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Fostering Computational Thinking in Primary School through a LEGO®-based Music Notation

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Abstract

This paper presents a teaching methodology mixing elements from the domains of music and informatics as a key enabling to expose primary school pupils to basic aspects of computational thinking. This methodology is organized in two phases exploiting LEGO® bricks respectively as a physical tool and as a metaphor in order to let participants discover a simple notation encoding several basic concepts of the classical musical notation. The related activities, grounded on active learning theory, challenge groups of students to solve musical encoding problems of increasing difficulty.

Keywords: Music; Education; Visual Programming

1. Introduction

The field of informatics is gaining an increasing interest from the teachers community, and in particular several concepts from this discipline tend to be taught more and more in non-vocational schools programs, even in the early phases of education. Focusing on primary schools, the vein of computational thinking is now inspiring several learning activities; the goal is to teach how to tackle problems in view of finding out possible solution schemes apt to be automatically carried out by a computer. This kind of activities lets pupils confront with several scientific aspects, such as the ability to abstract from experience, to formally describe a problem-solving process, and to test the validity of the latter. This approach can be highly effective in gently introducing young students to the scientific domain, so as to increase the chances that they will pursue studies in a STEM (Science, Technology, Engineering and Mathematics) field. Within this process, informatics obviously plays a key role and can be considered as an inspiring source for several activities.

The fact that pupils are very young is challenging, both in terms of carefully selecting which subjects are more appropriate to be approached,[1,2,3] and in critically evaluating the fact that the so-called *digital natives* have already been exposed to technological devices such as smartphones and tablets. Consequently, the educational effort should go in the direction of letting pupils *understand* – rather than use – such devices. Another critical point concerns

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the teaching methodology to be adopted. In fact, there are several alternatives with respect to the traditional *direct* transmission of knowledge supported by standard frontal classes. Finally, the choice of informatics as a teaching subject can highly benefit from the interdisciplinarity typical of this field, where teachers can select non-technical working examples drawing from a wide spectrum of subjects.

In this work we try to put together these three fundamental issues by proposing an active learning unit dealing with the representation of information and aiming to let primary school pupils discover a simplified musical notation. The activity is supported by the *algomotricity* learning methodology,[4] and it is organized in two main phases: in the first one pupils are asked to physically manipulate LEGO® bricks and they are guided into the discovery of a simple yet expressive musical notation. In the second one students are asked to work in small groups in order to solve musical encoding exercises of increasing difficulty, possibly with the support of a specially conceived software that helps pupils in applying this notation by arranging *virtual* LEGO® bricks.

The paper is structured as follows: Section 2 briefly summarizes the recent research results in the area of informatics teaching, with special emphasis on the learning methodologies we refer to. Section 3 illustrates the proposed approach, detailing its musical and computational aspects and describing the developed musical notation to be used during the learning activities. Finally, a number of clarifying examples will be presented in Section 4. Some concluding remarks end the paper.

2. Background

Starting from a description of the educational frameworks we refer to, this section describes how a suitable mix of concepts from the musical and informatics domains can lead to an effective learning experience.

2.1. Computational Thinking

There has been a recent interest in studying how learning activities in the early stages of education may benefit from considering the field of computer programming, or more in general expose pupils to problem-solving activities involving processes such as abstraction, iteration, critical thinking or debugging, or more in general related to *computational thinking* skills[5,6,7,8,9,10]. In particular, while approaching the basic concepts and the strategies related to coding, students can develop specific logical-cognitive abilities, with positive future effects in terms of meta-knowledge and skills[11].

2.2. Algomotricity

Algomotricity[4] is a learning methodology specifically focused in conveying concepts from the informatics field[1], deeply rooted on laboratorial/group activities and in the realm of active teaching[12]. As such, learning in these activities doesn't rely on a *direct* transmission of knowledge: instead, a *facilitator* simply orients participants in their autonomous discovery of concepts.

In particular, the approach aims at fostering a view of informatics as a scientific discipline dealing with the automatic processing of information, rather than the mere ability of using software applications or technological devices[13].

Using as references the problem-based learning framework[14] and the experiential learning theory[15], an algomotorial laboratory typically starts with the description of a problem that pupils are asked to solve, working in small groups and engaging in tangible/manipulative activities that let them gently approach a topic to be further investigated. This topic is further developed in a second phase promoting an abstract reformulation allowing each participant to build a mental model and to test it. In order to meet, at least in part, the expectations of pupils, who indeed tend to identify informatics with the use of computers, the activities end with a computer-based phase. In these activities, students are confronted with specially conceived software applications, in the idea that the preceding phases have raised their proficiency in using these applications in order to solve specific problems.

Among the several subjects that algomotricity has been applied to (including for instance the representation of information[16], the introduction of programming[17] and the use of recursion as a solving strategy[18]), a recently proposed

[1] The neologism "algomotricity" is a portmanteau combining the words "algorithm" and "motoric".

musical coding activity[19], described more in depth in Sect. 2.3, is based on a visual language that lets pupils describe the execution of a simple musical score using typical constructs of programming languages such as variables and iteration. In Sect. 3 we propose a similar activity based on the use of LEGO® building bricks in an algomotricity context, in order to drive primary school students to discover how to represent music scores through a notation alternative to the traditional one.

2.3. Music and Computational Thinking

Music promotes the integration of several key dimensions of the human being, such as the perceptual, motor, affective, social and cognitive ones[20], and thus it can have a profound impact in the education of young students. Indeed, basic aspects of music naturally relate with analogous aspects of human life (e.g., rhythm, melody, and harmony on the one hand, and physiology and emotion on the other one), and listening, exploring and analyzing represent fundamental activities at the basis of the development of meta-cognitive skills such as attention, concentration, and control. Finally, computational thinking attitudes such as analysis, synthesis, problem posing, argumentation, and rule application can be effectively fostered in the early stages of education through music[21,22,23,24].

As a consequence, there is a growing interest in blending musical and computational thinking concepts in education, both with the aim of using one of these subjects in order to convey the other one more effectively, and in a truly interdisciplinary teaching approach.

As for the use of new technologies, they can support and enhance how music is learned and taught: just to state an example, when learning a musical notation, a proper audiovisual feedback (that is, the graphical rendering of a specific score and the corresponding audio reproduction) may extremely enhance the self-consciousness level of the learners. Moreover, an automated environment can be conceived to further improve self-consciousness, for instance by adding the possibility to start peer discussion / review / seeking activities, as well as to get expert / teacher advice.

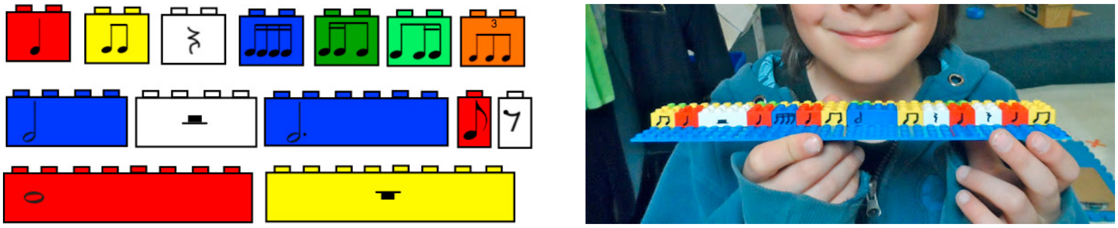
There is therefore an urgent need to provide new approaches and methodologies to teach music *and* informatics, with an appropriate technological support, in schools. This issue has been reviewed and discussed in[25], where the transformation of music education and – more in general – of schooling are highlighted.

The literature has plenty of references to music-based approaches to computational thinking. As a first example, consider the programmable robots vein initiated from the works inspired by Music Information Robotics[26,27,28]. Fixing the focus on initiatives devoted to young students, we can mention *Play-I*[2], a robot that can move around, express character using sounds and lights, and respond to a number of external stimuli. Through a tablet-based app, children can program the robot to play music and dance during the performance. Another example is *Wigl*[3], an interactive educational robot able to hear notes from any instrument and to respond with real-world movements and lights. Another interesting initiative is *Note Code*, a music programming puzzle game designed as a tangible device coupled with a graphical user interface[29]. The actions of tapping patterns and placing boxes in proximity enable programming these entities to store sets of notes, play them back and activate different sub-components or neighboring boxes.

Moving to the field of coding-oriented approaches to music teaching,[19] proposes a visual programming environment based on Google Blockly[4], whose language includes instructions that enable students to build and play musical sequences. Once executed, programs play these sequences and draw on screen the corresponding musical scores in common notation.

Thus, a suitable learning framework can improve music skills and, at the same time, it can convey computational thinking concepts. Such a framework should rely on some symbolic language to encode musical elements: the next section describes a notation specially conceived to be used with primary school students. This notation has a complexity intentionally kept to a minimum, and it can be naturally taught in an active environment through the use of LEGO® bricks.

[2] `https://www.makewonder.com/`
[3] `http://wiglbot.com/`
[4] `https://developers.google.com/blockly/`



(a) Blocks and rhythmical patterns. (b) An example of rhythmical composition.

Fig. 1: A LEGO®-based representation of rhythm in use at the Lego Music center.

3. LEGO® Music Notation

The usual way a score is currently represented in our culture is called *Common Western Notation* (CWN). In a nutshell, CWN is the notation system that – in standard cases – uses a five-line staff as a framework upon which pitches are indicated by placing round notes on the staff lines or between them. For more details about CWN, please refer to a music notation manual such as [30].

LEGO® Music Notation (LMN) is an alternative way to represent music scores through bricks properly placed over a building baseplate. Standard LEGO® blocks have the shape of a parallelepiped, sized $W \times H \times D$, standing for width, height, and depth respectively. In the following, we will adopt the convention that the latter parameter is not expressed in the representation of brick size, being implicitly set to the default value $D = 1$, unless this dimension is associated to a music parameter.

3.1. Pedagogical Aspects

The main research questions that emerged in the preliminary phase of this work were: 1) if, 2) how, and 3) to what extent a learning activity based on LMN could foster computational thinking aspects. In fact, such a proposal seems to be significantly different from other initiatives aiming at the same goal, but more explicitly linked to the concept of *coding*, such as those mentioned in Sect. 2.3.

Nevertheless, some crucial points at the basis of our approach move in that direction. First, coding does not mean programming, but rather it implies the development of logical thinking in learners. Besides, the aspects of problem solving, physical and logical manipulation, abstraction and conceptualization are typical of a conceptual design that encourages the development of computational-thinking skills. As explained in the next section, all these aspects can be adequately promoted by LEGO®-based didactic activities.

As it concerns the use of LEGO® bricks, it is worth pointing out the following considerations.

- A gamification approach fosters the engagement and motivation of students, with significant improvements in terms of attention to reference materials, participation and proactivity [31].
- At an early age, LEGO® blocks provide a more familiar and simplified language to represent music with respect to CWN, being suitable to both musically trained and untrained pupils. During an educational activity, the brick set can be increasingly extended, going from basic shapes and a limited palette of colors to non-standard pieces and a wide chromatic range. In this way, it is also possible to tune the didactic experience on the basis of students' age, music knowledge, level of attention and engagement.
- The musical meaning of brick characteristics – shape, color, position over the board, etc. – can be reconfigured, thus supporting multiple and heterogeneous encodings of a music score. This characteristic will promote conceptualization and abstraction skills.
- The LEGO®-based approach can be easily and profitably combined with *algomotricity* (see Sect. 2.2), in order to plan learning units including a manipulative phase followed by a computer-based phase.

3.2. Related Works

A number of educational activities has focused on the use of LEGO® bricks to convey music concepts. For example the LEGO® Music Center[5] invites its students to create rhythmical patterns by combining predefined LEGO® blocks, as shown in Fig. 1. In this proposal, the length of bricks corresponds to a fixed time subdivision containing different patterns. A similar approach, once again focusing only on rhythmical aspects, was explored in[32].

As we will clarify in next sections, there are significant differences from our proposal, above all concerning the general approach. First, in the mentioned works only the rhythmical description of music is taken into account, whereas other dimensions such as melody, harmony, and instrumentation are not explored.

Concerning related works, it is worth citing LEGO Music[33], a multi-touch tabletop application that uses LEGO® bricks as physical representations for musical notes in order to illustrate composition principles and musical operations like transposition, inversion, and retrograde.

In all the described experiences, blocks present a predefined meaning, thus forcing students to adhere to that convention and limiting their creativity and abstraction efforts. The main aspect of novelty of our proposal is the possibility to change the association between spatial and physical properties of blocks on one side, and music dimensions on the other.

In conclusion, other LEGO®-based experiences had mainly the goal to teach music through a playful approach, whereas our ultimate aim is to convey computational thinking skills thanks to a combined use of music and LEGO®.

3.3. Notational Aspects and Remarks

The proposals mentioned in Sect. 3.2 and their experimental results demonstrate that rhythm can be intuitively explained and represented through LEGO® bricks, and this is one of the purposes of LMN as well. In the music field, rhythm can be seen as the timing of musical sounds and silences that occur over time. In most notational systems, including CWN, time is represented on the x axis of the score. Considering music representation over a physical medium, such as a paper page, it is often necessary to introduce line breaks when the page margin is reached, but this is just a practical expedient; in fact, together with a *page view* with line breaks, digital score editors usually present a continuous representation called *scroll view*. In conclusion, it is intuitive to map the rhythmic aspects of music onto the horizontal dimension.

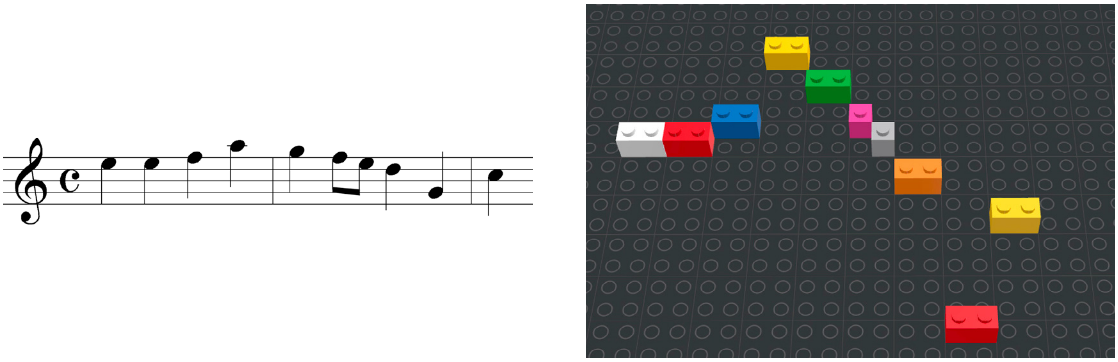
As it regards LMN, a 1xH brick can be assigned to the smallest rhythmical value in the score. Dimension H will be discussed later; for the sake of simplicity, let $H = 1$ for now. For example, if the sixteenth note is the smallest rhythmical value, that duration will be assigned to the shortest brick (i.e. 1×1), eighth notes will be represented by bricks twice as long as those (i.e. 2×1), quarters will be twice as long as eighths (i.e. 4×1), and so forth.

Blocks composed by an odd number of sub-elements can be used to represent dotted or tied notes. For instance, if the 1×1 brick is assigned to an eighth note, a 3×1 brick represents a dotted quarter note, a 5×1 brick a half note tied to an eighth note, and so on.

This approach can be opportunely extended to support more complex situations, e.g., scores including irregular groups. Let us consider a music piece with quarter notes, eighth notes and eighth note triplets: in this case, the quarter note should be represented by a block having a number of sub-elements divisible by 2 and 3; consequently, a good choice could be a 6×1 brick. Please note that, if there are no sixteenth notes in the score to be represented, the atomic 1×1 brick will never be used in such an encoding, which partially corrects the aforementioned assertion that the 1×1 brick has to be assigned to the smallest rhythmical value (i.e. a sixteenth note in a sextuplet).

Assuming that the score contains a melody for pitched musical instruments, the other basic aspect to encode is the tunes' melodic contour. Again, the experience drawn from CWN and other notational systems suggests the more appropriate dimension to exploit: pitches can be intuitively mapped onto the vertical dimension. As for W, we have to fix and explain the meaning of H values. The commonly-accepted Western tuning system is the twelve-tone equal temperament, which divides the octave into 12 parts called semitones, where the semitone is the smallest supported interval. Consequently, each vertical unit of the baseplate can be put in correspondence with a pitch of the tempered scale (i.e. C, C♯, D, etc.). Under this assumption, the bricks used to represent a melody must have $H = 1$; in fact,

[5] `http://elementarymusicresources.blogspot.ca/2013/05/centers-lego-music.html`



(a) Common Western Notation (b) LEGO® Music Notation

Fig. 2: Incipit of the Allegro from the *Symphony No.6, Op.68* by Ludwig Van Beethoven.

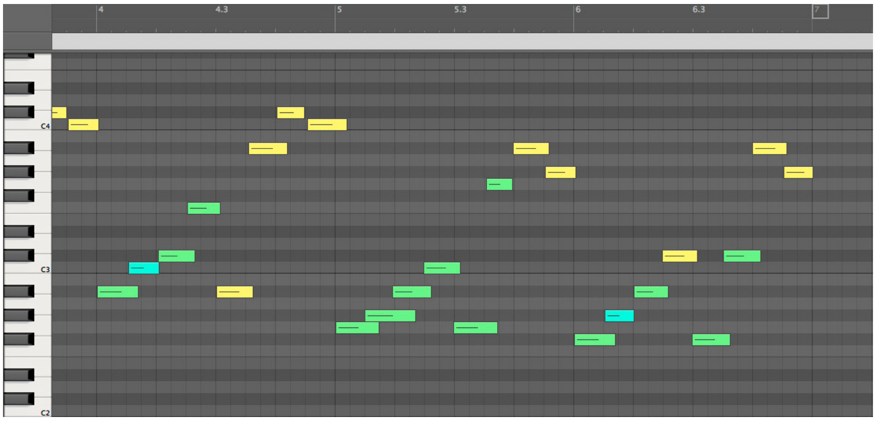


Fig. 3: A piano roll view of a music piece in MIDI format. The x axis represents quantized time, the y axis provides pitch information, and color is associated with MIDI channels, i.e. instrument timbres.

$H > 1$ would imply a tone cluster, namely a musical chord comprising adjacent pitches. Figure 2 shows an example of translation from CWN to LMN adopting such conventions.

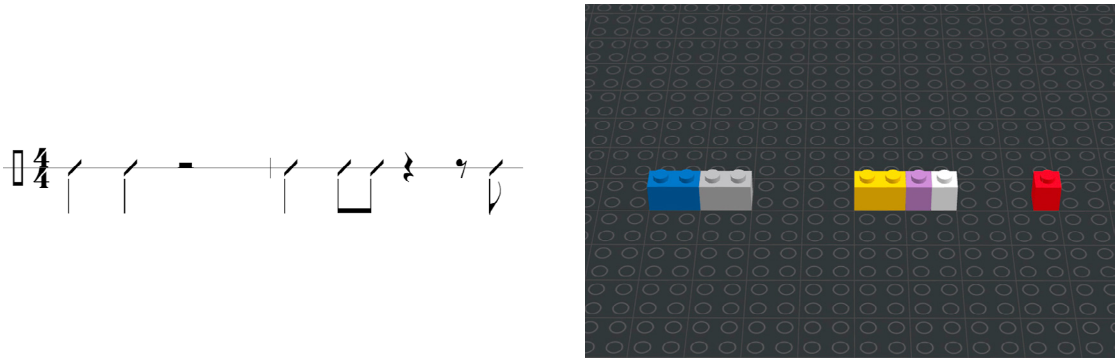
Please note that simultaneous bricks[6] can be positioned over the baseplate to encode chords, thus taking into account also the harmonic dimension of music.

The approach described so far, involving only brick width and height, works well for monophonic-instrument scores, where there is no need to track different voices and it is extremely unlikely that the same pitch is performed simultaneously. Conversely, in a multi-timbral context, different monophonic musical instruments or – in more general terms – different voices can be characterized through colors. Thanks to the availability of a wide palette[7], a great number of voices can be supported inside a single LMN score. In simple use cases, it is virtually possible to recall either the chromatic aspect of musical instruments (e.g., bright yellow ↔ trumpet and dark brown ↔ cello) or to create subjective associations (e.g., bright red ↔ bassoon and earth blue ↔ clarinet), thus providing students with a reinforcement technique based on colors.

It is worth underlining that the aforementioned way to link brick size, position and color to music parameters recalls the "piano roll" view in modern digital audio workstation software, typically used to display and edit MIDI note data, such as for instance in Fig. 3.

[6] If time is mapped onto the horizontal dimension, simultaneity means that – for a given discretized value of x – multiple blocks are present at different values of y.

[7] Currently, LEGO® bricks are available in almost 50 colors.



(a) Common Western Notation (b) LEGO® Music Notation

Fig. 4: A rhythmic example.

Fig. 5: Two possible reinterpretations based on different color-to-pitch associations.

Needless to say that other mappings are possible. For example, the *y* axis could be used to differentiate a number of unpitched musical instruments playing together rather than note pitches. In this way, a LMN score could contain multiple independent rhythmical lines, one per horizontal slice. In this case, the color parameter could be simply ignored, or reused for a different purpose (e.g., to encode dynamics).

Please note that changing on-the-fly the association between LMN and music parameters during an activity could be a good exercise for students to foster mental agility and independence from a specific representation of data.

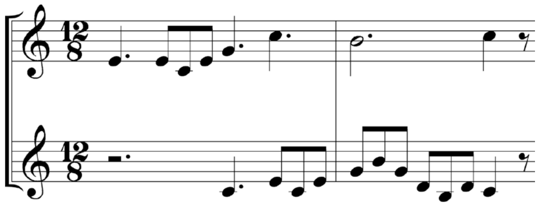
The examples discussed above have focused on a limited set of parameters – horizontal and vertical position over the board, size, and color – but this range could be extended. A quite obvious enhancement concerns the *z* axis, where either partial or complete brick overlapping could be allowed in order to support multiple performance of the same pitch by different voices. Another extension directly connected to the *z* axis consists in evaluating block depth to represent a new property. For instance, dynamic indications could be encoded by associating thin blocks ($D = 1$) with ***p***, and thick blocks ($D = 2$) with ***f***.

Additional characteristics of bricks could further extend the representation capabilities of LMN. For instance, contiguous bricks can be joined together through thin transparent blocks to tie the corresponding notes; non-parallelepiped shapes (e.g., bricks with slope) can be assigned to specific musical meanings (e.g., crescendo/diminuendo effects); and so forth. Some clarifying examples will be presented and discussed in the next section.

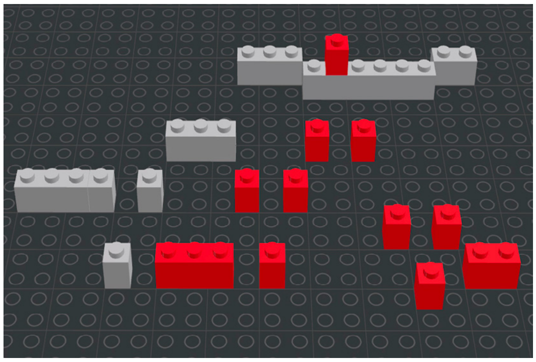
4. Examples

In this section we will show some assignments aiming at reconstructing increasingly complex music tunes through a proper combination of LEGO® pieces. In order to achieve this goal, students will be invited to analyze a piece of music, to exploit abstraction processes aiming to produce an LMN-based description, and – since the solution is not unique – to develop creativity and problem-solving skills. All these aspects are key components of computational thinking as well.

Algomotricity proposes an experiential learning approach occurring in three phases: 1) definition of the problem, 2) meta-cognitive reflection and construction of a mental model, and 3) hands-on experience. Consequently, even if LMN-based games are conceived for self-exploration of coding concepts, the pedagogical proposal should reflect the mentioned stages. The learning situation can occur both in a supervised environment, namely with the help of an expert, or in a peer-to-peer context, thus fostering students' self-regulation, critical skills, and social attitudes.



(a) Common Western Notation



(b) LEGO® Music Notation

Fig. 6: *Duettino* for 2 trumpets by Domenico Gatti (excerpt).

The first example focuses on purely rhythmic materials, recalling other experiences mentioned in Sect. 3.2. Figure 4(a) shows a simple score excerpt notated in CWN. Binding the horizontal dimension to time and – consequently – to rhythm, and using colors only to better mark distinct note events, Fig. 4(b) shows a possible solution of the problem in terms of LMN, where the rhythmical value of an eighth note has been arbitrarily put in correspondence with $W = 1$. In this assignment involving a single unpitched instrument, the vertical dimension has no specific meaning: for the sake of simplicity, in the proposed solution all bricks have been horizontally aligned. A possible improvement is to represent dynamics-related information on the vertical dimension, so that a 2×1 block stands for a "soft" quarter note, whereas a 2×2 block stands for a "loud" one.

In order to encourage other aspects of computational thinking, and specifically abstraction skills, the following step is to change the assignment of some parameters and let students understand how this affects the representation. For example, starting from the solution shown in Fig. 4, if we ask students to establish arbitrary correspondences among brick colors and pitches, we can obtain music fragments such as those shown in Fig. 5. This is a good exercise to challenge the analytical skills of students and to help them to develop mental flexibility.

A second exercise is presented in Fig. 6(a), proposing a music piece to be played by two musical instruments. The first question concerns the representation of multiple independent voices: a possible solution is to use colors, say light-colored pieces for the upper line, and dark-colored blocks for the lower one. Again, time is assigned to the horizontal dimension (one step corresponds to an eighth note), but now pitches are denoted by the vertical position of bricks (one step represents a semitone). As shown in Fig. 6(b), in a particular circumstance the two instruments play the same note, and so one of the corresponding LEGO® bricks must be stacked one on top of the other one.

As a final case study, let us highlight to what extent the abstraction process can be pushed in reinterpreting the same LMN score. First, even keeping the associations among music parameters and brick characteristics and positioning, it is possible to rotate the baseplate so as to originate completely different music scores; but, more interestingly, very heterogeneous results may emerge when such associations are left to students' interpretation and creativity. For instance, let us analyze the LMN score and some possible transcriptions into CWN presented in Fig. 7. The first CWN score is obtained by mapping the horizontal dimension onto time/rhythm, the vertical one onto pitches, and colors onto voices. Similarly, the second CWN score maps the horizontal dimension onto time/rhythm, but the vertical one is used to discriminate among multiple unpitched instruments (one per horizontal slice), and brick color carries dynamics information. Finally, the third score is obtained by reading time/rhythm information on the vertical dimension, assigning notes to different musical instruments on the base of brick colors, and creating an association among brick widths and scale degrees (e.g., 1↔C, 2↔D, 3↔E, etc.).

These examples seem to suggest a twofold way to structure a LEGO®-based learning activity. In the case of a known music piece to be encoded into LMN, analytical skills are necessary to correctly decode the input (modern notation, humming, etc.), whereas creativity is required to map the subset of music features to be represented onto available bricks. In the case of free composition of a LMN score, after such a "creative" step analytical skill are called for, first to establish a set of interpretation rules that is compliant with the LMN encoding (in fact, not all associa-

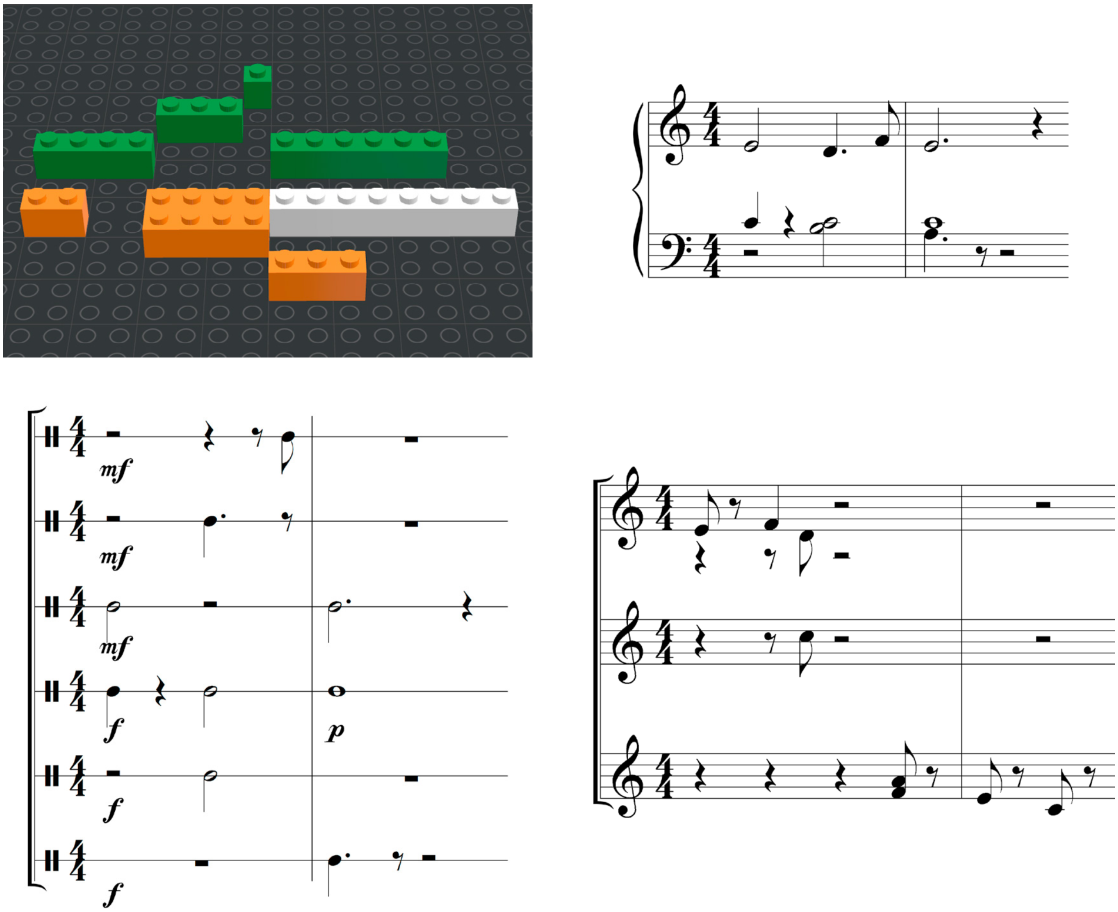


Fig. 7: A LMN score and some possible transcriptions into CWN.

tions produce valid results), and then to provide the corresponding CWN score (or another kind of representation or performance).

5. Conclusions

In this work we proposed a musical notation apt to be used within learning units based on the active teaching methodology and devoted to primary school students. This notation can be autonomously discovered by pupils through the use of LEGO® bricks, thus it can be used within teaching units based on the algomotricity approach. The resulting activities can have a twofold purpose: that of conveying computational thinking concepts (with special emphasis on information representation) through the use of musical notation, or – conversely – that of discovering a simplified musical notation and its formal description.

The activity can be coupled with an expressly designed software tool, whose implementation is currently at a mock-up phase. Such an application, written in HTML5 and JavaScript, will be publicly available via the Web. Conceived to be integrated within an algomotricity experience (see Section 2.2), it will implement the basic functionalities to choose brick colors and shapes, to place blocks over the baseplate, and to associate different musical meanings to the mentioned aspects. Besides, the Web application will include automatic playback features in order to reinforce learning and comprehension.

In the next future we plan to complete and test the software tool and to design the full learning activity, in order to be ready for a research-action experimentation in schools.

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