Exploration of Auditory Augmentation in an Interdisciplinary Prototyping Workshop

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***Abstract*—Auditory augmentation has been proposed as a specific, ambient sonification method. This paper describes an interdisciplinary workshop exploring this method by designing prototypes. Three of the prototypes are presented and discussed. Concluding on the workshop's results, the authors suggest a broader definition and deduce limitations of auditory augmentation.**

I. Introduction

Sonification, in the authors' definition, is the translation of information for auditory perception, the acoustic equivalent to data visualization [1]. Our institute pursues the Science by Ear (SBE) workshop series on sonification. Since 2005, four of these workshops took place. They explored sonification in an interdisciplinary, small group of attendees, and each had a different focus: The first workshop (SBE1) explored data sets in a variety of disciplines (from sociology to physics).[1] The workshop set-up has proven convincing, even if the large variety of disciplines and the scientific dialects of their communities were demanding for the attendees. SBE2 focused on physics' data[2] and SBE3 on climate data[3].

One of the lessons learned from hosting this series is to carefully balance the interdisciplinary, creative setting with well-prepared tasks. If this is achieved, the setting provides a fruitful development of prototypes, as shown in this paper. The layout of the workshop is discussed in Sec. II. In the fourth edition (SBE4), the focus was less on a specific data domain but instead on exploration of a specific sonification method: Auditory augmentation has been proposed by Bovermann et al. [2] as altering the characteristics of structure-borne sounds for the purpose of supporting tools for data representation. Besides this term, many notions and systems following a similar idea have been published, as discussed in Sec. III. As exemplary data set used in this exploration, we chose data of in-home electric power consumption. Section IV introduces our working definition of auditory augmentation and three of the prototypes developed on three hardware platforms. Finally, in Sec. V, we discuss some answers to our research questions, and conclude in Sec. VI.

[1]SBE1: http://sonenvir.at/workshop/
[2]SBE2: http://qcd-audio.at/sbe2.html
[3]SBE3: https://sysson.kug.ac.at/index.php?id=16451

II. Workshop layout

The workshops of the Science by Ear series are structured as follows. About 20 people with different backgrounds are invited to participate: sound and sonification experts, researchers of a certain domain science, and composers or sound artists. During the workshop, they take the roles of programmers, sound experts, data experts, and others (e.g., moderators of the teams). One workshop takes place on three or four days. After some introduction, participants are split into three to four teams of about five people. Each team is working on one sonification task with a given data set for three hours. Team members always include a moderator who also takes notes, and one or two dedicated programmers who implement the ideas of the team. The prototyping sessions combine brainstorming, data listening, verbal sketching, concept development, and programming. After each session, the teams gather in plenum to show and discuss their prototypic sonifications. Besides the hands-on character of the workshops, there is a certain challenge between teams to produce interesting results within three hours. Data sets, tasks, and software are prepared by the organizers in order to ensure that technical obstacles can be overcome within the limited time.

Within SBE4, the fourth edition of the workshop series, the method of auditory augmentation has been explored. This implied another level of complexity, as not only the data and the software needed to be prepared by the organizers and understood by the participants, but also possibilities and restrictions of the provided hardware systems had to be communicated.

Including the authors, 19 participants took part. Eleven of these can be counted to the sonification community (but with varying backgrounds in sciences, arts, and humanities), while the rest included two media and interaction experts, two composers, two sound engineers, one musicologist, and one sociologist. Participants divided in seven at pre-doc and twelve at post-doc level or above; in three female and 16 male participants. Not all of them took part throughout the whole workshop, leading to varying group sizes of three to six for the prototyping sessions.

III. Related work on auditory augmentation

The concept of auditory augmentation has been proposed by Bovermann et al. [2] as "building blocks supporting the design of data representation tools, which unobtrusively alter the auditory characteristics of structure-borne sounds." One of these authors' examples eliciting the concept is 'WetterReim' [3]. An ordinary laptop keyboard is equipped with a contact microphone, recording the typing sounds. The microphone signal is filtered with varying parameters that depend on the weather condition. The output is played back in real time and fuses with the original sound to a new auditory gestalt. In short: depending on the weather outside, typing on the keyboard sounds different.

The concept of auditory augmentation has been discussed to be extended to the more general *blended sonification* [4] which "describes the process of manipulating physical interaction sounds or environmental sounds in such a way that the resulting sound carries additional information of interest while the formed auditory gestalt is still perceived as coherent auditory event." Blended sonifications "blend into the user's environment without confronting users with any explicitly perceived technology". In consequence, they provide an ambient sonification channel. Blended sonification is similar to or even encompassing auditory augmentation but takes into account environmental sounds, in addition to structure-borne sounds. A different generalization of auditory augmentation is given by Weger et al. [5] who "define *augmented auditory feedback* as the artificially modified sonic reaction to physical interaction". Augmented auditory feedback can become an auditory augmentation if it conveys additional information. For the context of SBE4 we decided to stick to the original term *auditory augmentation* with a new working definition that incorporates the prepared platforms and tasks (see Sec. IV-A).

Looking at a broader context, auditory augmentation is part of *Sonic Interaction Design (SID)* which has been defined by various authors with different focuses: Rocchesso et al. [6] defined that it "explores ways in which sound can be used to convey information, meaning, aesthetic and emotional qualities in interactive contexts." Franinović and Serafin [7] set the focus more on phenomenology and perception: "Sonic interaction design [...] [considers] sound as an active medium that can enable novel phenomenological and social experiences with and through interactive technology." Auditory augmentation is certainly part of sonic interaction design, and it is within the scope of this paper to elicit the specificities about it.

We found a few more SID systems in the literature that are closely related to auditory augmentation, especially regarding its focus being an ambient display. For instance, Ferguson [8] developed a series of prototypes which are similar to the ones that emerged from our workshop. One example is a wardrobe door that plays back a sonification of the daily weather forecast when opened; Ferguson uses the term *ambient sonification systems*.

Kilander and Lönnqvist developed *Weakly Intrusive Ambient Soundscapes for Intuitive State Perception (WISP)* [9] in order to "convey an intuitive sense of any graspable process" rather than a direct information display. In a ubiquitous service environment, individual notifications are presented with a sound associated to the user. Playback volume and reverb are used to convey three levels of intensity of the notification. High intensity is mapped to a dry, loud sound, while low intensity is saturated by reverb, giving the impression of a far sound. Finally, a similar project has been realized by Brazil and Fernström [10] who explored a basic system for an ambient auditory display of a work group. The presence of colleagues is sonified as a soundscape of individual sounds, each time a person enters or leaves the workplace. The proposed system utilizes auditory icons [11, p. 325-338] for creating a soundscape and is not based on auditory feedback as was the case in WISP.

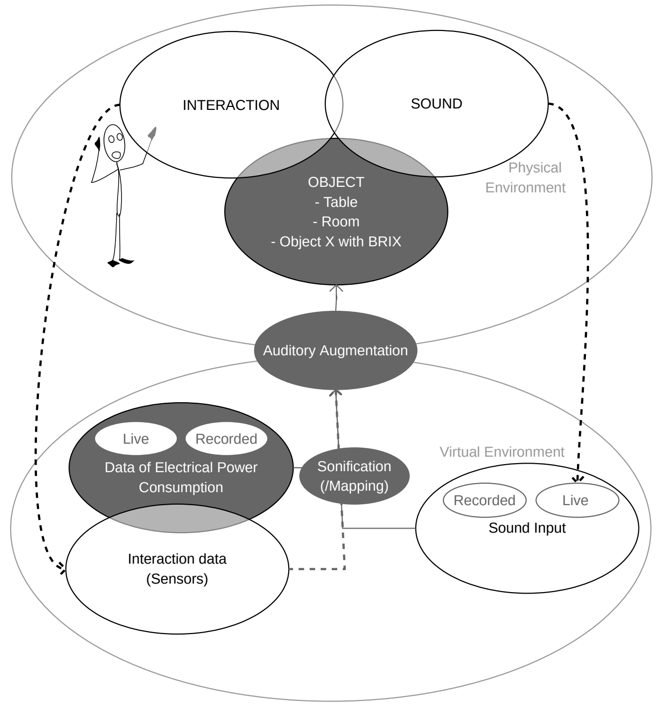


Fig. 1. Sketch of our working definition of auditory augmentation. Three mandatory elements are shaded in gray: an object delivering either sound input and/or interaction input, data, and sonification of these data which is auditorily augmenting the object in a closed feedback loop.

IV. Science by Ear 4

A. Working definition of auditory augmentation

SBE4 provided a set-up for exploring auditory augmentation and defined that

> Auditory augmentation is the augmentation of a physical object and/or its sound *by sound* which conveys additional information.

As sketched in Fig. 1, three elements are needed for auditory augmentation:

1) Physical *objects* in a physical environment. In our workshop setting, these were a table, a room, or any sensor-equipped physical object. These objects may produce a sound, or not; users might interact physically with them, or not. In some cases, the sound is a result of the interaction, but does not have to be. *Either* of these

inputs has to be there: real-time sound input *or* real-time data input from the interaction.
2) *Data* that are sonified. These can be real-time data or recorded data; in the setting of the workshop, we chose data sets of electric power consumption. The sonification may use ‘natural’ sound input (real-time sound or field recordings), or may be based on sound synthesis. Further input for parametrizing the sonification can stem from interaction data.
3) The *sonification* is played back in the physical environment, auditorily augmenting the physical object we started from.

In short, for auditory augmentation we need an object which produces sound or is being interacted with, data, and their sonification.

B. Interaction platforms

The various possibilities of auditory augmentation have been explored on three different platforms during the workshop.

1) ROOM: The ROOM is situated in the institute’s main performance and lecture hall, equipped with a 24-channel loudspeaker array on a half-sphere for ambisonic sound spatialization [12]. Furthermore, there are five microphones mounted permanently to allow for a virtual room acoustics. For SBE4 we prepared to work with both live sound input from the microphones of the virtual acoustics system and additionally added ambient sounds.

2) TABLE: The TABLE is an experimentation platform developed within an ongoing PhD project (see [5]). Technically, it incorporates a wooden board or table (depending on its orientation in space) equipped with hidden contact microphones and exciters or additional loudspeakers; a marker-based optical tracking system locates the position of any object or hand interacting with the surface. Any sound produced on the TABLE is recorded and can be augmented in real time through a filter-based modal synthesis approach. The prepared setting for the workshop allows to change the perceived materiality in a plausible way while, e.g., knocking or writing on it.

3) BRIX: Our co-organizers (see Acknowledgment) provided their BRIX system [13], [14]. This system has been developed to allow for simple prototyping of interactive objects. In the prototyping sessions with the BRIX, the team could choose an interaction scenario with any object, equipping it with BRIX sensors and/or with microphones. Sensors that have been prepared for the workshop include accelerometer and gyroscope, as well as light, proximity, humidity, and temperature sensors.

C. Data sets

Next to the three hardware platforms described above, we prepared three data sets of electric power consumption. The data sets are of different nature (real-time vs. recorded data) and therefore propose different tasks, i.e., real-time monitoring as opposed to data exploration. The teams had to develop scenarios that support the saving of electric energy consumption.

1) REAL-TIME: The REAL-TIME data set was provided as a real-time power measurement of five appliances at our institute’s kitchen (see [15] for how this system has been used before). Alternatively, the teams could attach the measurement plugs to any other appliances during the workshop. The sampling interval was about one second; data was sent over OSC, with a measurement range between zero and 3 000 Watt. Measured kitchen appliances were dish washer, coffee machine, water kettle, microwave, and fridge.

2) PLUGWISE: The PLUGWISE data set stems from a private household where nine appliances’ loads have been measured for one year with a sampling interval of 10 minutes. Measured appliances comprise: kitchen water kettle, ceiling light and media station in the living room, fridge, toaster, dehumidifier, dishwasher, washing machine, and TV.

3) IRISH: The IRISH data set stems from a large survey of smart meter data in Ireland, collecting data of 12 000 Irish households over 1.5 years with a sampling interval of 30 minutes [16]. We extracted 54 households for each combination of three family structures (single, couple, family), two education levels, and two housing types (apartment vs. detached house).

D. Resulting prototypes

During the three days of the workshop, four parallel prototyping sessions took place; one for each of the three data sets and an open session on the last day where chosen prototypes were refined. An overview of all the resulting prototypes is shown on the SBE4 website[4]. In this paper, we only focus on three exemplary cases: *sonic floor plan*, *writing resonances*, and *standby door*, realized with the three different platforms respectively (see Fig. 2).

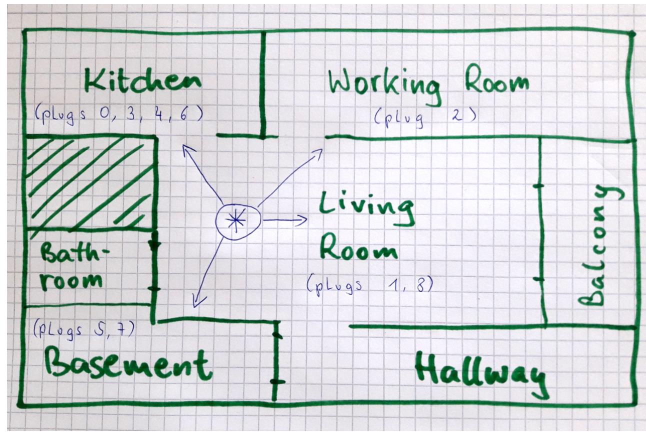
1) Sonic floor plan (ROOM): The real-time data set used in this scenario provided data of electric power consumption of different devices in one specific household. The team developed a scenario with an assumed floor plan of the household (see Fig. 2a). Feedback on energy consumption is played back in one room (e.g., a media room) on a surround sound system. A sound occurs periodically after a specified time, as well as when a person enters the room. The appliance that currently consumes the most energy defines the direction for sound spatialization. Environmental sounds from outside the building are captured by a microphone. These are played back in the room with loudness and position depending on the level of energy consumption. As only the power consumption of the appliance with the highest load is sonified, even small standby consumption may attract attention, e.g., when no major energy consumer is active.

2) Writing resonances (TABLE): Writing resonances is the most ‘classical’ example of auditory augmentation during the workshop, because it is based on structure-borne sounds and therefore clearly fulfills the initial definition of Bovermann et al. The scenario is to provide feedback of in-home power consumption through an auditorily augmented writing desk (see Fig. 2b), based on the system presented in [5]. The

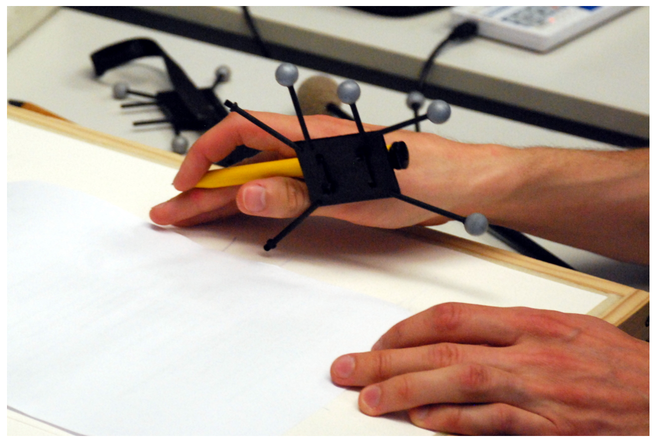
[4]SBE4: https://iem.at/sbe4

table is augmented through additional resonances, based on a physical model. The size of the modeled plate is controlled in real time by the total amount of electric power consumption, employing the metaphor of a larger table (i.e., deeper sound) when more power is consumed. With the augmentation being only a modulation of the existing interaction sounds, the sonification only gets audible through interaction with the table; the feedback is therefore calm and unobtrusive. The primary task is writing, but also an active request of information by knocking is possible. This prototype has been extended in the fourth, open session, allowing for a modulation of individual partials in order to additionally convey information concerning the different appliances' individual power consumption.

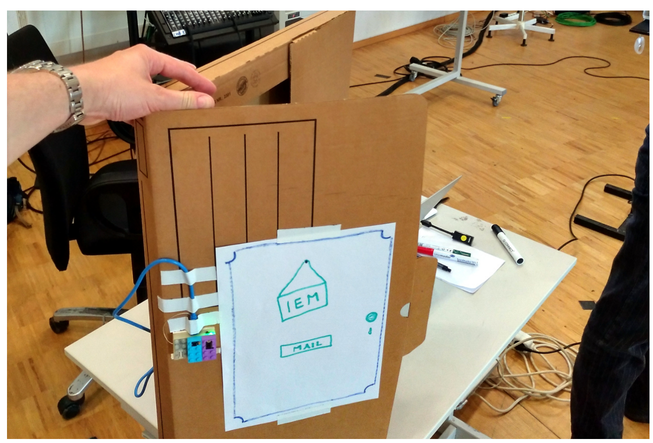
3) Standby door (BRIX): This scenario augmented our institute's inside entry door (see Fig. 2c for the prototypic mockup). Most potential for saving energy lies in the reduction of standby consumption. Therefore, when the door is opened, e.g., in the morning, the standby consumption over the recent past is communicated through a simple parameter mapping sonification. The playback speed depends on the assumed stress level of the user, derived from the opening speed of the door. In the open prototyping session, this approach has been extended to be able to sonify individual appliances. For intuitive discrimination between them, the sonification is based on synthesized speech. When opening the door, an emotionless computer-voice says 'coffee machine', 'microwave', and the like, with timbre, loudness, or other parameters controlled by how much electricity this specific appliance has used over night.



(a) *Sonic floor plan.*



(b) *Writing resonances.*



(c) Standby door.

Fig. 2. Three of the prototypes that have been developed during the workshop.

V. Feedback and Analysis

We explored four main research questions by applying various analysis methods on the results of the workshop. Plenary sessions with discussions of the presented prototypes have been recorded and partially excerpted. Additional inputs are written notes, code, and demo videos resulting from the prototyping sessions. All these inputs led to fundamental considerations on auditory augmentation and how it can be used, but also to general feedback concerning sonification, workshop setting, or design issues.

A. Peculiarity of sound in augmented reality

Augmented reality usually refers to a mainly visual system. But if this concept is transferred to audio, why then is listening to the radio not 'auditorily augmented reality'? Or is it? The underlying question is: what are the peculiarities of sound in the context of augmented reality?

Concerning the radio, the answer is relatively clear. In the visual domain, augmented reality usually does not include an overlay of a video on top of the visually perceived scene if there is no direct connection between them [17]. Applying this argumentation to the auditory domain, the radio (being an overlay to the acoustic environment) does not directly interact with the physical environment of the user and therefore can not be regarded as augmented reality.

A more profound analysis of this question is without the scope of this paper. Still, a few things came up during the discussions in the workshop. On the one hand, sonification is challenging because visual and auditory memory work differently, and therefore two sonifications are more difficult to compare than two static visualizations. These and other challenges are well known, see for instance [18]. On the other hand, designing for sound creates new perspectives, e.g., on the quality of an interaction. One participant reported, his group had discussed the nature of an interaction in their scenario (in the *standby door* prototype, the quickness of opening the door is related to the user's mood). Even if sound is not involved directly, thinking about the design is different with sound "deep in our minds" (participant P10).

To conclude, 'auditorily augmented reality' clearly behaves different from its visual counterpart, and this fact deserves more systematic research.

B. Definition and limitations of auditory augmentation

One purpose of the workshop was to develop and test our working definition which is deliberately wide to incorporate different platforms. The question is, if this definition is more useful.

Our working definition of auditory augmentation has not been questioned within the workshop; therefore, we would like to propose it for future applications. Still, one aspect deserves more attention than has been discussed above, as came up during the final discussion round. The definition starts from an object that is being interacted with, i.e., a primary task of the user with the object is pre-assumed. "Having a concrete task helps to design" (P1), and helped the teams to elaborate their scenarios during the sessions. During the final feedback round, however, it has turned out that *the task* is an ill-defined entity. Does it relate only to the interaction between user and object? And if the object is augmented, and its sound conveys additional information, is there such a thing as a monitoring task? Does only a goal-oriented activity comprise a task or can it be a by-product of daily "state of being" (P7)?

We conclude that auditory augmentation always involves a primary task, may it be goal-oriented or not (e.g., writing on a desk in the *writing resonances* prototype or just being in the media room of the *sonic floor plan*). This task should not be disturbed by the augmentation, but rather the augmentation adds a secondary task of monitoring.

C. Relationship between sound, data, and augmented object

In addition, we aimed at exploring the qualitative factors between object and sound in the context of auditory augmentation. Which qualities are needed to (fully) describe their relationship? For example:

- Is the sound, in relation to the object, plausible? Is the mapping of data to sound intuitive/metaphoric?
- Is the augmented object more useful, or more fun than the original one? Does its affordance change and is the original interaction, i.e. the primary task of the user with the object, disturbed?

A central issue that has been raised throughout the workshop was in how far objects change in perception when they are auditorily augmented. This experience, "you can only get it if you interact yourself" (P1).

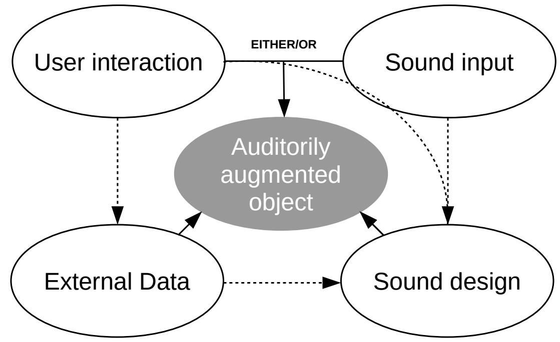


Fig. 3. An auditorily augmented object is influenced by three elements: either of the user interaction or the object's sound, external data, and the sound design used in the sonification.

For comparison between the three exemplary prototypes (Sec. IV), we analyzed the qualitative behavior of input elements on auditory augmentation. Abstracting from Fig. 1, we identify four of these elements: user interaction, input sound, external data, and sound design. This more abstract concept of auditory augmentation is shown in Fig. 3. We assume that more coherent relations between user interaction, input sound, external data, and sound design lead to higher naturalness and intuitiveness of the auditory augmentation system. Multiple dependencies are possible, even though not all are needed for auditory augmentation:

- User interaction may influence external data, e.g., turning on the water kettle while its electric power consumption serves as data. The task of writing by hand, however, does not directly modulate in-home electric power consumption.
- Data may have a close link to sound design, utilizing either direct sonification (e.g., audification [11, p. 301-324]) or a fitting metaphor, e.g., a larger desk with lower pitch representing a larger energy consumption.
- User interaction may directly influence sound design, in all cases where sounds are augmented that have been produced by the interaction.
- Sound input may not be stemming from the interaction but from an external source; still it may influence sound design, e.g., when using environmental sounds from outside the windows as in the *sonic floor plan* prototype.

In conclusion, it seems that a more natural prototype of auditory augmentation has more coherent relationships between user interaction and/or sound input on the one hand, and external data and sound design on the other hand.

D. Perceptual factors of data and sound

As a final research question, we aimed at sketching out perceptual factors of data and sound concerning auditory augmentation systems. What is the capacity of information that can be conveyed with auditory augmentation? Which data are suitable for it? Which factors play a role for blending the augmented object in the environment: is it unobtrusive but salient enough in order to be perceived? Of course, a full analysis of perceptual factors can only be a result of evaluation that was not within the scope of the workshop. However, some ideas emerging from the final discussions may serve as a basis for future investigations.

As one participant articulated, auditory augmentation works best with low-dimensional data – "otherwise you are not augmenting the object but creating a nice sonification" (P7). The information capacity, i.e., the level of information that can be conveyed, is rather low for the examined platforms. Especially for ROOM and TABLE, only the reverberation of the room – respectively the resonances of the structure-borne sounds – can be changed, with only few levels that can be differentiated perceptually. The BRIX system is more flexible in design, therefore no general conclusion can be drawn. Sonifying is difficult under these conditions, because "it boils down to the question which dimensions you chose and which ones you leave out" (P11).

In the *writing resonances* prototype, the developing team found a borderline for perception. Depending on the quickness of parameter changes, sounds lost their gestalt identity with the interaction, i.e., sometimes the sounds were perceived as separate auditory events played from the loudspeakers – despite measured round-trip latency below 5 ms. This example shows that perception is very sensitive and systems need to be well evaluated.

E. General feedback

Next to finding some insights on the aforementioned research questions, the analysis of SBE4 provided some feedback on the workshop setting itself, as well as on general design issues.

A general issue of sonification is its right to exist – referring to Supper's thesis "about community's struggles to have listening to scientific data accepted as a scientific approach" [19]. Useful and meaningful sonifications are difficult to come up with, which raised the question, "why sonify at all"? It was part of the workshop design to develop useful scenarios for the pre-defined platforms. This worked well for the prototypes presented in this paper, but not for all.

Generally, feedback on the workshop design was positive. The interdisciplinary, hands-on sessions were "so enriching" (P1). Participants further reported that they had "really time to try out something" (P2) – even if a certain approach did not work out in the end, there was learning even by dead ends. However, it was remarked that the prepared platforms had "narrowed down" (P3) possible paths of design. Some participants articulated the wish to be more free in designing interaction scenarios independently from a platform (P3, P5), but the prepared setting was very time-efficient. Most prototypes have reached a promising state after the three hours' sessions: "there are nine prototypes that are really worthwhile considering and working on in the future" (P4).

One participant (P1) raised the issue that designing ambient displays means designing for the background, while in the designer's mind the sound is in the foreground: "we have an excitement for sound and sonic display". Therefore, it would be important to cultivate a beginner's mind – something, he stated, that has been well achieved with the interdisciplinary workshop setting for most of the participants. Another general design-issue concerns the difference between prototypes and final products. The realized prototypes are meant to be listened to for a longer period of time, but designers only hear them for a short period of time (P8). Furthermore, for the purpose of demonstration and presentation, prototypes need to exaggerate, while in final products the appropriate settings are usually less salient. Participants who worked with iconic sounds of audio recordings stated that some cartoonification is needed (e.g., through post-processing or re-synthesis of the sounds), because "for ordinary people they all sound the same" (P9).

VI. Conclusion

Within this paper, we conclude on results from an interdisciplinary workshop exploring the concept of auditory augmentation. The workshop resulted in nine prototypes and, among others, recorded discussions that have been analyzed. Concluding on this material, we propose to use the term auditory augmentation with a new, broader definition: auditory augmentation is the augmentation of a physical object and/or its sound *by sound* which conveys additional information.

General considerations for auditory augmentation are summarized as follows.

Auditory augmentation requires a primary task of a user with an object; this task is not explorative data analysis. One reason is that data for auditory augmentation needs to be low-dimensional. Another reason is the differentiation between auditory augmentation and sonification. By augmenting an object auditorily, a secondary task of monitoring in the background turns up. This task must not interfere with the primary task.

There seems to be a quality of 'naturalness' (affecting also the 'intuitivity') of systems of auditory augmentation. The most natural systems have several coherent relationships between the four possible input factors, user interaction and/or sound input, with external data and sound design. We envisage exploring this hypothesis further.

There are borderline cases of perception, where the fusion of auditory gestalts between the original sound and the augmented one does not work anymore. The influencing factors need to be explored systematically.

Finally, the analysis of the final discussions during the workshop proved that the developed workshop setting is convincing. It establishes an interdisciplinary, playful atmosphere of research by design. The balance of possible ingenuity and well-prepared tasks, platforms, and data sets are crucial for a successful event.

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