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Indice

3D printing in preschool music education: Opportunities and challenges

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Abstract

In this paper we explore the potential of 3D printing in the context of preschool music learning, with the aim of making visible its educational value. After analyzing embodied and enactive approaches in preschool and the adoption of tangible interfaces for music education, we review novel technologies in the field of additive fabrication and 3D printing and highlight their potential for music learning. Subsequently, we propose didactic experiences based on a manipulative approach and using already-available or user-customized 3D models. Finally, we present a case study that investigates alternative forms of music notation.

Keywords: 3D printers; Music Education; Tangible Interfaces

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1. Introduction

The importance of music education for preschool children has been explored in a number of scientific works. For example, Rauscher and colleagues (Rauscher et al., 1997) suggest that music training can cause long-term enhancement of preschool children's spatial-temporal reasoning. Anvari, Trainor, Woodside and Levy (2002) examine the relations among phonological awareness, music perception skills, and early reading skills in a population of 4- and 5-year-old children, identifying a link between music and early reading skill. Yazejian and Peisner-Feinberg (2009) critically discuss the beneficial effects of offering specialized music and movement curricula to preschool-age children.

Several musical features can be visualized by spatial representations. Relevant examples include the *tonnetz*, a spatial scheme showing triadic relationships upon which tonal harmony is based (Cohn, 1998); the neumatic notation of Gregorian chant; chironomy, a form of conduction where hand gestures indicate pitch and rhythm details; and so on. These suggest the idea that the spatial positioning of sounds conveys meaning about their inner nature and element organization.

This coupling is also driven by the implicit knowledge of musical language (Tillmann, Bharucha, & Bigand, 2000). Continuous passive exposure to structured stimuli (speech, music, spatial relationships, sensorimotor information, etc.) builds an inner knowledge about them. A recent study by Corrigall and Trainor (2010) has shown that children in preschool age have implicit harmonic knowledge, including chord functions, harmonic relations, and harmonic rhythm, indicating that harmony perception begins to develop earlier than previously suggested. A structured and exhaustive discussion of the above concepts, in the context of technologically-augmented music education, is provided by Mandanici (2017).

In this work, we propose music activities in preschool age based on 3D printing, analyzing different use cases and discussing advantages and drawbacks of this approach.

The paper is structured as follows: in Section 2 we will introduce the subject of embodiment and enaction, in Section 3 we will review available 3D-printing applications for music, in Section 4 we will specifically address preschool music education, and in Section 5 we will focus on a case study for melody, rhythm and timbre learning.

2. Embodiment and Enaction

According to traditional views, perception is a process in the brain that constructs an internal representation of the world, and, eventually, action follows as a subordinate function. The implicit assumption is that the causal flow between perception and action is primarily one-way: perception is input from world to mind, action is output from mind to world, and thought (cognition) is the mediating process. More recent theories have questioned such a modular decomposition, claiming that it is not possible to disassociate perception and action schematically, and that every kind of perception is intrinsically active and thoughtful.

2.1. Embodied and Enactive Knowledge in Preschool Children

As stated by Noë (2005), only a creature with certain kinds of bodily skills (e.g., a basic familiarity with the sensory effects of eye or hand movements, etc.) can be a perceiver. In their influential work, Varela, Thompson and Rosch (1991) present an *enactive* conception of experience, which does not occur inside the perceiver, but is rather something that the perceiver enacts while exploring the environment. Similarly, the term *embodied cognition* highlights that cognition depends upon the kinds of experience that are generated from specific sensorimotor capacities.

Children in preschool years provide a paradigmatic example of these concepts. The theory of child's cognitive development by Bruner (1968) states that the first way of representing the world is by enactive knowledge. Any event is represented through appropriate motor responses (e.g., building with bricks, riding a bicycle, whistling, etc.), by which children learn to discover the world, the relationships among objects, cause-effect relationships, and the characteristics of the environment that surrounds them. Knowledge is gained through perception-action in the environment, as well as integration and complementation of multimodal information coming from the various senses (De Götzen, Mion, Avanzini, & Serafin, 2008).

It is often difficult to distinguish between exploration and play: during the sensory-motor development, very young children need to explore first to be able then to proceed to playful behavior, which is one of the most important activities for their development; by playing, children start to explore the world and to acquire and master new skills which can be vital for them.

The "open-ended" nature of the interaction is another important aspect: a child's ability to access an object, and to reinvent new ways of using it, provides surprise and engagement. As explained by Resnick (2007), the challenge for the interaction designer is to develop features that are specific enough to be quickly understood by children, but at the same time general enough to let children imagine new ways to use them.

2.2. Tangible Interfaces for Education

Tangible User Interfaces (TUIs) are interfaces in which a person interacts with digital information through physical objects and the environment. TUIs build on principles derived from embodied cognition as described above, by taking advantage of the human ability to grasp and manipulate physical objects and materials. As such, they enable action-centric interaction in place of information-centric interaction, because they promote more physical and bodily actions compared to traditional WIMP (Windows-Icons-Menus-Pointers) graphical user interfaces.

Constructive building blocks exemplify such action-centric interaction approaches, with a specific focus on education. One of the pioneering works in the digital domain was by Papert (1980). More recently, Ishii (2008) proposed the term "tangible bits" to denote approaches that give physical form to digital information and make bits directly manipulable, thus increasing learning performance and empowering collaboration. However, the use of constructive building-blocks can be traced back to hands-on education ideas proposed by Frobël and Montessori at the turn of the 20th century; Zuckerman Arida, and Resnick (2005) propose a framework for thinking about tangible interfaces in education, which builds directly on the ideas of Frobël and Montessori. Several recent studies have investigated the potential benefits of TUIs for supporting learning with very young children, see for instance the extensive review by Baykal and colleagues (2018) about the relevance of TUIs as complementary tools for early spatial learning in cognitive development.

With respect to other disciplines, the use of TUIs for music education has been comparatively less studied. One well known tangible music interface is the *Reactable*, originally conceived by Jordà and colleagues (2007) and depicted in Figure 1: it is based on a round table where several musicians can share the control of the musical instrument by caressing, rotating and moving physical artifacts on the luminous surface, constructing different audio topologies in a kind of tangible modular synthesizer. The objects represent the building blocks of electronic music, such as sound sources, filters and modulators, and interact with each other based on proximity and affinity. As such, the *Reactable* has been mainly exploited as a collaborative tool for music performance while its uses for music education have been under-explored. However, this kind of interfaces provide a very appealing scenario for music learning and playful interaction, by allowing intuitive relationships between tangible objects and musical features, as discussed in the introduction. They can also facilitate collaboration, by allowing several children to be active simultaneously, and inclusion, by allowing visually impaired children to discover the functions of objects through their shape and texture.

Figure 1. Users interacting with the Reactable

3. 3D printing for Music

As explained by Campbell and colleagues (2011), currently in-use 3D-printing techniques are a subset of so-called *Additive Manufacturing* (AM). In general terms, AM can be defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM, 2012). The AM process begins with a 3D model of the object, usually created by computer-aided design (CAD) software or a scan of an existing artifact. Specialized software slices this model into cross-sectional layers, creating a computer file that is sent to the AM machine. The AM machine then creates the object by forming each layer via the selective placement of material, adding layers of material on top of each other until the original projects turn into 3D objects.

Years ago, the most popular term to refer to this kind of technology was *rapid prototyping*, but nowadays a new definition has gained popularity: *3D printing*. This term embraces a wide range of applications, including design and concept modeling, fit and function testing, custom and replacement part manufacturing, either short-run or series production. Consequently, prototyping remains an important use case, but it is only one of many.

A potential problem of 3D printing technology is the need for modeling skills. In the past, this activity was a prerogative of highly-specialized professionals, e.g., architects, designers and engineers. Sophisticated applications, such as Autodesk AutoCAD,[1] Rhinoceros,[2] or 3D Studio Max,[3] were required. In this sense, much has been done to improve software tools and to simplify the modeling process. Currently, there are solutions conceived to let even preschool children easily model simple objects. An example is Doodle3D Sketch,[4] whose interface is shown in Figure 2: its us-

Figure 2. The interface of Doodle3D Sketch

[1] https://www.autodesk.it/products/autocad/
[2] https://www.rhino3d.com/
[3] https://www.autodesk.it/products/3ds-max/
[4] https://www.doodle3d.com/

er-friendly and playful design lets the user obtain 3D prints from hand-made 2D drawings.

In accordance with the different meanings and goals of 3D printing, in the field of music we can list a number of possible applications. The first one, close to the idea of producing custom sounding objects, is the design and modeling of musical instruments or smaller replacement parts. For example, some idiophone instruments can be easily modeled, thanks to the intrinsic simplicity of their body. In these cases, the main limitation concerns printable materials, which in low-budget solutions is usually plastic. It is worth underlining that, in recent times, there have been noticeable advancements, including multi-material printing through the *PolyJet* technology (Vaezi, Chianrabutra, Mellor, & Yanget, 2013) and the fabrication of metallic components by using the Selective Laser Melting technology (Loh et al., 2015); unfortunately, these processes are complex and require expensive devices.

Intriguing examples of non-idiophone musical instruments that can be produced using consumer 3D printers are the concert flute described by Zoran (2011) and the *hovalin*,[5] an acoustic violin whose shape and dimensions are inspired by the Stradivarius model.

Another common application of 3D printing techniques to the field of musical instruments is the production of replacement parts, e.g. reeds or mouthpieces, as shown in Figure 3. There may be multiple reasons to do this, including low-cost prototyping of user-tailored parts or the reconstruction of missing elements for ancient musical instruments (Best, 2014).

Concerning 3D printing in music education, this subject will be addressed in the next section.

[5] http://www.hovalabs.com/hova-instruments/hovalin

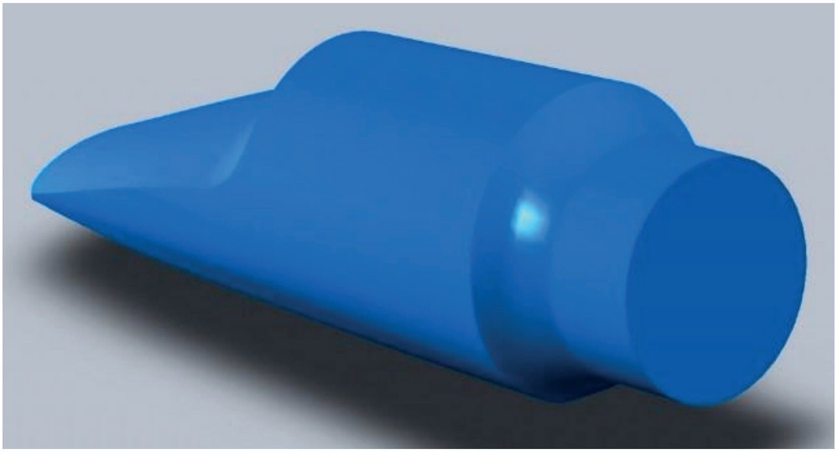

Figure 3. A raw 3D model of a mouthpiece

4. 3D printing for Preschool Music Education

Some advantages of 3D printing technology in the education of preschool learners extend beyond music: the development of visuo-spatial abilities, the establishment of relations among models and the corresponding physical objects, the improvement of abstraction skills, the possibility to implement manipulative activities, etc.

Narrowing the field to music education, there are not only additional advantages strictly related to music training, but also extra-musical effects described by scientific literature (DeVries, 2004), including phonemic awareness in beginning readers (Gromko, 2005), the promotion of spontaneous speech in physically handicapped preschoolers (Harding & Keith, 1982), and a better integration of impaired children in group activities (Robb, 2003).

When designing a 3D-printing educational experience, there are technological issues to consider. The limitations of low-cost 3D printing in an educational framework have been reviewed by Canessa, Fonda and Zennaro (2013). A hard limit is the reduced space available for printing, typically 20x20x20 cm. However, a larger object could be formed by assembling many small parts, as in the already mentioned case of the *hova-*

lin. At present, another aspect to consider is the printability of plastic materials only, which has a clear impact on music applications. For example, many independent experiments conducted on the *hovalin* pointed out some negative aspects mainly due to the material in use, concerning a considerable weight of the instrument and its limited sound radiation if compared to a traditional violin. Other problems concern the wear of plastic materials and the different behavior they present when interacting with the instrument body, as in the case of plastic flute keys.

Nevertheless, 3D printing offers relevant opportunities of young music learners, allowing to build low-cost and customizable didactic objects.

The activities we will propose can occur both in a classroom setting and out of the school. The key requirements are:

- The availability of a 3D printing system. As mentioned before, there are low-budget solutions and ready-to-use printing environments, easy to install and configure even in a home environment;
- The presence of a tutoring figure who can profitably guide the child in his/her learning path, fostering engagement and creativity, providing explanations and clarifications, and solving those practical and technological issues that could cause frustration in the young learner.

Offering a library of already-available 3D models to be printed or slightly customized during home or classroom activities, as proposed in Section 4.1, could encourage also very young learners, as well as tutoring actors (e.g., teachers, parents, etc.) who are not confident with new technologies. The additional ability to build teaching/learning resources from scratch presents further advantages, whose didactic valence will be discussed in Section 4.2.

The examples mentioned below do not claim to be exhaustive; rather, they aim to provide a broad picture of 3D printing applicability to preschool music education, ranging from the fabrication of sounding objects to tangible representations of musical instruments.

4.1. Using Predetermined Models

In this section, we will review some opportunities offered by the availability of predefined 3D models designed for music education of preschoolers. The fabrication of the corresponding physical objects does not require particular technological skills, but only a suitable 3D-printing equipment.

Recalling some proposals mentioned in Section 3 and applying them to the preschool case, ad hoc 3D models can be used to produce, for instance, toy instruments. In the part related to music education of the *Orff Schulwerk* method (Orff & Keetman, 1977), the authors mention some pitched and unpitched percussion instruments, such as miniature xylophones, marimbas, etc.; apart from the aforementioned issue concerning materials, these simple musical instruments are easy to be modeled in a 3D printing ecosystem.

Another application for preschool music education is the recognition of the shape of musical instruments through a visual and haptic approach that can be reinforced by selected listening activities and live performances. Even if a scaled model of a complex musical instrument can be hard to find, simplified 3D shapes can be easily obtained by extruding 2D contours (see Figures 4a and 4b) without affecting the efficacy of the didactic experience.

Besides, 3D-printed objects can foster an early learning of organology, i.e. the science of musical instruments and their classification, including technical aspects of how instruments produce sound. Even if learners are very young, the availability of tangible examples to be observed, manipulated and – in some cases – even practiced may help them understand non-trivial subjects, such as the role of sounding components in idiophone instruments or the way a reed works. Teachers can focus on characteristic parts of an instrument, for example the mouthpiece of a trumpet, the reed of a clarinet, or the curl of a violin.

A different approach consists in printing action figures that depict music players together with their instrument. In this case, free 3D models are more difficult to find and more time-consuming to print, but this kind of educational resource presents noticeable advantages: first, such a gamification approach recalls other figurine-based games familiar to children, like toy soldiers and farm animals; besides, it can be used to show not only the shape of instruments, but also the posture and playing technique of performers; finally, action figures can be profitably employed to exemplify ensembles and seating layouts

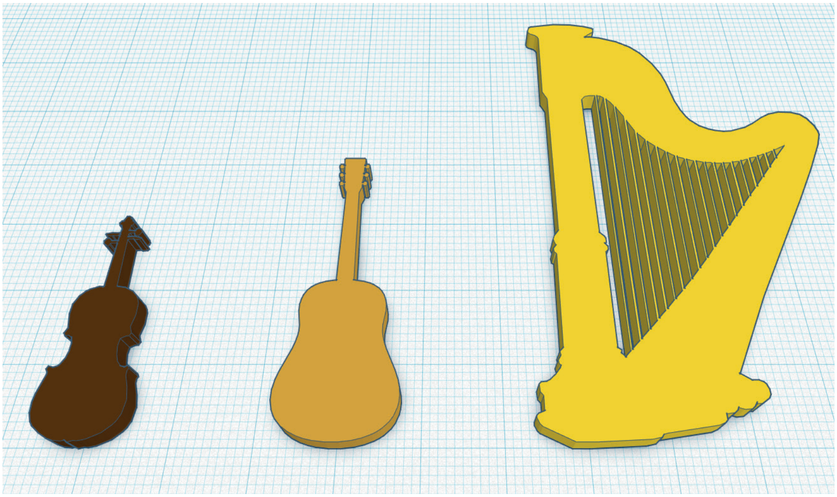

Figure 4a. 3D models of musical instruments obtained by the extrusion of 2D shapes

Figure 4b. The corresponding printed objects

(Koury, 1986). An example of a full orchestra produced with 3D printing techniques is shown in Figure 5.

Figure 5. A 3D-printed orchestra produced by the Musical Instruments Museum of Phoenix, Arizona

As it regards technological issues, scale models and action figures can be conveniently resized to be fabricated even through low-budget 3D printers. The time required depends on the size and level of detail: even if current technology is quite slow for this kind of models, action figures can be printed before the experience and preserved for future use; conversely, simple objects like 3D shapes of instruments can be printed also on the fly.

The possibility to alternate different materials and multiple colors during a single print job may greatly improve not only the aesthetics, but also the teaching effectiveness of printed objects (Eisenberg, 2013). Currently, these features are not implemented in low-end devices, but, thanks to the raising interest about 3D printing, we can expect rapid innovations in the short term.

4.2. Defining and Customizing Models

The definition of new models from scratch, as well as the customization of already-available ones, can add further educational value to the experience. These processes can be carried out by the teacher, e.g. in response to learners' requests, or demanded to young students under the guidance of a tutor.

A first aspect to consider is the educational value of seeing in first person the transition from a model on pc to a real-world object: watching the layer-by-layer process of fabrication allows to open the black box and understand the physical characteristics of objects. This is particularly true when the features of the original model are changed on demand. Focusing on musical instruments, meaningful questions are: How may the alteration of geometric properties (e.g., the dimensions of the bars in a toy xylophone) affect the production of sound? What does the introduction of an additional finger hole imply in a woodwind instrument like a recorder? What is the timbre effect of producing a thinner or a thicker vibrating plate? These questions can be answered practically, by altering suitable parameters of the original models and fabricating the corresponding objects.

Another possibility consists in unleashing children's creativity by inviting learners to design their own musical instrument. Most results will likely fall into the category of unpitched percussions, but there are also examples of simple vibrating bodies able to produce pitches, like a reed or a Jew's harp.

The already mentioned problem concerning the skills required for 3D modeling, above all in the context of preschool education, can be solved (or, at least, mitigated) by ad hoc software applications. In fact, in addition to professional software, simplified modeling tools have appeared on the market, including:

- *Microsoft 3D Builder*, available as a free download for Windows 7 and later versions;
- *Doodle3D Transform*,[6] a tool conceived for children and designers with no specific skills that extrudes both hand-made and imported 2D images;
- *Autodesk TinkerCAD*,[7] a simplified interface available online for 3D modeling.

[6] https://www.doodle3d.com/
[7] https://www.tinkercad.com/

5. Case Study

In most geographical areas, Common Western Notation (CWN) is the standard way to encode notated music. In this case study, we want to focus on another largely used abstraction, more likely to be understood by children in preschool age: the piano-roll model, often adopted in modern digital audio workstations (see Figure 6). In this model, the characteristics of music (pitch, duration, timbre, etc.) are intuitively linked to geometric and chromatic properties of shapes located on a 2D plane, where the horizontal axis conventionally provides a quantized representation of time, the vertical axis is connected to the concept of pitch, and the color is used to identify different instruments. Even if they are not equivalent from the expressive point of view, it is possible to convert CWN into a piano-roll representation and vice versa, so the latter can be employed also as a simplified approach to foster an early study of "traditional" music notation.

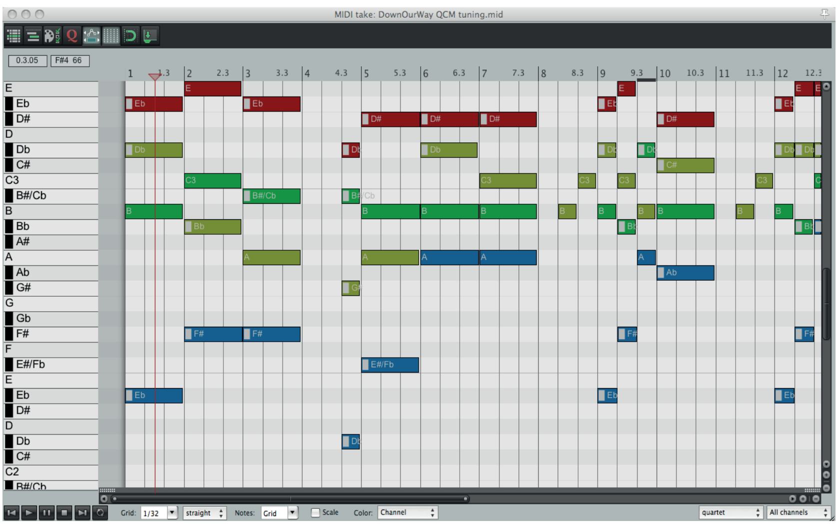

Figure 6. Piano-roll view in Cockos REAPER

As discussed by Baratè, Ludovico and Malchiodi (2017), this model can be profitably used to improve computational thinking and abstraction capabilities, e.g., by customizing the association between shapes, axes, colors on one side and musical characteristics on the other: axes can be swapped, pieces can be translated and rotated, colors can discriminate pitch or duration instead of timbre, and so on.

In the perspective of piano roll modeling, 3D printing technology can be used to generate solid blocks to be placed on a physical baseplate, instead of relying on a virtual, computer-based representation.

In the case of already-available blocks (see paragraph 4.1), the haptic approach should encourage children in linking physical properties of blocks to music parameters through manipulative activities. It is worth pointing out that the ability to build these relationships implies the development of abstracting attitudes.

Within an educational context, the design and fabrication by children of user-defined blocks, as proposed in paragraph 4.2, introduces new creative, expressive and self-reflection possibilities. For example: How to represent a new musical parameter, say dynamics? Possible answers include: by changing the general shape of the block, assigning this parameter to thickness, printing a conventional sign over the block, etc. Conversely, how to interpret a non-standard block, like a trapezoidal instead of rectangular shape? In these cases, the educational experience is even enriched by mistakes and misunderstandings, provided that a tutoring figure can explain and guide the young in the learning process. Concerning preschool children's invented musical notations, it is worth mentioning the research by Domer and Gromko (1996).

Let us now compare the 3D-printing approach to a similar activity conducted on paper. The main advantages are: the fabrication of 3D objects that implicitly allow more significant manipulations with respect to 2D paper fragments; the availability of a third dimension to represent musical parameters; the possibility to embed custom signs or to confer roughness effects to surfaces, which is particularly useful, e.g., for visually impaired children.

With respect to predefined building blocks, e.g. LEGO bricks (Ludovico, Malchiodi, & Zecca, 2017), a 3D printing environment presents a number of advantages, letting children: define their own shapes and choose custom colors, thus fostering their creativity; play an active role in the design phase; see in first person the fabrication of objects. Moreover, blocks can be shaped with materials and dimensions suitable for children of a given age. Figure 7 shows the 3D models of “piano-roll style” music blocks to be fabricated and later used to compose a music tune, whereas Figure 8a and 8b illustrate two compositions. In the case that vertical steps are mapped onto halftones, Figure 8a shows the encoding of a major scale, while moving the third block one step below would produce the corresponding minor scale; Figure 8b is the representation of the popular nursery rhyme entitled “Frère Jacques”.

In these didactic experiences, the role of the tutor is fundamental: he/she helps in the design and fabrication phase, guides learners in the understanding of musical parameters and their counterpart on 3D objects, stimulates their skills by changing associations, avoids frustrating situations and finds amusing and addictive ways to reinforce learning, e.g. by playing the resulting tune or organizing challenges among children.

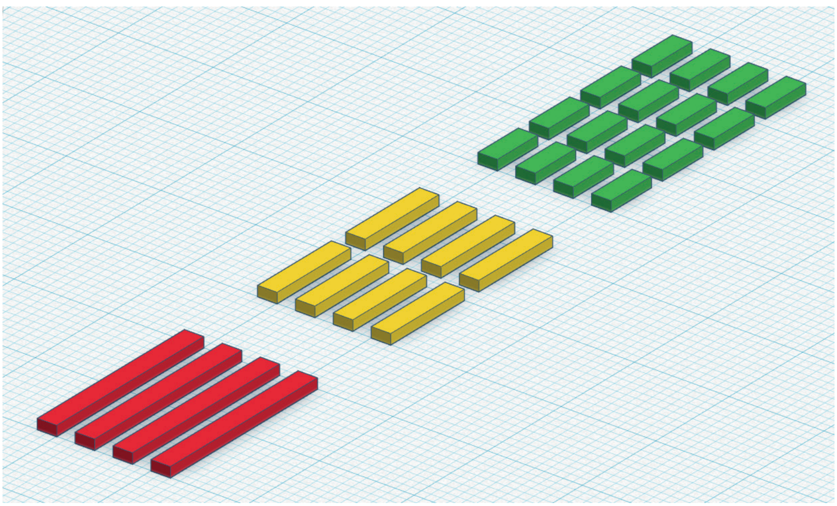

Figure 7. Modeling music blocks in a 3D CAD design tool

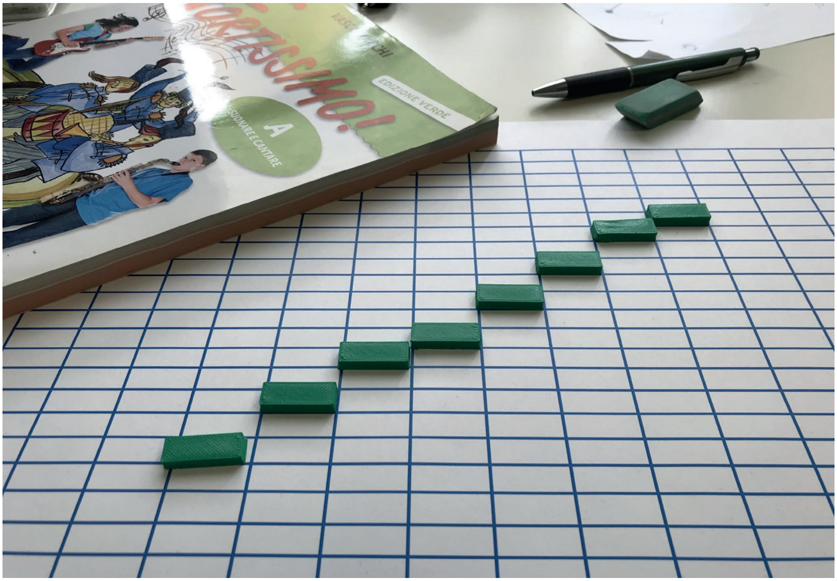

Figure 8a. A major scale represented through 3D-printed blocks

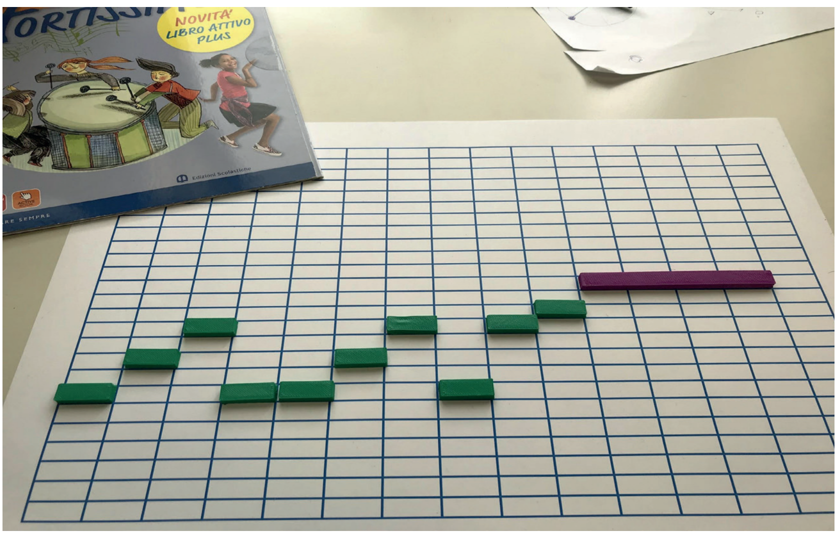

Figure 8b. "Frère Jacques" represented through 3D-printed blocks

6. Theoretical Valence of the Case Study

The case study described in the previous section, dealing with 3D fabrication finalized to the representation of music notation, can now be analyzed in the light of the theoretical constructs enounced in the first part of the paper.

Please note that the educational experience can occur in different phases: children learn during the design of blocks for notation (abstraction skills), during the use of the 3D tool to shape them (technical skills), during the physical manipulation of blocks to produce or reproduce a given music tune (self-reflection skills), and during the analysis or the performance of the resulting layout (critical and analytical skills). Depending on the target age, the level of music knowledge, and the educational goals, the experience can be subdivided into simpler sub-tasks or administered only partially.

Concerning *enaction*, defined in the paragraph 2, this kind of approach invites the user to acquire knowledge while exploring different environments: software, music notation, physical space, etc. A typical example is the adoption of *trial and error* techniques – a typical method of problem solving characterized by repeated attempts which are continued until success or withdrawal – during digital fabrication: blocks could not reflect the expected result or be unusable for user's goals, and in this case they can be redesigned and/or refabricated.

Concerning *embodiment*, each step of the proposed experience, from design to implementation and experimentation, is tightly linked to the concept of tangible user interfaces. Users are required to understand the relationship between the physical space (the score) and fabricated objects (the notes), and to develop sensorimotor capacities as well as manipulative abilities to achieve the intended final result.

7. Conclusions

In this paper, we have pointed out the potential of 3D printing in the context of preschool music learning and teaching, underlining its educational value (also in extra-musical fields) and listing a number of heterogeneous applications easily implementable through low-budget devices. Various approaches have been explored, including the adoption of already available models as well as the design and fabrication of user-defined 3D objects.

Examples of didactic activities may include the recognition of musical instruments and their subparts, the exploration of sound generation techniques, the design and fabrication of sounding objects, and the investigation of alternative forms of music notation.

For future work, we are planning to further investigate these proposals and implement them as learning practices to be experimented and assessed in preschool and out-of-classroom contexts.

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