Pendaphonics: A Tangible Pendulum-Based Sonic Interaction Experience

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ABSTRACT
Pendaphonics is a tangible physical-digital-sonic environment and interactive system that engages users in individual, collaborative, group, and distributed interactive experiences. The development of this system, as an element of urban revitalization and as a trans-disciplinary research endeavor, presents strategies for the design and evaluation of low-cost, flexible, and distributed tangible interaction architectures for public engagement, expression, and performance. Pendaphonics is installed in a public media arts space, where over 200 people experienced it during the environment’s opening event. Internationally, interaction laboratories at five research universities are advancing explorations of Pendaphonics. This paper presents the development process and findings from observation and evaluation of people using Pendaphonics; diverse social interaction patterns among performers and the general public are discussed. In particular, we identify the repeated and sustained invitation to interact -- created by the cyclic motion of a pendulum’s simple harmonic oscillation -- as a new tangible interaction modality for human computer interaction, in 3D physical-digital-sonic environments. An investigation of this and related elements of Pendaphonics’ large-scale tangible interaction scenarios are articulated, along with descriptions of the system’s broad potential as a compositional and choreographic tool; an educational exhibit and classroom manipulative; and as an interface that facilitates playful interaction, exploration, discovery and creativity.

Keywords Interaction Design, Sound and Music Experience, Tangible User Interfaces

1. INTRODUCTION
This paper presents the trans-disciplinary design, development, and evaluation of Pendaphonics, a large scale tangible media system that creates and connects interactive physical-digital-sonic environments for collocated and distributed individuals, pairs, and groups. This Pendaphonics installation and environment was developed as part of an urban revitalization effort coordinated by the Platform4 exhibition space of Aalborg, Denmark and through a collaboration between new media researchers (musicians, designers, and interaction researchers) from Aalborg University’s Department of Media Technology, and Arizona State University’s School of Computing and Informatics and Arts, Media, and Engineering program (see www.pendaphonics.com for further information and video demonstration).

Throughout the development of the system this team has made contributions to the theory and practice of tangible media design and installation development. Pendaphonics realizes a low-cost, distributed, and flexible architecture and environment through the combination of off-the-shelf components with novel tangible designed elements and innovative software modules and interaction paradigms. These make contributions to the state-of-the-art systems and practices in the New Interfaces for Musical Expression (NIME), Human Computer Interaction (HCI), and Tangible User Interface (TUI) communities, providing new large-scale and low-cost tangible possibilities for immersive environmental interactions with sound, musical instruments, spatial interaction, and distributed hybrid physical/digital media systems. Hundreds of people have used the Pendaphonics system, thus allowing for the assessment of interaction patterns through direct user observation and descriptive video analysis. The paper closes with a discussion of the potential of Pendaphonics as a music composition and choreographic tool, educational exhibit and classroom manipulative, and as an interface that facilitates playful interaction, exploration, discovery (eureka moments) and creativity.

2. BACKGROUND
The Pendaphonics system and research agenda is positioned at the confluence of several research communities, (e.g., NIME, CHI, and TUI communities). The NIME conferences began in 2001 (the first NIME meeting formed as a workshop at ACM SIG-CHI, and was attended by two of the authors of this paper). In the NIME discourse, novel methods of controlling sound are used in order to create interfaces and new techniques for performing and creating music and sound. Many of the affordances enabled by Pendaphonics advance this category of interactions, enabling deep exploration into the world of sonic interaction design and music.

Recent projects that include large-scale interactive musical performance systems and/or public installations include the work of Todd Machover; the Toy Symphony [1], and the Brain Opera [2], among many others such as Tina Blaine’s Jam-o-drum [3]. Similar to these, Pendaphonics is an intuitive interface that supports the natural interaction of both naive and expert users. Gil
Weinberg has also employed this style of interaction in his Musical Playpen [4] and in his multi-player instrument, Squeezables [5].

Related research areas that Pendaphonics centers upon are the domains of responsive environments and interaction design pursued by the HCI and TUI communities. In this respect, Pendaphonics advances agendas of novel interaction paradigms [6][7], the development of robust low-cost ubiquitous and pervasive systems for public use [8], and computer supported distributed collaboration tools [9]. The NIME, HCI, and TUI communities have been actively engaged in creating systems that merge the physical and the digital realms and have found that sonic environments are a particularly rich arena to explore this agenda for advanced media systems [10][11].

Within the spectrum of this hybrid NIME-HCI-TUI research, Pendaphonics drew inspiration from each of the research team member’s prior work. The most explicit connections came from the BoingBoing interface [12]. BoingBoing, like Pendaphonics, uses variable-length pendulums as an interface for the control of sound (see Figure 1). However, the BoingBoing interface operates on a much smaller scale than Pendaphonics – while the desktop-sized BoingBoing focuses entirely on personal musical expression as a new means of music performance, Pendaphonics both enlarges and enhances many aspects of BoingBoing, as it extends the research agenda and allows several new interaction modalities (discussed in section 5). Related inspirations also came from the intuitive, tangible, and ambient interactions advanced in the Circles of Life project in which participants were invited to toss a pebble into a pond and were greeted by a cascade of choreographed ripples generated from a distributed sub-surface robotic system [7], and additional inspirations came from the playful interactions afforded by the Sprock-IT [13] interactive robot and by Totemagi interactive playground concepts [14].

Figure 1. The BoingBoing interface provides a musician with four sensor-equipped ping-pong balls (pendulum lengths can be adjusted by raising or lowering the rods). Each ball has a 2-axis accelerometer inside, and there are also rotary knobs above each of the balls to adjust parameters such as pitch, etc.

### 3. CREATING PENDAPHONICS

In this section we present the development and evaluation of Pendaphonics. We start with the context and motivation for the development of Pendaphonics. We then discuss the role and contributions of transdisciplinary methodologies and development strategies employed by the Pendaphonics team. This section continues with a description of the system architecture that was implemented and the physical design and installation of Pendaphonics and its hybrid physical-digital environments. The section ends with a discussion of iterative design processes and the diverse elements of the interaction scenarios and design implementations that are fundamental to the flexibility and success of the Pendaphonics system.

#### 3.1 Context and Motivation

The Pendaphonics system was developed within the broader context of an expansive multi-year harbor and city renovation effort initiated by the Aalborg Kommune, in Northern Denmark. The redevelopment is geared toward the beautification and development of urban life in the heart of the historic city; the old industrial plants of this city are undergoing a transformation. A major multi-use urban plaza environment, NordKraft is being developed to include retail shopping, cinema-plex, restaurants and office spaces. The harbor is being redesigned to welcome people into an urban park that reconnects the city with its waterfront, via docks, swim halls and concert spaces. At the easternmost end of Aalborg’s historic industrial complex the former shipping warehouses and silos are beginning to be transformed in part through the efforts of Platform4, an emergent art collective and event coordination organization that is bringing together new media researchers from Aalborg University, and beyond.

One of the major ideas behind Platform4’s exhibits and community is to make a platform for software-based artworks that are embedded in a physical installation and exhibited as interactive games or compositions (that are or can be) performed by musicians and dancers. This notion of the art gallery as an open and shared interface is one of the main motivations of the Pendaphonics teams efforts to design, fabricate and distribute Pendaphonic elements amongst a very broad community of composers, artists and scientists who in turn are engaged in diverse settings and agendas. The physical presence and software capabilities of the Pendaphonics installation at Platform4 provide built in modalities and affordances that can be addressed and leveraged by a network of contributors. Providing these “creative restrictions” regarding the space of action and physical parameters, Pendaphonics challenges its users and developers to engage in concept development on both software and tangible user interaction levels. Ultimately, this installation will be part of a world-wide scenario of different physical installations that are available as “platform galleries” (current systems are deployed in Aalborg, Denmark; Tempe, AZ; Cambridge, MA; Princeton, NJ; and New York, NY). Several software developers are beginning to explore these interfaces and are advancing them toward a new generation of Pendaphonics systems (broader discussion of these is beyond the scope of this paper). Seen from a user’s perspective, as Pendaphonics systems are permanently installed, diverse interaction scenarios can be experienced in these “platform galleries”. Over a longer time period the same group of users will have the opportunity to explore and practice with an array of Pendaphones. They will also be able to compare and evaluate the embedded artworks, compositions and interactive games.

In the development of Pendaphonics, we actively compared and contrasted the different physical affordances given by BoingBoing’s [12] small pendulums and Pendaphonics large pendulums. In the design of musical performance interfaces, it should be noted that ease of use is not necessarily of primary importance; in fact, musical instruments that require skill and dexterity can provide enhanced entertainment value and extra appreciation from the audience [15]. The primary musical
Figure 2. Pendaphonics employs a CPU running Max/MSP/Jitter, video projector with virtual 3D environment, 12-channel audio interface and speakers at each pendaphone, x-y-z sensors, CREATE USB Interface boards, and tangible bob inviting co-located and distributed interactions.

Figure 3. (Equation 1) The period (T) of a pendulum is determined by this equation, where: 1 is the moment of inertia of the pendulum about the pivot point, L is the distance from the center of mass to the pivot point, m is the mass of the pendulum, and g is the acceleration of gravity.

While the BoingBoing interface allows musicians to control periods of oscillation between approximately 100-800 milliseconds, Pendaphonics allows for oscillation periods of between 1 and 3.5 seconds (as determined by the possible lengths (L) of the hanging pendulum (Figure 3). The shorter periods from BoingBoing lead to certain audible qualities in the resulting sounds that are recognizable to our ears, relating to things like bounces, collisions, trembles, shudders, and shakes, while the longer periods from Pendaphonics lead to more cyclic musical elements such as rhythmic sounds and larger musical forms. However, Pendaphonics can still be used to control lower-level (musical note-type) events through intentional movements with the pendulum’s bob such as holding the bob without releasing it to create a DJ Scratching effect and/or plucking the string of the pendulum (Figure 7). While there are many tangible interface research opportunities for Pendaphonics, the initial realization of Pendaphonics took the approach of a public interactive installation, which provides a different set of goals for the sonic interaction design and user experience as compared to musical performances (additional modalities and the broader potential of Pendaphonics is discussed further in section 5). However, it should be noted that while a public installation is not necessarily conducive to highly developed musical expression, Pendaphonics is nonetheless capable of generating interesting beat patterns with overlapping periodicities in this setting, thereby bringing about fascinating musical polyrhythms when multiple users are engaged.

3.2 Transdisciplinary Methodologies

Each of the four authors, who collaborated on the realization, installation and distribution of the Pendaphonics system, have different theoretical and applied backgrounds, which span electronic engineering and sound design, music composition, interactive media, game design, HCI, industrial and product design, educational technology and fine art. This interdisciplinary collaboration made it possible to design and execute advanced and innovative concepts for exhibition layout, including the implementation of hardware and software in the Platform4 exhibition space and similar installations at remote locations. Furthermore it was possible to explore diverse tangible interaction modalities afforded by the hybrid physical, digital, and sonic environments.

The team brought synergistic methodologies and development strategies to the project, including improvisation tools that facilitated the acting out of interaction scenarios, even before any equipment or prototypes were constructed or functional. Strategies for rapid prototyping allowed for explorations of counter weighting mechanisms and bob “form and function.”
3.3 System Architecture and Environments

The first installation of Pendaphonics is now a permanent environment at Platform4 art space in Aalborg, Denmark. It was an invited project for the grand opening in August 2008. We conceived and proposed it as a networked platform for both soundscape exploration and musical ensemble-style interaction. While this installation is itself distributed throughout the gallery, when remote locations are set up and activated, the Pendaphones becomes a musical link between people around the world. At this time there are Pendaphone systems installed at research locations in Aalborg, Denmark (in the Medialogy program), Arizona State University (in the Motivational Environments research group), University of Oslo (in the Four Ms Laboratory), MIT Media Lab, and at Princeton University (part of the Princeton Laptop Orchestra, PlorK).

The primary installation at Platform4 consists of 8 interactive sonic pendulums with low-cost game controller sensors called the Gametrak (http://www.in2games.uk.com/) which employ a clever method of measuring the x-y-z coordinates of their motion (see Figure 3). The original electronics in the Gametrak was discarded due to its proprietary nature (it only works with some software), and we instead use the CREATE USB Interface (CUI) [18] to digitize the sensor inputs. This provides us with a high-resolution (12-bit) analog to digital conversion and plug-and-play USB-HID (Human Input Device) data format. It is also possible to send Open Sound Control (OSC) format data with the CUI by using µOSC [19], and we are planning to switch to this in the near future. A single CUI board features 13 analog inputs, allowing four x-y-z sensor units from the Gametraks (i.e. four Pendaphones) are connected to one CUI. The software for Pendaphonics was created in Max/MSP/Jitter, and a virtual 3D environment (Figure 4) was created both for testing and real-time display of positions and motions of the 8 pendaphones.

The physical installation of Pendaphonics in Platform4 gallery space was consistent with the research group’s flexible and iterative development philosophies. This was important so that the development could apply well to other Pendaphonic modalities and distributed installations. The physical installation was kept very simple. It consisted of a painted circular wooden platform suspended in the center of a 5 x 5 meter space bounded by four cement columns. Four cords extending horizontally to each column suspended the platform. On the platform there was a game controller and a speaker. Electrical cables for the sensor data and for audio signals were wired from the game controllers to the CUI boards and to the speakers. Strain relief was provided for the wires. The bob was hung from the game controller so as to “float, neutrally buoyant (counter balanced).”

Participants manipulate a spatial soundscape that is directly controlled by the positions and motions of each of the Pendaphones. Each of the Pendaphones can be raised and lowered between 0–3 meters in height, and the trajectory of their swings directly controls the sounds emanating from a loudspeaker mounted above each Pendaphone. Multiple channels of loudspeakers are used to spatially distribute the sounds that are generated, enhancing the sense of physical immersion in the space. The physical setup is designed to be flexible and can be adapted to many different exhibition spaces and applications.

3.4 Iterative Interaction Design

The Pendaphonics installation exists on multiple levels. At one level it exists as a public installation, where people can walk into the pendulum area and put the pendulums into motion. Another, more complex level has been developed, where musical/sonic games with rules that need to be learned and agreed upon in order for participants to engage. At a third level, the installation can form a space for performance. Here we will discuss the first level.

In the exhibition at Platform4, three different interfaces were implemented. These were all directed towards the intuitive investigation of the interface, where exhibition visitors activate a soundscape in the space. The sound feedback systems have so far been simple and relatively logical. Well known metaphors have been used, such as the idea of the turntable, where a rhythmical soundtrack is played back. Clockwise rotation plays the sound forward, and counter clockwise rotation plays the soundtrack backward; the polar velocity of the swing changes the playback.
speed. Another sound feedback system consisted of percussion sounds that were mapped to cue points along the 360 degrees of the pendulum swing. Every thirty degrees a percussion sound was activated. The percussion sound changed pitch, depending on how high or low the pendulum was positioned in the air, and the audio frequencies percussion sound was filtered according to the amount of acceleration. The third sound feedback system was a musical piece composed by Mads Weitling (see http://www.kiloton.dk/). It consisted of a pre-composed soundscape, where the pendulum movement generated tones that mixed in with the soundscape and varied in texture and velocity.

Pendaphonics has been and will continue to go through multiple design iterations; new physical design solutions and the corresponding interaction possibilities will be explored on an ongoing basis. Each integrated designed solution will encourage new interaction possibilities. To date the following set of interaction frameworks have been explored:

- Sound ball improvisation tool
- Sound transfers and sound traveling (locally and networked), possibly incorporating hanging loudspeakers embedded in the bob, providing natural Doppler and “Leslie” effects
- Diverse ways of throwing and catching sounds through physical actions with the pendaphones
- Plucking the pendulum strings to set up future events or trigger special effects (either sounds or visuals)
- Detection of user’s direct interaction with bobs while the string is motionless, e.g. w/ embedded accelerometers
- Detection of spatial interaction between two or more bobs
- Diverse game/play scenarios
- Individual instruments versus one collective instrument
- Physical vs. virtual presence, movement, and representation

These interaction frameworks certainly have different meanings and affordances, depending on the exhibition context (e.g. section 5 discusses several modalities for Pendaphonics as installation, science, play, choreography, composition and as a distributed network of interactive environments).

Likewise, various types of physical designs of the Pendaphonic bobs have been considered, iteratively evolved, and to some greater or lesser extent implemented. The bobs' form and features also support diverse contexts and scenarios, in their own right. Obviously, the shape of each pendulum is important in terms of the swinging patterns that it will generate. Different tactile and ergonomic features also change the way users interact with the pendulums. Visual and sonic appearance, too, give users an impression of what actions they may engage in and what experiences they can expect to obtain through their interactions.

In terms of the physical shape of the pendulums, the variety of shapes and position of weighted areas in the shapes has been discussed according to their physical impact it will have on the swinging patterns. Regular, symmetrical shapes with a weight point at the bottom will result in regular circular movements, while irregular shapes and shifted weight points will result in chaotic swinging patterns. Furthermore, these swinging patterns can be emphasized if a laser light is placed at the bottom of each pendulum.

If the pendulums contain localized sound, i.e. has a speaker in them, they would spread sound into the surrounding space according to their swinging patterns. Additionally, sound could also be recorded into the pendulum. This sound could then be and activated later or sent to another pendulum. In terms of incorporating light into the pendulums, so that they become illuminated, or contain “cell structures” or “veins” of light, there have been considerations regarding light behavior. Blinking patterns can respond to physical interaction and they can indicate a networked identity between the pendulums. Controllable color lights (DMX protocol) have been installed in the space where Pendaphonics is installed at Platform4, and future work will involve the control of these lights from the primary Pendaphonics computer. This can be done responsively, in reaction to users’ actions, and/or it can be an interactive game, where the lights encourage particular actions from the participants.

A significant consideration has been applied to the ergonomic shape and tactile experience of each pendulum. Several iterations, such as soft and malleable shapes versus hard and contained shapes, furry versus blank surfaces, sticky versus dry surfaces and warm versus cold materials such as wood or metal were considered, and many were tested. Multiple round shapes were compared to stick-like shapes and tear-drop organic shapes.

Ultimately, this process lead to the installation at Platform4 consisting of a molecule of white plastic balls that can be illuminated, when colored light is directed towards them. The final design process entailed synthesizing the practical and experiential requirements into a functional and appealing physical shape. Taking advice from the product design mantra that, “form follows function”, the Pendaphonics team agreed that the core objectives of the pendulum bob elements should be to appeal as tactile, neutral, inviting, cool, clean and simple interactive elements through their form, function and facilitation of user experience.

Towards realizing these core objectives, several prototypes were developed, guided and inspired by the physical dimensions and location of the Plaform4 gallery space, where they were exhibited. Initially the team pursued an approach to this challenge that emphasized the design of the pendulums as an interior design opportunity within a large space. The cavernous physical space led the team to explore designed forms that evoked elegant solutions from the realms of stalactites and organic shapes from the plant kingdom.

In a number of these design iterations the pendulum string was covered to integrate it with the bob. This integration resulted in a visual connection of the physical appearance of the installation upwards toward the ceiling, splitting participants' attention between the bob element, and the Pendaphonic infrastructure, at the ceiling. While the stalactites approach was successful on the organic level, it also had the effect of drawing users attention upward away from the interaction element, the bob. Through testing, observation, and feedback, the team determined that this design was too distracting from the core objectives. Thus, a new approach was taken. Since it was important that the design of the bob not divert the users' attention from the sonic reactions they experience as a result of their interactions with the Pendaphone, the bob was re-designed to have a neutral and simple appearance. This eventually resulted in the bob seen in Figures 5, 6, and 7. On a metaphorical level this bob is atom-like with its cluster of "particles". Additionally, the cyclic elliptical path of a Pendaphonic bob references the motion of an electron orbiting the nucleus of an atom. On a larger scale, the human participant in the Pendaphonic experience is engaging in a similar action providing the activation-energy for the systems’ oscillation. On a practical and physical level, the bob consists of multiple elements
purposefully connected in a loose, yet robust, manner to achieve a lively, rich, and tactile feel. Ergonomically, the bubbly shape can be grabbed and manipulated easily by children and adults, alike. The rounded shapes, and the simple and clean materials invite users to touch the bob and explore different types of interactions with little fear of injury or of damaging it. The bob is also easy to repair in case someone happens to detach one of the elements; that said, it is also robust and there has been no need to repair any of the bobs throughout the hundreds of participant interactions.

4. USER EXPERIENCE EVALUATION

This section discusses the descriptive and qualitative video analysis of user interaction as they engaged in Pendaphonics diverse modalities within the Platform4 gallery space and during pre-installation pilot studies. This analysis followed a structured approach, observing individual users; adults and children and, separately, children and children; and adults and adults interacting as diads. Furthermore, this section discusses the interactions of multiple Pendaphones in a co-located space and how these relate to a group of people in the space. Additional studies of children and adults interacting as larger groups and distributed interactions using Pendaphones are within our immediate research agenda.

Pilot study of user interactions: Even before the Pendaphonics system was completely installed, at a time when the pendulum bobs were hung but were not yet providing interactive sonic responses to users' manipulations, a child who was about 5 years old and an adult care taker started playing with one of the Pendaphones. Even without sonic events, this interaction was particularly intriguing because the child, as if by instinct, started throwing himself after the bob, like a cat chasing after a toy.

Individual users: From a TUI and HCI perspective, one of the most important findings has to do with the cyclic nature of Pendaphonic interactions. Since Pendaphones are pendulums they behave as simple harmonic oscillators, swinging repeatedly in an arc or ellipse away from and back toward each individual participant. This cyclic effect differs significantly from most other interaction devices, and serves as an ongoing and iterative “invitation” to engage and re-engage the user(s). This effect opens up the possibilities for many new and interesting interaction modalities. It is also one of many elements that makes the Pendaphonic system so engaging, even for a single individual exploring the system alone. Through observations of children and adults interacting with Pendaphonics on their own, it was clear that there was significant opportunity for self-expression. Experimentation with continuous motion patterns that generate physical and sonic feedback is compelling. Different individuals focused on very different elements of the system. Some specific examples include, one child enjoying playing alone with a Pendaphone in front of the projected 3D virtual Pendaphone environment that depicted the interactions of the 8 other Pendaphones throughout the gallery. Through his interaction with the system the child was able to observe how his physical manipulations of his pendulum bob had a real time impact on the 3D virtual model and the activation of the other bobs (e.g. through events triggered by bob to bob proximity). Another child particularly enjoyed the plucking feature and continuously engaged in explorative strumming actions at various locations throughout the range of his Pendaphone. Adults tended to be more reflective and deliberate in their interactions, sending the bob in one circle at a time and holding the bob in various places to explore its feedback. They were also more likely to interact with a Pendaphone by moving it through space in their hand rather than releasing the bob. Another interesting observation was that adults were also more likely to reach and grab for the string than children who were usually more focused on the bob, itself.

Adults/Child Dyads: One of the typical shared eureka moments for adult/child dyads occurs when either the child or the adult realizes, and shares their new understanding, that Pendaphonics responds to the back and forth swing of the bob, and related interactions, by providing different sounds (e.g. higher and lower pitched sounds) depending on the vertical level of the bob. Discoveries, such as this one were shared with a great enthusiasm and many excited laughs. Often adults were more verbal about their discoveries. For example, adults tended to share their understandings by explaining them to the children. However, adults where typically less physically active than children so they usually did not have as much first hand experience with the system. Thus, children frequently had the opportunity to discover and provide explanations of their own interaction insights to their parents as well. In this respect, the system demonstrated its ability to facilitate inter-generational knowledge transfer, communication, shared understanding, appreciation, exploration, learning, and bonding experiences. The exact nature of these experiences is, of course, be dependent on the adult/child relationship, i.e. whether the pair exploring Pendaphonics was an adult with a young child, a tween (~8-12 year-olds), or a teenager. The research team is eager to explore the potential of these interactions in future work.

Figure 5, 6, and 7. Left (5), in Platform4’s gallery a Pendaphone bob with a projected 3D environment; top right (6), three suspended Pendaphones; bottom right (7), a child plucking the string while holding the Pendaphone bob steady.

Child/Child Diads: Children, interacting with the system, exhibit an extremely high level of physical activity. They often throw themselves after the bob to catch it. They have many different ways of passing the bob to each other e.g. using serve-like and blocking-like gestures – e.g., while playing a volleyball-like game. They were also observed throwing the bob like a basketball, engaging in both over and under hand throws. They even kicked the bob to each other. They would run after the bob to get to it first – sometimes even to the extent that they lost their balance and/or dove for the bob. They use their hands as a bat
and/or a racket. They engaged in energetic and continued jumping, twisting, stretching, and a great deal of general enthusiasm. They sometimes even tried to make the system challenging or impossible for other children, e.g. taller children will at times place the bob out of reach of shorter children either vertically or by sending the bob in an orbit around the other child.

*Adults interacting in a group:* Adults were observed to engage in the following interactions: experimenting, engaging in mini - performances, pointing, discussing the interactions and experience, trying to explain and figure out how the Pendaphonic system worked e.g. asking each other about the sensors and technology behind the composition of the DJ-scratching/waving interaction. They would also tend to send the bob orbiting within a circle of people surrounding a Pendaphone, one person would then grab the bob, engage in some DJ-scratching movements and send it orbiting again. Another person would then redirect the orbit, changing its direction by gently dragging and/or holding the bob by the string. Adults exhibited a broader range of levels of engagement than children, some would be actively manipulating the Pendaphones movements, while others might be enjoying the performance, tapping to the rhythm of the music. Bouncing to the beat (“pseudo dancing”), and hanging out together -- “chilling”. Children tended to be either more fully engage or disengaged when they were “done”.

**Pendaphone to Pendaphone interaction:** Another parameter that adds an extra dimension to Pendaphonic interactions is that the system can factor into its feedback the relationship between each of the many individual Pendaphones. At times, this might take into account, only adjacent Pendaphones, include all of the collocated elements, or even extend to distributed Pendaphones. Parameters might include the proximity of Pendaphones, synchronized movements, mirrored interactions, coordinated speeds, etc.

### 4.1 Experience Summary

We expected that there might have been some negative experiences related to Pendaphonic interactions, such as the Pendaphone getting stuck out of reach, or elements of the system breaking in public, or individuals pulling the bobs too far beyond their physical limits, or the occasional unexpected bob hitting someone by accident, but by and large we saw little to none of these events occur.

The user observations demonstrate that Pendaphonics has a broad appeal to diverse users. It offers a compelling experience for adults and children alike, and is engaging both when explored as an individual, a diad, or a group. The system provides a “low floor” – an intuitive experience that is generally physically engaging and intrinsically motivating. The more users investigate the sound feedback system, the more they find that even small changes in movement cause variations in the sound, which indicates that more complex interaction can be learned and used in a performance modality. In general the Pendaphonics installation was found to be broadly accessible, simultaneously engaging to multi-generations and approachable for people with a diverse range of physical abilities.

In future research we will explore the system’s affordance for developing a “high ceiling” – does it still engage users after the fascination of novelty is over and how well does it lend itself as a framework for exploring and creating artistic complexity. This type of investigation will require that it is possible for a user to acquire a skill set that enables them to excel in their use of the platform (e.g. like an instrument or an open-end system like LEGO blocks). Toward this goal the system will be used in the following ways: 1) As a platform for composing music, 2) As an integrated part of a dance performance 3) As a longer term, interactive art installation in a public space. We have observed diverse constellations of children and adults interacting with the Pendaphones either as individuals, diads, mixed diads, or adult groups. We will also study if a larger group of children can learn from each other and, ultimately, if they can successfully coordinate their actions in order to generate specific sounds and coordinated patterns.

### 5. CONCLUSION

Pendaphonics was developed as a reconfigurable, permanent, public installation, in which individual units, Pendaphones, can be rearranged within an exhibition space to promote the embedded sonic artwork and interaction framework. As such, they can function as a physical platform and gallery installation for multiple sonic artworks that can be exhibited over time or cycled through. Based on the experiences from the public exhibition at Platform4, we are engaged in several new Pendaphonic directions:

- A musical instrument and performance tool: Sound and music compositions as well as choreography can be composed, practiced and performed spatially by musicians and/or dancers with the Pendaphonics system. We are actively using the system in these contexts ourselves, and have invited other musicians and choreographers to explore and use the system in their work. A full concert of works composed for Pendaphonics is a near term goal.
- A math and science manipulative: Through the elucidation of several mathematical and physical theories that are connected to the movement of a pendulum, Pendaphonics can be experienced in a science museum and/or classroom setting where the sonification of the motions of a pendulum can emphasize concepts that are otherwise difficult for learners to experience and interpret (e.g., elliptical planetary orbits and chaos).
- A playful tangible gaming interface: The already rich social interactions that have been observed and the many tangible interactions that have been developed indicate that many types of social games can be developed that leverage any or all of the following parameters: repeated “invitation” to interact, swing direction, angle, speed and acceleration, swing type (circular or elliptical), swing radius, pendulum height, and plucking of the pendulum strings.

Many researchers and participants have now been utilizing the Pendaphonics system. User observations have indicated that the installation has great impact both as a permanently installed exhibit and as a remote/traveling interactive installation, in which new game and performance concepts can be implemented and tested by a network of software-based artists, composers, game designers and researchers. The physical co-located presence of eight or more pendulums offers a compelling spectrum of user interactions that encourage the general public to collaborate in a novel social context toward generating meaningful soundscapes and mutual experiences.

In addition to the importance of the bob design as an enticing interactive tangible object, one of the strongest affordances of the Pendaphonics system is the repeated and sustained “invitation” to interaction that it presents. This invitation is created by the pendulum’s (Pendaphones’) simple harmonic oscillation motion,
and its implementation embodies a novel and useful tangible interaction scenario for the NIME-HCI-TUI communities to leverage, through the advancement of 3D physical-digital-sonic environments and related research. Furthermore, the broad range of interaction parameters implemented within the Pendaphonics system can also be utilized to present fine resolution interaction patterns, through which performers and expert users can express themselves, after having extensive practice and/or training with the co-located and distributed elements.

The permanent presence of Pendaphonics in both public exhibits and university laboratories is contributing to the rapid evolution of the tangible and sonic development of Pendaphonics systems. To date, Pendaphonics has been realized as a tangible pendulum-based sonic interaction experience that has been designed to encourage complex dynamic social user interaction with the aim of supporting users to express themselves individually and as members of an interactive ensemble. Through collaborations with domain experts, artist collectives, and institutions (e.g. the Mars Education Program and Exploratorium in San Francisco) the Pendaphonics team is actively engaged in taking the next steps to advance Pendaphonics’ diverse modalities as a: musical instrument and performance tool, math and science manipulative, and a playful tangible gaming interface that promotes inter-generational creative play and discovery.

6. ACKNOWLEDGMENTS
We wish to acknowledge and thank Platform4 and Aalborg Kommune for providing the opportunity and for their support in the development and installation of Pendaphonics. We also thank T.C. Electronic for their generous contribution of a StudioKonnet firewire audio interface during the installation opening. We want to thank Stefania Serafin for the use of her Tibetan Singing Bowl physical model, and Patrick Lu at Arizona State University’s Arts, Media, and Engineering Program for their assistance with acquiring equipment, the physical installation process, and website.

7. REFERENCES