AudioCubes: a Distributed Cube Tangible Interface based on Interaction Range for Sound Design

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ABSTRACT
AudioCubes is a novel tangible user interface allowing any person interested by sound design such as sound creators, and music trainers to intuitively explore and create dynamically changing sound. A new sound is created by manipulating distributed cube tangible user interface that can be coupled wirelessly by locating them in the interaction range of each other on a table. At any time, a sound processing network combines operational properties of AudioCubes, such as location on a plane or in space, movement, arrangement with other cubes, and layout. Sound algorithm parameters and the configuration of the sound processing network can be changed simultaneously, allowing a fast and convenient exploration of sound creation space that creates a new interaction technique for creating sounds.

Author Keywords
Contextor, interaction range, interface coupling, sound design, tangible user interface.

ACM Classification Keywords
H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems – *Audio input/output*. H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Input devices and strategies, Interaction styles, Prototyping, User-centered design*. H.5.5 [**Information Interfaces and Presentation**]: Sound and Music Computing – *Signal analysis, synthesis, and processing*. J.5 [**Arts and Humanities**]: Performing arts.

INTRODUCTION
A tangible user interface (TUI) [6,10,25] is usually defined as a graspable physical user interface that is built from any kind of physical objects (e.g., surfaces, volumes, toys, everyday objects) and materials (e.g., plastic, wood, metal). The major TUI interaction technique is based on direct manipulation of the physical objects (e.g., manually, via a motor or a computer) instead of traditional widgets (e.g., radio button, push button) through a mouse, keyboard, or any other pointing device. A TUI invites users to manipulate physical objects that either embody virtual data or act as handles for virtual data [8]. TUI Physical objects provide end users with a lot of potential benefits such as: natural interaction (intuitively [8] and cognitively acceptable [19] interaction), good affordance [20], ecologic interaction (no particular physical device such as a mouse is required), distributed interaction [11], multiple physical configurations [14], two-handed input [26], spatial and haptic immediate feedback [24], and multi-user input [22,29].

TUIs have been considered for sound and music creation (e.g., [1,3,9,12,13,15,29] because they have always been creative tasks in which the musician or artist has a direct interaction with a musical instrument. Even when electronic musical instruments became popular and available to more musicians in the late seventies, artists still had a direct dialogue with their synthesizers and keyboards, through the use of physical sliders, knobs, buttons, and displays. When personal computers became affordable and widespread, they were introduced in recording studios and used by musicians and artists for composition and sound design. These computers became powerful enough to run real-time sound processing software, and companies started to design and sell professional audio software that would run on any standard personal computer with an audio interface. Over the past years, considerable efforts replaced the physical hardware interfaces and equipment from the past with software running on a computer, which is by now so powerful that almost an entire recording studio can fit on it.

However, with the equipment virtualization, the users lost touch with the hardware interface, which has by now been reduced to pictures of knobs and sliders, often perfect software replicas of their physical counterparts. Due to this virtualization, the relationship between the arrangement of widgets in the software application and the physical knobs and sliders on the hardware control surface has been equally lost, thus confusing users largely [7]. There could be so many widgets that the novice user would not understand how to take advantage of all the possibilities: “a GUI is not optimal for interacting with an auditory experience” [25]. In particular, it is impossible to manipulate more than one widget at a time while performers are able to act of several physical controls simultaneously. Because of all these reasons, the music performance needs to be supported by a TUI that combines the facilities provided by physical hardware and software so as to recreate the lost touch. The AudioCubes system attempts to alleviate these shortcomings by providing a distributed cube TUI based on interaction range for helping multiple users to create sounds.

The remainder of this paper is structured as follows: the next section reports on how AudioCubes have been developed by describing their functioning, how they can be coupled, how they have been implemented and designed. The third section reports on experiments conducted to assess the usage quality of AudioCubes. The fourth section compares AudioCubes with respect to the state of the art. The fifth section concludes the paper by summarizing the original aspects of AudioCubes and discussing future avenues of this work, towards a framework of physical objects.

DEVELOPMENT OF THE AUDIOCUBES SYSTEM

Description of an AudioCube

An AudioCube is a cube TUI made out of a plastic material that contains a digital signal processor (DSP) with optical sensors and emitters (infrared, red, green, and blue LEDs). The sensors and emitters receive and send audio signals which are generated or processed by the signal processor in the cube. Each cube is powered by a rechargeable battery pack and can be configured by a software before being used via a cable. By positioning the cubes relative to each other and moving them around, e.g., on a table or on any other surface (Fig. 1), a signal processing network can be created. A musician may use this TUI to learn a new way of interacting with sound and music.

Operational properties. Since an AudioCube could be considered as a sensor, it can be characterized by *operational properties* [2,4] that describe the performance of an entity observing a physical phenomenon. We adapt these properties for the purpose of characterizing an AudioCube:

- *Resolution* (the smallest variation possible of the phenomenon that can be captured): if a cube is moved a few millimeters (~5 mm), a change could already be noticed.
- *Latency* (time elapsed between a stimulus of the phenomenon and the response of the system): from a system viewpoint, it depends on the network complexity [0,01 sec ; 0,1 sec], but from the human viewpoint, the system seems to work in real-time.
- *Sampling* (the minimum amount of time between two sensing): the detection is roughly at 60Hz.
- *Frequency* (minimum and maximum frequency for emitting or receiving sounds): [140 Hz,280 Hz]. For instance, in Fig. , two cubes (green and red) are emitting a sawtooth wave at frequencies 140 Hz and 280 Hz respectively. The blue cube receives and mixes both signals.
- *Stability* (ability of the cube to not indicate any variation if the phenomenon does not vary): very high.

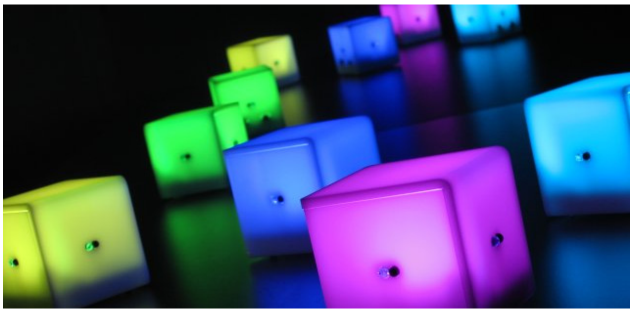

Figure 1. A set of AudioCubes operated on a table.

- *Minimal range* (r_{min}=minimum distance for a cube to be coupled with another one): this depends on how cubes are coupled, but in general, a 0.5 cm distance already works.
- *Maximal range* (r_{max}=maximum distance for a cube to be coupled with another one): 50 cm (Fig. 2).
- *Range angle* (φ= maximal angle of range detection): 30°.
- *Measurements* (all dimensions of the cube): side=70 mm, weight ≈ 300 g, color palette = 4096 possible colors.
- *Autonomy* (maximal duration of functioning before running out of power): 3 hours.
- *Orientability* (ability of the cube to change its interaction range): all cubes are manually operated since their purpose is to response to user's manipulation.
- *Calibrating* (ability of a cube to fine tune, tweak its parameters so as to optimize its functioning in a given environment): semi-automated since it could be manually regulated through a configuration software which suggest default values. For a sound sensor cube, for instance, the parameter "sound level" determines the minimal ambient sound level beyond which the cube should be sensible.
- *Life duration* (estimated life duration of a cube): more than 2 years - probably 5 years or so.

Based on the range angle, the minimal and maximal ranges, the *interaction range* of an AudioCube is defined as the interaction region in which coupling may occur. *Coupling* is defined as the act of linking entities such that they can provide together a new set of functions that would not be otherwise possible [5]. When a cube is placed in the interaction range, respectively outside, of another one, it is said to be *in range*, respectively, *out of range* (Fig. 2).

Functional coverage. This represents the set of functions provided by a cube based on the principle that one or many functions could be assigned to each face of a cube. Therefore, an AudioCube may hold zero, one, or many functions for each face. A non-exhaustive list includes [2]:

- *Detection* (ability of the cube to detect a particular phenomenon): presence/absence of a cube in the interaction range, presence of multiple cubes in the interaction range.
- *Identification* (ability of the cube to recognize a particular instance of a class of cubes): identification of the cube type which is either *emitter* (e.g., play a sound, play a MIDI file, produce a background music, play a previously recorded sound), *receiver* (e.g., microphone, record a sound), or *transceiver* which combines an emitter and a receiver (e.g., special effect, dimmer, amplifier).

- *Tracking* (ability of the cube to follow continuously a detected and/or identified phenomenon): tracking of cube distance, angle after moving, rotating, permuting faces. For this purpose, a description of all cube operations based on the cube group [17] is embedded in the system.

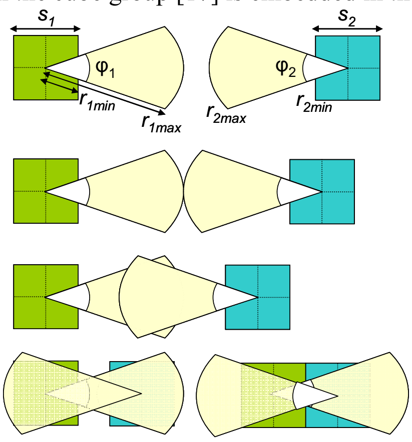

Figure 2. Interaction range of AudioCubes.

Fig. 2 graphically depicts a top-view of a two-cube interaction based on their interaction range, where C_1 has an emitter face and C_2, a receiver face. The C_1 cube of side s_1 has an interaction range which consists of a sector of angle φ_1 (if viewed from the top) ranging from minimal range r_{1min} to maximal r_{1max}. Another cube C_2 could have another s_2, φ_2, r_{1min}, and r_{2max}. In Fig. 2a, the two cubes are out of range and, therefore, cannot be coupled to combine their respective functional coverage. In Fig. 2b, the two cubes are joined since their interaction ranges share a point. In Fig. 2c, the two cubes are in range and could therefore be coupled. Cubes can be moved close to each other depending on their minimal ranges (Fig. 2d and e). Since an AudioCube may hold several functions for each face, they can be combined with each other in multiple configurations such as: single input by facet (Fig. 3b involved a green cube receiving from the green and the purple cubes), multiple inputs by facet (Fig. 3a combines a green cube and a blue cube received by the green cube), single output by facet, multiple outputs by facet, and multiple input/output by cube. Of course, AudioCubes should not necessarily be aligned or coplanary (in the same plane). For instance, they can be stacked, piled, rotated in order to induce a particular configuration. Only when two or more cubes are in their respective interaction range, they can be coupled together. The next subsection investigates how and when.

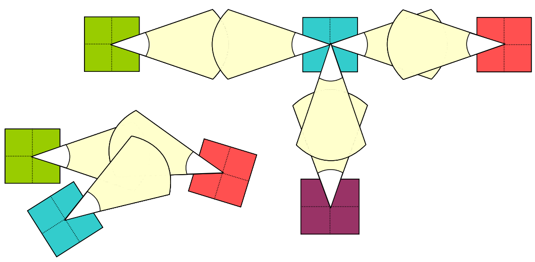

Figure 3. Various AudioCubes configurations.

Coupling and uncoupling of AudioCubes

Let us examine closer how two cubes could be coupled and uncoupled according to the notion defined in [5]. A cube is said to be *locked*, resp. *unlocked*, when it is already in use and cannot be used in another interaction. For instance, an amplifier may receive in input only one sound; as soon as a sound arrives, it cannot accept anymore another sound to amplify. It then switches its status from unlocked to locked. Two cubes are said to be *couplable* if all conditions required to be coupled are satisfied. These conditions include not only that each cube is in the interaction range of the other one and vice versa, but also that the corresponding faces are compatible (e.g., an emitter and a receiver). If at least one condition is not satisfied, they the cubes are said to be *uncouplable*. Two cubes are then coupled when the coupling has been established. If a cube becomes out of range of another one, then decoupling occurs. A cube enters in its *decouplable* status after been coupled. It is possible also to force a cube not to decouple by setting its decouplability to false. For instance, once a cube is coupled, it cannot be decoupled. After being decoupled, a cube returns to its uncoupled status. Fig. 4 depicts a state-transition diagram with 8 status and 18 transitions possible for two cubes to be coupled and decoupled. It can be generalized for more than two cubes by reproducing the second sub-part.

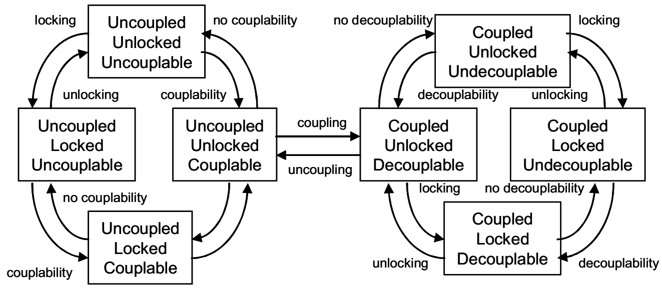

Figure 4. Coupling and uncoupling AudioCubes.

Implementation of the AudioCubes System

An AudioCube consists of a TUI allowing users to interact in parallel with a variety of passive or active objects [25], in order to interact with a computer system. Each of these objects can be arranged in space independently. The spatial relationships of these objects are sometimes used to control the computer system. In other cases, the objects can be combined to create a larger structure [25,26]. In some systems, the objects are active, contain electronics, and process data independently, and in other cases, they are passive objects associated with data or programming code stored on the computer system. The computer system can be separate, or it can be contained within the interface itself, i.e. a processor embedded in each object. Some TUIs combine these interaction modes and properties. For this purpose, our interface consists of a collection of cubes made from a translucent material. Each cube contains battery-powered electronics capable of processing sound in real-time. The electronics can be connected through a cable with a PC to download new sound processing algorithms to the cube.

When the cable is disconnected, the cube runs the software by itself while being powered by its rechargeable battery. Each of the cubes sends sound to its neighbors using infrared light, and receives sound from its neighbors simultaneously, also using infrared light. Sound is emitted and received through the faces of the cubes. By positioning the cubes on a table and moving them relative to each other, we can create a dynamically changing network of independent sound processors. This network is dynamically composed according to the notion of logical contextor [4], which derives particular context fro the cubes layout. The properties of the electro-optics embedded in each cube contribute to the timbre and overall character of the sound [1]. The light received from the environment in the infra-red band of the spectrum will also influence the transmitted signals. We argue that this is an advantage, as our TUI will blend with the environment in which it is used, resulting in auditory results with a controllable unpredictability. To reach this implementation, we went through a series of 3 design steps which are reported in the next subsection.

Design process of the AudioCubes System

Step 1: User inquiry. When the ideas for the AudioCubes system were first initiated, it was clear that the cubes, as expected, would be complex mechanically, electrically, and at the level of software engineering. It would also take a long time to prototype the system and physically build it. For this purpose, a user inquiry has been conducted among five artists and musicians in different composition areas to identify a further list of requirements, among which were:

- The ability to use the cubes in three dimensions.
- Each face of the cube should do something.
- Built-in memory to record and play back sound.
- Displays to understand what the cubes are doing (e.g., dot-matrix displays, alphanumeric LED displays).
- Push buttons, rotary knobs, and tactile controls to change settings on the cubes.
- Battery-powered and the ability to charge the cubes in parallel and very quickly: at least 6 hours of autonomy and charge time less than one hour.
- Easy to connect to a desktop computer to change its behavior.

More requirements were gathered, some of them to be considered, some others to be forgotten: one example being to attach a display to the cubes that would give an overview of their state and parameters, the same problem described in *MediaBlocks* [24]. To classify these requirements, a TUI paper prototype was created.

Step 2: Static TUI prototype. To understand which of these requirements were of utmost importance and which matter the most, we created a number of TUI prototypes (Fig. 5a) which we constantly carried around and showed to our potential users. Paper prototyping is classical for traditional GUIs, but poses some new challenges for TUIs since the TUI is not digital. It therefore needs to be augmented with other modalities of interaction during the prototyping phase such as gesture, sound, voice. For this purpose, we firstly created paper prototypes of 8 cm-side Cubes, which should be about the right dimensions [14,24]. The informal TUI prototyping sessions would take about an hour. We would first explain what these cubes would do, mentioning that they had a computer system inside capable of processing sound, and they would transmit sound to each other. The sound would come out each of the faces, and the colors of the faces indicated what the function of the face was. Among the questions we asked were the following:

- What sound do you expect these cubes to make when you move them? Make a sound with your voice while you move the cubes around on the table.
- What do you think about the size of the cubes?
- How would you position these cubes on the table? Why did you position them this way? Would you like to arrange them in space? How?
- How would you transport these cubes if you have to use them in a different location?
- Do you think that the orientation of the cubes matters? How? What do you expect the cubes to do with the sound when they process it?

A variety of answers to the questions were received, classified and sorted according to level of importance, frequency, appropriateness, and feasibility. The results of these prototyping sessions initiated designing the first hardware test platform (Fig. 5b).

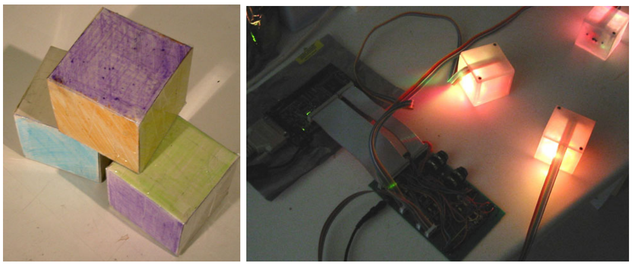

Fig. 5. AudioCubes paper prototypes, first hardware tests.

Step 3: Dynamic TUI prototype. To understand which of these requirements where a priority to them and which mattered the most, we created a number of dynamic working TUI prototypes. The first system consisted of a Texas Instruments DSP development kit to which we connected our own printed circuit board with the electronics specific for the audio cubes (analog filters, audio jacks, etc). Each of the small cubes we connected to the board had only one face that worked and would connect through a flat cable to the board. So, the total system corresponded to the functionality we expected the final AudioCube to have 6 inputs and 6 outputs (one for each face). This first prototype demonstrated that the assumptions we made about the hardware and software we were planning to develop were more or less realistic, and inspired us to design the next platform (Fig. 6). The enclosure of the cubes was lasercut and assembled using screws (in contrast to the manual bandsaw and glueing). The electronics were upgraded with a lithium-polymer battery pack and the necessary battery management electronics. In addition, the cubes now supported 4 audio inputs and outputs (the top and bottom face of the cubes are still not used because of mechanical limitations). The mechanical enclosure was designed using a solid modeling package and laser-cut, the printed circuit boards inside each cube were designed using a PCB CAD package and manufactured by a local board house. All of the surface-mount soldering work and testing was done at the Percussa offices. The electronics consist of a low-cost processor with additional memory, capable of sound processing in real-time (sampling rate 12,500 Hz at 8-bit resolution) and a number of color LEDs (red, green and blue) for displaying the cube's function, with variable intensity for mixing, similar to the parameter display in the Parameter Bars [13], and infrared LEDs and phototransistors (for sound transmission). Ten cubes were built using this last hardware design: six cubes were capable of signal processing, three cubes were only capable of converting the received optical signals to an audible sound signal (to be amplified by an external amplifier) and one special cube contained an omnidirectional microphone, pre-amplifier and optical transmission electronics.

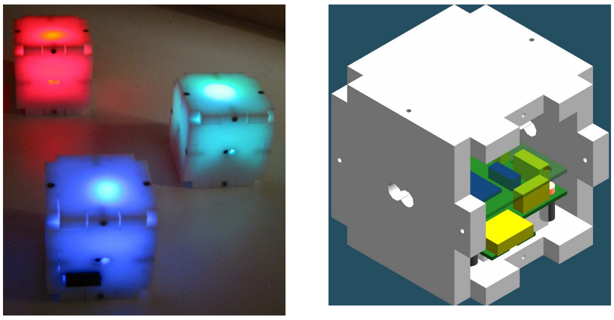

Fig. 6. Current battery-powered cubes and a screenshot of their mechanical design.

EVALUATION OF THE AUDIOCUBES SYSTEM

User Testing of AudioCubes

Method. The test setup that was created to test the AudioCubes system is first explained. After designing and building the AudioCubes system, we wanted to test our TUI in a realistic setting with users of all types. While discussing the requirements of our system with artist and composer Peter Swinnen, he invited us to test the AudioCubes in an art installation at the Time Canvas festival organized by Champ D'Action, an art organization in Belgium. The festival was organized in the museum of contemporary arts in Antwerp (MUHKA), and we would get a space of 10 by 10 meters, 4 meters in height (Fig. 7a,b). For this space we designed and built a wooden cabinet, cubic, with sides 1 meter in length. Inside the cabinet, sound speakers and a mixing board were installed. The cabinet itself connected to the mixing board internally through audio cables, and the AudioCubes we placed on top of the cabinet connected to the cabinet using short (1 meter) ¼" jack cables (Fig. 7b). This black cabinet was installed between 4 pillars in the middle of the space. In addition, we installed a camera, about 3 meters away from the cabinet, in such a way that it would not interfere with our users which would walk up to the cabinet and start moving the AudioCubes around. This camera would continuously record the users' hands that would move the cubes around in relation to each other (4 hours of unedited video), and would give us some idea about what type of interaction and relationships our users were expecting.

Fig. 7. User observation camera and cube table with amplification at the MUHKA museum ; Audiocubes connected to table amplifier through audio cables.

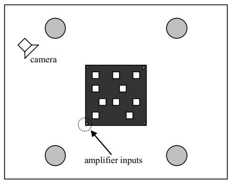

Fig. 8. Table and camera setup diagram

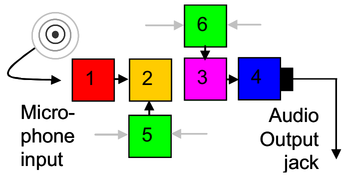

Fig. 9. AudioCubes connect to table amplifier through audio cables

When the museum opened, the AudioCubes were installed on the table (Fig. 8) and arranged them in the standard configuration as shown in Fig. 9. We first define the functions of each of the cubes to give the reader a better understanding of what this configuration does. These functions were suggested by Peter Swinnen, to communicate a certain artistic statement that fit within the Time Canvas festival held at the museum:

1. (**Red**) This cube contains the omnidirectional microphone, records sound from its environment, and broadcasts this sound to its neighbors using infrared light. The color of this cube remained static.
2. (**Yellow**) This cube ran a variation of the granular synthesis algorithm, which recorded incoming sound through its faces, stored the sound in its memory, and read randomly in this memory, broadcasting segments of the earlier recorded sound to its neighbors. The sound segments broadcasted could vary in length and pitch depending on the signals received through its side-faces (above and below the yellow cube in the diagram). The color of this cube changed to red or green, according to the signal which was broadcasted.
3. (**Purple**) to alter the sound of the yellow cube, a biquad filtering algorithm was implemented on this cube. The cube records the sound it receives from its neighbor, filters the sound, and broadcasts it again to its neighbors. The settings for the digital filter are continuously changed through the signals received through its side-faces (above and below the purple cube 3 in Fig. 9). The color of this purple cube changed to red or blue according to the signal that was broadcasted.
4. (**Blue**) the blue cubes in the setup were responsible for converting the sound transmitted optically by the cubes

in its environment to a real sound signal which could be amplified by a regular sound amplification system or headphones. In our setup, these cubes connected to the sound cabinet underneath through standard audio cable. The color of these cubes remained static.

5. (**Green**) to change the settings which were embedded in the yellow and purple cube, we had to point some signal at the side-faces of these cubes. Since an audio signal changes very rapidly, it would be better if we could point a slow-changing signal at these cubes. Therefore, we created a special cube that emits a slow-changing random signal. The parameters of this random signal can be changed through its side-faces. The color of these green cubes remained static. These cubes do not produce any audible sound in isolation. Hence we arranged them to be next to the yellow and purple cubes in our standard setup.
6. (**Green**) Same as cube 5.

When the museum visitors arrived, we observed them from a distance as they walked up to the cabinet and looked closely at the AudioCubes which were producing sound in relation to the environment, and were arranged in this standard pattern. We would wait for them to explore the installation, move the cubes around, and see if they would have the patience to understand how the cubes worked and how they could gain control over them (Fig. 10a,b).

Fig. 10. One of the museum visitors explores the possibilities of the AudioCubes ; Dance students interact with AudioCubes

If they seemed desperate after 15 minutes of trying, we would explain the standard configuration to them. If this was inadequate to illustrate how the system worked and get their creativity flowing, we pointed out some simple experiments they could conduct with the cubes. Among these experiments were, pointing the microphone at the jack-cubes (created feedback), adding a filter to this feedback loop, adding the yellow cube, moving a green cube, etc. Most of our test subjects remembered the standard configuration and the function of each of the cubes, even after changing their locations. We suspect that this is possible due to the colored light emitted from the cubes as well as the spatial relationship between the cubes [8]. We tried to tell users as little as possible since the goal of our experiment was to collect objective information on the usability of our TUI.

Results and discussion

We now present some observations we recorded during user testing as we watched the video material after the art installation (visit http://www.percussa.com/ for the video material):

1. **Classical dance students (ballet).** A group of 8 students (Fig. 10b) approach the table, mostly female, around the age of 20. They are immediately intrigued by the changing colors of the cubes. They move the cubes in rectangular patterns, without lifting them from the surface. It is striking that the movements they make are very elegant and continuous, as if their background in dance classes influences they way they interact with the tangible user interface. One of the girls 'breaks' the standard configuration in such a way that the sound completely comes to a halt, and wonders why it stops working, and exclaims 'oh no, I broke it'. She assumes that if she taps the cube on its top face, that it will start working again, and makes a waving motion with her hand trying to get it running. After a while the students realize the relationships between the cubes are very important, as well as their orientation, and are able to solve the 'puzzle' in about 15 min.
2. **Festival organizer.** She approaches the table, stares at the cubes, and tries to understand what happens when she rotates one of the cubes around its axis (the red cube with the microphone). She is puzzled as the sound stops when the cube is rotated. She tries to understand how the system works, experiments with the order in which the cubes are on the table, and approaches the system largely as a puzzle. She seems to move the cubes according to patterns used in a board game of checkers.
3. **Random nearby performing artist.** The artist moves the cubes around, positions them next to each other, notices that aiming the red cube at the blue cube creates a loud feedback tone. Subsequently, he moves other cubes in the line of sight of the red and blue cube, and notices how the feedback changes. By carefully positioning the cubes and moving them millimeter by millimeter, he manages to create interesting changing feedback tones. This very subtle control over the sound created by the tangible user interface suggests that our users experience a learning process for parameter control similar to that of the electric guitar [13]. This artist uses the mechanical properties of the cubes to change the sound and is not as interested in what the cubes actually do.
4. **Older random visitor.** This man approaches the table, and immediately tries to stack the cubes vertically, and tries to understand if anything changes in the sound. Since this does not change anything, he is puzzled for a moment and then looks at one of the art installation supervisors to see if he can explain how the system works.
5. **Collaborative session.** A few different people approach the table and start to 'puzzle' together. It seems as if they try to derive the function of the cubes or how the system works from the colors. In this session, the users expect to be able to see changing colors in response to their actions, which is not happening in our case since the colors

are controlled by the sound which is output, not the parameter values which are changed as the cubes move.

6. **Young girl (~ age 5).** The girl and her mother approached the table and we noticed the girl was afraid of the loud feedback-like sounds our art installation produced, which pointed out to us that their was not yet an accurate enough control over the general amplitude of the communicated signals between cubes. After moving the cubes over a longer distance, which lowered the sound volume, our test subject played around with the cubes for a few moments and had an enjoyable experience.
7. **Teenager (~ age 12).** This user approached the cubes and immediately noticed how the sound can be changed by only changing their orientation. Subsequently he noticed the feedback tone that occurred when the red cube was directly pointing towards a blue cube, and starting breaking the light beams connecting both cubes to stop the sound. By repeating this on/off sound in a regular pattern, he was able to re-create a convincing fire alarm. He did not see an immediate interest in using the system as a puzzle, but was more interested in the variety of sounds.
8. **Random visitor.** The woman approaches the table, listens carefully to the sound, moves a cube, tries to derive the workings of the system by isolating a cube and understanding how this cube by itself works, then goes on and listens closely to the cube and assumes the cubes are making sound (which is not the case, the amplification system is under the table and cannot be seen by visitors).

After setting up the aforementioned test installation and recording all the video material, we noticed that we might have missed some details of the interaction of our users with the AudioCubes system. Therefore, it would be better to film the interaction with the cubes closeby. Of course, this raises the question whether our test subjects would be more reserved or shy and would rather not touch the TUI and explore its possibilities. We will need to look into this matter more closely in the future and try alternative observation approaches, as well as pose the right questions to learn more about the flaws in the system.

RELATED WORK

AudioCubes are simultaneously related to cube-based TUI and TUIs for sound design. Therefore, AudioCubes are compared with respect to states of the art in both domains.

Cube-based tangible user interface

Among the first who relied on cube for TUI, Suzuki & Kato developed AlgoBlocks [22], a system that transforms the Logo programming language to the tangible domain blocks stand for commands, actions, and arguments in physically connected sequences of cubes in order to define a program. After them, several works exploited the cube as a TUI volume because of its proven cognitive abilities [19] and affordance for any user [20]: for managing large sets of data in an information system [8], as a display device [10], for interacting with multiple spaces [18], in navigation [27], in 3D interaction [28,29], in architecture design [21], and in teaching and learning [22,23].

Tangible user interfaces for sound creation

Over the past few years, there have been some attempts to develop TUIs for sound and music. *Block Jam* [12] consists of a number of rectangular blocks, each having an LED matrix display with an integrated push button and rotary parameter control. By connecting a number of blocks together and connecting the system to a computer using one of the blocks, it is possible to control a sound application running on the computer. While this constructive assembly system certainly has interesting properties, it requires the user to keep track of two completely different GUIs (because sound processing and control are separated). Moreover, it does not take advantage of spatial relationships between blocks because the blocks need to connect mechanically. In *Audiopad* [14], the user moves passive objects on a table on which a GUI is projected. The location of the objects is detected using table embedded electronics and sent to the computer. By changing the spatial relationships between the objects, the user can change parameters in the sound application running on the computer. Mixing physical objects with the GUI in this way is debatable as the system requires an expensive video projector and camera-based recognition techniques, and a separate computer for operating the GUI and processing the sound. Because the objects are passive and cannot communicate in any way with each other, this TUI only exploits spatial relationships and is not a constructive assembly sys-tem. The *Musical Trinkets* [14] and Datatiles [10] TUIs use similar RF technology. *Datatiles* [16] and *Mediablocks* [24] both consist of passive objects which are associated with electronic data stored on computer systems, and are primarily used to communicate relationships between these data files, thus limiting the flexibility and possibilities provided by the TUI objects. Augmented reality techniques (such as camera-based interaction and projected interface) are used in *AudioPad* and in a series of similar systems like *The Music Table* [3], *Augmented Groove* [15], *ReacTable* [9]. These systems are different TUIs as they do not attach any behavior to the TUI objects: only the camera detects the gestures on the physical objects and interprets them to produce music, but the objects do not contain themselves the functions needed to create sound.

The systems reported above generally share the following shortcomings: each physical object is attached to only one parameter at a time, thus preventing the user to manipulate several objects simultaneously to create sound; the TUIs do not truly mimic the reality where several high-level functions are operated by the performer, not just parameters; the TUI objects should be either physically connected to work together or be captured by video image processing; the physical arrangement of TUI objects is often not considered in the interaction and when it is, the objects could only be arranged on planes, not in space; too often, a secondary GUI is required to operate the system, which implies the total system is not really a TUI; finally, the TUI objects do not provide any user feedback during interaction, they remain basically passive. In the evaluation, we saw how AudioCubes release the performer from these constraints.

AudioCubes is different from related work in that

- They are not attached to a single sound parameter, but to a complete sound creation function whose parameters are concurrently governed depending on state, position, rotation, and dependencies with other AudioCubes.
- They can be manipulated together (as much as the human hands can manipulate) to discover dependencies among cubes, to create sound effects instead on controlling one parameter at a time. For instance, combining the rotation of several cubes together create a sound effect that would be difficult to obtain otherwise. It could be one cube at a time, two cubes moving together, one in each hand, or two cubes in one hand and another cube in the dominant hand.
- No physical connection is required to operate AudioCubes; objects can be arranged spatially independently of each other; AudioCubes are an embedded TUI: no additional GUI is needed

CONCLUSION

In this paper, we introduced a novel TUI for sound exploration, which fits in the constructive assembly class while exploiting spatial relationships. It is original with respect to the state of the art and to some of the shortcomings identified. Each AudioCube is a real TUI object with optical feedback of its functioning. We showed in what cases our TUI can be more intuitive to use than a software user interface, and how the interface was conceived, prototyped and physically constructed. For more information on the AudioCubes, including pictures and video material, please visit http://www.percussa.com and http://www.bertschiettecatte.com.

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