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Tape music archives: from preservation to access

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Abstract This article presents a methodology for the active preservation of, and the access to, magnetic tapes of audio archives. The methodology has been defined and implemented by a multidisciplinary team involving engineers as well as musicians, composers and archivists. The strong point of the methodology is the philological awareness that influenced the development of digital tools, which consider the critical questions in the historian and musicologist's approach: the secondary information and the history of transmission of an audio document.

Keywords Cultural memory · Audio collections · Tape music · A/D transfer · Metadata

1 Introduction

Magnetic tape for audio recordings was invented by German Fritz Pfleumer in 1928, building on the invention of magnetic wire recording by Oberlin Smith in 1888 and Valdemar Poulsen in 1898. High-speed reel-to-reel tape recorders rapidly became the main recording format used by professional recording studios, and they maintained their supremacy until the late 1980s, when digital audio recording techniques began to support other types of media. Inexpensive reel-to-reel tape recorders were also widely used for voice recording at home and for linguistics and anthropology research activities. However, despite the importance of sound archives, the international scenario is alarming (e.g., cataloguing standards not always adequately implemented) and aggravated by the short life expectancy of audio media (years or decades, as opposed to centuries or millennia for conventional tangible cultural heritage).

In [38], the authors discuss the results ascertained from several audio documents preservation projects and the techniques used. The present paper takes one step forward by defining, on the basis of international experience gained by the authors in the last twenty years, a philologically informed methodology that covers the whole archival process from the active preservation of sound documents to the access to digitized files by means of several computer interfaces (web based or mobile based), designed, again, by following philological and musicological approaches. The work presented in this paper has been carried out by a multidisciplinary team: the paradigm has not been that of working separately and merging the results, but rather of merging the working methods and achieving new results together. The structure of the paper is sketched below.

Section 2 deals with the active preservation of audio documents (for an introduction to the topic, see [4,17,26]), presenting the innovative concept of quality control during the analog–digital transfer of the audio signal and discussing some chemical analyses on tapes. The audio document can be associated with the physical carrier on which it is recorded, and to the audio player (gramophone, tape recorder/player) defining the listening experience. Audio recorders/players are characterized by (i) a rapid change and improvement

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of the technology and (ii) a fast obsolescence of hardware. Since, in many cases, the musical works are indissolubly linked to the production systems—in particular in the field of tape music[1]: from a philological point of view, it is interesting to study the audio document in relation to its original recording/playback device. In this sense, it is important to preserve the behavior and peculiarities of such devices.

The preservation of electrophone devices is a new and interesting field, with many unanswered questions and open problems. In particular, the devices should be preserved not only for museum exhibitions, but also to safeguard their functionality. In Sect. 3, the paper proposes to transpose the categories of passive preservation and *active preservation*[2]—usually applied to document preservation [9]—to the field of recording/playback devices. The authors are convinced that—similarly to the audio documents field—active preservation of recording/playback systems is needed in order to prevent this equipment from disappearing, and it is desirable because it is the only way to introduce in this field the "preserve the content" and "distribution is preservation" concepts [20]. Specifically, active preservation of electrophone devices allows to access them on a wide scale (e.g., it may allow to access the instruments in virtual spaces that can be reached even remotely by large communities of users). Active preservation of electrophone equipment represents a major technological and scientific challenge. It requires to analyze, understand and simulate the behavior of complex devices, assembled from several components, some nonlinear, some having partially unknown characteristics. The approach to active preservation proposed in this paper amounts to developing virtual counterparts in the digital domain, which retain as much as possible the characteristics of the original, analog devices. In this sense, the virtual device should be the equivalent of the "access copy" [9] in the field of audio recordings preservation. The human–computer interface provided by the digital virtualization of recording/playback systems offers the same functionality and allows the same gestures of the original analog devices, producing a listening experience in agreement with the first "legitimate direction" of the preservation of audio history [47], namely "the perpetuation of the sound of an original recording as it was initially reproduced and heard by the people of the era."

An assessment of a virtual device proposed in Sect. 3 is discussed in Sect. 4, with some very promising results.

It must be remarked that tape music is the most challenging musical content to preserve and analyze on a magnetic tape, as it presents issues that do not exist in other scenarios:

- tapes were physically manipulated with cuts, splices, etc.;
- annotations crucial for the music performance were sometimes applied on the tape itself, and a formal score was seldom produced;
- as a general rule, the composer considered the technical possibilities and the constraints of the specific recording/playback device he/she was using, exploiting them, sometimes overcoming them by modifying the device with the help of technicians;
- the presence of concrete and/or electronic sounds together with acoustical instruments makes it difficult to distinguish between audio corruptions and intentional alterations.

Furthermore, magnetic tapes are the most demanding audio media to handle, because of the unrivaled possibilities for manipulation they offer and because of their frailty and short lifespan. As our methodology was perfected for the most challenging musical content on the most demanding audio medium, we believe it can be extended to other media and genres, e.g., Western classical music, opera, ethnomusic, speech corpora.

2 Methodology for preservation

Preservation is "both labor intensive and expensive" [29, p. 7]: dealing with delicate documents of high cultural value, it requires resources (in terms of equipment, infrastructure and trained personnel) and a good coordination. It does not coincide with the digitization of the audio materials, as is often thought: it is a intellectual and practical process that includes all the steps from the preservation planning to the creation of the services that will allow final users to access the documents. Figure 1 summarizes this process.

"It is not simply a case of buying some equipment, connecting it and starting work" [6, p. 81]: political, ethical, methodological and logistical operative choices must be made in order to define a preservation plan that takes into account (i) the objective of the operation, (ii) the budget extent and (iii) the eventual time frame limitations. On top of this, the long-term storage and the access systems must be prepared. The main aspects to consider before starting the digitization can be expressed in the form of direct questions or checklists [6, p. 81], [29, p. 7], as outlined in the following list.

1. What is the objective of the digitization?

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[1] An innovative music genre of the second half of the twentieth century, representing a paradigmatic case of recorded sound art with great implications on the musicological analysis side as well as on the preservation side. Tape music evolved along with technologies for music postproduction, embracing most genres and esthetics trends of recorded sound arts [37].

[2] In this context, passive preservation is meant to defend the original system from external agents without altering the electronic components, and active preservation implies a virtualization of the equipment using a simulation.

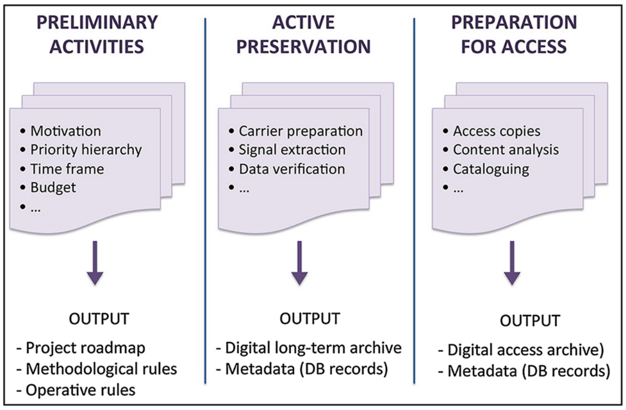

Fig. 1 Preservation process from preliminary activities to access

2. What is the number, the type and the condition of audio documents (requiring survey and diagnostic tools)?
3. The availability of functioning technical equipment, compatible with the recording formats of the documents (problem: sometimes the recording format can only be determined by playing the documents. Is the equipment available? Where? Are there experts capable of discerning the formats? What if the document is damaged and requires restoration to be played?).
4. Are there limitations to the project's time frame?
5. Who will actually perform the job? Where?
6. Long-term storage system for the maintenance of the digital archive of preservation copies.
7. Long-term storage for the physical source documents, which must be maintained for future comparison with the digital copies or for another digitization.[3]
8. Copyright issues on the digitized material.

In order to transfer the audio content from an old tape or an old record onto new media that are supported by an adequate maintenance system, and eventually to the Internet by means of applications developed on purpose, it is necessary to extract the audio signal from the source carrier and to document every piece of information that comes with the document. During this process, the history of the transmission of the document may be violated, and the documentary unity can be broken, with the result that the digital copy of the tape or record is not trustable in terms of authenticity, and that very likely it does not meet the highest standards for the audio format in the preservation field.

Reliability, accuracy and authenticity need to be a primary concern in long-term preservation. Today, the authenticity of digital materials is difficult, if not impossible, to prove [22]. One digital document without certain provenance can compromise the reliability of the entire archive, nullifying the digitization campaign with incalculable loss of time, money and even cultural materials (in case the originals became unaccessible). Documenting the process that generated the preservation copy is particularly important in the audio field, because the medium from which the signal was extracted might be irrecoverable—in case of advanced degradation, with subsequent impossibility of future comparisons to determine a document's authenticity. Another reason why it is so important that the audio signal is accurate is the fact that during the preparation for access the signal is often (and desirably) fed to algorithms for the automatic extraction of audio features for analysis and classification [31,34]. Inaccurate signals impede the correct execution of these algorithms, as reported in [46].

Despite the large attention that digitization and audio archives have received in the last decades, the authors believe that not enough attention has been paid to quality control procedures, as they first pointed out in [12]. A fervid debate on the ethics of preservation, restoration and re-recording was started in 1980 with the "Proposal for the establishment of international re-recording standards" by William Storm [47]: as the debate went along, it stayed crystal clear that the fundamentals of the practice of preservation were:

- "accurate, verifiable, and objective" procedures [47, p. 35];
- measurements based on an ideally objective knowledge;
- modern playback equipment, fully compliant with the format specific parameters of the recordings;
- a careful documentation of all measures employed and of each manipulation applied (ensure reversibility) [44].

2.1 A computer science approach

The restoration of the physical carrier and the procedure of the signal transfer still rely, and will probably keep relying in the future, on the operator's experience (evaluation and choice of intervention). However, a lot can be done in terms of automation of the repetitive tasks such as file manipulation [9, p. 13], which characterize many archival routines, with the benefit of decreasing the operator's cognitive load and of minimizing the introduction of unwanted errors into the system—with domino effects in the accuracy and trustability of the entire collection and on the performance of algorithms for audio features extraction. It is scientifically proven that the introduction of errors is an intrinsic factor in low-level and repetitive tasks, such as those involved in the preservation process [23].

"Ideally, an audio preservation workflow would also involve the services of a specialized programmer. [This] cuts costs, saves time and reduces the opportunity for human error" [19, p. 9]. Involving a computer programmer in a preservation project (or hiring one as a permanent employee

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[3] "Many institutions have regretted the premature destruction of originals after making copies that proved to be inferior" [24, p. 13].

in an archival institution) is a smart choice that pays off right from the short time. The field of audio preservation is one that calls for shared protocols and well-defined standards, but the day-to-day management of all sorts of file (which clearly characterizes big archive in a different measure than small archives) must be necessarily entrusted to a professional programmer—who, very importantly, understands the complex reality of a cultural institution and has the skills to lead an effective communication with the counterparts from the world of the humanities. In the authors' experience, there are many small- to medium-size archives that would highly benefit from an in-house computer programmer [11, p. 11], and the reason why they do not have one is that they actually ignore how great the benefit would be, rather than not being able to afford another employee. Some of the authors have carried out several research projects involving some of the finest historical sound archives in Europe (Paul Sacher Stiftung (CH), Archivio Luigi Nono, Arena di Verona, Scuola Normale Superiore di Pisa (IT), etc.) and have spent some years literally working within the archives' walls, in a daily coexistence that allowed both the scientific staff and the archival staff to gradually and mutually know each other. These experiences taught the importance of cross-domain collaborations, based on daily interaction, which may be the key to novel research results in an authentic multidisciplinary spirit, as recently theorized by [2].

2.2 Active preservation: the tape as cultural object

The process of physical degradation that characterizes every type of audio carriers can be slowed down by means of correct preservation policies, but it cannot be arrested. Therefore, the survival of the information contained by the document is possible only by renouncing to its materiality, through a constant transfer of the acoustic information onto new carriers. This is possible because audio (and video) recordings are characterized by a dichotomy between the content and the container—obviously unlike other traditional art forms and/or historical documents.

The process of preservation includes a number of steps that involve the direct manipulation of the audio document. Such steps are included in the middle part of the scheme depicted in Fig. 1. Digitization (or remediation in the case of digital source documents) is *necessary* to prevent the documents from degrading to the point where the information they store is not accessible anymore, and it is *desirable* because it allows to copy and distribute them on a wide scale thanks to digital technologies. This is also the main part of the preservation process where manual skills are important. It is important to know how to *handle* historical audio carriers correctly, not unlike a restorer working on a painting or another piece of cultural heritage. Acoustic information can be extracted and then delivered, from the physical source carrier, but if the carrier is damaged (Fig. 2) before signal extraction, then all the information is irreversibly lost. The practical knowledge that early generations of technicians and audiophiles gained on the field is priceless. However, today it is necessary to foster scientific research to formalize that knowledge and to perfect the restoration methods—as the audio carriers get more and more fragile as they age, and the risk of damaging them increases. Acknowledging that the scientific literature is scarce in relation to the importance of this field and of the size of the global community who is engaged in this field, the authors started a number of experiments in collaboration with experts in the chemical and mechanical field (Department of Industrial Engineering—Chemical sector, at the University of Padova).

Fig. 2 Close-up of a damaged tape. Source: Centro di Sonologia Computazionale (CSC)

2.3 Chemical analyses

Each type of audio carrier degrades in time according to its chemical properties (magnetic tapes showing different problems than wax cylinders and so forth). See Sect. 2.4 for some examples. Therefore, the study of degradation mechanisms in these carriers is a broad sector of knowledge and an active field of research.

The analyses conducted by the authors to this day include: Fourier transform infrared (FTIR) spectroscopic analysis in ATR, thermogravimetrical analysis (TGA), scanning electron microscopy (SEM), acetone extraction test, acidity test and X-ray diffraction. The type of carrier considered is magnetic tape, in the light of its importance in the history of recorded sound. In particular, the authors aimed at investigating the recovery procedure commonly applied to magnetic tapes that suffer from a syndrome characterized by undesirable shed, stickiness or squeal. This syndrome is known as Soft Binder Syndrome–Sticky Shed Syndrome (SBS–SSS [10, p. 54]). Since thermal treatment is the most common remedy for tapes affected by SBS–SSS, it was decided to study the thermal behavior of some tape samples. The analysis employed is the TGA, which uses heat to drive reactions and physical changes in materials. TGA provides a quantitative measurement of any mass change in the polymer associated with a thermal degradation [32]. It is a destructive method (which means that the tape sample is not readable anymore—however, only 14 mg of tape is needed, which requires that only half a centimeter is cut off the tape end). The tape samples have been brought from 20 to 700 °C, with a ramp of 10 ° per minute. Conversely, the FTIR is the most extensively used technique for the investigation of polymer structure and for the analysis of functional groups [45]. It is a nondestructive method. The analysis has been performed in conjunction with the attenuated total reflectance (ATR) technique, allowing the analysis of non-transparent materials. The SEM analysis allows the observation of the tape samples at a resolution better than 1 nm. It requires that the sample is coated in gold, but it allows a detailed view of its morphology. Figure 3 shows the non-homogeneous surface of the sample. The oblique grooves are the result of the friction between the tape and the play head, with foreign matter such as dust specks on the tape or on the head. Such grooves are not strictly a sign of degradation, albeit they do not appear spontaneously as the tape is kept in the box: they are caused by replay—and the older the tape, the deeper the grooves, as the material of which the tape is made grows softer with aging. So the grooves might have been there for decades, or they might be the result of today's replay during digitization: the observation of the tape before replay is the only way to detect a damaged surface, otherwise not visible. Figure 3 also shows that the magnets are oriented in a preferential direction, that is characteristic of the magnetized system.

While the results of the exploratory analyses do not yet allow the definition of a specific protocol for the thermal treatment of each magnetic tape, some basic observations were drawn. In the first place, the variety of materials revealed by the preliminary characterization (FTIR), with the specific chemical properties of each material, cannot be reduced to one single treatment in terms of temperature and duration. This is an important discovery, because today there is no distinction between thermal treatments aimed at tapes of different brands and models (and state of preservation). It is also hard to measure the severity of the syndrome (see Sect. 2.4). Secondly, it has been proven that water, a presumed responsible of the stickiness, is a negligible presence in the tape: it is certainly involved in the process of hydrolysis, but it does not reside *in* the tape. In the third place, it is important to have learned that the treatment as it is generally carried out (at temperatures between 50 and 54 °C) does not apparently alter the tape physical properties (the TGA shows that in average no significant loss of weigh/heat occurs before over 100 °C). This ensures that the treatment does not damage the tape, even when the desired results are not produced, which is important because "lack of understanding of the sticky shed problem" (see Sect. 2.4) "does not justify inaction on the part of audio archivists, since sticky shed grows gradually worse over the years" [36, p. 3]. In other words, current methods can keep being applied without major concerns until a scientific protocol is available. Of course, the question of the documents not responding to the treatment remains open, and it is not possible to find alternative solutions at the moment.

2.4 Signs and syndromes of degradation

To date, standard evaluation techniques for all the types of signs and syndromes of degradation that affect audio media are missing and so are automatic diagnostic tools. As a consequence, it is impossible to formulate an *objective* assessment, not just among archives across the world but even within the same archive. Examples of existing methods include FACET (Field Audio Collection Evaluation Tool) [30], developed at Indiana University, AVDb (Audio and Moving Image Survey Tool) [21], developed at Columbia University [48].

The authors have attempted a unified vocabulary of syndromes [7] for eight different types of carriers: open-reel tape, compact cassette, compact disk, digital audio tape, digital non-audio carrier, phonographic disk, microcassette, minidisk. The vocabulary was obtained crossing several publications by the main active voices in the preservation community, namely [18,25,48] and the "Technical Glossary of Common Audiovisual Terms" of the National Film and Sound Archive (NFSA) of Canberra (Australia) [49]. The result is a set of 49 different types of conditions, to each one of which a rating scale of five steps is associated to express the severity of the condition. Each condition has a textual definition and is enriched with multimedia documentation, which keeps growing as more case studies are gathered during the laboratory work. Figure 4 shows the detail of a magnetic tape showing evidence of magnetic coating shedding (in particular, portions of the magnetic side of the tape stuck to the back side of the tape next coil).

The authors' approach does not aim at defining a priority for digitization for a collection of audio documents, but at describing as objectively as possible the state of preservation of one single documents when it is being digitized. Secondly, some symptoms cannot be detected unless the carrier is played, such as SBS–SSS (see Sect. 2.3) for compact cassettes or as gummy deposit due to degraded joints for open-reel tapes. Besides, visual inspection of audio carriers should be only performed by highly trained personnel, in possess of a good knowledge of present and past recording formats, combined with personal experience on the field. Chemical analyses are key to advance the understanding of all the listed conditions.

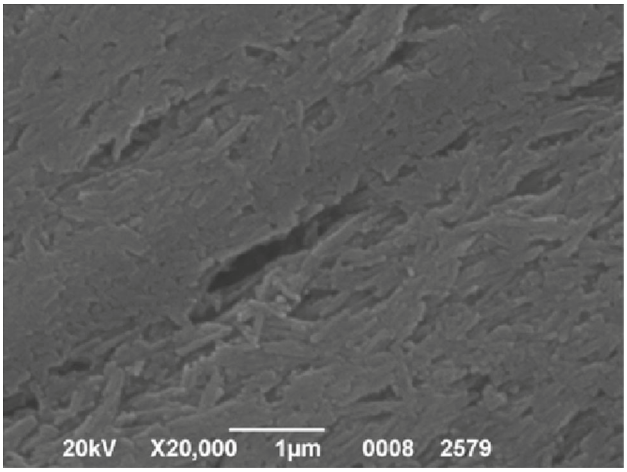


Fig. 3 SEM analysis of a tape sample. *The first number from bottom left* of both figures is the voltage used to accelerate the electron beam (20 kV); the *second* is the magnification rate (×2000 on the left and ×20,000 on the *right*); the *third* is the scale (the white segment above indicates the proportion, here 10 and 1μm); the *progressive number* in the analysis session; the sample identification number

Fig. 4 Tape shedding

2.5 Metadata are key to preservation

The role of metadata in digital long-term archiving is paramount. This is true for born-digital documents, but it is also true for digitized documents. In case of missing/inadequate metadata for digitized documents (in this sense, effective descriptors that help us retrieve and identify a digital object), it is still possible to go back to the physical carrier and check all the information for authenticity and consistency. But we should always think as if the physical carrier was not there, because this is going to be the case in a couple of years/decades time. Maintaining the reliance on the physical carrier is simply a poor metadata strategy.

Born-digital documents do not relate to any physical carrier, apparently fixed (not changing), available, authoritative. They lack materiality since the beginning of their existence. Obviously they are stored on some physical digital device, but without a number of steps that involve more software and hardware, they cannot be accessed. The contrast with a physical magnetic tape is evident: a tape can be manipulated, looked at, smelled. And the sense of touch, vision and smell bring *essential* information on the object. An example of why the sense of smell is important is the so-called vinegar syndrome, a form of decay in cellulose acetate tapes that first manifests itself with a marked vinegar smell, thus being easily detectable by olfactory inspection. Because sensory perceptions are part of our everyday experience, we tend to underestimate their absence. An effective image to help us grasp the importance of choosing our metadata well could be the following: let us imagine what kind of information we get from a tape that we hold in our hands, that we can turn around, smell, put on a reel-to-reel recorder and play back and forth. This does not seem extraordinary as this is what one is normally supposed to do with a tape. Now let us imagine that the tape is gone for good. We still want to learn all about that tape and its precious content, but what we hold in our hands is literally *nothing*, thin air. Where do we get all the information from? And how? This image should force us to start thinking also about *what* information we want. If the digitization of a tape only focuses on the audio (signal and metadata), the information lost in the process is great: physical properties like the color and smell, besides all the other sensory information that we get from the manipulation of a physical tape in our hands. Professionals involved in preservation should be at service of the future generations, trying to transmit *all* the information possible (which we have because we are still blessed with having the physical tapes), *minimizing* the loss of information during the creation of the preservation copy. Ideally, people in a hundred or three hundred years should not regret not having the physical tape because some essential information is missing—although they might regret not having the tape just as we regret not having some perishable object that disappeared in the past centuries.

Metadata are key because they are the *only* way to retrieve and give a correct interpretation of data that lacks physical existence. This is true for all digital data, but even more in the perspective of for long-term preservation. This concept is being stressed although it may seem understood in the digital libraries community, because in the authors' experience most archives still underestimate the importance of good metadata—or, rather, they will agree on their importance in words, but their actual metadata sets prove that they have never imagined what it would be like if the physical object was not there anymore.

Several research projects on metadata (PREMIS, Planets, etc.) have been financed in the past years, but the core issue remains the implementation of those projects results into the actual practices for audio preservation. The general trend is still that of focusing on audio metadata, or to rush the compilation of the content descriptors (cataloguing), often entrusted to the operator in charge of the digitization, who is not the ideal person for the job (the cataloguing should be carried out by a team of experts each time specialized in the recordings content). For example, one of the aspects that characterizes the approach developed and adopted by the authors at the Centro di Sonologia Computazionale at the University of Padova is the video shooting of the digitization process, namely a close-up of the reel-to-reel recorders heads (for open-reel tapes) as the tape is being played. The video, synchronized with the audio signal, ensures that the eventual information present on the carrier is captured and preserved (physical conditions, presence of intentional alterations, corruptions, graphical signs). The video also offers the possibility of correlating corruptions of the magnetic tape (Fig. 5) to irregularities in the extracted audio, which is indispensable to distinguish between intentional and unintentional alterations during the recovery process. Finally, the video may prove a precious source of information for the extraction of further features with future methods (see Sect. 3.2.1). The production of a video recording is not a common practice in preservation, but it is highly advisable where the line between the artifact (carrier) and the content is blurred (e.g., tape music compositions, where the audio on the tape is almost as important as the evidence of the compositional process introduced by the composer himself on the tape, like splits, text).

3 Methodology for access

While the current debate is at least aware of the problems connected with music preservation, it often disregards an essential aspect of music: the access, the listening. Traditional access instruments, mainly developed for other kinds of materials, are inadequate for tape audio documents. Nowadays, the majority of documents in the sound archives are made accessible to scholars on compact disks or "iTunes-like" software on a personal computer. This kind of access is incomplete when the copy does not allow access to metadata and ancillary information, as discussed in Sect. 2.5. In a broader sense, such a limited access is unfaithful to the peculiarities of the original (analog) of the time—sometimes to the point where the listening experience is substantially affected. Consider, for instance, musical open works such as *Votre Faust* or *Scambi* from French composer Henri Pousseur: both works contemplate a number of sequences that can be arranged by the listener in several different ways according to a set of rules. While laying out the structure of such works, the composer obviously exploited the physical characteristics of the media (vinyl disks in the former work, tape segments in the latter) where music was recorded, including the silence while changing the media.

Fig. 5 Still image from a video captured during signal extraction. *Source*: Centro di Sonologia Computazionale (CSC)

Extending the concept in [5], the emulation of the tape recorder and the carrier is not necessary and not recommended, since a lot of works are required for a provisional solution. The correct way to follow is the virtualization of the carriers and of the replay support that guarantees a faithful access and a durable solution.

Commercial software packages that reflect some characteristics of analog players (e.g., a gramophone) exist, but the virtualization is often incomplete and inaccurate. In contrast, the authors of this article have already been active in designing accurate virtualization tools. In [40], a web application is presented that aims at recreating the experience of a gramophone. In [15], the first Android app for tablets is discussed that recreates the experience of a reel-to-reel audio tape recorder; the paper also illustrates a rigorous, methodological framework for a faithful access to digitized tape music recordings—based on the process detailed in [9,38]. The present article can be seen as a further step toward more complete and accurate access tools for audio archives. After summarizing the cornerstones of a sound access methodology (Sect. 3.1), the latest results are presented concerning the access to tape music archives via both mobile devices (Sect. 3.2) and web browsers (Sect. 3.3). The software solutions the authors have been developing highlight the role and characteristics of tape media and the tools needed for playback. Evidence is also provided (Sect. 4) for the soundness of this access methodology, and for the preservation methodology as well—evidence gathered via several past and running projects and via dedicated interviews.

3.1 Objectives for access and interaction

As stated in [15], the general objective for access and interaction is the same as the one for preservation, that is, to be *faithful*: as every piece of information originating from the original media must be faithfully perpetuated, so the presentation of such information must be as faithful to the original experience as possible. Fidelity develops along three main dimensions:

- faithful audio playback,
- faithful simulation of the experience of interacting with the playback device and
- faithful reproduction of all the metadata and contextual information.

In what follows, the main issues connected with each of the three dimensions are briefly sketched; the interested reader is referred to [15] for a complete discussion.

- *Audio playback* The three main features that influence the playback of a tape are the number of audio tracks, the tape replay speed and the equalization curve. The number of tracks can vary from 1 to 24. As modern, mainstream audio playback devices (CD decks, PCs, smartphones, tablets) provide only two output channels, accessing audio documents with more than two tracks is clearly non-trivial: a track management tool and/or a multitrack simulator must be provided for proper listening. The case of quadraphonic (that is, 4-track) audio playback is particularly significant since 4 was a popular choice for the number of tracks in the field of tape music. As far as tape speed and equalization curves are concerned, several standards exist depending on the class of the tape recorder (professional, semiprofessional or consumer), the year and the country of the recording. Furthermore, the equalization curves change depending on the tape replay speed. Since no real playback device supports all speeds and curves, a choice must be made to pursue fidelity to a particular device or to relax the fidelity constraint with the aim of easing the work of the scholar.
- *Playback device* To reproduce the experience of operating a tape recorder, the aspect of the device itself must obviously be replicated in full: in particular, the replica must consider the aspect of the tape reels, tension arms, tape lifters, buttons, switches, knobs, indicator lights, displays and gauges. The aspect of displays and all moving parts must be updated in real time. Building such a reproduction on computer devices, let them be desktop or mobile, is relatively easy for those elements where only the senses of sight and hearing (recall that elements such as switches produce noise by design as a mean of giving feedback to the user) are involved, since nowadays all computer devices provide true-color, high-resolution screens and decent-quality audio output. The reproduction is more challenging for the elements that exert the sense of touch, prominently all the actuators: in this case, mobile devices have an advantage because they are endowed with touch screens. However, other features (e.g., quadraphonic audio) are more easily implemented on desktop machines because of their superior computing power and possibility of customized hardware configurations. In general, a trade-off on the acceptable level of fidelity must be agreed upon during the design phase. Further hazards to fidelity are due to the fact that the aspect and even the number of elements to reproduce depend on the specific model of tape recorder, and it is usually unpractical to reproduce many.
- *Metadata and contextual information* Like in [15], the term “metadata” is hereby used for content-dependent information that can be automatically extracted by the audio signal, and the term “contextual information” for the ancillary, content-independent materials such as the annotations on the tape carrier. Both forms of information are accessed using a combination of textual, photographic and video documentation. Photographs are useful to report accurate information about labels, edition boxes and other attachments, as well as clearly visible carrier corruptions. A video of the tape during playback is a powerful tool to ensure the preservation of information on the original media, as discussed in Sect. 2.5. Metadata and contextual information can be clustered into three groups: *general information* (it unambiguously identifies the audio document and its origin); *audio content information* (it contains data on the audio file such as the file format, plus data on the digitization process such as the tape speed and equalization curve used), and *original content description* (it collects information, such as the tape width, which can be extracted from the original carrier, usually through visual inspection). Identifying which documentation should be provided is not trivial, and, again, no general solution exist since different groups of users—for instance, musicologists and the general public—have different needs.

Albeit the authors advocate that a high degree of fidelity must be attained along all the three dimensions, they are also aware that fidelity must be implemented in a sensible way. This aspect was hinted at, but not fully developed, in [15]: cases exist where being overly faithful does not add to the interaction experience and it just makes the access to documents more involved. For instance, recall that tape replay speed and equalization were mentioned as two fundamental features to be provided by a virtual tape recorder. However, no reel-to-reel tape machine exists that plays all six standard replay speeds [27]. If fidelity requirements are followed to the letter, it is impossible to play all tapes with a single virtual interface. This is particularly aggravating for scholars, who are the target of the access interfaces developed by the authors. In this case, it may be more sensible to augment a knob so that all the replay speeds are available even if the actual device did not provide them. The same observation holds for equalization curves. As the equalization curve chosen during digitization may be wrong for the lack of proper documentation, it is sensible to give a scholar the possibility of listening to a document with any equalization curve, including a “flat” one (i.e., the possibility of listening to the digitized audio without any equalization applied), seldom available in actual devices. In this way, the scholar can point out the correct curve aurally [28]. Another example is the access to quadraphonic documents: the scholar benefits from the possibility of listening to a subset of the tracks, or freely reassigning the tracks to the output channels, even if such operations were not possible with actual tapes. It must be noted that some quadraphonic documents have already been subject to notable errors during transfer—errors that can be handled with a track management tool—because of lacking documentation or scant attention to source consistency [14].

A second group of features that deviate from fidelity with the aim of simplifying the access to documents is populated by algorithmic functions that highlight relevant information in a smart, non-trivial way. The authors believe that such functions are very important and will find increasingly wider application in the future. There are several examples of possible functions, leveraging on techniques from the fields of data mining, machine learning and computer vision: for instance, relevant documents may be retrieved by humming a tune, or possible forgeries may be spotted out automatically by examining a document for audio clues and so on. A function for *intelligent, assisted access* is now implemented in one of the access interfaces implemented by the authors: it is described in Sect. 3.2.1.

3.2 Mobile-based access and interaction: REMIND

With their affordable price tag and remarkable hardware specifications (touch screen, high-resolution 3D graphics, computing power which steadily increases year over year), high-end mobile devices strike a fair balance between multimedia and multisensory capabilities, flexibility and ease of implementation without the complexity and costs of deploying supplementary custom hardware. This is the reason why the authors have developed REMIND, an app that recreates a virtual tape recorder on Android tablet devices. In what follows, the basic features of the app, described in full in [15], are briefly sketched, and then some novel, previously unpublished features, recently added to the app, are illustrated.

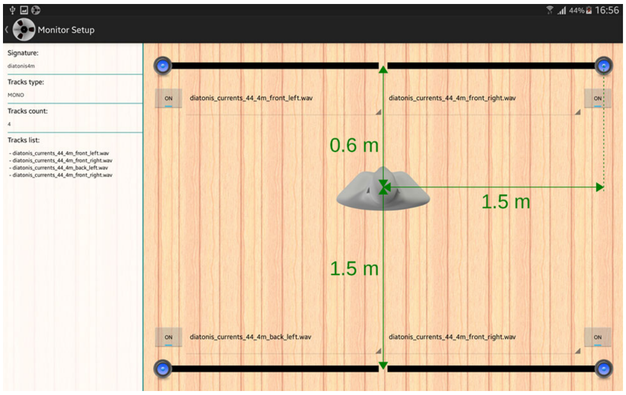
The REMIND app provides a representation of the Studer A810-VUK two-track, reel-to-reel tape recorder (see Fig. 6) where the recording functions—including the separate console with the recording controls—have not been implemented since only pre-recorded tapes must be accessed. The user interface is *skeuomorphic*, i.e., it retains and exploits the appearance and behavior of the original, physical device. Touch-based actuation of buttons and switches is possible. The tape reels are faithfully reproduced; the speed of each reel is, of course, proportional to the amount of tape in the reel, which, in turn, is updated in real time during playback. All four reel playback speeds available in the actual tape recorder, that is, 30, 15, 7.5 and 3.75 in. per second, are supported by the app, thus providing a full coverage of the most popular playback speeds. The coverage of equalization curves is also excellent, as both the ubiquitous equalization curves (CCIR and NAB) of the actual Studer device are also implemented in the app. A “flat” curve is also provided for scholarly purposes, as explained in Sect. 3.1. A video of the actual tape (see also Sect. 2.5) is run in a separate window to keep it readable. Readability constraints banned smartphones from the list of supported devices. Smartphone screens are unacceptably smaller than a real tape recorder; indeed, it is advised to run REMIND on tablets with a 10-in.—or larger—screen. The video is, of course, appropriately updated even when the tape is not moving at nominal speed (e.g., rewinding, fast forwarding).


Fig. 6 A Studer A810 (VUK version) tape recorder

The main UI of the app (Fig. 7), which is also the first to be presented to the user at launch, handles the skeuomorphic UI of the virtual tape recorder. Five buttons in the upper right corner provide access to

- the audio track configurator, where tracks can be assigned to physical audio channels and processed by the quadraphonic engine, if appropriate;
- the novel tape analysis features (full details are provided in Sect. 3.2.1);
- metadata and contextual information;

Fig. 7 Main UI of the REMIND app



Signature:
diatonis4m

Tracks type:
MONO

Tracks count:
4

Tracks list:
- diatonis_currents_44_4m_front_left.wav
- diatonis_currents_44_4m_front_right.wav
- diatonis_currents_44_4m_back_left.wav
- diatonis_currents_44_4m_front_right.wav

diatonis_currents_44_4m_front_left.wav
diatonis_currents_44_4m_front_right.wav
diatonis_currents_44_4m_back_left.wav
diatonis_currents_44_4m_front_right.wav

Fig. 8 Quadraphonic engine: the measures of the virtual listening space (in *green*) are superimposed to a snapshot of the Android activity that allows the user to adjust the position of the virtual monitors (color figure online)

– other ancillary functions, such as the general settings for the app, a list of all the music pieces stored in the device and the online help.

Since many of the settings should not be tampered with by the casual user, such as a visitor to a record collection, they can be password protected.

The audio backend of the REMIND app supports audio sources with one, two or four tracks, again covering a significant fraction of the audio documents recorded on tapes. The availability of more than two hardware audio channels is nonexistent in consumer devices such as Android tablets. As a consequence, REMIND renders the quadraphonic scene on two hardware output channels. Quadraphonic functions are managed with a separated UI (see Fig. 8): since actual Studer A810's do not support four tracks, this design choice also serves the purpose of implicitly indicating to the user that the four-track functionality goes beyond the virtualization of the original tape recorder. In the dedicated UI, audio tracks can be freely mapped to four virtual output monitors within the limit of one track per monitor. The position of the monitors in the quadraphonic listening space can be adjusted: the audio backend processes the tracks before mixing them to hardware channels so as to reconstruct the quadraphonic scene. The limited computing power of mobile devices is reflected on the backend, which is constrained to headphone-based rendering and relies on four strong auditory cues [3] only: the interaural time difference, the interaural level difference, the absolute loudness level and the ratio of direct to reverberant energy. The authors plan to enhance the audio backend as hardware capabilities of mobile devices evolve. The audio backend in REMIND also performs equalization, sampling rate conversion to simulate the various tape speeds, waveform reversion to play the tape backwards.

All the metadata and contextual information about an audio document are stored in a single folder and described by an accompanying XML file. XML files are read during the initialization of the app or after a refresh action from the user. This file organization makes adding or removing an audio document a matter of copying or deleting the corresponding folder. The adoption of the standard XML format fosters interoperability with future external tools, such as a centralized application for the management and customization of access copies that is currently under development. External tools may be an useful addition to the preservation workflow, but REMIND is designed to be as self-sufficient as possible: to this aim, a dedicated section of the app provides not only tools to import documents by scanning the file system for properly structured folders, but also tools to

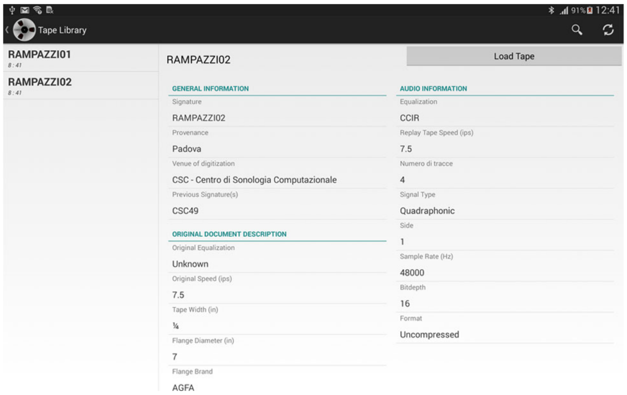
– create new documents by manually filling in the metadata and connecting them with the appropriate media files,
– edit the metadata of an existing document so that information can be corrected of updated.

The operations of creation and update of the access copies can be disabled with a password to cope with the restrictions some institutions impose on their archives.

Metadata and contextual information are displayed in a multipane layout (see Fig. 9): the user can select a document in the left pane and then access the corresponding information—including multimedia files—via the right pane. The REMIND app also includes a search module based on signatures and a tool to export the entire database in XML format.

3.2.1 Intelligent, assisted access

As already pointed out, the authors advocate that computer-based implementations of playback devices must be faithful to the original, but not to the point of impeding features that simplify the access to documents. Such features may be trivial deviations from the interface of the original device



RAMPAZZI01
8:41
RAMPAZZI02
8:41

RAMPAZZI02

GENERAL INFORMATION
Signature
RAMPAZZI02
Provenance
Padova
Venue of digitization
CSC - Centro di Sonologia Computazionale
Previous Signature(s)
CSC49

ORIGINAL DOCUMENT DESCRIPTION
Original Equalization
Unknown
Original Speed (ips)
7.5
Tape Width (in)
¼
Flange Diameter (in)
7
Flange Brand
AGFA

AUDIO INFORMATION
Equalization
CCIR
Replay Tape Speed (ips)
7.5
Numero di tracce
4
Signal Type
Quadraphonic
Side
1
Sample Rate (Hz)
48000
Bitdepth
16
Format
Uncompressed

Fig. 9 Playlist activity: contains metadata and contextual information of the access copies

Fig. 10 An intermediate step in the detection of “anomalies” on the tape. Three anomalies have been detected, as shown by the *colored contours*; false positives will be discarded in a next step of the algorithm (color figure online)

(e.g., an additional button), but, more importantly, they can also be non-trivial computing functions that highlight relevant information in an intelligent fashion. The REMIND app is now evolving along this direction. The present section introduces a first, previously unpublished example of an advanced function that simplifies access: the automatic detection of “anomalies” on the tape by analyzing the tape video with computer vision techniques. The term “anomaly” hereby covers both intentional (e.g., annotations) and unintentional (e.g., tape corruptions) alterations on the tape. The automatic detector builds a list of all such alterations and present it to the user for further analysis. Thanks to the detector, a scholar is spared the trivial but strenuous task of looking at an entire video just to spot anomalies out, and she/he can concentrate her/his energies on the smarter task of classifying and studying such anomalies.

The detector is designed for videos taken with regular cameras, but it can be adapted for strip cameras. Given that the detector must process videos from several different playback devices, taken from slightly different perspectives and under different—sometimes varying—lighting conditions, robustness was the first design requirement. The second requirement was that the detection algorithm should be fast, so that is can be run on a mobile device (or, on a PC, much faster than real time). The final algorithm adopted in REMIND can be subdivided into four steps.

1. Detection of all the moving regions in the video.
2. Extraction of the contours of each region.
3. Removal of false positives.
4. Motion tracking.

In the first step, a background subtraction algorithm is applied to the video, masking out all the non-moving part of the frame and trying to identify where the tape is. Morphological operators [35] are then applied with the aim of reducing local noise, which takes the form of spurious pixels. Even after the noise reduction step, some moving regions may lay outside the zone detected as “tape.” This is not necessarily an issue: indeed, an algorithm that is flexible enough to preserve such regions at this stage is the only way to cope with anomalies where the tape partly folds and dislocates from its correct position during playback. False positives are removed with a higher-level analysis at a later stage in the detector pipeline.

In the second step of the detection algorithm, the contour of each moving region is calculated and then delimited with a rectangle. An example of this step is visible in Fig. 10. The use of rectangles makes tracking the motion of the regions easier.

The third step of the algorithm is designed to eliminate false positives. The step is heuristic in nature and is based on the following observations: the anomalies are on—or near—the tape; the tape itself occupies only a fraction of the frame; hence, anomalies cannot be bigger than a threshold; anomalies moves with the tape; therefore, they must cross the whole frame in a nearly straight, horizontal line. By combining such observations, regions that clearly cannot be real anomalies can be discarded with limited computing effort. It must be remarked that our algorithm is tuned to provide a high recall rate (ideally, 100%) at the expense of precision. It is more important not to miss any true positive than to minimize false positives; the user can quickly eliminate residual false positives from the (usually short) list of results with a few clicks. As a side benefit of our compromise between recall and precision, the algorithm can be faster and can operate with less memory resources.

In the fourth and last step of the algorithm, the motion of the regions is tracked so that each anomaly is reported only once and when it crosses a specific point in the frame, which can be arbitrarily set. When this point is reached, the current frame is saved and added to the list of results for the user, together with the current tape playback time.

In our plans, future improvements of the algorithm will not target recall, but the possibility of automatically providing to the user a rough classification of the anomalies with machine learning techniques.

3.3 Web-based access and interaction: REWIND

In recent years, the introduction of new web technologies and standards, such as HTML5 and the Web Audio API, has increased the capabilities of web browsers, enabling the creation of rich interactive audio experiences without relying on external technologies such as Adobe Flash or Java [39]. The use of browsers as a platform for complex audio applications provides notable advantages. First of all, a web application does not need any installation of external software or any configuration of the work environment: users have only to type in the right URL. This fact has a significant impact on usability [50]. Furthermore, applications designed to run in the browser offer incomparable portability across mobile and desktop platforms [41]. It must also be remarked that the use of web technologies also implies some limitations and trade-offs. Web applications are written with JavaScript, the only general-purpose language built into all browsers, and JavaScript cannot guarantee a real-time execution of the application. This can be an important limitation for a wide range of audio real-time applications, where high latency can impact negatively on musical performance [50]. The application described in this paper is not affected by this problem, because a small latency is tolerable.

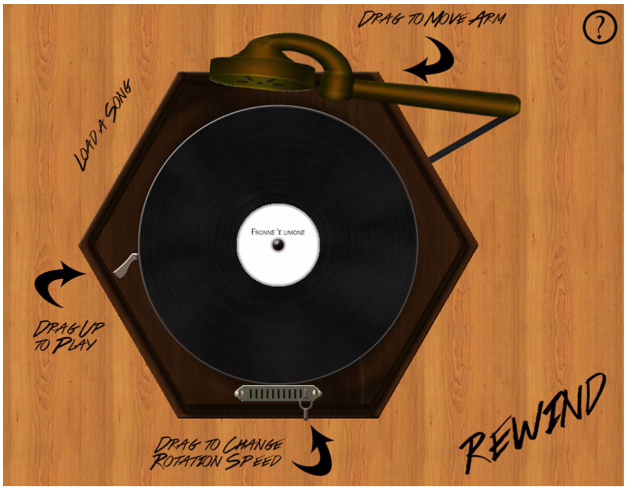


Fig. 11 Main UI of the first REWIND interface: a virtualization of a gramophone

Fig. 12 Main UI of the last REWIND interface: a virtualization of a tape recorder

Figure 11 shows the first web interface offering a philologically aware virtualization of a music playback device described in [40] and called REWIND (Restoring the Experience: Web Interfaces for accessiNg Digitized recordings). Starting from the knowledge acquired in the first project and stimulated from the success achieved by this kind of interfaces among archivists and musicologists [15], a new web interface has been developed and is illustrated in this paper. This second project aimed at virtualizing a reel-to-reel tape recorder, thus providing the main features of this kind of device that have already been discussed in Sect. 3.2: users can therefore access a digitized tape following peculiarities and limitations of the original physical carrier. The user interface of this new REWIND application (Fig. 12) is, again, inspired by the Studer A810 tape recorder (Fig. 6).

The web application is designed for a LAMP (Linux, Apache, MySQL and PHP) software stack, and it is developed using mainly HTML5, CSS3 and JavaScript. The application relies on some external libraries, and chiefly on jQuery, which is used to manipulate the HTML page and to manage graphical effects while ensuring cross-browser compatibility and Web Audio API [1], which is used to manage audio components. The dependence on Web Audio API prevents compatibility with Internet Explorer. REWIND supports both WAV and MP3 files, but for a remote use it is suggested to use the latter.

As far as audio playback is concerned, REMIND makes four tape replay speeds available: 30, 15, 7.5 and 3.75 in. per second. Two equalization curves are supported: CCIR and NAB. Table 1 summarizes the supported standards. A “flat” curve is also provided.

The equalization curves are the same of [40]—as a matter of fact, they are also the same supported by REMIND (see Sect. 3.2)—but they are implemented with a different approach with respect to the former web application. The audio graph at the core of REWIND is connected to

Table 1 Equalization time constants of Studer A810

	30 ips (76.2 cm/s)		15 ips (38.1 cm/s)	7.5 ips (19.05 cm/s)	3.75 ips (4.76 cm/s)
AES	17.5/∞ µs	CCIR	35/∞ µs	70/∞ µs	90/3180 µs
AES	17.5/∞ µs	NAB	50/3180 µs	50/3180 µs	90/3180 µs

a `ConvolverNode` [1] that implements a real-time convolution between the audio signal and the equalization curve preloaded during the initialization phase. The only limitation of the web application is the possibility of using only mono- or stereo audio files. This design choice aims to reduce the amount of memory consumed by the application, thus ensuring compatibility with a wider set of devices with limited resources. The audio source buffer is duplicated, and the new buffer is inverted in order to implement the rewind function of the virtual tape recorder. The audio source and its reverse are `AudioBufferSourceNodes` [1], not `MediaElementAudioSourceNodes`. This architecture proved necessary to realize the replay speed mechanism: the former kind of node changes the replay speed correctly, whereas the latter changes it using in-browser algorithms that modify the speed while maintaining the original pitch.

The skeuomorphic user interface of REWIND provides the main controls of the Studer A810 tape recorder and two knobs to change equalizations and replay speeds. In this case, the rotation mechanism of the knobs has been simplified with HTML buttons so as not to impair the ergonomics and usability of the interface (the interaction is usually performed with a mouse). This choice provides a second advantage: it improves the compatibility with browsers.

Metadata and contextual information are collected in a relational database. The interface provides access to a reduced set of metadata, but it displays the video of the tape synchronized with the audio. The container is an HTML5 `<video>` tag. The choice of maintaining two different sources for audio and video is motivated by two main reasons.

- `MediaElementAudioSourceNode` does not offer the possibility of switching the replay speed (as described in the previous paragraph) correctly, therefore precluding the use of a single multimedia file.
- It is not necessary to cut and synchronize the audio and video of the preservation copies: it is enough to use simple cutting points.

4 Assessment of methodology

The usefulness of the REMIND app (see Sect. 3.2) was assessed with 20 music professionals of different age, experience and competences. The results of this assessment are presented in this paper for the first time. The music professionals are hereby identified with the labels “P1”–“P20” to keep them anonymous. The following personal information about the professionals was recorded as relevant to the study: main occupation, professional experience (measured in years), age, primary work tools. Such information is summarized in Tables 2, 3, 4 and 5. As a general remark on the subjects involved in the assessment, it must be pointed out that, on average, they are very experienced (Table 3): 13 out of 20 subjects (65%) have more than 25 years of professional activity, and 5 (25%) have more than 40. As a consequence, the subjects also tend not to be young (Table 4), with the median age being 50 years. The main occupation of the professionals (Table 2) is more varied, but, all in all, our sample

Table 2 Main occupation of the 20 professionals recruited for the assessment of the REMIND app

Main occupation	Professionals
Composer of electronic music	P1–P8
Musicologist, instructor (conservatory)	P9–P13
Musicologist, instructor (university)	P14–P17
Musicologist, Ph.D. in musicology	P18–P20

Table 3 Experience of the professionals

Experience	Professionals	Count
Up to 5 years	P1, P2	2
From 5 to 10 years	P3, P18, P19	3
From 10 to 15 years	P20	1
From 15 to 20 years	P4	1
From 20 to 25 years	None	0
From 25 to 30 years	P9, P14, P15	3
From 30 to 35 years	P5, P10, P16	3
From 35 to 40 years	P11, P12	2
From 40 to 45 years	P6, P13	2
More than 45 years	P7, P8, P17	3

Table 4 Age of the professionals

Age	Professionals	Count
Below 30	P1, P2	2
From 30 to 50	P3, P4, P18–P20	5
From 50 to 70	P5, P6, P9, P10–P16	10
More than 70	P7, P8, P17	3

Table 5 Tools used by the professionals involved in the study

Age	Professionals	Count
Max	P1–P5, P9, P12, P18, P20	9
Pure Data	P6	1
Audio editor	P1–P3, P5, P6, P9–P16, P18–P20	16
Music-composing software	P1–P3, P5, P6	5
Open-source software	P18, P19	2
Custom software	P15, P20	2
Listening to CDs	P5, P7–P16, P18, P20	13
Listening to vinyls	P17	1
Computer	P8	1
Scores	P5, P7, P8, P11, P13–P17	9
Study of the tools of the composer	P13	1

is split almost in half between musicologists and composers of electronic music. Both occupation and age have an impact on the work tools used by the professionals (Table 5). Composers and young subjects are, on average, more accustomed to the use of software tools, while musicologists rely more on listening to vinyls/CDs and on the direct study of the scores and other artifacts. However, 19 out of 20 professionals already utilize at least one computer tool during their work, the only exception being P17.

During the assessment, the music professionals were first toured through the main functions of REMIND, then allowed to interact with the app themselves (one of the authors of this paper was always present to answer any questions that might arise) on a 10-in. tablet and finally asked a set of 14 questions about their experience with the app. The questionnaire was designed to investigate whether specific choices in the app design (e.g., the navigation structure) were perceived as appropriate, and to what extent the app met the need of the professionals. The full questionnaire, with the actual text of all questions, is available in Appendix 1. Questions were answered on a five-level scale, with 0 always denoting the most negative opinion (“no,” “strongly disagree,” “totally lacking,” “completely inadequate” and “completely useless”) and 4 the most positive (“yes,” “fully agree,” “nothing is missing,” “perfectly adequate” and “very useful”). Non-numerical comments were also encouraged, especially for questions Q9–Q12, and recorded during the interviews. The answers of the professionals are summarized in Table 6. Full numerical answers are reported in Table 7 of appendix.

All in all, REMIND was received very positively by the professionals that were interviewed, regardless of their age and level of experience. The youngest and less experienced professionals—chiefly P1 and P2, but also P19—tended to be a bit less captivated. However, the app was consistently judged clear (Q1, Q2), self-explanatory (Q4) and easy to navigate (Q3). Nobody found any task to be unexpectedly difficult (Q9). A tablet was considered the right device for the app (Q8), and the touch screen a comfortable mean of interaction (Q5), albeit two professionals—P8 and P17—stated that it would be better to have a larger touch display. All the features implemented in REMIND were consistently regarded as useful (Q12). Even the skeuomorphic interface was generally credited as an interesting plus (Q6). Nonetheless, the professionals were eager to compromise fidelity for comfort: nearly all of them asked (Q7) for philologically questionable means of accessing music. Besides random access, the professionals asked for what the authors call “assisted access,” and chiefly for further automatic means of searching noises/defects, sounds or user-defined sound structures, even across several pieces of music. The structures should be defined via a formal grammar or, more conveniently, by recording the professional who plays them. Search results should be, of course, easy to listen and annotate. This wish for assisted access proves that the authors are evolving REMIND in the right direction. The professionals also demanded additional metadata and features currently not implemented in the app; hence, the low mean scores registered for questions Q10 (metadata) and Q11 (features). As it can be seen from Table 7, composers were happier than musicologists about metadata, but, of course, we regard musicologists as a more reliable source of advice on the topic. The most requested metadata were aimed at better documenting the defects on the tape, the instruments/equipment used during the original performance and the recording equipment itself. A significant number of professionals also asked for the possibility of adding custom metadata and annotations. Concerning features, the most requested additions were the possibility of analyzing the waveform and the spectrum of the signal (spectrogram, periodogram) and, again, the possibility of adding notes and bookmarks. Regardless of their severe judgement for Q10 and Q11, an overwhelming majority of the professionals declared that REMIND already has the potential of making their work more accurate (Q14), albeit not faster (Q13). Indeed, professionals such as P17, who are basically avoiding software tools in their work, tend to be particularly

Table 6 Summary results from the assessment of the REMIND app

	Mean	Median	Min	Max
Q1: Does the app always present information in a clear fashion?	3.7	4	3	4
Q2: Are text messages and icons clear and unambiguous?	3.4	3	3	4
Q3: Is the navigation structure easy to remember?	3.8	4	3	4
Q4: Is the app sufficiently self-explanatory?	3.5	3	3	4
Q5: Is the touch screen a convenient mean of interaction?	3.7	4	3	4
Q6: Is the skeuomorphic interface actually interesting?	3.2	3	1	4
Q7: Is it correct to have sequential access as the only option?	0.3	0	0	1
Q8: Is the physical size of the tablet adequate?	3.8	4	2	4
Q9: Were all tasks as easy as expected?	4.0	4	4	4
Q10: Are metadata complete, with no useful metadata missing?	1.8	1	1	4
Q11: Is the app complete, with no useful function missing?	1.6	1	0	4
Q12: Are all implemented features actually useful?	4.0	4	4	4
Q13: Would the app allow you to work faster?	1.8	2	0	3
Q14: Would the app allow you to work more accurately?	3.2	3	1	4

Ratings were given on a five-level scale from 0 (most negative) to 4 (most positive)

enthusiastic about the novel user interface of REMIND, about its ease of use and about the perceived impact of the app on the quality of their work.

As for the additional features requested, they are being evaluated for inclusion in future versions of the app, at different stages. Frequency analysis will be among the first additional tools to be added in a future release: even before the assessment, the authors were already aware that such a tool is definitely valuable. Non-sequential access, albeit technically easy, may be added at a later stage, since its proper inclusion in a philologically aware context requires a deep meditation on the design of the user interface.

5 Conclusions

This paper presents, for the first time, the full process for handling tape music archives, a process that encompasses the study of the chemical processes that deteriorate tapes (for others in-depth detailed chemical analyses, see [8]), the preservation of the tapes themselves (passive preservation), the transfer of the information on digital media (active preservation), the philologically aware access to the digital content. As discussed in Sect. 1, the fact that the process can be applied to tape music archives makes it extensible to other kind of audio media archives, e.g., Western classical music, opera, ethnomusic, speech corpora. Indeed, tape music is the most challenging genre, concentrating in itself all the issues (the composer directly manipulates the audio media, the score is often missing, the presence of concrete and/or electronic sounds together with acoustical instruments makes analysis difficult) that are typical in audio archives. As a proof of this statement, the authors completed in 2016 a research project on the active preservation of two collections of the "Teatro Regio di Parma" historical archive, thus successfully applying the process described above to opera and pop/rock music.

As a next step, the authors will enhance the REMIND and REWIND access tools (see Sect. 3). Besides incorporating the suggestions that emerged from the assessment of REMIND (see Sect. 4), the authors plan to include:

- de-noise (and de-crack, de-hiss, de-click) tools, allowing the users to improve the SNR of audio signals. The algorithms described in [13,16,33] will be considered (if the audio documents are recorded in a live scenario, using microphone arrays, see [42,43]);
- machine learning techniques to automatically find the correct equalization curve.

The process is the result of an ongoing effort involving several professionals with complementary backgrounds (musicians, musicologists, chemists, engineers) over multiple decades and spanning numerous research projects. Significant progress has been made with respect to [38], with tangible success, as documented in the following additional research projects carried out after the paper was published: 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).

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Table 7 Full quantitative answers for the assessment of the REMIND app

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14
P1	3	3	3	3	3	1	0	3	4	4	0	4	1	1
P2	3	3	4	3	4	3	0	4	4	1	1	4	2	3
P3	4	4	4	4	4	1	0	4	4	4	0	4	1	1
P4	4	4	4	4	4	4	0	4	4	4	3	4	3	4
P5	4	4	4	4	4	4	0	4	4	2	2	4	3	4
P6	4	3	4	3	4	3	0	4	4	1	3	4	2	3
P7	4	4	4	4	4	4	0	4	4	4	4	4	0	4
P8	3	3	3	3	3	3	1	2	4	2	1	4	0	3
P9	4	4	4	4	4	3	0	4	4	1	2	4	3	4
P10	4	3	4	3	4	3	0	4	4	1	1	4	2	4
P11	3	3	4	3	4	3	0	4	4	1	1	4	2	3
P12	4	3	4	3	4	3	1	4	4	1	1	4	2	4
P13	3	3	3	4	3	3	0	4	4	1	0	4	2	3
P14	4	4	4	4	4	3	0	4	4	1	2	4	2	3
P15	4	3	4	3	3	4	0	4	4	1	2	4	1	3
P16	4	3	4	3	3	4	0	4	4	1	2	4	2	4
P17	4	4	4	4	4	4	1	3	4	2	3	4	3	4
P18	3	3	4	3	4	4	1	4	4	1	1	4	2	2
P19	3	3	3	3	3	3	1	4	4	1	1	4	1	3
P20	4	4	4	4	4	4	1	4	4	1	1	4	2	3

Questions were answered on a five-level scale from 0 (most negative opinion) to 4 (most positive opinion). Professionals are identified with the labels “P1”–“P20” to keep them anonymous

Appendix: Assessment data

This appendix contains supplementary material about the assessment of the REMIND app (see Sect. 4). The assessment was based on a set of 14 questions, which are reported below.

Q1. Does the app always present information in a clear fashion?
Q2. Are text messages and icons clear and unambiguous?
Q3. Is the navigation structure (that is, how information is divided into several screens) easy to remember?
Q4. Is the app sufficiently self-explanatory?
Q5. Is the touch screen a convenient mean of interaction?
Q6. Is the skeuomorphic interface actually interesting, or do you consider it a secondary detail?
Q7. Do you think it is correct to offer no way of accessing music beyond sequential access (e.g., no random access)?
Q8. Are the dimensions of the tablet adequate?
Q9. Were all tasks easy (that is, no task that was thought to be easy proved difficult in practice)?
Q10. Are metadata complete (that is, no useful metadata is missing)?
Q11. Is the app complete (that is, no useful function is missing)?
Q12. Are all implemented features actually useful?
Q13. All in all, do you believe the app would allow you to analyze a piece of electronic music faster?
Q14. All in all, do you believe the app would allow you to analyze a piece of electronic music more accurately?

Full answers from the professionals are available in Table 7.

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