR application.

Samsung Gear as well is very convenient because it has functionalities too and it has the advantage to be portable, but the quality depends on the graphic card of the mobile used along with it. However, once an application has been built in Unity for Oculus Rift, it can be easily exported for Samsung Gear as well, without any further modifications.

Fig. 4 – View of the stage from one of the seats of the theatre of Kazinedes at Gortyna in the VR application.

The VR application includes six of the Roman theatres of Crete (Fig. 1). The main menu shows six panels with the name of each theatre and with an image of its 3D model.

Once the user targets the name of the theatre he/she wants to explore, after three seconds the user will automatically enter the selected theatre and he/she will be in the orchestra facing the stage and the scene building. In this position, the five icons (book, images, drawings, location and details) are visible and they can be selected (Fig. 2).

If the user looks around, he/she will see several icons representing two theatrical masks, used to indicate the seats of the cavea, that can be selected. Targeting one of the couple of masks, the user will automatically move to the position occupied by the icon from where he/she can look at the stage, and at the same time listen to the auralised file (Fig. 3). Moving across the different positions indicated by the masks, the user will be able to appreciate the diverse acoustics according to the distance from the source and to the architectural characteristics of the space (Fig. 4).

During the creation of the VR application, some issues arose. One of the main issues concerned the size of the application: several scenarios (six different 3D models of theatres accompanied by the correspondent terrains) are contained in the Unity project plus videos, audios and images for each one of them. The application is consequently very heavy in terms of volume size. In order not to burden it even more, some modifications have been made, as decreasing the quality and the length of the videos and removing trees from the 3D models. The second issue noticed is that the visualization through Oculus is not optimal: it is not completely clear, the pixels and the grid between the pixels are visible, producing the so-called "screendoor effect" (the Oculus version used during this research is the development kit 2). This feature makes it harder to focus on details, therefore also reading texts might be annoying through Oculus.

The next step to improve the VR application dedicated to experiencing and knowing the Roman theatres of Crete, will be to create an evaluation test about the ease of use, the ease to learn from the application, the level of entertainment, the level of comfort in using Oculus. The questionnaire will be presented to people of various age, various type of education, and various cultures.

Once the VR application about the Roman theatres in Crete will be improved and enhanced, it would be interesting and attractive to use it directly in the involved archaeological sites. The 3D models along with a VR application facilitates the learning process so that visiting an archaeological site is going to become both an educational and exciting experience. Such a formative experience will motivate a larger part of the society to visit archaeological sites and museums, facilitating the economic and scientific growth of these cultural institutions.

3. Conclusion

This paper briefly shows the current relationship among archaeology, auralisation and digital applications plus a new approach and a new VR application that exhibits the fruitful combination of the above-mentioned different disciplines.

The cooperation of such disciplines is offering a unique experience for visitors of museums and archaeological sites. Such kind of experiences can be a powerful instrument to attract society towards culture and history with the resulting educational enhancement of people. This aspect is without any doubt important and specialists should improve the number of similar products addressed to the general public. However, this is not the only advantage of combining archaeology, auralisation and digital media, and unfortunately, other meaningful aspects are still a bit neglected.

Auralisation should be considered a real technique to apply in many archaeological contexts and not only churches or ritual spaces. The research about acoustics in ancient theatres can be expanded with a deeper archaeological focus: what kind of performances used to take place? Which were the subjective perceptions and the feelings theatrical performances used to evoke? Did ancient theatres have different acoustic quality according to the cultural and technical knowledge of the place? In addition, more sites should be considered as Roman basilicas where the emperors used to communicate with people, ancient courts, *mausoleum* and other funerary spaces, battlefields, prehistoric settlements, with subsequently other questions as: did ancient people use sounds to provoke specific emotions in the in individuals?

The study of acoustics and the auralisation of such places will highlight new insight into past civilizations. Planning a standard methodology for the auralisation of ancient spaces would provide a rigorous approach that would assure consistent and meaningful results. In order to achieve important archaeological information from auralisation, scholars from different disciplines must cooperate at the same level and towards the same directions to answer punctual research questions. Among the specialists, beyond archaeologists, historians, acousticians, actors, experts of psychoacoustics are also indispensable. The combination of psychoacoustics and archaeology would determine a phenomenological approach able to investigate the perceptions of past societies in specific contexts or events.

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ABSTRACT

This paper aims to present the advantages of including auralisation techniques in archaeology. Archaeology can benefit from auralisation under several aspects. Not only does it offer the possibility to live a unique experience listening sounds originated within ancient buildings, but it allows to formulate subjective interpretations of the quality of the audio of a specific space. In addition, the subjective feeling evoked by the auralised audio can be further investigated through psychoacoustics analysis. The combination of archaeology and auralisation is also attractive for the general public thanks to digital applications that can be employed for educational purposes. The involvement of society through digital applications is important to bring it near to research and archaeology. After a short literature review about the implementation of archaeology, auralisation and digital applications, the final elaboration of a PhD research will be presented: the development of a virtual reality app that shows the 3D reconstruction of six Roman theatres in Crete, including the virtual auralisation from different seats within the theatres. The VR app is the ultimate product of a research that studied hypothetical reconstructions of the Roman theatres in Crete through 3D visibility analysis and virtual acoustics analysis. Through the VR app, users will not only experience an ancient performance in different Roman theatres, but they will also be able to observe the influence of architecture on the sound.

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NOT ONLY PAPER: COMPUTER ENGINEERING TO CONTRAST THE ECLIPSE OF THE AUDIO DOCUMENTS. THE CASE STUDY OF A PERSONAL ARCHIVE

1. Introduction

The introduction of electronic and information technology into art gave rise to new challenges for archives and for the preservation of cultural heritage. If technology has been a stimulus to new forms of artistic creation, at the same time it also becomes the cause of their rapid deterioration and an ever shorter life expectancy. Their great dependence on technology makes them particularly vulnerable and there is a serious risk of losing an important part of today's culture. Music, also due to its immaterial nature, was one of the earliest types of art to explore the creative use of new technologies: new musical forms have assumed an increasingly artistic importance since the second half of the last century (Bressan, Canazza 2014).

The conservation of this heritage presents very different problems from those posed by traditional artworks. To safeguard this heritage, it is not enough to digitize the content of recordings and documents, but the performance practice must also be preserved. That is, it is necessary to preserve all the elements that allow us to understand and reconstruct the set of production processes of the work, from the specific details of the composition to the technological system and the operating practices used (Pretto *et al.* 2018).

Notice that the performative or behavioral aspect is rarely documented in detail, and when it is, the documentation refers to the technology of the time in which the work was produced. Often only the author's notes and annotations in his personal archive are available. Therefore, every effort must be made to keep and make accessible all information relating to the work, the equipment used and the performance practice. To this purpose it is very important to properly address the problems of personal archives preservation and access (Orio *et al.* 2009).

This paper is organized as follows: the first part discusses the main issues for the conservation of audio documents; then it presents a well-tuned *re-mediation* methodology, an artificial intelligence based approach to detect audio tape *discontinuities* and finally access tools for renovating the listening experience of old analogue media. The second part first discusses the issues for personal archive preservation in the digital age, focusing on archive content and inventory description and detailing how audio documents should be preserved. Then we present, as a case study, the design and development of an information management system allowing the long-time preservation and the access to different documents, among them: audio, letters, musical scores, and manuscripts. Finally we draw some concluding remarks and give directions for further work.

2. Computer engineering and audio documents

Many documents are in the analog domain (e.g., paper, magnetic tapes, phonographic discs, film). These must be transferred in the digital domain, in other formats with different encoding (re-mediation), for public access (access copy) and long-term preservation (preservation master, stored in different copies and locations, locally and in the cloud).

The fifty years of experience gained at the Centro di Sonologia Computazionale (CSC) in music production has led to the definition of a scientific methodology of the audio documents active preservation (Fantozzi *et al.* 2017) based on two pillars: (a) the multidisciplinary nature of the team researchers involving engineers, musicians, musicologists, composers and archivists, and (b) the philological accuracy with which the digital tools developed preserve the history of the transmission of the audio document, thanks to the set of metadata and ancillary information included in the digital master conservation (Verde *et al.* 2018).

The original document active preservation phase must produce a digital conservation master that meets the requirements of reliability, accuracy and authenticity. An exhaustive documentation of the entire conservation process, including a description of any restorative interventions carried out on the original support, assumes particular importance in order to preserve the history of the transmission of the object under protection. In accordance with international provisions, the transfer process is divided into three phases: preparation of the support, transfer of the signal and processing of the collected data (Bressan, Canazza 2013). Each phase in turn includes many steps that involve different professional figures: archivists, chemists, composers, engineers, musicians, musicologists, audio technicians. The result is a multidisciplinary work whose success also depends on the dissemination and sharing of these practices among the archives.

Even before the analog/digital (A/D) transfer of the signal, complete photographic documentation must be collected to testify the conditions in which the material is concerned, and information on the support that would be lost with its future deterioration (any signs written on tape, size, etc.). The study of the degradation mechanisms of magnetic tapes is a wide and still open field that must take into account the chemical characteristics of each material (Bressan, Canazza 2015; Bressan *et al.* 2016). Equally complicated is the measure of a syndrome degree in a tape, some of which, such as Soft Binder Syndrome-Sticky Shed Syndrome (SBS-SSS), can only be diagnosed at the time of A/D transfer. Actions such as the visual inspection of the document and any recovery treatments, cannot be underestimated and must be entrusted to specialized personnel able to access appropriately equipped chemical laboratories. It is necessary to objectively describe the state of conservation and define a priority order of intervention before proceeding with the A/D transfer of the signal. The use of modern reproduction machines appropriately calibrated and compliant with the recording format of the document in question is recommended. In particular cases, such as the collections of electroacoustic music archives, it is advisable to combine the audio monitoring of the document with the video recording of the tape running on the player. The video will integrate the series of ancillary information that complete the digital conservation master and may be future object of study, leaving traces of any corruption or signs of processing present on the tape (which can be extraordinarily informative from the musicological point of view). Extracted data must be validated with appropriate software in order to ensure the authenticity of the document and help in the philological study of the document.

The preservation of audio documents has as its natural objective of allowing scholars and/or the general public to access the information stored. This phase cannot involve the preservation master, which must be left unaltered: appropriate access copies must therefore be created. Only the latter can be used by third parties and can be subject to digital restoration for concert purposes or for a commercial edition.

2.1 *Re-mediation*

The archives must (i) minimize the information loss with respect to the original document (audio information, metadata and contextual information), and (ii) keep track of the document provenance, of the re-mediation process (Fig. 1) and of the re-mediation system.

The preservation master includes: (i) a list of all the files contained in it, information on the origin of the original document, the data relating to each audio file, the location where the A/D transfer took place and the technician responsible for the transfer; (ii) the audio data at high resolution (96kHz/24bit); (iii) photographic documentation of the support, its case, box or envelope and accompanying material, and a technical sheet describing the transfer; (iv) video recording of the tape running on the player; (v) first level metadata: three types of audio data checksum; second level metadata: technical specifications of the file formats included in the preservation master (BWF/WAVE, pdf, ...).

2.2 *Artificial Intelligence for musical cultural heritage*

An initial visual inspection of the original (analogue) document by the technician may show the presence of several alterations of the carrier (tape,

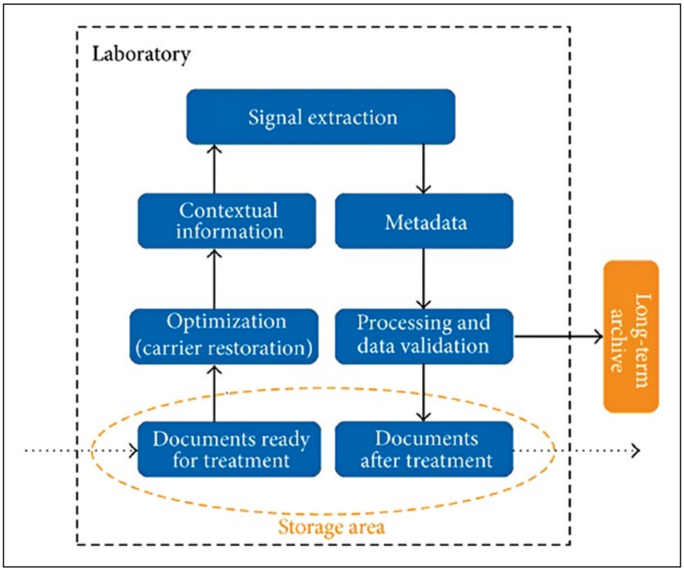

Fig. 1 – Scheme of the re-mediation process. Each step is articulated in procedures and sub-procedures.

film, paper) such as blocking, leafing, windowing, spoking, or embossing, fungi and molds. This first stage is essential to determine whether or not the carrier has to be restored prior to digitization. Nonetheless, some corruptions and other *discontinuities* can only be detected during the digitization process, after the visual inspection. Consequently, both these two stages become particularly important to evaluate the preservation condition of the document.

The term Point of Interest (POI) will be used henceforth to indicate all the carrier alterations (or discontinuity or irregularities) from its original manufacture state that are visually detectable. Although not strictly an alteration, manufacturers may print their brand name or logo on the carrier itself (on the back of the tape, on the box of the film, on the envelope of the paper). As necessary and useful information for the identification of the document, brand markings will also be considered a discontinuity.

All the POI included in the methodology defined at CSC during are listed below:

– L-M splices (*lmsp*). Splices of leader tape to magnetic tape (or vice versa).
– M-M splices (*mmsp*). Splices of magnetic tape to magnetic tape.
– Brands on tape (*b*). Most of the brands consist of the full name of the tape manufacturer, logo, or tape model codes. The brand changes in size, shape, and color, depending on the tape used, thus complicating the classification task.

Fig. 2 – Area of the tape recorder reading head.

– Ends of tape (eot). It refers to what happens when the tape reaches its end of playback, at which point it is neither under tension nor in contact with the capstan and pinch roller. The distinguishing visual characteristic of this class is the tape coming free – or completely detached – from the capstan.
– Damaged tape (*da*). It groups all kinds of damages on the surface of the tape and alterations of the tape shape. This class includes:
a) Ripples. This is formally known in the cataloguing rules as "kink" or "wrinkle," these may be a single crease on a layer of tape or multiple creases in the tape. This class groups all the alterations in the shape of the tape, such as cuppings and damages on tape edges.
b) Cupping. An abnormal flexure of the tape surface across or along its width, due to different rates of shrinkage along the substrate and recording layers.
c) Damage to tape edges. It occurs when the edges do not appear flat or straight.
– Dirt (*di*). Tape contamination and dirt: presence of mold, powder, crystals, other biological contaminations, or similar sullying.
– Marks (*m*). Signs or words written on the back of the tape (i.e., the non-magnetic side) or on the adhesive tape of splices. Similarly, the presence of ink or dye on the surface of the tape, or writings on the back seeping through the tape to the front, comprise the phenomenon of "bleeding".
– Shadows (*s*). The class contains frames in which shadows or reflections are temporarily cast on the tape by external objects in motion.

The *Video Analyzer* software developed at CSC aims to detect the significant frames from the digital video. The detection is focused on two areas. The first one is the reading head of the tape recorder (Fig. 2). The second one is under the pinch roller (Fig. 3). The *eot* and *s* irregularities are detected

Fig. 3 – Area under the pinch-roller.

Fig. 4 – A POI pop-up with a frame of a splice correctly detected. The technician in the digitizing lab can confirm or reject the correctness of the result.

evaluating the pinch roller change of position. The others are evaluated in the first area. Significant frames are extracted comparing consecutive frames. If there are important color changes between the two frames (Fig. 4) the last one is indicated as significant. The implementation is based on OpenCV libraries.

The CSC proposes an algorithm that classifies the images provided by the video analyzer using the neural network GoogLeNet, Keras libraries and TensorFlow.

A good data set for supervised training must be large enough to cover the different circumstances that may occur. In addition, class imbalance should be minimal: the number of elements in each class must be similar. Our data set was built from more than 100,000 documents obtained from a number of preservation projects carried out at CSC. Among others, the most representative are: Paul Sacher Stiftung Archive, Luciano Berio's collection (tape music, electronic music); Luigi Nono Archive, all collections (tape music, electronic music); Teatro Regio di Parma, all collections (opera, Western classical music, pop/rock); Tullia Magrini Archive (ethnomusic); Istituto per i Beni Artistici, Culturali e Naturali of the Region Emilia Romagna (ethnomusic, speech), Fondazione Giorgio Cini, Venezia. Pretto *et al.* (2020) describes the projects and summarizes results, reporting statistical data.

The accuracy measured is in the range of 70% to 100%, depending on the carrier and on the discontinuity. It is the first approach of this kind in the scientific literature, and the positive results prove its potential. To obtain a more reliable tool, however, a larger and more balanced data set of frames is required to train the convolutional networks. Moreover, further research can improve the detection rate and the classification quality.

2.3 *Preservation is nothing without access*

The access methodology is complementary to that of active preservation (see Section 2.1), sharing its ultimate goal: to obtain a copy as faithful as possible to the original. Fidelity must be assessed according to three distinct criteria: (a) the reproduction of the audio content, (b) the simulation of the original listening experience, and (c) the completeness of metadata and contextual ancillary information. The first criterion is mainly determined by three factors: number of tracks, playback speed and equalization. The first factor is essential as an analog magnetic tape can accommodate 1 to 24 different sound tracks. It is evident, for example, that a stereo CD-A player is not suitable for the reproduction of audio coming from the dubbing of a multitrack electroacoustic music tape, not allowing the acoustic projection of the different tracks independently. As for the second factor, it is not uncommon to find sections of the same tape recorded at different speeds. The methodology perfected at the CSC in Padua foresees the memorization in the conservation master of several digital copies of the tape reproduced at different reading speeds: also in this case the passage from one speed to another is far from easy using general purpose digital readers. It is even impossible with CD-A players. The reproduction speed is also closely linked to the equalizations: as the first one changes, the characteristics of the filtering curve also change. If this is not considered, the listening will no longer be faithful to the original document.

Since electroacoustic music on magnetic tape is strongly linked to the physical medium and the recording system, the virtual simulation of the peculiarities of the device and its use is a necessary step to satisfy the second criterion. Traditional access methods, such as the CD-A edition or listening through software jukeboxes, are inadequate to restore the listening experience of old analogue media, as they do not respect the characteristics of the original document, in addition to not providing adequate access methods to metadata and ancillary information. The reproductions of the appearance, of the commands (real-time modification of the speed and equalization) and of the moving parts of the tape recorder (running of the tape) are important to make the virtualization of the playback tool complete. CSC (Canazza, Fantozzi, Pretto 2015) has created various software for mobile devices and for web access to the most popular readers of analogue sound documents of the 20th c. (e.g., tape recorders, gramophones, turntables). An example is shown in Fig. 5. The main activity of REMIND app provides a skeuomorphic representation of the Studer A810-VUK 2-track audio recorder. The overall appearance of the tape recorder is virtualized with touch buttons (play, stop, fast forward, rewind and reset of the timer) and knobs (allowing to change replay speed and equalization). A video shooting, synchronized with the audio signal, of the original magnetic tape is shown. Several other features are represented, such as the movement of the tape with the rotation speed of each reel that is proportional to the amount of tape left in the reel and the timer. The user interface (UI) is implemented with a custom Java subclass of the

Fig. 5 – The main activity of REMIND app. A video of the original tape is shown outside the body of the tape recorder to improve its readability.

standard Android class View. Nearly all of the UI classes that appear in the main activity are custom: not only for the personalization of the appearance and behavior of the UI elements, but also to exploit hardware acceleration. The custom UI elements are 3D objects rendered into a Canvas allowing a consistently high frame rate for moving objects, and, at the same time minimizing the impact on the CPU. This choice also simplifies the scaling of the elements to support multiple display resolutions.

Looking ahead, these algorithms will be implemented online and will be able to virtually reproduce an analog player. Users will thus be able to benefit from access copies, free of charge or with subscription services, and these software applications will be useful in the musicological analysis.

3. The case-study of a personal archive

3.1 *Personal archives*

Personal archives represent a particular type of private archives whose characterizing and unifying element is the individual who produced them. This peculiarity makes them organic complexes, within which the individual parts acquire full meaning. All media – not only paper – are considered to be relevant sources as long as this relates to the life, memories and experiences of a person. The material is no longer exclusively of a written, photographic, audio or video nature; more and more new kinds of materials are present with specific conservation problems. The archives of certain professional categories can be peculiar for the type of material stored: for example, the architects' archives generally preserve, in addition to letters and other documents commonly found in private archives, materials such as drawings, sketches, tempera, collages and other materials referable to project drawings, as well as, in the most fortunate cases, collections of models. The musicians' archives store musical instruments and audio documents. The heterogeneity of the materials stored in the private archives requires particular care and a well-tuned scientific methodology.

Until a few decades ago, personal archives were not objects of archival interest: considered *different archives*, they aroused historical, historical-artistic, or literary attention for a particular preserved document. Personal archives as independent nuclei developed at the moment in which the greater awareness of each individual to be able to be an *artifex* of his own destiny and that his life experiences can be a potential source of historical and cultural interest. Traditionally, documents that are maintained by an organization vs. by an individual or a family have been considered distinct entities. Today's archivists recognize that both are bodies of interrelated materials that have been brought together because of their function or use. Archivists respect and seek to maintain the established relationships between individual items in records groups and in personal papers (Daniels 1984).

This recognized importance poses new challenges to the management and preservation of personal archives, which are often born without the long-term preservation aim. The heterogeneity of the materials stored, the peculiarities of each archive, the differences in the criteria and purposes of the individual, who produced the archive, requires a specific effort for the analysis, management, preservation and access of the archive content.

Many see the digital age as bringing an opportunity to leave an important legacy for future generations. During the past decade archives embraced digital technology to enhance user access and experiences and long-term preservation. The use of digital technologies encourages visitors to actively engage with the archive in a remote way. Due to the lower economic profitability compared to large archives, due to the lack of attention of national and international archival associations, due to the scarcity of funds, due to the difficulty, for a small archive, of getting to use archival/IT experts, and despite the archival/cultural importance of the documents in their possession, personal archives often have not yet adopted information technology. Existing systems are very often specific to the archive for which they were made. For instance, the database management systems included in http://www.archivi.beniculturali.it/ (Italy) and in http://www.archivesportaleurope.net/home (Europe) only allow to trace where a particular personal archive is kept, whose existence is already known; there is a lack of standardized tools for searching within archives.

The consolidated methodologies for institutional archives are not always sufficient to manage this new type of archives, with their peculiarities. It is therefore worth discussing the most appropriate methodologies. The methodology, in addition to considering the analysis of the content and the organization of the archive, must also oversee the design and development of the computer system for the management and the access to the archive, also in view of the evolution of information technology. Standardized tools must be provided for interoperability between different systems.

3.2 *Inventory description*

The term *fond* is often used in the Continental system to indicate the entire body of records of an organization, family, or individual that have been created and accumulated as the result of an organic process reflecting the functions of the creator (Pearce 2005). It should be viewed primarily as an *intellectual construct* and thus as the conceptual *whole* that reflects an accumulation process of the records which themselves exhibit a natural unity (Cook 2011).

Before addressing any description, a global examination of the fond, a sort of overview from above, is particularly indispensable for personal archives. These archives are generally devoid of repertoires but lacking in indications on the criteria adopted in the conservation of the papers. Dealing diligently with one document after another, neglecting the archival ensemble, its history and internal stratifications at various levels limits the correct historical-biographical placement of the papers, making the description incomplete, if not downright misleading. In all cases in which a personality has kept private documents accumulating them without apparent organization or directions, the archivist can and must try to immerse himself in the subject's working method through the traces that may have remained, then bringing him back to the organization of his papers. The archive should also keep track of the organization that the person had given himself.

Especially for personal archives, the inventory description must provide information both on the archival unit in question as well as on the producer subject and on the historical context, and at the same time make clear and explicit the relationships between the units and the complex they belong to. Librarian-economic descriptions, often managed through software designed for book cataloguing, which in the past were used for personal archives, present this main shortcoming: they do not sufficiently highlight the links between an archival unit and another. Often, the literary or artistic importance of individual documents preserved in personal archives, such as can be considered *artistic objects* even beyond the historical context in which they are located, requires an analytical description. The inventory structure proves to be the fundamental tool for a global vision of the archive. A specific search can then be very well supported by descriptions managed on a database, the more appreciable the more the computer tool is able to reproduce the complexity of the documents. Today there is a tendency to consider as *objects* archival documents that were once divided between archives, libraries and museums (books, photographs, prints, collections of postcards, ornaments, relics, medals). The information management system should allow the virtual recomposition of personal archives divided among several institutions, cities or countries. Alongside the classic juxtaposition of multiple inventories, it should be possible to achieve a real virtual integration of both descriptions and documents in digital form. Without forgetting, however, that the inventory description has a completely different purpose from digital reproduction: it is a *mediation tool* allowing the scholar to trace, define, identify, understand the document, where digital reproduction is the very useful and perfect copy of the original document.

4. Case-study: electronic music

4.1 *Luigi Nono and Luigi Nono Archive*

Among the various activities that CSC is carrying out (Canazza, De Poli 2019), the personal archive of the Luigi Nono Archive Foundation (ALN) is an important case-study, because both the interest raised by the Archive at the musicological and cultural level, and the heterogeneity of the materials contained, but also because Luigi Nono worked at the CSC in 1984 to create the computer part of his last opera *Prometeo-Tragedia dell'ascolto* (1984-85).

Musical language of Luigi Nono (Venice, January 29, 1924-Venice, May 8, 1990) in the 1950s clearly places him as one of the major exponents of the post-Webernian avant-garde, but his artistic personality expresses the desire to overcome the formalisms of serialism in order to re-propose the unity of the sound phenomenon in a highly original way. In 1956 *Canto sospeso* (for solo voices, chorus and orchestra, based on texts from letters of members of the European Resistance movement who were condemned to death) was the first of his works to gain international recognition.

In the 1960s he began working at the Studio di Fonologia Musicale of the RAI in Milan, discovering the musical potential of the electronic medium, used both independently and as part of compositions for soloists, ensembles, large orchestras and in musical theatre works. In those years his research on sound and electroacoustic space merged with a very strong ideological drive on a political level, intensely felt, which was reflected in the compositions of this period and which placed him in a unique position on the post-war musical scene. These works include *La fabbrica illuminata*, *Ricorda cosa ti hanno fatto in Auschwitz*, *A floresta* é *jovem e cheja de vida*, and the opera *Al gran sole carico d'amore*, premiered in 1975.

The composition ... *sofferte onde serene* ... (1977) marked the turning point towards a new, more introspective creative period, which evolved in the 1980s into a research path with the Live Electronics of the Experimental studio der Heinrich Strobel Stiftung des Südwestfunks E. V. in Freiburg (Breisgau). In the space of a few years, Nono renewed his compositional technique, conditioned by the rigidity of magnetic tape, creating a group of soloists specialised in the technique of 'mobile sound', in the use of micro-intervals and in interaction with live electronics. Starting with *Das atmende Klarsein* (1981), for bass flute, small choir and live electronics, the journey towards the opera *Prometeo, tragedia dell'ascolto* with texts chosen by Massimo Cacciari, for soloists, choir, four instrumental groups and live electronics. The first performance took place in 1984 in the Church of San Lorenzo in Venice, where Renzo Piano built an architectural structure with the aim of gathering performers and audience inside a *new instrument* for listening to music in space[1].

ALN was created in December 1993 in Venice, through the efforts of his widow, Nuria Schoenberg Nono, for the purpose of housing and conserving the Venetian composer's legacy. ALN was declared "of local interest" in

[1] For an in-depth study of Luigi Nono's work, see De Benedictis, Rizzardi 2018.

1994 by the Veneto Region (Italy) and 'of considerable historical interest' in 2000 by the Archival Superintendence, Italian Ministry of Cultural Heritage.

The Archive was founded as an Association, later transformed into a Foundation (FALN) in 2007 and thereafter placed in its current location, the ex-convent Saints Cosma e Damiano, on the island of Giudecca in Venice. The Archive's activities are supported by public bodies, national and international sponsors, and by the generous contributions of the Friends of the ALN.

The Archive preserves manuscripts of Nono's compositions, in particular sketches and preparatory studies (2300 sheets); a collection of open reel tapes (230) and audio-cassettes (90) consisting of recordings of Nono's works as well as preliminary studies and material for his electronic compositions (sound sketches of considerable importance), and several interviews; manuscripts of essays, articles, lectures and lessons (12,000 sheets); Nono's correspondence; Nono's library encompassing over 10,000 volumes (many with marginalia) reflecting the breadth of his interests: music, literature, politics, philosophy, fine arts and sciences; concert programs, reviews and magazine articles; video tapes documenting his life and works and a collection of photographs and slides (6500); Nono's LP record collection of more than 1200 records[2].

4.2 *Documents storage*

ALN stored all data in the cloud, keeping a copy locally (on redundant NAS), both of the documents in high resolution and of the compressed files. The aims are: performance, scalability, availability, and long-term preservation. The storage resources are scaled to adapt the possible fluctuations in demand (by the ALN) without upfront investments or resource supply cycles, automatically creating and storing copies of all audio-video-images-documents objects. The data are available at any time to both the Archive and to the users (with different access levels) and are protected from failures. Data are stored and protected from unauthorized access with encryption features and access management tools developed on purpose. Public access is blocked to all objects at the account level and the system operates compliance programs, such as the General Data Protection Regulation, adopted in April 2016, that has superseded the Data Protection Directive and became enforceable on 25 May 2018 (Blackmer 2016). The storage system offers robust capabilities to manage access, cost, replication and data protection. Because the system works with AWS Lambda, the archive stores log activities and defines alarms. The system is able to perform big data analysis across objects inside the archive with query-in-place instruments.

[2] See Dal Molin 2016 for an exhaustive report of the personal papers included in the ALN.

4.3 *Archive management software system*

An archive management software system was developed, combining independent modules and using different programming languages and technologies (mainly Java, MySQL, PHP, and shell scripting). The main purpose is to support the process of active preservation of the documents according to the methodology described above. The expected users are archivists of the archive and scholars and in this sense the user interface assists the operator in (i) the creation of the digital preservation copies and (ii) metadata extraction and ingestion into the database.

The strength of the module is that it ensures the alignment between the data on documents (audio/video/manuscript/etc.) and their metadata in a relational database, minimizing the cognitive load of the operator and reducing the processing time required by each preservation master. The software implements redundant data integrity verification procedures, and optimizes the workflow by batch processing large sets of data and metadata, progressively storing the complete preservation copies in the cloud digital

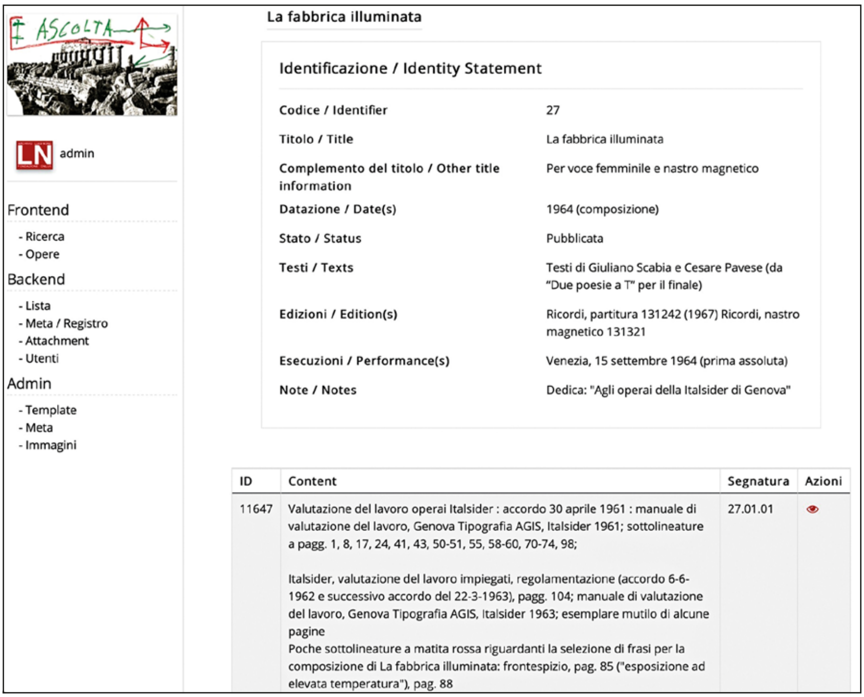

Fig. 6 – Identity statement of *La fabbrica illuminata* (a musical work by Luigi Nono, 1964).

preservation archive. The software is designed to assist the preservation process, and to preserve the entire workflow, allowing backward analyses of the processing times, dates, data flow, etc. It includes several modules: particularly innovative is the module for the description of the signs and symptoms of degradation at the audio-video carrier level. The information system has been online since July 2021. All users can access the database locally in ALN. Users are able to carry out their queries remotely as well, through a web interface linked to the Fondazione ALN website (http://www.luiginono.it/en/). Figs. 6, 7 e 8 show examples of the *La fabbrica illuminata* (a musical work by Luigi Nono, 1964): 1) identity statement; 2) manuscripts digitized; 3) audio tracks.

Italian legislation strives to guarantee access to the documents, safeguarding the rights of the creators, persons or organizations involved. In line with these principles, first of all, one needs permission either from the creator or his/her heirs and (for letters that are not part of the Luigi Nono's collection) from the preserver. Where the Fondazione ALN does not have a written release, users must obtain authorization themselves, with the eventual mediation of the Foundation. It should be noted that preservers have sometimes only provided copies of letters for cataloguing purposes and not for consultation. On presentation of the required authorization, the ALN staff check and eventually censor the text of the letters, removing any sensitive or classified data from consultation, in accordance with Chapter III of the 2004 Legislative Decree 42 (*Codice dei beni culturali e del paesaggio*). The user does not receive originals but photocopies of the selected documents for consultation only, which confirms the usefulness of the description of the original document offered in the database. The publication of a part or the whole of a transcript is subject to approval from the copyright owners. This also applies to the publication of photographic reproductions.

Following methodology described above, the link between the preservation copy (and therefore the original document) and the *re-mediated* access unit is maintained by means of the relationship between the audio track associated with the unit and all the audio tracks coming from the preservation copies that were used by Luigi Nono and co-workers to produce it. With this structure, the presentation of the data can concern the general public (interested in the content of a unit), as well as musicologists willing to study the philological reconstruction of the source, or the physical characteristics of the original carrier. Obviously, and very important, the users can trace the information of a preservation copy starting from the result of the queries on the content and vice versa. For each carrier (audio: magnetic tape, phonographic disc, wax cylinder, etc.; paper, in the case of manuscripts), all the relevant characteristics have been identified, which have been formalized in a set of

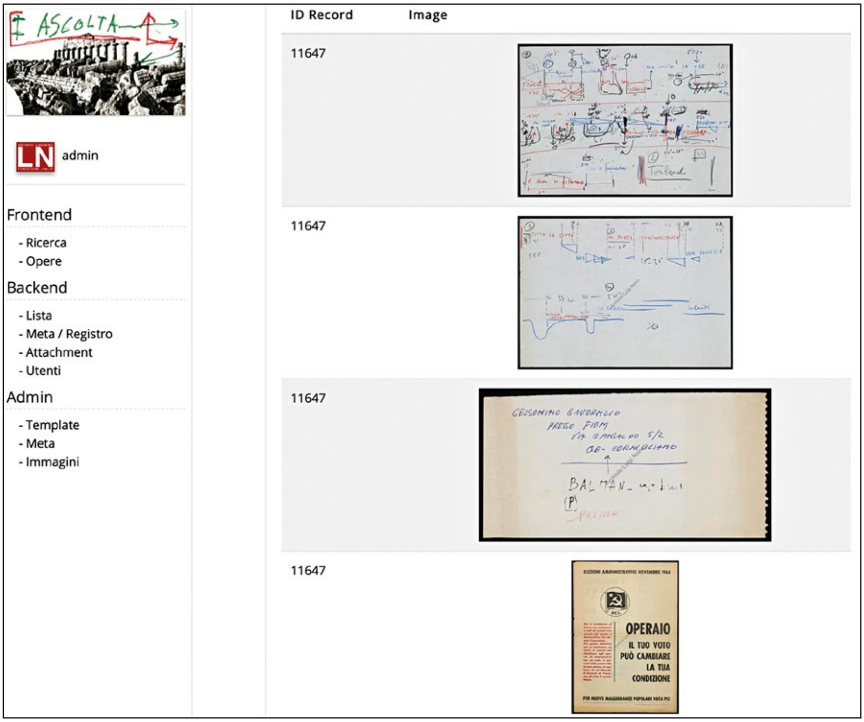

Fig. 7 – Access to digitized manuscripts.

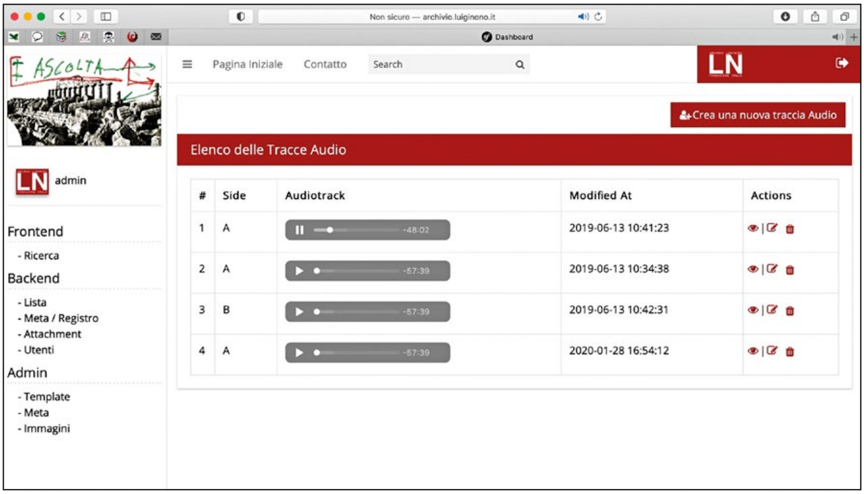

Fig. 8 – Audio file (an example of four channels tape).

attributes represented in the database project. There are some intersections among the attributes of different types (e.g., for all the audio documents, the registration technique must be specified); the superset of all attributes constitutes the original document table in the database.

In some cases, no control is required in the user interface (where a component that allows the user to make a selection from a controlled vocabulary). In these cases, the most appropriate value will be entered in the database in a transparent way to the user, to deprive her/him to insert a not valid value, because of distraction or incompetence. In this sense, the user interface includes a limited number of components.

The system is able to minimize the introduction of errors, not only by filtering the interface components, but also by filtering the values that are presented in the components, and which depend on the type of support considered. For example, the *speed* attribute is shared by the compact-cassette, micro-cassette, open reel and phonographic disc. For the first three, the tape speed, for the last one, the angular speed of the disc. The component for selecting the speed is not included in the interface even if the user is working on a compact-cassette, since it is assumed that the tape speed for the cassettes is always 4.75 cm/s; for the micro-cassettes is 1.2 cm/s and 2.4 cm/s. These values are not valid for the open reels, for which valid values are 4.75 cm/s (intersection with audio cassettes), 9.5 cm/s, 19 cm/s, 38 cm/s and 76 cm/s. Finally, the valid values for phonograph records, expressed in revolutions per minute (rpm): 16 rpm, 33 1/3 rpm, 45 rpm, and 78 rpm.

The software is able to create preservation copies of the documents, to share access copies; to catalog the mediated resources for access; to check the integrity and internal consistency of the archive documents; create backup copies of data and metadata.

5. Conclusions

In this article, we first presented a scientific methodology for the audio documents active preservation and access, developed thanks to the fifty years of experience gained at CSC in music production: a well-tuned *re-mediation* methodology, an artificial intelligence based approach to detect audio tape discontinuities and access tools for renovating the listening experience of old analogue media. Then the problem of preserving and accessing all the information related to the artworks stored in the author's personal archive was addressed. We presented in detail, as a case study, the design and development of an information management system allowing the long-term preservation and the access to different documents, among them: audio, letters, musical scores, and manuscripts of the personal archive of Luigi Nono. Our approach is based on two pillars: (a) the multidisciplinary nature of the team researchers involving engineers, musicians, musicologists, composers and archivists, and (b) the philological accuracy with which the digital tools developed preserve the history of the production and transmission of the audio document.

Multimedia and interaction technologies have promoted the creation of new artistic typologies that integrate the various forms of communication in a single artwork and that allow the performer (or the public in the case of installations) to modify the structure and response according to their own behavior. The sector that encompasses these experiences is called media art. We can observe that media art is both material and performative: it is as artifactual or object-centric as performative or behavior-centric and it exhibits a variable form, much like music.

We believe that our methodology has general value, therefore can be fruitfully applied to other forms of media art and to other personal archives, different from electronic music composers, but also the practical findings we illustrated for our system can be inspiring in a wide range of contexts. One of the strengths of this project consists in having defined an original scientific methodology in the field of digital preservation, characterized by the fact of targeting the type of European personal archives, and having successfully applied it to a real archive, obtaining concrete results. The majority of the personal archives of the 20th c. are nevertheless kept outside the State Archives by a myriad of public or private institutions, often with few funds and personnel. The consolidated methodologies for institutional archives are not always sufficient to manage this new type of archives. An interesting open issue, not sufficiently discussed yet in the literature and archival practices, concerns the standardization of these small, personal, multimedia archives. Standardized tools must be provided for interoperability between different systems. Our proposal can be a step toward the possibility that personal archives interconnect with each other, creating a large network.

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ABSTRACT

Music was one of the earliest kinds of art to explore the creative use of electronic and information technologies: new musical forms have assumed an increasingly artistic importance since the second half of the last century. Technology, at the same time, also is the cause of their rapid deterioration and risk of disappearance. The conservation of this heritage presents very different problems from those posed by traditional artworks. To this purpose this paper first presents some results for the conservation of audio documents: a well-tuned re-mediation methodology, an artificial intelligence based approach to detect audio tape discontinuities and access tools for renovating the listening experience of old analog media. To safeguard this heritage, it is not enough to digitize the content of recordings and documents, but all the related information, collected on the author's personal archive, must also be accessible. The second part of this paper presents in detail, as a case study, the design and development of an information management system allowing the long-time preservation and the access to different documents, among them: audio, letters, musical scores, and manuscripts of the personal archive of an important electronic music composer.

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