xCoAx 2015
Computation
Communication
Aesthetics
and X

Glasgow
Scotland
2015.xCoAx.org

# Sonically Tangible Objects

**Hanna Schraffenberger**
Media Technology Research Group, LIACS, Leiden University, Leiden, The Netherlands
h.k.schraffenberger@liacs.leidenuniv.nl

**Edwin van der Heide**
Media Technology Research Group, LIACS, Leiden University, Leiden, The Netherlands
Studio Edwin van der Heide, Rotterdam, The Netherlands
e.f.van.der.heide@liacs.leideuniv.nl

**Keywords:** Presence, Tangibility, Augmented Reality, Virtuality, Perception, Interaction, Haptics, Sound, Touch, Binaural Audio, Tactile Stimuli, Gesture Control, Haptic Interfaces, Sound Interfaces

A unique power of virtual objects is that they do not have to look, feel or behave like real objects. With this in mind, we have developed a virtual cube that is part of our real, physical environment but, unlike real objects, is invisible and non-tactile. 'Touching' this virtual object triggers binaural sounds that appear to originate from the exact spot where it is touched. Our initial experimentation suggests that this sound-based approach can convey the presence of virtual objects in real space and result in almost-tactile experiences. In this paper, we discuss the concept behind, implementation of and our experience with the sonically tangible cube and place our research in the context of tangible interaction, perception and augmented reality.

## 1 Introduction

With the advent of augmented reality (AR), the virtual has become part of our environment in a profoundly new way. Virtual objects are no longer confined to virtual spaces, digital devices and displays. Rather, virtual objects can appear in and inhabit our real, physical space and act as if they were actually present in our otherwise real environment.

Much research in augmented reality focuses on making virtual objects as real as possible. Researchers and developers strive for photorealism and aim for scenarios where virtual objects cause the same occlusions and shadows as physical objects (see, e.g., Gibson and Chalmers 2003). Similarly, scientists include physics simulations to make virtual objects adhere to physical laws and move like real objects (e.g., Kim, Kim, and Lee 2011). In line with this, there is a focus on tangible interfaces and techniques that allow users to interact with virtual content in the same way as they would with real physical objects (e.g. Billinghurst, Kato, and Poupyrev 2008; Buchmann et al. 2004).

Our research follows another direction. Instead of imitating reality, facilitating physical interaction or simulating real-world properties, we want to create new experiences that have no equivalent in a purely physical world. We are interested in how augmented reality scenarios can differ from strictly physical, 'unaugmented' environments.

In this project, we explore a new, non-visual way of conveying the presence of virtual objects in real space. Presence is often associated with the experience of 'being present in a virtual environment'. However, we believe that another form of presence, namely in the sense of 'something virtual being present in our real environment', is key to augmented reality experiences. With this project, we explore whether the presence of virtual objects can be experienced through a combination of touch gestures and spatial sound.

The project presented in this paper is motivated by two underlying considerations. Firstly, virtual objects do not have to look or behave like real objects in order to be a believable part of our real, physical space (cf. Schraffenberger and Heide 2013a). Secondly, virtual objects could potentially be perceived differently from how real objects are perceived.

Inspired by this, we have developed a new kind of virtual object – the so-called sonically tangible cube. Unlike real objects, this cube is invisible and it does not provide tactile feedback. However, 'touching' the virtual cube triggers binaural sounds that appear to originate from the exact spot where it is touched. Our initial experiments show that through this sonic feedback, virtual objects can gain an almost-tactile quality and appear as if they were actually present in real space. It is this idea of making virtual objects both tangible and present through spatial sonic feedback that distinguishes "sonically tangible objects".

Several questions have fuelled the development of the virtual cube and our research into sonically tangible objects. First and foremost we were wondering if it is possible to leave out the tactile component in tangible interaction. If there is no tactile stimulation, would the virtual object still be perceived as part of real space – and if so, would it be experienced as an object with a tactile, physical component? We were intrigued by how it could feel to touch an object that provides no tactile sensations. Furthermore, we were eager to learn more about how virtual objects can differ from real objects.

While we provide preliminary answers to these questions, the focus of this paper is on the underlying concept of sonically tangible objects. (So far, inferences regarding the perceptual qualities of the cube are based on informal testing and on our subjective experience with the cube).

The central idea – that the cube is tangible but not tactile – calls for a distinction between the terms tangible and tactile. In this paper, things are called tangible, if they can be perceived by touching or being in contact with them. Only objects that also stimulate the tactile receptors (as found in the skin and tissue) are referred to as tactile. This understanding leaves room for objects that are tangible but not tactile.

The paper consists of 4 sections. In the following section (2), we share choices made and insights gained during the development of the project, describe the setup and implementation of the sonically tangible cube and discuss our experience with it. Following this (3), we compare the project with related work and place it in the context of pertinent research fields, such as perception research, augmented reality and tangible interaction. The paper ends (4) with a reflection on the project and possible directions for future research.

## 2 The Sonically Tangible Cube

The sonically tangible cube is a virtual object. It is unlike any real object in the sense that it is non-tactile, invisible and lacks physical properties, such as weight and temperature. It does, however, have sonic and spatial properties such as a shape, texture and loudness. Although the cube has no tactile component, its presence can be perceived through touch. When fingers enter the cube, sound appears to originate from where the virtual object is touched. The resulting sonic feedback not only corresponds to the fingers' positions but also fits the movement of the fingers. Fast finger movements result in more agitated soundscapes while slower movement causes less dense, more distinct feedback. As the cube is non-solid, fingers can move through it and explore its inner texture.

## 2.1 Implementation and Setup

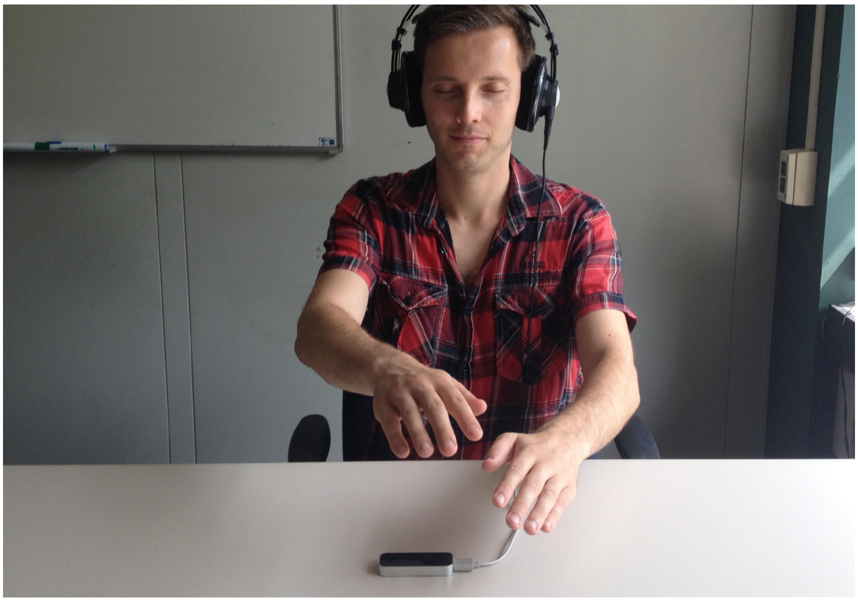

**Fig. 1** A colleague explores the virtual, invisible and non-tactile cube. A Leap Motion Controller is used to track the position of his fingertips.

The virtual cube is 20 cm x 20 cm x 20 cm of size and it floats 10 cm above the work desk of one of the authors. The technical setup consists of a Leap Motion Controller (www.leapmotion.com), which detects the position of the participant's fingertips in real space. It is placed on the desk and senses hand movement above the device (see Figure 1). A custom *Max* (2014) patch, which runs on an Apple Mac mini, interprets the data provided by the Leap Motion. Interfacing with the Leap Motion device is realized with a Max external object 'aka.leapmotion' by Akamatsu (2014). In our current setup, the frame rate of the Leap Motion device is around 57 fps when the office is naturally lighted and slightly above 200 fps when the amount of interfering infrared light is reduced by darkening the room. The Max patch evaluates whether and where the participant is touching the cube on the basis of the fingers' coordinates. If the fingers are located within the 20 cm x 20 cm x 20 cm area that has been defined as the cube, their movement triggers pre-recorded binaural sounds. This interpretation of the finger position works for every finger independently and allows the participant to explore the cube with up to ten fingers at a time.

Constraints of the current setup are that the sound only matches the fingers' position if the participant is sitting at the right spot and directly facing the cube. Also, due to the frame rate of the Leap Motion device, very fast hand-movement can cause a mismatch between the hand-position and the spatial information of the triggered sound. Moreover, finger movement is sensed best, if the hands are held horizontally.

## 2.2 Development

The sonically tangible cube was developed in an iterative process during the course of several months. In the course of the project, the authors acted as researchers, developers and participants. Additionally, colleagues were asked to provide feedback and describe their experience with the cube on occasion.

From the beginning, we have explored the idea of making virtual objects *tangible* and *present* through sonic feedback. The topic of (in)visibility was left aside for future research and hence, many evaluations have been conducted with closed eyes. Two determining observations and decisions were made concurrently in the early stages of the development process.

### Shape

One of the two early decisions regards the shape of the object. We have started out with several simple geometric shapes and figures such as lines and planes and cubes. Our initial experimentation indicated that it is very difficult to experience a plane or a line. Running one's hands freely through a three dimensional object and exploring its boarders and inner texture offered the most intriguing, tactile-like experience and promised to convey an object's presence best. Hence we have decided to focus on a cube-shaped virtual object.

### Binaural Audio

The other decisive observation concerns the sonic aspect of the project. In the beginning, simple synthesized clicks were played back in mono (feeding the identical signal to both the left and the right channel) through closed Beyerdynamics DT 770 Pro headphones whenever a virtual object was touched. This was done in order to learn about the effects of linking movement in a certain area to a basic sonic response. However, our initial trials showed that the resulting experience was closer to being informed that one's hand had entered a predefined space rather than a direct sensory experience of an object in space. This did not come as a complete surprise. After all, interacting with real objects and materials – crumbling paper, scratching on a surface, typing on a keyboard or moving the mouse – causes sounds that originate from the objects themselves and from the position where they are touched rather than spatially uncoupled mono signals.

This is where the idea of using binaural audio in order to make the sounds originate at the fingertips came into play. Binaural audio is based on the notion that hearing makes use of two signals: the sound pressure at each eardrum (Møller 1992). If these two signals are recorded in the ears of a listener, the complete auditive experience – including the three dimensional spatial information of the sounds – can be reproduced by playing the signals back at the ears.

In order to investigate the potential of binaural recordings, we conducted some simple initial experiments. For example, we recorded the sound of someone knocking on the closed office door and the sound of the ringing phone while working in the office. From these initial experiments it became clear that binaural audio indeed can convey the desired experience. When listening back to those recordings later on, the sounds seemed to originate from those exact spots where they originally had happened. The virtual ringing of the phone was practically indistinguishable from a real call. The simple knocking sound was powerful enough to create the illusion of 'someone actually being behind the door', and hence proved capable to communicate the presence of something or someone in real space. The use of binaural recordings has since grown into a key aspect of the project.

The move to binaural audio went hand in hand with a switch to open AKG K702 headphones. Due to the open nature of the headphones, the recorded sounds mix in with the sounds naturally present in the environment. This additionally supports the experience that the virtual sonic object is inhabits our real physical space rather than a virtual or separate space.

## Recordings

What should the virtual sonic object sound like? The choice of using binaural recordings introduced the question of what to record. We were searching for sounds that (1) are abstract (do not invoke the idea of a specific real object), (2) have a tactile quality and (3) support the idea of a non-solid object/material that allows the fingers to move through it. Several different sound sources have been tested during the development: for example, foils, paper, plastics, packaging materials from everyday objects, rattles and empty bottles. All sounds were produced by interacting with the materials with the hands and fingers. This choice was based on the assumption that sounds that actually are created by hand/finger movement are more likely to fit the exploratory hand gestures of the participant and more likely to create a tactile-like experience. (In the same sense as the sound of squeaking nails on a chalkboard can be an almost-tactile, physical experience, even if someone else is scratching the board). For the current implementation of the sonically tangible cube, we have settled on the sound of aluminum foil, produced by squashing a tiny plastic bag filled with small crumbles of the foil.

To make the sounds appear as if they originate from the position where the cube is touched, a custom set of binaural recordings has been prepared. For this, we have divided the cube into 64 sub-cubes of 5 cm x 5 cm x 5 cm (see Figure 2). Five-second samples of aluminum foil sounds were recorded at all 64 positions within the cube. For this, we used a ZOOM H4 audio interface and two DPA 4060 microphones. The microphones were placed slightly above the ear-entrance of one of the authors and the sound was recorded with a basic Max patch. For the recordings, the author successively produced the desired sound by squashing the little plastic bag and rubbing the aluminum crumbles against each other at each of the 64 subareas. Aside from this, the author was sitting motionlessly in front of the desk, facing the cube just like participants do during the experience (see Figure 1).

## Sound Design and Mapping

When a participant interacts with the cube, the positions of his/her fingers determine which of the 64 recorded audio samples are played back. If a finger is placed in a sub-cube, the corresponding recording is activated. However, first tests showed that simply playing back the recordings resulted in a sound that only matched the fingers' positions, but not the different variations in hand and finger movement (slow, fast, no movement, etc.). Hence, we have experimented with more complex settings that map the movement of the fingers to parameters in the sound design.

Our current implementation knows two sound design settings. Both react to each finger individually. The first setting makes use of granular synthesis. Here, the change of a finger's position triggers the playback of an audio grain that is taken from the binaural recordings. Each grain is between 10 ms and 20 ms long and is varied slightly in pitch/playback speed.[1] Furthermore, a random offset is used to vary the position in the binaural recording from where the grain is taken. This causes every grain to sound differently, which is crucial for the believability of the experience.

The second setting follows a similar underlying idea. Here, the binaural recordings are layered and looped. A faster movement activates more layers. Each active layer loops the five-second recording, starting at a random position within the sample and playing it back with a slight variation of speed/pitch.[1]

1 The changes in playback speed also influence the spatial characteristics of the sounds. However, as those variations were minimal this effect was negligible.

Both settings result in a louder, more complex and dense soundscape if the finger moves fast and in a softer, less dense but more distinct soundscape if the movement is slow. As this happens for each finger individually, the amount of fingers used by the participant has a similar effect: The more fingers are involved in the exploration, the denser the sound. The two settings differ with respect to textural nature of the sound. Whereas the granular synthesis results in a more gritty and rough soundscape, the layered loops produce a thinner, airier sound texture.

For either setting, movement is necessary to 'excite' the virtual cube and to elicit sounds. No movement results in silence, even if the hand is placed in the cube. However, as it is impossible to keep one's fingers completely still, occasional slight tremble of the digits will cause corresponding sound output.

## 2.3 Experiencing the Cube

How does the cube feel – does the experience really differ from simply moving one's hands through thin air? Do we perceive the cube as present in space, do we perceive it as tangible? It is important to systematically investigate this by performing experiments with a group of unbiased participants in the future. In the following, we discuss our own experience with the sonically tangible object and compare it to known experience.

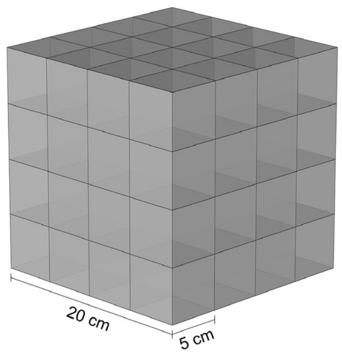


**Fig. 2** The sonically tangible cube was divided into 64 sub-cubes. A binaural recording was made at all 64 positions. Image of the cube contributed by Wim van Eck.

On one level, the experience can be compared to moving one's hand through a beam of light. We can clearly see the beam's presence in space, but we cannot feel it. Similarly, in the case of the cube, there is no traditional tactile feedback but our ears still tell us that something is there.

On another level, experiencing the cube better compares to feeling out a physical object blindly with one's hands. After all, it is only through the physical act of touching that we can perceive the cube in the first place. There is no notion of the object, unless one is in contact with it. Also, like in typical haptic perception, the experience of the object takes time and happens through exploratory gestures with one's fingers. Furthermore it is similar to touching a real object in the sense that this, too, can cause sounds at the corresponding position.

Yet, the experience is also inherently different from interacting with a physical object. One can, for example, not hold, move and turn the object. Instead, it is possible to move right through the cube and explore its inner texture and structure. Also, it is impossible to simply follow the contour of a sonically tangible object and to explore its shape that way (cf. Lederman and Klatzky 1987). Rather, the contour can be perceived by repeatedly crossing (zigzagging around) the boarder of the object and moving in between the sonic space of the cube and the silent space surrounding it.

Last but not least, interacting with the cube has similarities with playing gesture controlled open-air instruments such as the Theremin. (The Theremin is played by moving one's hands in the space between two antennas.) Also here, movement in space results in sonic output that corresponds to the position of the hands.

While it remains difficult to put the experience of the cube in words, one thing seems clear: Touching the cube is different from simply moving one's hands through thin air. When we move our hands through air, we feel nothing but empty space. The cube, in contrast, inhabits the space. While empty space simply is experienced as empty, the cube is experienced as something that is present and that can be touched. Although the experience is not tactile in the traditional sense, it definitely has tactile-like aspects.

## 3 The Cube in Context

Our project is multi-disciplinary; it draws from and contributes to various fields of research, such as augmented reality, tangible interaction and perception. In this section, we take a second look at the cube and discuss the virtual sonic object in the light of related research.

### 3.1 Tangibility and Presence

The cube deals with (in)tangibility, requires active bodily engagement and it explores the possibilities of a tangible experience without tactile stimuli. As such, our research relates to the field of tangible and embodied interaction. Furthermore, the cube is concerned with the presence of virtual objects in real space, and hence relates to the field of augmented reality. Tangibility and presence are closely linked. Presence is a necessary condition for tangibility. We can only touch an object, if it is present. If we touch an object, we and the object are both present in the same space – at least in a mediated way.

In a broad sense, the sonically tangible cube relates to all projects, where virtual objects are perceived as present in real space. In particular, it relates to those projects that use sound and/or tangible interaction to convey the presence of (invisible) virtual objects in real space.

A project where the presence of something virtual is perceived tangibly is Sekiguchi, Hirota, and Hirose's (2005) so-called Ubiquitous Haptic Device. The little box, when shaken, conveys a feeling of a virtual object being inside the device. Similarly, a wearable haptic device by Minamizawa et al. (2007), called the Gravity Grabber, allows participants to perceive the ruffle of the water in a glass, although he/she actually is holding an empty glass.

Projects that let a participant experience the spatial presence of "something that is not really there" by means of sound are Cilia Erens' and Janet Cardiff's sound walks (Erens, Cardiff, cf. Schraffenberger and Heide 2013b). Both artists use binaural recordings of everyday sounds that blend in with the sounds present in the real environment when the participant navigates the space and listens to the composition on headphones. Listening to the binaural audio creates a hybrid space in which the virtual and the real coexist, relate to one another and create "a new world as a seamless combination of the two" (Cardiff).

A discussion of Janet Cardiff's work by Féral (2012) also helps our understanding of sonically tangible objects. The researcher defines "presence effects" as the feeling that an object (or body) is really there, even when one knows that it is not. This relates to the experience of the sonically tangible cube. While the ears make it feel as if the cube is present, the lack of tactile (and visual) stimuli informs us that nothing is there.

## 3.2 Open Air Instruments & Sound Installations

Our project relates to the field of sonic interaction. In particular, it relates instruments and installations that use hand or body gestures in free space to produce sound, such as the above mentioned Theremin. Like our research, such gesture instruments and installations are based on a mapping between body movement and sound.

The artwork 'Very Nervous System' (1986-1990) by David Rokeby is an early example of an interactive sound installation where body movement in open space generates sound. However, the sound of such artworks and instruments like the Theremin usually does not appear to originate from the location of the movement, which is a key difference from sonically tangible objects. Furthermore, with few exceptions, they do not (try to) express the presence of virtual objects in space.

One exception – an instrument that actually does convey the presence of virtual objects in space – is the invisible drumkit by Demian Kappenstein and Marc Bangert (*The Invisible Drums of Demian Kappenstein and Marc Bangert.* 2011). In their invisible setup, each virtual drum is placed at its regular position in space. Hitting the invisible virtual drums triggers pre-recorded samples of a real drumset. The position of the sticks and the speed of the movement determine which sample is triggered. Similarly to the cube, the virtual drum kit becomes perceivable through the interaction.

### 3.3 Human-Computer Interaction

One possible area of application for sonically tangible objects is the field of Human-Computer Interaction, and in particular intangible displays. Intangible displays are visual virtual interfaces that appear in mid-air, in front of a user's eyes. Aside from simply displaying information they also allow for interaction: Users can touch virtual objects, such as buttons, with their physical hands. However, intangible displays do not provide tactile feedback when they are touched. Chan et al. (2010) address this lack of tactile feedback by providing visual and audio feedback. In their experiments, they played short sounds whenever participants touched the surface of the intangible display. Their project differs in the sense that sound is used to inform the user about the fact that they have successfully touched the object (as feedback) and not as an integral part of the object.[2]

Another related HCI project is the so-called BoomRoom (Müller et al. 2014). In this room, sounds seem to originate from certain spots in real space (this is realized with a circular array of 56 loudspeakers and Wave Field Synthesis). These sounds can be 'touched' in order to grab, move and modify them. Although related, their project differs in the sense that it focuses on the localization and direct manipulation of sound rather than on the presence and tangibility of virtual objects.

### 3.4 Perception

#### Haptics

The sonically tangible cube is perceived by explorative hand gestures. This links it to the field of haptics. Haptic perception typically involves active exploration (Lederman and Klatzky 2009). Haptics is commonly understood as a perceptual system that derives and combines information from two main channels: kinesthetic perception and cutaneous sensation (Lederman and Klatzky 2009). Cutaneous sensation is derived from the receptors that are found across the body surface and that allows us to feel, for example, pressure or temperature. The kinesthetic channel refers to perception of limb position and movement in space, which is derived from the receptors embedded in muscles, tendons and joints.

Kinesthetic perception also plays a key role in the perception of the virtual cube – it provides the participants with the

2 Although originally not intended this way, the concept of sonically tangible objects could be used to improve the interaction with intangible displays. It could increase the spatial presence of the display, provide better feedback about the users hand position and movement through the display and is likely to make the "the awkward feeling of 'touching' a mid-air display" (Chan et al. 2010, p. 2626) less awkward and more tactile-like.

information about where and how fast their fingers are moving in space. This awareness is crucial in order to link what one hears to one's movement in space. What makes the perception of the sonically tangible cube different from common haptics is the lack of cutaneous feedback (including tactile sensations). Rather than 'feeling something at the position where they touch an object' the participants 'hear something at the position where they touch the object'.

## Tactile Illusions and Cross-modal Interactions

The sonically tangible cube aims to create a tactile-like experience. There are several studies that indicate that sound can influence actual tactile experiences. The "Parchment-skin illusion" (Jousmäki and Hari 1998) shows that modifying the sounds that accompany hand-rubbing can influence the tactile sensation of the skin. It was found that accentuating the high frequencies can lead to the experience of a higher level of skin roughness. Hötting and Röder (2004) have discovered another auditory-tactile illusion. In their experiment, one tactile stimulus was accompanied by several tones. As a result, participants reported that they perceived more than one tactile stimulus. What sets these illusions apart from our cube is that in both cases, the participants were presented with a tactile stimulus.

## Sensory Substitution

The cube relates to projects that use sound to substitute touch. One such sensory substitution system is F-Glove (Hafidh et al. 2013). This haptic substitution system aims at helping patients that suffer from the symptoms of Diabetic Peripheral sensory Neuropathy, such as sensory loss at the fingertips and resulting difficulties with manipulating objects. F-Glove uses audio feedback to inform the patients of the pressure they apply to objects. The volume of the sound is mapped linearly proportional to the applied pressure. Unfortunately, it is not clear whether the system simply informs the patients of the pressure they use via sound or whether they start experiencing pressure directly, via the auditory sense. Naturally, the experience of the cube is quite different from not having a sense of touch, as your hand can simply reach through the virtual sonic object.

## 4 Reflection & Outlook

With the sonically tangible cube we have introduced a prototype of a sonically tangible object and a new, sound-based form of augmented reality. The proposed cube is invisible and non-tactile. According to our experience, it is nonetheless perceived as spatially present in our real, physical environment. This suggests that virtual objects do not have to look or feel like real objects in order to be a believable part of our real, physical space.

The virtual cube is non-tactile and yet tangible. The experience of the cube can be seen as one possible answer to the question of how it could feel to touch an object that provides no tactile feedback. According to our impression, the virtual sonic object offers an almost-tactile experience that has no equivalent in a purely physical world. However, this still has to be confirmed by experiments with unbiased participants.

The current implementation of the cube primarily serves as a proof of concept. While we are happy with its current state, we have many ideas on how to improve the cube and explore the concept of sonically tangible objects further.

Concerning the sonic qualities, future experiments can reveal which sounds are most suitable for creating tactile-like experiences and possibly test whether sounds that are created with the hands work best. It would be interesting to find out more about how to sonically represent imaginary material and communicate different densities, textures and shapes with sound.

So far, we have chosen to work with binaural recordings. In the future, it will be valuable to explore computational methods for simulating the sounds' origins in space. If this is successful, it will be much easier to allow participants to move through space freely and experience the cube from different positions. Furthermore, it will be simpler to create polymorphic sonically tangible objects of different shapes and sizes and to place them at various positions and in different spaces.

One aspect that was left aside so far is the topic of (in)visibility. This offers several intriguing directions for future research. For example, we are eager to learn how participants interpret the absence of visual clues. On the one hand, it might lead to a contradiction between senses: "I can hear it, but I see that nothing is there". On the other hand, it could be interpreted as a *property* of the object: "Something is there, it is *invisible*". Further, it would be interesting to compare the experience of the cube with open and closed eyes, and, as an additional condition, also add a visual dimension to the cube (e.g., by means of a head-mounted display) to learn more about the influence of (in)visibility on the experience.

One limitation of this research is that so far, our inferences are based on informal tryouts and our own subjective experience with the cube. Our experience might not fully represent how others perceive the cube and we cannot entirely rule out the possibility that it is influenced by the expectations and hopes we have for the project. We plan to extend the presented research and conduct experiments with unbiased participants in the near future.

Due to its interdisciplinary nature, the project has also raised questions that go beyond our own area of expertise. For example, it would be interesting to learn more about what happens on a perceptual level. Are sound and kinesthetic information combined, similarly to how cutaneous information and kinesthetic information are integrated in traditional haptic perception? Can the combination of spatial sound and kinesthetic information lead to cross-modal interactions? What happens if the spatial information of the audio does not match the position of the fingers? Do we perceive the lack of tactile stimuli as "something missing" and do we fill in this information? We have put much emphasis on describing the concept in a way that allows other researchers to reproduce it and join our investigation of sonically tangible objects.

## Acknowledgements

We want to thank all participants, colleagues and friends who interacted with the sonically tangible cube and/or provided feedback throughout the development of this project. In particular, we want to thank Wim van Eck for creating the image of the cube. Furthermore, we want to thank the reviewers for their valuable response.

## References

**Akamatsu, Masayuki.** 2014. *aka.leapmotion (Version 0.21).* Max external. Creative Commons Attribution 3.0 Unported License. http://akamatsu.org/aka/max/objects/.

**Buchmann, Volkert, Stephen Violich, Mark Billinghurst, and Andy Cockburn.** 2004. "FingARtips: Gesture Based Direct Manipulation in Augmented Reality." In *Proceedings of the 2nd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia (GRAPHITE '04),* 212–221. ACM.

**Cardiff, Janet.** *Introduction to the audio walks.* http://www.cardiffmiller.com/artworks/walks/audio_walk.html.

**Chan, Li-Wei, Hui-Shan Kao, Mike Y. Chen, Ming-Sui Lee, Jane Hsu, and Yi-Ping Hung.** 2010. "Touching the Void: Direct-touch Interaction for Intangible Displays." In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10),* 2625–2634. ACM.

**Erens, Cilia.** *The Audible Space.* http://www.cilia-erens.nl/cilia-erens-2/?lang=en.

**Féral, Josette.** 2012. *How to define presence effects: the work of Janet Cardiff.* Edited by Gabriella Giannachi, Nick Kaye, and Michael Shanks. 29–49. Routledge.

**Gibson, Simon, and Alan Chalmers.** 2003. "Photorealistic augmented reality." In *Eurographics 2003 Tutorial.* Granada, Spain, September.

**Hafidh, Basim, Hussein Al Osman, Majed Alowaidi, Abdulmotaleb El-Saddik, and Xiaoping P. Liu.** 2013. "F-Glove: A glove with force-audio sensory substitution system for diabetic patients." In *2013 IEEE International Symposium on Haptic Audio Visual Environments and Games (HAVE),* 34–38. IEEE.

**Hötting, Kirsten, and Brigitte Röder.** 2004. "Hearing cheats touch, but less in congenitally blind than in sighted individuals." *Psychological Science* 15 (1): 60–64.

**Jousmäki, Veikko, and Riitta Hari.** 1998. "Parchment-skin illusion: sound-biased touch." *Current Biology* 8 (6): R190–R191.

**Kim, Sinyoung, Yeonjoon Kim, and Sung-Hee Lee.** 2011. "On Visual Artifacts of Physics Simulation in Augmented Reality Environment." In *Proceedings of the 2011 International Symposium on Ubiquitous Virtual Reality (ISUVR '11),* 25–28. IEEE.

**Lederman, Susan J., and Roberta L. Klatzky.** 1987. "Hand movements: A window into haptic object recognition." *Cognitive Psychology* 19 (3): 342–368.

**———.** 2009. "Haptic perception: A tutorial". *Attention, Perception, & Psychophysics* 71 (7): 1439–1459.

*Max.* 2014. Visual programming language. Verison 6.1.9. https://cycling74.com/products/max/.

**Minamizawa, Kouta, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi.** 2007. "Gravity Grabber: Wearable Haptic Display to Present Virtual Mass Sensation." In *ACM SIGGRAPH 2007 Emerging Technologies (SIGGRAPH '07).* ACM.

*The Invisible Drums of Demian Kappenstein and Marc Bangert.* 2011. Blog post, October. http://www.moderndrummer.com/site/2011/10/the-invisible-drums-of-demian-kappenstein-and-marc-bangert.

**Møller, Henrik.** 1992. "Fundamentals of binaural technology." *Applied Acoustics* 36 (3–4): 171–218.

**Müller, Jörg, Matthias Geier, Christina Dicke, and Sascha Spors.** 2014. "The BoomRoom: Mid-air Direct Interaction with Virtual Sound Sources." In *CHI '14 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 247–256. ACM.

**Rokeby, David.** 1986–1990. *Very nervous system* (interactive sound installation), http://www.davidrokeby.com/vns.html

**Schraffenberger, Hanna, and Edwin van der Heide.** 2013a. "From Coexistence to Interaction: Influences Between the Virtual and the Real in Augmented Reality." In *Proceedings of the 19th International Symposium on Electronic Art, ISEA2013,* edited by K. Cleland, L. Fisher, and R. Harley, 1–3. Sydney.

**———.** 2013b. "Towards Novel Relationships between the Virtual and the Real in Augmented Reality." In *Arts and Technology,* edited by Giorgio De Michelis, Francesco Tisato, Andrea Bene, and Diego Bernini, LNICST 116:73–80. Springer Berlin Heidelberg.

**Sekiguchi, Yuichiro, Koichi Hirota, and Michitaka Hirose.** 2005. "The Design and Implementation of Ubiquitous Haptic Device." In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC '05),* 527–528. IEEE.