Music Tangible User Interfaces and Vulnerable Users: State of the Art and Experimentation

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Abstract. Tangible user interfaces (TUIs) let users manipulate digital information with their bodies and perceive it with their senses. This concept can be applied to the control of digital musical instruments and, in a more general context, music-oriented devices. Specifically addressing vulnerable users, namely people in a condition of cognitive and/or physical impairment, this paper presents the state of the art about music TUIs and describes an experiment conducted on a small group. The methodology consisted in building user-tailored experiences to let participants acquire basic musical skills with a hands-on approach implemented through an ensemble of digital instruments. The achieved results included both the improvement of music competencies in vulnerable users and the acquisition of soft skills.

Keywords: Music · Tangible User Interfaces · Computer-supported education · Educational vulnerability · Social disadvantage · Accessibility · Educational poverty.

1 Introduction

A relevant research question in the field of sound and music computing concerns if and how technology can bridge the gap between musical activities (including learning, composition, performance, etc.) and physical and cognitive users' impairments.

The scientific literature shows that digital technologies can help in a number of ways: for example, a computer-based system can substitute and/or augment a standard musical instrument [22,33,43], pave the way for unleashing creativity [47,48,60], provide alternative interfaces suitable to overcome impairments [31,35,51], and encourage the development of music-related skills [5,10,54]. According to [45], music teaching through information technology can also affect behavior relating to learners' online learning attitudes, music learning motivation, and learning engagement. The ubiquity of portable devices (notebooks, tablets, smartphones, etc.), equipped with ad-hoc hardware accessories, suitable software tools, and easy-to-use interfaces, can represent a solution even in vulnerable contexts.

Please note that disability and aging are not the only factors that hamper the development of musical skills; also conditions of social disadvantage may constitute a barrier [14,36,46].

Music is learned and taught in multiple ways depending on the socio-cultural contexts in which learning occurs, and musical activities should be culturally responsive and meaningful so as to respond to diverse learning contexts [13]. Critical aspects such as user-friendliness, usability, accessibility, affordability, and suitable use of multimodality must be considered.

In this work, we propose the use of tangible user interfaces both as musical instruments to use in conjunction with traditional ones and as an orchestra. The goal of the experimentation we conducted was to foster musical expressiveness and interaction between users in conditions of social disadvantage. Participants were characterized by cognitive and/or physical impairments or they had a background of educational poverty.

The key research questions we aim to answer are:

- RQ1. Can tangible user interfaces encourage the acquisition of basic musical skills in socially-distressed subjects?
- RQ2. Can an ensemble of music tangible user interfaces foster soft skills such as socialization and cooperation among peers?
- RQ3. Can these results be measured or somehow assessed?

In the following, we will try to answer these questions. To this end, the present work is organized as follows: Section 2 will define the concept of tangible user interface (TUI) and provide the state of the art; Section 3 will focus on music TUIs; Section 4 will describe the experimental activities, including some previous experiences, the details of project "Note Digitali", and the experimental setting; Section 5 will focus on the results achieved and propose possible strategies to measure users' performances; finally, Section 6 will draw the conclusions.

Please note that this paper is an extension of the work presented at the 5th International Conference on Computer-Human Interaction Research and Applications (CHIRA 2021) [12].

2 Tangible User Interfaces

Tangible user interfaces (TUIs) replace the graphical user interfaces (GUIs) typical for user interaction in computing systems with real physical objects. The key idea is to give digital information a physical form and let these physical forms serve as a representation and control for digital information. A TUI lets users manipulate digital information with their bodies and perceive it with their senses. One of the pioneers in tangible user interfaces is Hiroshi Ishii, a professor at MIT who heads the *Tangible Media Group* at the MIT Media Lab. His particular vision for TUIs, called *Tangible Bits*, is to give physical form to digital information, making bits directly manipulable and perceptible [40]. *Tangible Bits* pursues the seamless coupling between physical objects and virtual data.

TUIs aim to overcome some limitations posed by classic computer interaction, offering intuitive ways to build complex structures, manipulate parameters, and connect objects. TUIs use physical forms that fit seamlessly into a user's physical environment, giving physical form to digital information and taking advantage of haptic-interaction skills [41]. All physical objects can potentially be a part of a digital user interface [39]. For example, if an object, which is part of a TUI, is moved or put in a specific position, a digital signal will be sent from either the tangible object itself or from another device that senses the object.

Currently, there are different research areas and applications related to TUIs. For instance, tangible augmented reality implies that virtual objects are "attached" to physically manipulated objects; in tangible tabletop interaction, physical objects are moved upon a multi-touch surface; moreover, physical objects can be used as ambient displays or integrated inside embodied user interfaces.

Since TUIs make digital information directly manipulatable with our hands and perceptible through our peripheral senses, this approach can be particularly effective for young [68] and disadvantaged users [1,17,28].

One of the scenarios where TUIs are particularly effective is gamification. Focusing on recovering from physical impairments, games can be used to increase the motivation of patients in rehabilitation sessions. Motivation is one of the main problems evidenced in traditional therapy sessions, often hampered by the repetitive nature of exercises. Most studies show that effective rehabilitation must be early, intensive, and repetitive [16,59]. As such, these approaches are often considered repetitive and boring by the patients, resulting in difficulties in maintaining their interest and in assuring that they complete the treatment program [59]. On the other hand, due to their nature, games can motivate and engage the patients' attention and distract them from their rehabilitation condition. On one side, they require some motor and cognitive activity, and, on the other, they can offer feedback and levels of challenge and difficulty that can be adapted to the patients' skills. We can see similar advantages in the development of domain and soft skills for other categories of impaired users.

Serious games are an option that provides learning combined with entertainment. The locution "serious games" refers to playful activities that provide training and physical or mental exercise in a fun and enjoyable way [25]. These games can be not only a way to prevent the feeling of loneliness [24], but they can also enable social interaction [30]. During the last decades, digital games have become a popular leisure activity.

A quite obvious field of application for tangible interfaces is the overcoming of visual impairment through gamification [49,55,58]. Different forms of physical impairment have been addressed as well.

For example, *Handly* is an integrated upper-limb rehabilitation system for persons with neurological disorders [65]. *Handly* consists of tangibles for training four-hand tasks with specific functional handgrips and a motivational game.

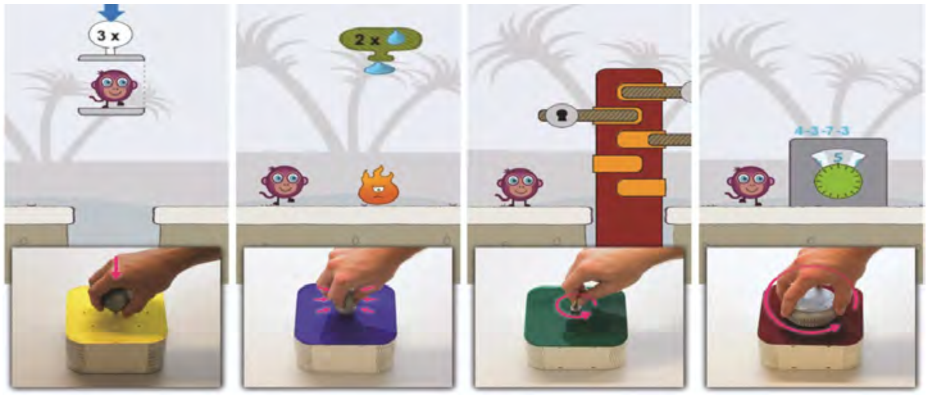

Fig. 1. The user interface and some gestures supported by *Handly*. Images were taken from [65].

The system consists of four tangible training boxes, which each present one essential grip and associated hand task: push-pull, squeezing, knob turning, and key turning (see Figure 1). *Handly* combines tangibles specifically designed for repetitive task-oriented motor skill training of typical daily activities with serious gaming, thus offering a comprehensive approach. *Handly* focuses on therapy for various neurological disorders that can cause functional disabilities in the hands.

Segara is an integrated hand rehabilitation system for patients with rheumatoid arthritis (RA) very similar to *Handly* [69]. *Segara* consists of tangibles for training six tasks with Interactive functional handgrips and a motivational serious game (see Figure 2). It shows that a system combining games and tangibles to enhance hand rehabilitation is feasible and highly appreciated by patients.

Resonance is an interactive tabletop artwork that targets upper-limb movement rehabilitation for patients with an acquired brain injury [26]. The artwork consists of several interactive game environments, which enable artistic expression, exploration, and play. *Resonance* provides uni-manual and bi-manual game-like tasks and exploratory creative environments of varying complexity geared toward reaching, grasping, lifting, moving, and placing tangible user interfaces on a tabletop display (see Figure 3). Each environment aims to encourage collaborative, cooperative, and competitive modes of interaction for small groups of co-located participants.

NikVision is a tangible tabletop based on a user-centered design approach for the cognitive stimulation of older people with cognitive impairments and dementia problems in nursing homes [18]. The general experiences of the users when working with the tangible tabletop were assessed and applied to the design of new cognitive and physical stimulation activities. From these experiences, guidelines for the design of tangible activities for this kind of user were extracted for the design and evaluation of tangible activities that could be useful for other researchers. *NIKIVision*'s game activities are specially designed for the elderly

Fig. 2. The user interface and some examples of activities with *Segara*. Images were taken from [69].

and have different levels of difficulty and audio feedback. The list of activities includes:

- *Clothes Activity* — Based on the daily task of getting dressed, users interact with the tabletop by using different objects with realistic drawings of pieces of clothing and letters. Fine motor skills are addressed when users have to pick up the two-dimensional objects to place them on the tabletop;
- *Shapes Activity* — Users have to select the indicated geometrical shapes and situate them on the box displayed on the tabletop;
- *Roads Activity* — Focusing on upper-half motor skills, users have to move the object on the tabletop surface by following a virtual road, also avoiding physical obstacles in the most difficult levels. The objects with which the users interact are different handles designed to stimulate different kinds of grabbing actions.

It is worth remarking that, when the applications are not explicitly conceived for impaired users, gamification can also pose critical issues. For example, Smith and Abrams [63] explore the issue of access to digital technology by using the lens of accessibility. More specifically, this paper considers the needs of all learners, including those who identify as disabled, and raises important inquiries about equity and access to technological instructional materials. Notably, online courses enhanced with gamification elements present potential access barriers and challenges to learners who identify with auditory, cognitive, neurological, physical, speech, or visual disabilities.

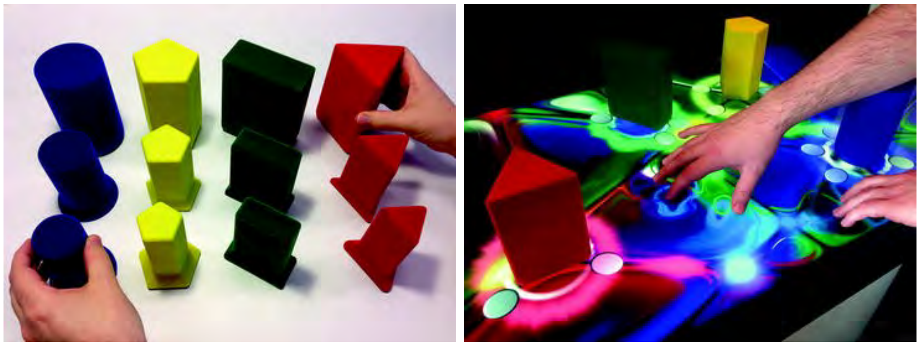

Fig. 3. The user interface and a play session of *Resonance*.

3 Tangible User Interfaces for Music

Music TUIs apply the concept of tangible interfaces to the music field. As demonstrated by the scientific literature and a number of commercially-available applications, TUIs are being profitably used in musical performances and music therapy.

A tangible interface provides the user with a physical way to interact with music and sound parameters. In this sense, the advent of digital technologies paved the way for innovative and original approaches. Music TUIs can play a number of roles: for example, synthesizers to generate sound, sequencers that perform audio samples and mix them together, remote controllers for music and sound parameters, or interfaces for music-related games.

A key concept is the one of *music embodiment*: it can be defined as a corporeal process that enables the link between music as an experienced phenomenon and music as physical energy [44]. This process focuses on the cognitive relationship that ties musical subjects and objects, an idea critically analyzed and reworked by Schiavio and Menin [61].

Music TUIs are a technological means able to support and encourage music embodiment, thus breaking down the barriers that hinder musical creativity and expressiveness, especially in young people and impaired performers. On one side, a tangible interface offers a physical way to interact with music and sound parameters, somehow recalling the kind of interaction of traditional musical instruments; on the other side, it can simplify the process, e.g., making it more accessible and intuitive.

In the following, we will mention some musical applications (Section 3.1) and then we will focus on the *Kibo*, namely the device that we adopted in our experimentation (Section 3.2).

3.1 Musical Applications of TUIs

Many music TUIs are based on *fiducial markers*, or simply *fiducials*, namely objects placed in the field of view of an image-recognition system with functions of control, user input, reference, or measure. Examples of fiducials include:

- 2D markers, e.g. barcode systems or pictograms [29];
- basic 3D geometrical shapes, e.g. multi-faceted cubes [57];
- 3D printed objects, e.g. diorama models of musical instruments [4].

For example, the principle of fiducials is fully exploited in the *Reactable*, a digital musical instrument developed by the Music Technology Group at the Universitat Pompeu Fabra in Barcelona [42]. The *Reactable* employs fiducials to generate and control music and sound parameters. This device has a tabletop tangible user interface formed by a round translucent table used as a backlit display. Special blocks called *tangibles* (see Figure 4) can be placed on the table and moved by the user according to the intended result; their geometrical and spatial characteristics are detected in real time by the image-recognition system, that, in turn, pilots the virtual modular synthesizer to create music or sound effects. Currently, there are two versions of the *Reactable*: *Reactable Live!* and *Reactable experience*. The former is a smaller, more portable version designed for professional musicians. The latter is more similar to the original *Reactable* and suited for installations in public spaces.

Another fiducial-based framework for music is *D-Touch* [20], which defines a class of tangible media applications implementable on consumer-grade personal computers. *D-Touch* fiducial markers for music-performance applications are shown in Figure 5.

BeatBearing is a do-it-yourself (DIY) project.[3] This tangible rhythm sequencer is made of a computer interface overlaid with the grid pattern of metal washers and ball bearings. The system is controlled by an Arduino microcontroller.

Many working prototypes have been described in the scientific literature.

In 2001, Paradiso *et al.* reviewed some initiatives based on magnetic tags, including *Musical Trinkets*, an installation based on tagged objects publicly exhibited first at SIGGRAPH 2000 and, several months later, at SMAU in Milan [52].

In 2003, Newton-Dunn *et al.* described a way to control *Block Jam*, a dynamic polyrhythmic sequencer using physical artifacts [50]. The idea of a tangible sequencer addressing the preparation and improvisation of electronic music is also the foundation of a more recent platform called *mixiTUI.* [53].

Modular sound synthesis is addressed by the *Spyractable* described in [56]. This platform reconfigures the functionality of the *Reactable* and redesigns most features, adjusting it to a synthesizer's needs.

[3] https://www.jameco.com/Jameco/workshop/JamecoFavorites/beatbearing-rhythm-sequencer.html

Fig. 4. The fiducial markers of the *Reactable*. The picture is taken from [23].

The *MusicCube*, described in [2], is a wireless cube-like object that lets users physically interact with music collections using gestures to shuffle music and a rotary dial with a button for song navigation and volume control. In 2008 Schiettecatte and Vanderdonckt presented *AudioCubes*, a similar product consisting in a distributed cube interface for sound design [62].

Finally, it is worth mentioning the *TuneTable* [67], a platform based on programmable fiducials for music coding (Figure 6). This approach was assessed in a computational musical tabletop exhibit for the young held at the Museum of Design, Atlanta (MODA). Workshop activities had the goal of promoting hands-on learning of computational concepts through music creation.

For a more up-to-date and comprehensive review of music TUIs in the scientific literature, please refer to [8].

3.2 Kodaly *Kibo*

The *Kibo* by Kodaly is a wooden board presenting eight unique geometric shapes that can be inserted into and removed from suitable slots. This device, also sensitive to pressure variations on single tangibles, returns the dynamic response of a polyphonic acoustic instrument.

The main control over music parameters is realized through a set of 8 easily-recognizable tangibles, shown in Figure 7. Each object has a different shape fitting in a single slot. Tangibles present symmetry properties so that they can be rotated and flipped before being inserted in their slots. They have a magnetic core, consequently, they can be also stacked one on top of the other. The body of

Fig. 5. The fiducial markers of *D-Touch*. The picture is taken from [20].

the *Kibo* contains a multi-point pressure sensor that allows the detection of the insertion and removal of tangibles. The characteristics of the sensor make the instrument both extremely sensitive and very resistant. Concerning the former aspect, it is sufficient to bring a tangible closer to the body to trigger a reaction; similarly, the gentle touch of fingers over an already plugged tangible is recognized as a pressure variation. Concerning robustness, the *Kibo* has been designed to tolerate strong physical stresses, like punches and bumps. A distinctive feature is the possibility of detecting pressure variations over tangibles.

The *Kibo* can be connected via Bluetooth or USB to iOS and macOS devices running a proprietary app, that acts both as a synthesizer and a configuration center. Windows and Android operating systems are also supported via third-party drivers.

The communication between the controller and the app occurs by exchanging standard MIDI 1.0 messages. The MIDI engine integrated into the app supports up to seven *Kibo* units simultaneously, without perceivable latency. Being a fully compatible controller, the *Kibo* can also be integrated into any MIDI setup without the intervention of the app as a mediator.

In addition to the advantages of any music TUI, the *Kibo* was chosen for the "Note digitali" project because this device simplifies the establishment of a network of musical instruments working together like an orchestral ensemble [3].

Moreover, the app natively embeds three operating modes that are particularly useful in educational, rehabilitative, and therapeutic fields [9]:

1. *Musical Instrument Mode* — In this scenario, *Kibo*'s tangibles are usually mapped onto pitches. Associations between shapes and notes can be cus-

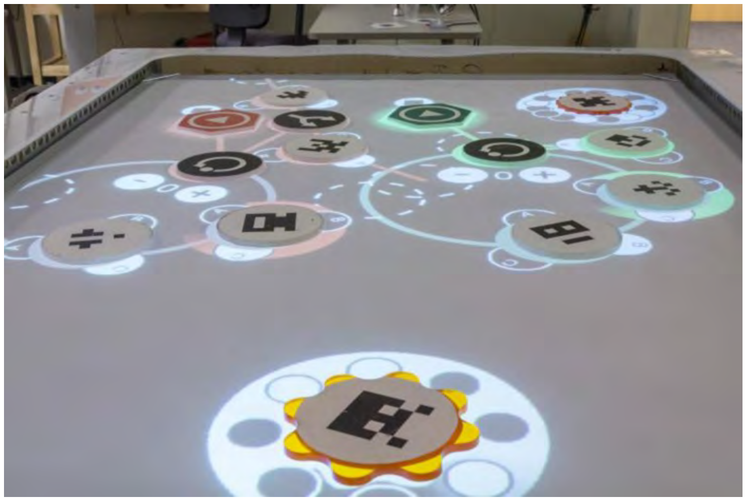

Fig. 6. The fiducial markers of *TuneTable*. The picture is taken from [32].

tomized; in this way, the device is not bound to a fixed association (e.g., a C-major scale), but it supports key changes, other scale models, non-standard note layouts, etc. Through suitable processing of MIDI messages, a single key could also trigger multiple musical events, e.g. custom chords or arpeggios. The metaphor of a keyboard controller is further extended by the *aftertouch* effect, namely the possibility to detect pressure variations over tangibles after note attacks;

2. *Beat Mode* — In this scenario, tangibles are mapped onto single percussive instruments. The pressure sensor, presenting a high level of resistance to strong mechanical stresses but also a noticeable sensitivity, allows effects ranging from hard mallet beats to delicate brush rubbing. With respect to the previous one, such an operating mode greatly simplifies the interaction and makes the performance more intuitive for beginners; for example, the melodic and harmonic dimensions of music are absent, and a number of musical parameters (e.g., the release time for notes) are ignored;
3. *Song Mode* — In this scenario, the *Kibo* is employed as a controller to trigger already available music loops. Tangibles are associated with mutually synchronized but independent tracks, like in a multi-track environment. When tangibles are inserted, the corresponding tracks are activated; when they are removed, tracks are muted (but they keep running silently, so as to preserve global synchronization). This type of interaction with music content is particularly suitable to engage users who are not able or do not wish to create their own music.

The reconfigurability of the *Kibo*, coupled with the adoption of standard communication protocols, enables numerous heterogeneous scenarios. Multiple *Kibo* units in an ensemble can be set to cover distinct note ranges and timbres, or

Fig. 7. The *Kibo*'s body and tangibles.

even to work in different operating modes, thus providing the teacher with great flexibility. Additional operating modes could be easily implemented by assigning other meanings, even extra-musical ones, to the MIDI messages generated by the *Kibo* via ad-hoc software interfaces.

4 Experimentation

4.1 Background

The current proposal is rooted in some previous music-therapy experiences conducted by the same working group with the help of digital technologies, as documented in [7,11]. Also in that case, the idea was to employ a computer-based interface in order to overcome the physical and cognitive impairments that often hamper musical activities in users with disabilities. Such a goal only partially overlaps the one of the "Note Digitali" project; in fact, in the scenario described below, not only impairments but also conditions of social disadvantage will be considered.

Other key differences with respect to the aforementioned experiences must be remarked. First, from a technical point of view, human-computer interaction did not occur through a music TUI but through the *Leap Motion* controller, an optical hand-tracking module able to detect and capture the movements of the user's hands with great accuracy [66]. The applicability of such a device to music recalls the concept of "air" musical instruments, i.e. virtual instruments employing depth cameras or other sensor systems to implement an interaction paradigm based on performing gestures in the air, without touching a physical interface [34]. Examples have been documented and discussed in [21], [27], and [64]. Conversely, the "Note Digitali" project (discussed later) employs the *Kibo*, the music TUI described in Section 3.2. Clearly, this kind of interface completely changes the human-computer interaction paradigm.

Moreover, in previous experiences, the musical performance mainly involved only the impaired user – interacting through the *Leap Motion* controller – and the therapist – playing a traditional instrument. The social aspects typical of making music together were limited to the relationship between a single learner and his/her educator. Conversely, the proposal detailed below will focus on peer-to-peer interaction between multiple performers, whereas the main roles played by the instructor will be to explain, help, and propose musical activities.

The scientific literature reports other experiences of ensemble playing on digital instruments. For example, the aspects of human interaction and communication in a digital music ensemble have been addressed by Hattwick and Umezaki [37,38]; Ben-Tal and Salazar proposed a new model for collaborative learning based on the connections between the technological tools and the social frameworks in emerging digital music collectives [15]; Cheng investigated the development of musical competency in a laptop ensemble [19].

With respect to other similar initiatives, our proposal presents novel features regarding the expressiveness of the selected digital device, the availability of a fine-tuned learning environment, and the attention paid to affective and emotional aspects. These characteristics will be better clarified in the next sections.

4.2 The "Note Digitali" Project

The initiative described in this work was launched in response to "Call 57" by *Fondazione di Comunità di Milano - Città, Sud Ovest, Sud Est e Adda Martesana ONLUS*. In this framework, the project "Note digitali" (in English: digital notes) provided the common umbrella to host different activities dealing with music and disadvantaged people. The project involved three partners:

1. *Laboratorio di Informatica Musicale* (Laboratory of Music Informatics), Department of Computer Science, University of Milan. Established in 1985, it is one of the most relevant Italian research centers dealing with sound and music computing;
2. *Casa di Redenzione Sociale* (House of Social Redemption), Milan. Founded in 1927, this institution has been conducting activities in both the social and cultural fields, specifically addressing problems linked to the context of the northern suburbs of Milan: fragmentation of the social fabric, widespread educational poverty, and lack of public spaces;
3. *Fondazione Luigi Clerici*, Milan. In operation since 1972, this foundation offers vocational courses and apprenticeship initiatives, also for adult and impaired students. The mission is to create a network able to integrate education and organizational skills in collaboration with public and private authorities, local institutions, trade associations, and social organizations.

Fig. 8. The hardware equipment used during the experimental activity: five *Kibo* units and an *Apple iPad*. The picture is taken from [12].

The project was conceived as an experiment of cultural citizenship where music turns into a means of self-empowerment and social cohesion. The goals included providing basic musical competencies and skills, fostering creativity, and, above all, encouraging interaction and socialization in vulnerable participants. The expected results included the promotion of participation in the socio-cultural life of the community by people with different types of disabilities, the perception of music as a means of aggregation, and self-empowerment, namely the self-discovery for the participants of their skills and abilities.

4.3 The Experimental Setting

Workshop activities were conducted in small groups under the guidance of an experienced tutor in a time span from December 2020 to May 2021.

The basic hardware equipment used during the experimental activity included 5 *Kibo* units connected to an Apple iPad via Bluetooth Low Energy (BLE), as shown in Figure 8. The room where most activities took place was also equipped with traditional and digital musical instruments, such as drums and an electric piano (Figure 9). This setting provided the tutor with many options, including the exclusive use of *Kibo* units (with or without the direct involvement of the tutor) and mixed performances with traditional instruments, specifically the piano and the ukulele. In the latter scenario, the tutor was the only performer enabled to play a non-digital instrument. Most participants had no previous music knowledge, so the function of the tutor was basically to explain musical concepts and guide learners toward an autonomous performance.

Fig. 9. The classroom where workshop activities took place. The picture is adapted from [12].

The current technical limitations of BLE currently limit the total amount of *Kibo* units simultaneously connected to a single mobile device: the maximum amount is 7. In the case of an expanded *Kibo* orchestra, such a constraint can be overcome by employing a higher number of devices suitably configured to communicate with a subset of *Kibo* units. Moreover, these TUIs can be used as standard MIDI controllers, thus operating in conjunction with other compatible hardware equipment.

As the participants admitted to the workshops were expected to present different types of impairment or distress conditions, the idea was to create small and homogeneous groups. Participants were subdivided into teams made of 4 people, in order to guarantee, on one side, a number of peers sufficient to foster social interaction and, on the other, let the tutor easily supervise and guide the experience. The tutor had background experiences both in music therapy and in digital music technologies.

Participants belonged to 3 categories:

1. young students aged 12 to 18 with psycho-social support needs;
2. adults aged 25 to 50 with cognitive and/or physical impairment;
3. children with special needs (in particular due to dyslexia, dyspraxia, and dyscalculia) aged 7 to 10.

The total number of participants was 20 (12 males, 8 females). They formed 5 teams: 2 teams (8 participants, 2 females) for the first category, 2 teams (8

Table 1. The detailed program of the workshop [12].

Unit	Task	Description
1	1.1	Presentation of participants and pre-test
	1.2	Introduction to the *Kibo* and its features
	1.3	The *Kibo* and piano interactive performance
	1.4	All participants playing the same rhythmic pattern
2	2.1	Theoretical fundamentals of melody and rhythm
	2.2	Playing a short piece as an ensemble
	2.3	Writing and reading a simplified score
3	3.1	Theoretical fundamentals of harmony and timbre
	3.2	Playing a piece with different musical instruments
	3.3	Making music together with a *Kibo* ensemble
4	4.1	Playing a song mixing *Kibo*'s operating modes
	4.2	Music improvisation inspired by paintings

participants, 4 females) for the second category, and 1 team (4 participants, 2 females) for the third category.

Each 4-people team attended a complete cycle made of 4 didactic units. Units were administered once a week and lasted 2 hours each. In this way, any cycle was completed in the time span of one month.

Table 1 shows the program of each educational cycle, divided into units and tasks. Depending on the characteristics of the team (age, type of impairment, previous music knowledge, level of attention, etc.), some adjustments were made on the fly by the tutor in order to fine-tune the educational activities. The basic idea was to drive learners along two parallel growth paths: on one side, improving their musical skills by gradually introducing new dimensions (rhythm, melody, harmony, timbre); on the other side, encouraging their interaction aptitudes through music (listening to the tutor's performance, playing alone, playing with the tutor, playing in an ensemble, playing together and improvising in front of an audience). Some tasks implied theoretical investigations and other tasks focused on practical activities.

The adoption of a music TUI was fundamental for breaking down the initial barriers (physical impairments, lack of instrumental practice, sense of insecurity or shame) and letting participants be involved in a musical performance in a very limited amount of time.

It is worth underlining the relevance of some tasks. Task 2.3 implied the ability to translate a sequence of musical events (possibly available in Common Western Notation format) into a sequence of pictograms referring to fiducials. In this way, learners were pushed to develop soft skills (teamwork, problem-solving, etc.) and the ability to reason abstractly. Task 3.3 asked participants to perform a music piece together by playing different roles: two leading voices, a rhythmic base, and a harmonic accompaniment. This task encouraged synchronization abilities, information exchange, and peer-to-peer cooperation. Finally, Tasks 4.1 and 4.2 explored the field of music improvisation, both mixing already available materials and playing freely under the influence of visual artworks. In the latter case, the portability of the system (the *Kibo* units and the tablet) was a key aspect to conduct such an experience in a museum with a collection of paintings.

5 Discussion

Before addressing the research questions posed in Section 1, it is worth reporting some general considerations about our experimentation.

The first observation concerns the choice of the device. The *Kibo* proved to be a good solution from many points of view, from technical aspects (e.g., easy device connection and communication) to physical ones (e.g., user-friendliness and robustness). Unfortunately, it is not an affordable product. At the moment of writing, in Italy, this device is sold for 900 to 1000€. Building an ensemble of *Kibo* units, including the need to have an Apple mobile device, is not a low-budget operation. From this point of view, a mixed approach that includes other traditional or digital instruments can help.

Concerning organizational aspects, a team composed of up to 5 participants was a good compromise. Conversely, the presence of a single tutor in the classroom did not guarantee fluid conduct of educational activities. In fact, she had to explain theoretical concepts, play an instrument, support impaired users, and, sometimes, even solve technical issues simultaneously.

The 2-hour length for lessons was adequate and generally appreciated by participants, but the number of didactic units per cycle should be increased in order to better cover the high number of subjects. For instance, the intriguing relationship between music and visual arts was confined to Task 4.2, but it could become the focus of a whole educational cycle.

Finally, in our experimentation teams were not formed according to previous musical knowledge but considering social conditions and impairments. On one side, this choice facilitated the cooperation between users sharing similar problems and the consequent fine-tuning of the program, but, on the other side, it merged people with different expectations into a single team. The *Kibo*, as well as many other music-oriented TUIs, is a facilitator for people with no music knowledge, but its limited possibilities can easily cause boredom and disengagement in more skilled users.

5.1 Answering Research Question 1

RQ1 aimed to investigate the applicability of a TUI-based approach to the acquisition of basic musical skills in vulnerable learners. This research question focused on individual experience, acquisition of knowledge, and development of music-related skills.

From classroom observations and user feedback, the *Kibo* proved to be a suitable tool to let users with no previous knowledge develop *musical intelligence*, namely abilities in the field of perception and autonomous production of music. The results achieved by all participants, including very young as well as impaired ones, included the ability to understand the main dimensions of music (melody,

Fig. 10. A physically-impaired and a visually-impaired user making music with the *Kibo* in the context of the "Note Digitali" project.

rhythm, harmony, timbre), recognize variations in some parameters (e.g., dynamics, tempo, instrumentation), and autonomously reproduce a simple tune. These achievements have been assessed through the instructor's observations.

If compared with the pre-workshop situation, the best results have been obtained by those participants who presented both physical and cognitive impairments (specifically, the second team of the second category). The members of this team had started from a lower level of knowledge, whereas other participants had recently studied music at school. Moreover, using an enabling technology was the only opportunity for them to make music, and, in most cases, this workshop was their first active musical experience. For these reasons, their reaction to the use of a TUI was enthusiastic. Figure 10 shows a wheel-chaired participant and a blind participant.

Another observation is more tightly related to the specific features of the *Kibo*. The geometric shapes of the fiducials proved to be suitable both to overcome visual impairments (tangibles were easily recognizable to the touch and pluggable into the slots) and cognitive ones (sequences of shapes were easy to remember also in case of memory deficit or inability to read a score).

5.2 Answering Research Question 2

One of the goals of the workshop was to emphasize a series of soft and transversal skills through the creation of shared musical performances. RQ2 aims to assess this kind of non-musical achievement.

Making music together as an ensemble requires the development of social skills, encourages cooperative aptitudes, and promotes the ability to listen to the other and perform in front of an audience.

For most teams cooperation did not represent a problem, rather it encouraged relations and strengthened the ties inside each group. For the first team, conversely, playing together was a real challenge. Let us recall that the members were children aged 12 to 14 with a difficult background, coming from a context of social fragility and educational poverty. The problems encountered with them were mostly behavioral: respecting others, listening without talking over, and playing the instruments at the right time. Luckily, the engagement due to making music together and the interest in the playful interface of the *Kibo* let them overcome internal conflicts and focus on a common goal.

The adoption of a TUI also encouraged problem-solving and abstraction skills, which are two key aspects of computational thinking. The problem to solve was how to reinvent a music score suitable both for people with no music knowledge and for impaired users. The solution was to translate music notation into *Kibo*'s symbols (see Figure 11).

The cooperation of each team member was fundamental for completing Task 3.3. Learners had to form a small musical ensemble where everyone should play an important part. The tutor guided the process so as to promote personal abilities without causing frustration in participants. Each team was able to apply the principles of self-regulation, also thanks to the distinguishing features of the TUI in use. For example, a blind girl who demonstrated a great, unexpected sense of rhythm could perform her part using the *Kibo* in Beat Mode; two young students autonomously decided to share the leading voice of a piece by playing it in turn in Instrument Mode; and less skilled users were able to participate taking benefit from the Song Mode.

More time would have been helpful to consolidate this work, but all the learners understood the meaning of working together and actively contributing to the achievement of a shared purpose.

5.3 Answering Research Question 3

RQ1 and RQ2 were answered through qualitative assessment. Conversely, RQ3 focuses on quantitatively-measurable results.

The necessary premise concerns the main goal of the project "Note Digitali", which was not intended to provide participants with specific musical skills but

Fig. 11. A music sheet for *Kibo* with fiducial symbols added by hand.

to let them interact and express themselves in a creative way. From this point of view, even if some activities addressed musical education (see Tasks 2.1 and 3.1), the development of music-related competencies was a sort of desirable side effect. For this reason, users' performances have not been recorded or tracked from a numerical point of view, even for those activities implying a predefined pattern to be reproduced (see Tasks 1.4, 2.2, and 2.3). Nevertheless, this operation could be easily performed by a computer-based system.

The most critical issue does not concern how to obtain values from a music TUI but how to assess the musical skills based on those values. In fact, as clarified in [6], the objective evaluation of users' performances in music is not a trivial task.

First, for an activity with very strict time constraints, the influence of delays in gesture acquisition, signal propagation, and recording can be a decisive factor. Suffice it to say that tolerable delays in digital audio workstations are in the range of 2 to 5 ms. Conversely, the BLE protocol itself can introduce undesirable lags. Clearly, slight delays would not influence the quality of performance as perceived by human players, above all if beginners or amateurs, but they would influence the automatic assessment by a computer system.

In addition, giving a score to a performance that diverges from the expected one is intrinsically complex. Music is made of many interconnected aspects – melody, rhythm, harmony, timbre, expression, etc. – and even a mistake involving a single dimension could have multiple interpretations. For example, detecting a 0.1s offset on a regular pattern of beats at a low metronome (e.g., 60 bpm, with each beat lasting 1s) would not be critical, but the same value measured on a smaller rhythmical value and at a higher metronome (e.g., 180 bpm) would have a much higher impact. This problem could be solved by using a relative instead of an absolute criterion to measure errors. But what about a melodic pattern where the performer is regularly 1 note ahead or an octave below? Even more so when participants are amateur musicians who suffer from some form of impairment that hampers their performance from a cognitive or physical point of view.

In conclusion, answering RQ3 is technically possible, but its feasibility depends on the context. It would be interesting to conduct this kind of analysis on music students from a conservatory or in a professional orchestra, whereas it makes little sense in a scenario where music expression is mainly intended to foster inclusion and break down barriers.

6 Conclusions

This paper elucidates the notable accomplishments achieved through the organization of ensemble playing sessions utilizing a music TUI, particularly concerning the augmentation of musical aptitude, social interaction skills, and soft skills among vulnerable users.

Unsurprisingly, the implementation of a music TUI proves instrumental in resolving the customary accessibility predicaments encountered by physically impaired individuals when engaging with conventional musical instruments. Within the ambit of the documented experiment, the majority of participants presented motor impairments, while a subset of these individuals also experienced visual impairments. For such users, a TUI serves as an essential enabling technology, facilitating their participation in musical performances. Many participants experienced the joy of playing music for the first time, fostering a collaborative environment. Overall, the experience yielded highly positive outcomes, evoking enthusiastic responses from the learners.

Furthermore, a TUI possesses the capacity to bridge the divide between cognitive impairments and a comprehensive understanding and engagement with various musical dimensions. In this context, the proficiency to read and memorize musical scores assumes nontrivial significance. Remarkably, not only were these impediments successfully surmounted, but the participants even managed to generate new musical scores, owing to the implementation of a simplified language and a gamification approach.

In summary, it became evident that engagement can push the boundaries of users, enabling them to achieve unprecedented outcomes. Employing a music TUI, with the guidance of a skilled tutor, fosters engagement and effectively diminishes initial barriers, thereby alleviating the sense of frustration frequently encountered by disadvantaged users, which often hampers their musical creativity and expressive capabilities.

It is important to note that the TUI not only serves as an empowering technology for impaired users who are unable to play traditional instruments, but it also stimulates creativity and facilitates musical expressiveness even after a relatively brief exploration period.

Acknowledgments This project has been funded by "Bando 57", a call promoted by *Fondazione di Comunità di Milano - Città, Sud Ovest, Sud Est e Adda Martesana ONLUS*. The authors wish to acknowledge their project partners: *Casa di Redenzione Sociale di Milano* (in particular, Luigi Codemo) and *Fondazione Luigi Clerici di Milano* (in particular, Federica Monguzzi). The authors also thank *Cooperativa Sociale Cura e Riabilitazione Onlus* for the support offered to impaired users.

References

1. Aljaam, J., Jaoua, A., AlHazbi, S., Hasnah, A., Karime, A., Elsaddik, A.A.: An assistive computerized system with tangible user interfaces for children with moderate intellectual and learning disabilities. International Journal of Emerging Technologies in Learning (iJET) **6**(2011) (2011)
2. Alonso, M.B., Keyson, D.V.: Musiccube: Making digital music tangible. In: CHI '05 Extended Abstracts on Human Factors in Computing Systems. p. 1176–1179. CHI EA '05, Association for Computing Machinery, New York, NY, USA (2005). https://doi.org/10.1145/1056808.1056870, https://doi.org/10.1145/1056808.1056870
3. Amico, M.D., Ludovico, L.A.: Kibo: A MIDI controller with a tangible user interface for music education. In: Lane, H., Uhomoibhi, J., Zvacek, S. (eds.) Proceedings

of the 12th International Conference on Computer Supported Education (CSEDU 2020) - Volume 1. pp. 613–619. CSEDU, SCITEPRESS - Science and Technology Publications, Lda., Setúbal (2020). https://doi.org/10.5220/0009805206130619
4. Avanzini, F., Baratè, A., Ludovico, L.A.: 3D printing in preschool music education: Opportunities and challenges. Qwerty - Open and Interdisciplinary Journal of Technology, Culture and Education **14**(1), 71–92 (2019)
5. Avanzini, F., Baratè, A., Ludovico, L.A., Mandanici, M.: A computer-based approach to teach tonal harmony to young students. In: Lane, H., Uhomoibhi, J., Zvacek, S. (eds.) Proceedings of the 11th International Conference on Computer Supported Education (CSEDU 2019). vol. 1, pp. 271–279. SCITEPRESS - Science and Technology Publications, Lda. (2019)
6. Avanzini, F., Baratè, A., Ludovico, L.A., Mandanici, M.: A web platform to foster and assess tonal harmony awareness. In: Lane, H., Uhomoibhi, J., Zvacek, S. (eds.) Computer Supported Education. 11th International Conference, CSEDU 2019, Heraklion, Crete, Greece, May 2-4, 2019, Revised Selected Papers, Communications in Computer and Information Science, vol. 1220, pp. 398–417. Springer International Publishing, Cham (2020). https://doi.org/10.1007/978-3-030-58459-7{_}19
7. Baratè, A., Elia, A., Ludovico, L.A., Oriolo, E.: The leap motion controller in clinical music therapy. a computer-based approach to intellectual and motor disabilities. In: McLaren, B.M., Reilly, R., Uhomoibhi, J., Zvacek, S. (eds.) Proceedings of the 10th International Conference on Computer Supported Education (CSEDU 2018), 15-17 March 2018, Funchal, Madeira, Portugal. pp. 461–469. SCITEPRESS - Science and Technology Publications, Lda., Setúbal (2018)
8. Baratè, A., Korsten, H., Ludovico, L.A.: A multidimensional-taxonomy model for music tangible user interfaces. Multimodal Technologies and Interaction (2023)
9. Baratè, A., Korsten, H., Ludovico, L.A.: A music tangible user interface for the cognitive and motor rehabilitation of elderly people. In: Constantine, L., Holzinger, A., Silva, H.P., Vanderdonckt, J. (eds.) Proceedings of the 6th International Conference on Computer-Human Interaction Research and Applications (CHIRA 2022). pp. 121–128. SCITEPRESS - Science and Technology Publications, Lda. (2022)
10. Baratè, A., Ludovico, L.A.: An open and multi-layer web platform for higher music education. Journal of e-Learning and Knowledge Society **16**(4), 29–37 (2020). https://doi.org/10.20368/1971-8829/1135356
11. Baratè, A., Ludovico, L.A., Oriolo, E.: Investigating embodied music expression through the leap motion: Experimentations in educational and clinical contexts. In: McLaren, B.M., Reilly, R., Uhomoibhi, J., Zvacek, S. (eds.) Computer Supported Education - 10th International Conference, CSEDU 2018, Funchal, Madeira, Portugal, March 15–17, 2018, Revised Selected Papers, Communications in Computer and Information Science, vol. 1022, pp. 532–548. Springer International Publishing (2019). https://doi.org/10.1007/978-3-030-21151-6_25
12. Baratè, A., Ludovico, L.A., Oriolo, E.: An ensemble of tangible user interfaces to foster music awareness and interaction in vulnerable learners. In: Constantine, L., Holzinger, A., Silva, H.P. (eds.) Proceedings of the 5th International Conference on Computer-Human Interaction Research and Applications (CHIRA 2021). pp. 48–57. SCITEPRESS - Science and Technology Publications, Lda. (2021). https://doi.org/10.5220/0010653400003060
13. Barton, G., Riddle, S.: Culturally responsive and meaningful music education: Multimodality, meaning-making, and communication in diverse learning contexts. Research Studies in Music Education p. 1321103X211009323 (2021). https://doi.org/10.1177/1321103X211009323, https://doi.org/10.1177/1321103X211009323

14. Bates, V.C.: Equity in music education: Back to class: Music education and poverty. Music Educators Journal **105**(2), 72–74 (2018)
15. Ben-Tal, O., Salazar, D.: Rethinking the musical ensemble: A model for collaborative learning in higher education music technology. Journal of Music, Technology & Education **7**(3), 279–294 (2014)
16. Burke, J., McNeill, M., Charles, D., Morrow, P., Crosbie, J., McDonough, S.: Augmented reality games for upper-limb stroke rehabilitation. In: 2010 Second International Conference on Games and Virtual Worlds for Serious Applications. pp. 75–78 (2010). https://doi.org/10.1109/VS-GAMES.2010.21
17. Carreño-León, M., Sandoval-Bringas, J.A., Alvarez-Robles, T., Cosio-Castro, R., Cota, I.E., Carrillo, A.L.: Designing a tangible user interface for braille teaching. In: International Conference on Human-Computer Interaction. pp. 197–207. Springer (2020)
18. Cerezo, E., Bonillo, C., Baldassarri, S.: Therapeutic activities for elderly people based on tangible interaction. In: ICT4AWE. pp. 281–290 (2020)
19. Cheng, L.: Musical competency development in a laptop ensemble. Research Studies in Music Education **41**(1), 117–131 (2019)
20. Costanza, E., Shelley, S.B., Robinson, J.: Introducing audio D-TOUCH: A tangible user interface for music composition and performance. In: Proc. of the 6th Int. Conference on Digital Audio Effects (DAFX-03), London, UK, September 8-11, 2003 (2003)
21. Dahl, L.: Comparing the timing of movement events for air-drumming gestures. In: International Symposium on Computer Music Multidisciplinary Research. pp. 3–21. Springer (2015)
22. d'Alessandro, N., Tilmanne, J., Moreau, A., Puleo, A.: Airpiano: A multi-touch keyboard with hovering control. In: Berdahl, E., Allison, J. (eds.) Proceedings of the International Conference on New Interfaces for Musical Expression. pp. 255–258. Louisiana State University, Baton Rouge, Louisiana, USA (May 2015). https://doi.org/10.5281/zenodo.1181434, http://www.nime.org/proceedings/2015/nime2015%5F261.pdf
23. Dance Music Northwest: The awesome instrument you've never heard of: Reactable. https://www.dancemusicnw.com/awesome-instrument-youve-never-heard-reactable/ (2015)
24. De Carvalho, R.N.S., Ishitani, L., Nogueira Sales De Carvalho, R., et al.: Motivational factors for mobile serious games for elderly users. Proceedings of XI SB games pp. 2–4 (2012)
25. Dörner, R., Göbel, S., Effelsberg, W., Wiemeyer, J.: Serious games. Springer (2016)
26. Duckworth, J., Mumford, N., Caeyenberghs, K., Eldridge, R., Mayson, S., Thomas, P.R., Shum, D., Williams, G., Wilson, P.H.: Resonance: an interactive tabletop artwork for co-located group rehabilitation and play. In: Int. Conf. on Universal Access in Human-Computer Interaction. pp. 420–431. Springer (2015)
27. Fan, X., Essl, G.: Air violin: A body-centric style musical instrument. In: NIME. pp. 122–123 (2013)
28. Farr, W., Yuill, N., Raffle, H.: Social benefits of a tangible user interface for children with autistic spectrum conditions. Autism **14**(3), 237–252 (2010)
29. Fiala, M.: Artag, a fiducial marker system using digital techniques. In: 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05). vol. 2, pp. 590–596 vol. 2 (2005). https://doi.org/10.1109/CVPR.2005.74

30. Fonseca, X., Slingerland, G., Lukosch, S., Brazier, F.: Designing for meaningful social interaction in digital serious games. Entertainment Computing **36**, 100385 (2021)
31. Frid, E.: Accessible digital musical instruments—a review of musical interfaces in inclusive music practice. Multimodal Technologies and Interaction **3**(3), 57 (2019)
32. Furness, D.: Prospective memory in normal ageing and dementia. Digital Trends (2016), https://www.digitaltrends.com/cool-tech/tunetable/
33. Gabrielli, L., Välimäki, V., Bilbao, S.: Real-time emulation of the clavinet. In: ICMC (2011)
34. Godøy, R.I., Haga, E., Jensenius, A.R.: Playing "air instruments": mimicry of sound-producing gestures by novices and experts. In: International Gesture Workshop. pp. 256–267. Springer (2005)
35. Gorbunova, I., Voronov, A.M.: Music computer technologies in computer science and music studies at schools for children with deep visual impairment. In: 16th International Conference on Literature, Languages, Humanities & Social Sciences (LLHSS-18) Oct. 2-4, 2018 Budapest (Hungary). pp. 15–18 (2018)
36. Harrison, K.: The relationship of poverty to music. Yearbook for traditional music **45**, 1–12 (2013)
37. Hattwick, I.: Face to face, byte to byte: Approaches to human interaction in a digital music ensemble. MFA, University of California-Irvine (2011)
38. Hattwick, I., Umezaki, K.: Approaches to collaboration in a digital music ensemble. In: NIME 2012 Proceedings of the International Conference on New Interfaces for Musical Expression. pp. 466–469 (2012)
39. Ishii, H.: Tangible bits: Beyond pixels. In: Proc. 2nd Int. Conf. on Tangible and Embedded Interaction. p. xv–xxv. TEI '08, Association for Computing Machinery (2008). https://doi.org/10.1145/1347390.1347392, https://doi.org/10.1145/1347390.1347392
40. Ishii, H.: The tangible user interface and its evolution. Commun. ACM **51**(6), 32–36 (jun 2008). https://doi.org/10.1145/1349026.1349034, https://doi.org/10.1145/1349026.1349034
41. Ishii, H., Ullmer, B.: Tangible bits: towards seamless interfaces between people, bits and atoms. In: Proceedings of the ACM SIGCHI Conference on Human factors in computing systems. pp. 234–241 (1997)
42. Jordà, S.: The reactable: tangible and tabletop music performance. In: CHI'10 Extended Abstracts on Human Factors in Computing Systems. pp. 2989–2994 (2010)
43. Ko, C.L., Oehlberg, L.: Touch responsive augmented violin interface system ii: Integrating sensors into a 3d printed fingerboard. In: Michon, R., Schroeder, F. (eds.) Proceedings of the International Conference on New Interfaces for Musical Expression. pp. 166–171. Birmingham City University, Birmingham, UK (Jul 2020). https://doi.org/10.5281/zenodo.4813300, https://www.nime.org/proceedings/2020/nime2020%5Fpaper32.pdf
44. Leman, M., et al.: Embodied music cognition and mediation technology. MIT press (2008)
45. Li, J., Wu, C.H., Lin, T.J., Chang, R.J.: Determinants affecting learner's behaviour in music education applying information technology. In: Proceedings of the 11th International Conference on Computer Supported Education - Volume 2: CSEDU,. pp. 424–431. INSTICC, SciTePress (2019). https://doi.org/10.5220/0007734404240431
46. McAnally, E.A.: General music and children living in poverty. General Music Today **26**(3), 25–31 (2013)

47. Mellor, L.: Creativity, originality, identity: Investigating computer-based composition in the secondary school. Music Education Research **10**(4), 451–472 (2008)
48. Morreale, F., De Angeli, A., Masu, R., Rota, P., Conci, N.: Collaborative creativity: The music room. Personal and Ubiquitous Computing **18**(5), 1187–1199 (2014)
49. Najjar, A.B., Alhussayen, A., Jafri, R.: Usability engineering of a tangible user interface application for visually impaired children. Human-Centric Computing and Information Sciences **11**(14), 891–921 (2021)
50. Newton-Dunn, H., Nakano, H., Gibson, J.: Block jam: A tangible interface for interactive music. Journal of New Music Research **32**(4), 383–393 (2003)
51. de Oliveira, P.A., Lotto, E.P., Correa, A.G.D., Taboada, L.G., Costa, L.C., Lopes, R.D.: Virtual stage: an immersive musical game for people with visual impairment. In: 2015 14th Brazilian Symposium on Computer Games and Digital Entertainment (SBGames). pp. 135–141. IEEE (2015)
52. Paradiso, J.A., Hsiao, K.y., Benbasat, A.: Tangible music interfaces using passive magnetic tags. In: Proceedings of the 2001 Conference on New Interfaces for Musical Expression. p. 1–4. NIME '01, National University of Singapore, SGP (2001)
53. Pedersen, E.W., Hornbæk, K.: mixitui: a tangible sequencer for electronic live performances. In: Proceedings of the 3rd international conference on tangible and embedded Interaction. pp. 223–230 (2009)
54. Pesek, M., Vučko, Ž., Šavli, P., Kavčič, A., Marolt, M.: Troubadour: A gamified e-learning platform for ear training. IEEE Access **8**, 97090–97102 (2020)
55. Pires, A.C., Marichal, S., Gonzalez-Perilli, F., Bakala, E., Fleischer, B., Sansone, G., Guerreiro, T.: A tangible math game for visually impaired children. In: The 21st International ACM SIGACCESS Conference on Computers and Accessibility. pp. 670–672 (2019)
56. Potidis, S., Spyrou, T.: Spyractable: A tangible user interface modular synthesizer. In: International Conference on Human-Computer Interaction. pp. 600–611. Springer (2014)
57. Rabbi, I., Ullah, S.: 3d model visualization and interaction using a cubic fiducial marker. In: De Paolis, L.T., Mongelli, A. (eds.) Augmented and Virtual Reality. pp. 381–393. Springer International Publishing, Cham (2014)
58. Ramos Aguiar, L.R., Álvarez Rodríguez, F.J.: Methodology for designing systems based on tangible user interfaces and gamification techniques for blind people. Applied Sciences **11**(12), 5676 (2021)
59. Rego, P.A., Moreira, P.M., Reis, L.P.: Architecture for serious games in health rehabilitation. In: New Perspectives in Information Systems and Technologies. vol. 2, pp. 307–317. Springer, Cham (2014)
60. Riley, P., Alm, N., Newell, A.: An interactive tool to promote musical creativity in people with dementia. Computers in Human Behavior **25**(3), 599–608 (2009)
61. Schiavio, A., Menin, D.: Embodied music cognition and mediation technology: A critical review. Psychology of Music **41**(6), 804–814 (2013). https://doi.org/10.1177/0305735613497169, https://doi.org/10.1177/0305735613497169
62. Schiettecatte, B., Vanderdonckt, J.: Audiocubes: A distributed cube tangible interface based on interaction range for sound design. In: Proc. 2nd Int. Conf. on Tangible and Embedded Interaction. p. 3–10. TEI '08, Association for Computing Machinery, New York, NY, USA (2008). https://doi.org/10.1145/1347390.1347394, https://doi.org/10.1145/1347390.1347394
63. Smith, K., Abrams, S.S.: Gamification and accessibility. The International Journal of Information and Learning Technology (2019)

64. Tarabella, L.: Handel, a free-hands gesture recognition system. In: International Symposium on Computer Music Modeling and Retrieval. pp. 139–148. Springer (2004)
65. Vandermaesen, M., De Weyer, T., Feys, P., Luyten, K., Coninx, K.: Integrating serious games and tangible objects for functional handgrip training: A user study of handly in persons with multiple sclerosis. In: Proc. of the 2016 ACM Conf. on Designing Interactive Systems. pp. 924–935 (2016)
66. Weichert, F., Bachmann, D., Rudak, B., Fisseler, D.: Analysis of the accuracy and robustness of the Leap Motion controller. Sensors **13**(5), 6380–6393 (2013)
67. Xambó, A., Drozda, B., Weisling, A., Magerko, B., Huet, M., Gasque, T., Freeman, J.: Experience and ownership with a tangible computational music installation for informal learning. In: Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction. pp. 351–360 (2017)
68. Xu, D.: Tangible user interface for children – an overview. In: Proc. of the UCLAN Department of Computing Conference. Citeseer (2005)
69. Zhao, X., Deng, Z., Jin, M., Li, X., Zhang, W., Jin, M., Ying, F., Wang, Q., Wang, G.: Segara: Integrating serious games and handgrip for hand rehabilitation in rheumatoid arthritis patients. In: The 9th Int. Symp. of Chinese CHI. pp. 101–104 (2021)