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iMuSciCA Workbench: Web-Based Music Activities For Science Education

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This paper presents the iMuSciCA Workbench, developed to address secondary school students with the aim to support mastery of core academic content on Science, Technology, Engineering, Arts, and Mathematics (STEAM) subjects, along with the development of creativity and deeper learning skills through the students’ participation in music activities. Herein, we focus on the technical implementation of the innovative music-related web environments hosted by the iMuSciCA Workbench.

0 INTRODUCTION

The iMuSciCA platform is a European-funded project that aims at providing a web-based workbench for the deeper learning of Science, Technology, Engineering, and Mathematics (STEM) subjects, by bridging STEM education with Arts (STEAM) and especially encouraging learners to participate in cocreative music activities [1]. Music plays a crucial role in cognitive development of humans from the early years of life as supported by multiple studies, which report that participation in music lessons is associated with higher academic abilities of students [2, 3].

Music and STEM resonate with each other within the iMuSciCA STEAM educational framework and work as a real paradigm of how art creativity can be fostered into STEM creativity and vice versa. iMuSciCA utilizes inquiry-based science education (IBSE) phases [4–7]—engage, imagine, create, analyze, communicate, and reflect—thus providing real evidence of the positive impact of the interaction between arts and science on the creativity and innovative thinking of learners. The main objective of the iMuSciCA project is to develop a set of practical activities for secondary education, in order to (i) give learners the opportunity to explore different phenomena and laws of physics, geometry, mathematics ,and technology through creative music activities, (ii) examine them from various viewpoints, and (iii) increase integration among various curriculum subjects contributing to innovative cross-disciplinary educational approaches.

This article is an extended version of the authors’ work originally presented at the WAC 2019 conference [8]. Additionally to the general architecture of the iMuSciCA web platform and its main components, in this paper, we introduce the iMuSciCA Learning Management System (LMS) that works as an entry point to the implemented Activity Environments (AEs). Furthermore, we describe a broad pilot-testing campaign that took place in three European countries, along with the usability assessment of the iMuSciCA platform as it was provided by trained educators.

1 THE IMUSCICA WORKBENCH

The iMuSciCA Workbench is the main web platform, in which the user is able to perform STEAM-related activities according to the iMuSciCA pedagogical framework. It provides a set of AEs and tools, categorized according to the different STEAM domains in music, science and mathe-

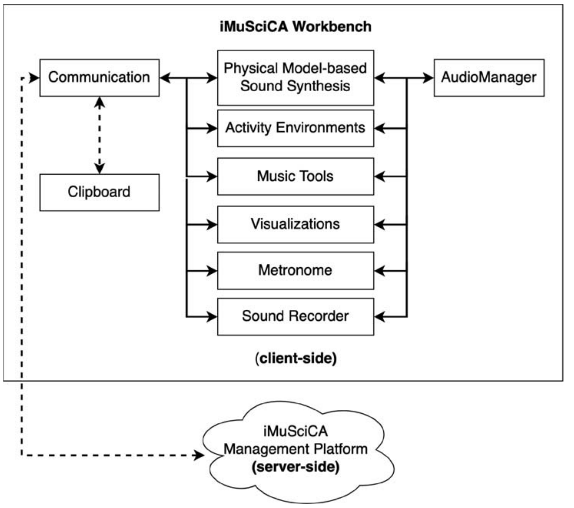


Fig. 1. General overview of the system architecture.

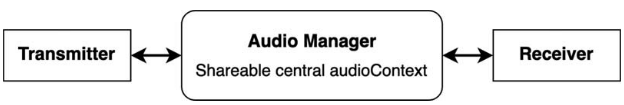


Fig. 2. The Audio Manager framework.

matics, engineering, and technology. The various tools and AEs are hosted in different web servers, hence the key role of the Workbench is to operate as the parent HTML document that loads the AEs as child *IFrame* elements, as well as provide a common communication framework for supporting their interoperability (see Fig. 1). The majority of the provided services are written in JavaScript and run on the user's browser (i.e., client side). Furthermore, our system provides cloud storage for saving user-generated data, such as 3D virtual instrument models and audio recordings. This functionality is handled by the iMuSciCA Management Platform (IMP), a server-side service [8]. The iMuSciCA Workbench can be accessed freely and it is available online (https://workbench.imuscica.eu/).

1.1 Communication Framework

The communication framework implements an internal protocol that was developed for exchanging information across the various AEs and tools. The communication protocol was implemented based on the *Postal.js* asynchronous in-memory message bus library, in order to facilitate the different performance delays of the AEs (https://github.com/postaljs/postal.js).

1.2 Audio Manager

Since audio data are generated and exchanged between a multitude of tools, the development of the Audio Manager framework (in order to have a centralized control throughout the iMuSciCA Workbench) was necessary. To this end, the *WebAudio* application programming interface (API) was employed for implementing the audio routing between the various audio modules, which can be working either as transmitters or receivers (see Fig. 2). When a tool or environment has to generate audio, it needs to get the *AudioContext* from the central Audio Manager of the iMuSciCA Workbench, create a transmitting node, and finally share it with the central Audio Manager by calling the corresponding function. The process followed in the case where a tool or environment wants to receive audio from the central Audio Manager is similar as well.

2 MUSIC TOOLS

2.1 Sound Recorder

The Sound Recorder (SR) tool enables the user to record the generated audio from the various AEs and tools that produce sound, as well as the microphone input. After the end of a recording, the user can play back the audio caption and save it to the IMP or copy it to the Workbench Clipboard. Additionally, the recorded audio is represented by a Blob object (i.e., raw data) that requires further compression in order to minimize its size and facilitate its transmission between the AEs via the communication framework, as detailed previously. To this end, all the compression and decompression processes are implemented with the *LZ-string* compression library (https://github.com/pieroxy/lz-string), which produces encoded 16-bit Unicode Transformation Format (UTF-16) strings that can be safely included in a *Postal.js* publish message.

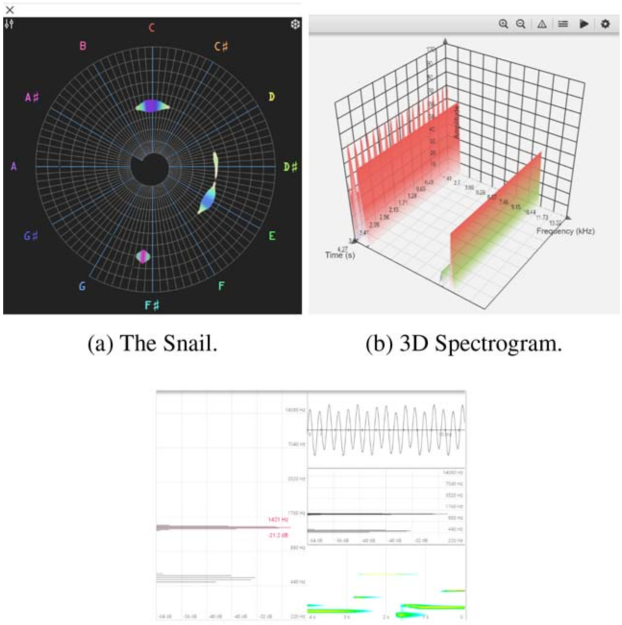
2.2 Metronome Tool

The Metronome tool (MT) provides the basic functionalities of an original metronome, including start, stop, and variable time signature (numerator and denominator) and resolution. The MT timer precisely calculates the beat intervals corresponding to the selected tempo, taking advantage of the accuracy of the *AudioContext.currentTime* property. A tool can retrieve from the Workbench MT information regarding the time and rhythmical configurations, as well as its events (pulses) in order to synchronize and schedule audio events.

3 PHYSICAL MODEL-BASED SOUND SYNTHESIS

The physical model-based sound synthesis engine utilizes a web port of Modalys [9], which tries to reproduce the sound of natural instruments as accurately as possible. Under this paradigm, sounding objects (strings, plates, bars, membranes, and tubes), described by their physical properties (such as geometry and material), can be linked with one another through specific interactions, such as striking, bowing, and blowing. The evolution of the physical model system is processed in real time according to the complex physics equations that rule the corresponding phenomena of both objects and interactions, resulting in a very subtle and lively sound.

The code base of the engine was originally developed in C++; in order to facilitate its usage in HTML5 environments, it was ported to JavaScript using the *Emscripten* (http://emscripten.org) transpiler and the *WebAssembly* framework (https://webassembly.org/). Then, a wrapper li-



(a) The Snail. (b) 3D Spectrogram.

(c) 2D Visualizations.

Fig. 3. The visualizations provided in the iMuSciCA web platform [8].

brary based on the *Web Workers* API was developed to enable the communication of the *WebAssembly* module with the Workbench Audio Manager and the rest of the AEs that employ the Modalys engine.

4 AUDIO VISUALIZATIONS

The iMuSciCA platform provides three visualization tools, namely the Snail, the 3D Spectrogram, and the 2D visualizations, which are briefly described as follows.

4.1 Snail

The Snail [10] is a real-time visualization application that incorporates an original spectral analysis technology, combined with a display on a spiral scheme, as it is depicted in Fig. 3(a). The center of the spiral corresponds to the lowest frequencies, and the frequencies gradually increase as the spiral extends outwards. Furthermore, each turn represents one octave so that the tones are organized with respect to angles. The spectrum analysis is displayed according to perceptive features, in a way that the loudness of the corresponding frequencies is mapped to both the line thickness and its brightness. The Snail was originally developed and implemented in C++, and it was ported to JavaScript using the *Emscripten* transpiler. The Fast Fourier Transform (FFT) algorithm runs on a *WebAssembly* module that communicates with the Audio Manager through an *ArrayBuffer*.

4.2 3D Spectrogram Visualizer

The 3D Spectrogram Visualizer (see Fig. 3(b)) utilizes the FFT of an *AnalyzerNode* in order to retrieve the frequency components that comprise the input signal originating from the main audio output of the Audio Manager. The required 3D graphics were developed with the *three.js* (https://threejs.org/) 3D library, which uses a *WebGL* renderer. On each frame, the rendering function checks if new data have arrived from the *AnalyzerNode* in order to update the displayed graphics with the current spectral values.

4.3 2D Visualizations

The 2D visualizations (see Fig. 3(c)) display the audio data of the Audio Manager main output node in three different HTML canvases; the first canvas displays the waveform in time domain, while the second and third canvases display the frequency domain analysis as it is computed from an *AnalyzerNode*. Specifically, the amplitude of the different frequency harmonics of the input signal (FFT) are displayed in the second canvas, while the third canvas presents the temporal variation of the signal frequencies (2D spectrogram).

5 ACTIVITY ENVIRONMENTS

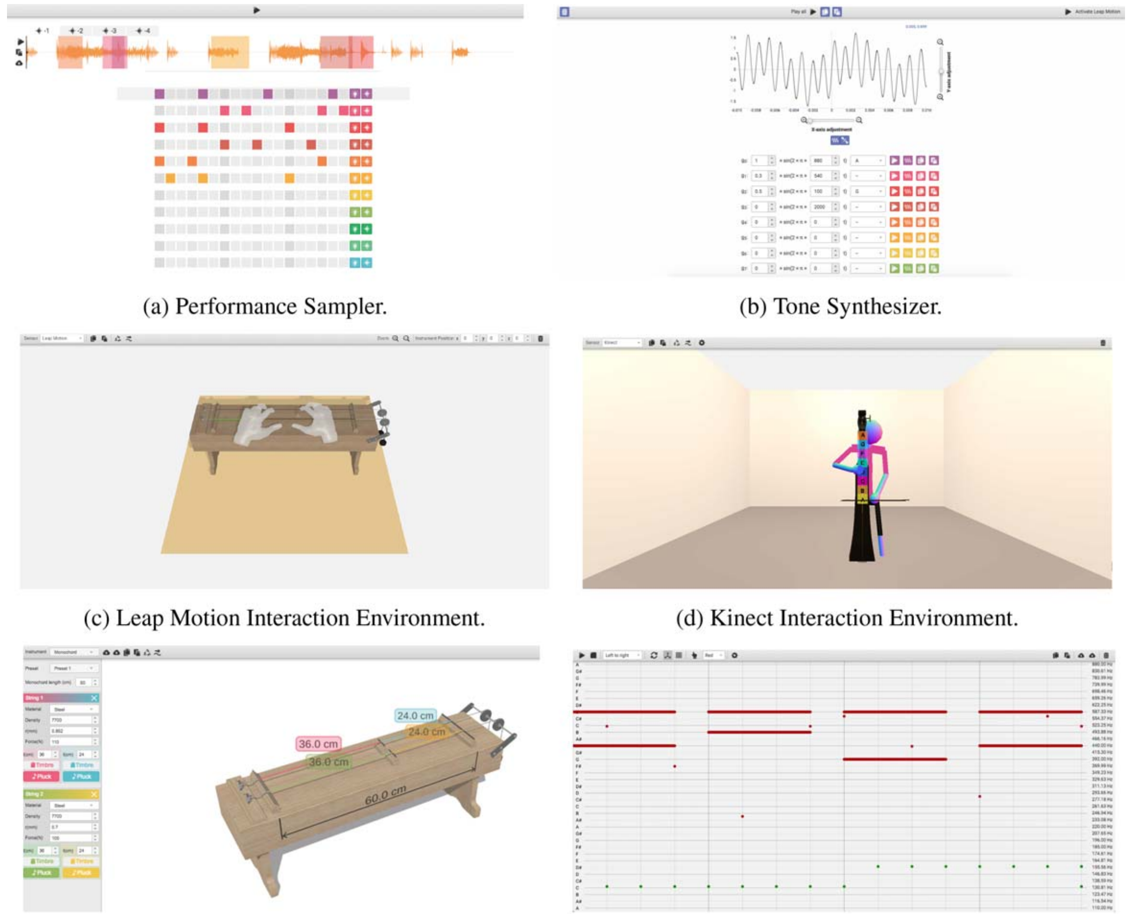
The iMuSciCA Workbench provides nine AEs in total. However, in this section, we focus only on those environments that support musical activities, including the Musical Whiteboard, Performance Sampler, Tone Synthesizer, 3D Instrument Design, and Interaction environments, as well as the Acouscope.

5.1 The Musical Whiteboard

The Musical Whiteboard (MW) is a web-based environment that enables the free drawing of music on touch-enabled computers [11]. The x-axis represents time, and the y-axis is mapped to the frequency domain that is displayed on the right in Hertz with a correspondence in notes on the left (see Fig. 4(f)). The user can draw on the canvas using either the mouse, his/her finger, or a stylus on a touch-sensitive computer, and the MW produces a live sonification of the drawn strokes. A variety of sound types (sinewave, triangle, sawtooth, and square waveforms) are supported, each represented by a particular, different color, thus enriching the overall music creativity. Once the tune drawing is complete, the user can play back the whole creation from left to right. For a wider range of frequencies, the user can use the zoom buttons to increase the frequency and time spans. Various options are available in the settings menu, such as activating the loop playback or the "snap-to-line" option, which constrains the strokes to be drawn on the note lines. The playback speed, time signature, and resolution are controlled from the Workbench MT.

5.2 Performance Sampler

The Performance Sampler is a tool that allows users to load up to four recorded waveforms (either from the clipboard or from the IMP), select parts from those recordings, and "program" the activation of each sample at specific time intervals through a sequencer matrix (see Fig. 4(a)). This tool is intended to allow exploration of compositions that can emerge from recordings created, for instance, with



(a) Performance Sampler. (b) Tone Synthesizer.

(c) Leap Motion Interaction Environment. (d) Kinect Interaction Environment.

(e) 3D Virtual Instrument Design. (f) The Musical Whiteboard.

Fig. 4. Screenshots of the music related Activity Environments provided by the iMuSciCA Workbench [8].

the 3D Instrument Interaction tool, in which users interact with virtual instruments in real time. The user can use up to 11 samples (number of rows in the sequencer matrix); the number of columns in the sequencer matrix depends on the time signature and time resolution selected by the Workbench MT and represents a duration of one bar. Additionally, the above factors affect the width of each cell in the sequencer matrix and the spacing between consecutive cells, giving a visual interpretation of the metrical setup of the Workbench MT.

5.3 Tone Synthesizer

The Tone Synthesizer (see Fig. 4(b)) is an environment for investigating the audio and visual behavior of combinations of sinusoidal functions. Moreover, the user can activate up to 10 sinusoidal waveform generators with a given frequency and amplitude and visualize, as well as listen to, the resultant waveform. It is also possible to load a “timbre” object exported from a virtual instrument, with the first 10 partials of the instrument being “assigned” to each sinusoidal element. In this case, the frequency and amplitude of the individual partials are adopted by the respective sinusoidal elements. In this sense, the waveform visualization is an analytic interpretation of the sinusoidal functions, rather than a representation of the actual produced waveform. The user can also manipulate the analytic waveform visualization by zooming in/out, moving horizontally/vertically, and applying optimal zoom, which focuses horizontally on two periods of the minimum frequency and vertically on the total amplitude of the waveform. Furthermore, by employing the Leap Motion sensor, one can utilize the Tone Synthesizer as a theremin-like digital musical instrument. Specifically, the amplitude and frequency values of the 10 sinusoidal elements are mapped to the x and y positions of the user’s fingertips, as they are calculated by the Leap Motion JavaScript SDK. The user needs to extend a finger in order to activate the respective sinusoid, whilst elements corresponding to nonextended fingers have zero amplitude. When the user activates the Leap Motion-enabled interaction, a graphical visualization provides real-time information about the frequency and amplitude that corresponds to each extended finger.

5.4 3D Virtual Instrument Design

The 3D Virtual Instrument Design environment (see Fig. 4(e)) enables the user to design 3D graphical models of predefined virtual instruments without requiring any advanced skills. Specifically, the environment provides six predefined instrument models, including circular and square-shaped membranes, a two-string monochord, a guitar, a tromba marina (bass monochord), and a xylophone. All 3D models are represented by the *Graphics Library Transmission Format* (glTF) format, which facilitates the data transmission throughout the iMuSciCA platform. In addition to the 3D editing functionalities, the user is able to modify and experiment with several physically based modeling parameters of the instruments, such as size, material density, and tension, and listen to the designed instrument through the Modalys engine.

The modular core engine is written in C++ and utilizes the *OpenGL* graphics library, thus enabling a cross-platform architecture. The proposed system utilizes the JavaScript port of the engine, which is produced with the *Emscripten* transpiler. In order to improve the environment performance and reduce its latency, the *WebAssembly* framework is utilized. From a technical perspective, the engine and the graphical user interface (GUI) are separate instances, meaning that the HTML UI communicates with the core engine through a proprietary API.

5.5 3D Instrument Interaction

The 3D Instrument Interaction environment enables the user to perform the 3D virtual music instruments by utilizing two motion sensors, namely the Leap Motion and the Microsoft Kinect sensors. Depending on the selected sensor, the 3D Instrument Interaction environment loads a different subsystem with the corresponding backend architecture. The different subenvironments are depicted in Fig. 4(c) and Fig. 4(d), respectively.

The main goals and technical details of the Leap Motion-enabled performance environment have been previously presented in [12]. Furthermore, previously developed heuristic-based interaction methods have been updated [12], while experimental deep Neural Network architectures have been employed for improving the gesture recognition module [13]. In this regard, new interactions were developed by introducing the virtual 3D models of a set of mallets, drumsticks, and a bow, in order to interact with the virtual xylophone, membranes, and the tromba marina, respectively. Specifically, when the user selects to play the xylophone or any of the two membranes, the position and orientation of his/her palm are mapped to a virtual mallet or drumstick, respectively. On the other hand, since performing the tromba marina entails continuous interaction between the movement of the bow and the string of the instrument, the user is required to perform a natural gesture, akin to holding a real bow, in order to control the horizontal movement of the virtual bow. Other supported modules that enhance the educational and creative aspects of the environment include a gesture recorder and a musical/rhythmical quantizer, enabling the user to edit his/her recordings while giving a deeper insight into his/her performances by reproducing the same visual and auditory feedback.

Regarding the Kinect-enabled environment, we have developed a local server written in C# that uses the *WebSocket* protocol for broadcasting the skeletal tracking data to the client, which, in our case, is the Kinect-enabled web environment. The server executable is available online (https://athena.imuscica.eu/software/kinect/-websocket/kinectImuscica.zip). The environment has been designed to support collaborative performances in which two players are able to perform different instruments [14], as well as support both hands as primary. Regarding the xylophone and the circular membrane, the instruments appear in front of the player's avatar for facilitating the subsequent interaction by using the hands as mallets. In the case of the tromba marina, the user's primary hand controls the virtual bow, whilst the nonprimary hand controls whether a note is played or not, depending on its position on the virtual fingerboard. The movement velocity of the primary hand also modifies the amplitude of the note. Similarly, in the case of the virtual air guitar, the user's primary hand performs plucking gestures to play chords, while the nonprimary hand selects the chord played through its placement in the virtual fingerboard. Furthermore, an automatic chord progression generation system has also been developed, facilitating dynamic interaction between the performer and the virtual air guitar [15].

All virtual instruments, excluding the tromba marina, produce sound by utilizing the "trigger" function of the Modalys engine, which is much faster and more computationally efficient, thus consuming less resources from the user's computer and improving the overall user experience of the AE. Since the tromba marina is a bowed instrument, it requires a continuous interaction approach for simulating the excitation of the string from the friction of the bow as it moves.

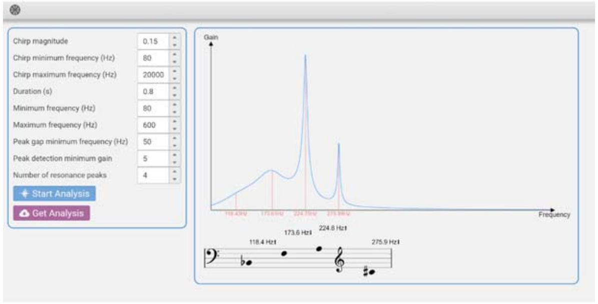
5.6 Acouscope

The Acouscope Environment employs a hardware device called HyVibe (https://www.hyvibe.audio/) that uses state-of-the-art actuation technology for identifying the frequency response of any surface. As presented in Fig. 5(a), the hardware comprises of two transducers: a) an electric actuator that is used for applying force on a surface and b) a piezo sensor for sensing and converting the reactive vibrations of the surface to an electric, measurable current. The transducers are connected through cable to a microcontroller that analyzes the frequency response of the surface through an embedded algorithm. The web interface (see Fig. 5(b)) communicates with the hardware through the Web Bluetooth API, in order to trigger the chirping sound that is sent to the attached surface via the electric actuator and then retrieve and display the FFT analysis of the vibration response, as it is sensed from the piezo sensor. Finally, the corresponding eigenfrequencies are visualized as a note sequence on a stave based on the *VexFlow* (https://www.vexflow.com/) music notation JavaScript library.

6 THE IMUSCICA LEARNING MANAGEMENT SYSTEM

From the user perspective, either being a learner or an educator, the iMuSciCA Learning Management System

(a) The HyVibe device.



(b) Acouscope Web Interface.

Fig. 5. The Acouscope system [8].

(LMS) is the main educational entry point to the AEs, and it is accessible online (https://lms.imuscica.eu). This LMS builds on top of a standard Moodle environment (https://moodle.org/). Furthermore, the LMS comprises the individual educational scenarios and their corresponding descriptions in a form that is adapted to learners, with directive links to the AEs and tools on the iMuSciCA Workbench. The LMS is also useful to organize and store the learning activities. Teachers and students need to create a personal account to gain access to the LMS. When users follow learning content through the LMS, they produce "activity" data (question/answers, marks, current progress within an activity, etc.), which are stored in a repository. This way, teachers can track the activities of the students and give online feedback. Additionally, teachers can either use the existing scenarios created by the iMuSciCA consortium or create their own and upload them on the LMS.

7 PILOT TESTING

The pilot testings of iMuSciCA were conducted in Belgian, French, and Greek schools from April 2018 to June 2019. The main sources of information and feedback that have been utilized in order to refine and improve the existing educational scenarios, as well as to provide feedback regarding the various iMuSciCA AEs as collated on the iMuSciCA Workbench, include the following:

- Feedback from educators participating in teacher training sessions or in the iMuSciCA Summer School, which took place from July 1–6, 2018, at Marathon, Greece.
- Constant feedback from the in-service teachers involved in the piloting campaigns at schools in Belgium, France, and Greece.
- The reactions and performance of the students, who have been learning with the iMuSciCA Workbench and related scenarios.
- Feedback provided by European students who participated in a one-week summer camp organized by the Ellinogermaniki Agogi school in Greece.

Table 1 summarizes the number of teachers and students who participated in the piloting phase of the iMuSciCA framework. Students were between 11 and 16 years old, while more than half of the responding educators were between 45 and 60 years old. Based on the piloting activities, detailed feedback was given to the developers of the different Workbench AEs and tools, on the basis of which all were updated. These updated tools formed, then, the occasion again to improve the scenarios. This feedback loop worked numerous times, and multiple documents, along with distant meetings, were organized to streamline the information flow between teachers, the pedagogical team, and developers. This makes the educational scenarios of iMuSciCA unique in their kind. For instance, the inquiry questions were optimized throughout most of the educational scenarios. Certain formulations, tables, and graphs were simplified, based on the experiences obtained by the in-classroom applications. Clearer examples were added, and sometimes, even activities, tasks, and exercises were rewritten, requiring new functionalities to be added to the different AEs by the developers of the platform.

Having as a starting point the Summer School at Marathon, 29 teachers from all around Europe were trained by the iMuSciCA consortium on the pedagogical framework and the AEs of the presented Workbench. After completing their training, the participating educators were working in small mixed groups involving at least one music and one science teacher in order to draft their own Educational Scenarios. At the end of the Summer School, the educators evaluated the usability of the platform. We follow the System Usability Scale (SUS), which is a reliable, low-cost usability scale that can be used for global assessments of systems' usability. It consists of a 10-item questionnaire with 5 response options for respondents, ranging from "Strongly agree" to "Strongly disagree." Furthermore, 5 questions have a positive connotation (e.g., Q3: I thought the system was easy to use); 3 questions have negative connotation (e.g., Q2: I found the system unnecessarily complex); and 2 can be characterized as neutral (e.g., Q4: I think that I would need the support of a technical person to be able to use this system).

Fig. 6 presents the usability assessment provided by the 29 educators. By analyzing the responses, it becomes obvious that the usability testing was done in a consistent manner. Statements with a positive direction generally reached values above the theoretical average. In turn, statements with a negative connotation scored below the theoretical average, thus supporting the positive assessments of the iMuSciCA Workbench. Finally, neutral statements were lo-

Table 1. Participants in piloting activities of the iMuSciCA framework in Greece, Belgium, and France.

Implementation in Real Classroom Settings				
	Greece	Belgium	France	**Total**
Students	226	364	50	**640**
Teachers	40	40	11	**91**
Summer Camp for Students				
Students	17	-	-	**17**
Summer School/Webinars/Workshops for Teachers				
Teachers	29	59	-	**88**

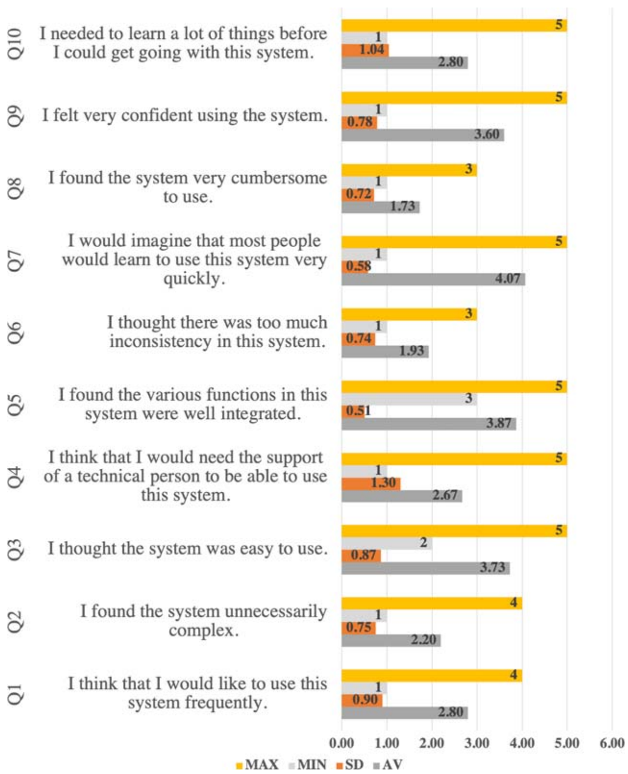


Fig. 6. Perceived usability of the iMuSciCA Workbench by educators.

cated around the theoretical average of 3. Overall the majority of educators believe that the iMuSciCA Workbench is both simple to use and well integrated, and thus, potential users will learn how to use the iMuSciCA Workbench equally easily.

8 DISCUSSION AND CONCLUSIONS

In this paper, we present the iMuSciCA Workbench, an innovative pedagogical framework with cutting-edge technologies for carrying out STEAM activities. Furthermore, the Workbench provides a set of musical AEs, as well as visualizations and various tools for supporting and enhancing the interdisciplinarity of the learning process.

From a technical perspective, our goal was to develop an easily accessible and operating system (OS)-independent platform. In this sense, we decided to implement the iMuSciCA Workbench as a web application by employing state-of-the-art web APIs and libraries. The various tools and AEs are hosted on different web servers, which are loaded as child *IFrame* elements within the iMuSciCA Workbench parent HTML document. In order to support their interoperability and handle the different performance delays, we developed a common communication framework based on the *Postal.js* asynchronous message library. Our system leverages the modular design of the WebAudio API for implementing the Audio Manager framework, which functions as a centralized controller for routing audio data across the AEs and tools. Additionally, the MT timer employs the accuracy of the *WebAudio AudioContext.currentTime* property for calculating the beat intervals of the selected tempo.

Large JavaScript objects, such as 3D instrument models (glTF format) and audio recordings (Blob objects), are compressed using the *LZ-string* library. This approach facilitates their transmission and minimizes their memory footprint. Computational-heavy AEs and tools were initially running as server-side services; however, the additional network overhead was an important drawback, affecting the overall user experience. After testing out various system architectures, we decided to employ the *Emscripten* transpiler and the *WebAssembly* standard in order to run these programs as client-side services, while the *Web Workers* API provided us the foundations for implementing the appropriate wrapper libraries.

The feedback from teachers emphasized the high standards they need in order to convert valuable ideas into educational realities. Teachers' contributions towards the process of developing the educational scenarios have, therefore, been crucial in capturing both the educational practice that emerges from their daily educational objectives and from the evolution of the available technologies of the iMuSciCA Workbench.

9 ACKNOWLEDGMENT

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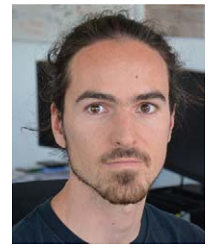
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