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Highlights

- An overview of sonic information design and sonic interaction design in relation to the three HCI waves
- A description of sketching practices in sonic interaction design
- A perspective projection of sound in interaction studies

Interaction by Ear

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Abstract

Speech-based interaction is now part of our everyday experiences, in the home and on the move. More subtle is the presence of designed non-speech sounds in human-machine interactions, and far less evident is their importance to create aural affordances and to support human actions. However, new application areas for interactive sound, beyond the domains of speech and music, have been emerging. These range from tele-operation and way-finding, to peripheral process monitoring and augmented environments. Beyond signalling location, presence, and states, future sounding artifacts are expected to be plastic and reconfigurable, and take into account the inherently egocentric nature of sonic interaction and representation. This contribution presents a subjective outlook on body-centered sound as a mediator of interactions in future mixed realities, populated by humans, artifacts and virtual representations. Scholars and practitioners are expected to address design issues, to develop evaluation methods, and to expand interaction design practices to be truly multisensory.

Keywords: Sonic Interaction Design, Sonic Information Design, Sonification, Auditory Display

1. Waves of sound in interaction

Sound has always been a presence in computing, either as a protagonist or as a shadow. Machines were imagined as conversational agents long before natural language processing became a mature field of computer science. However non-speech sounds have always been secondary, even though our everyday interactions are largely affected and mediated by noises of many kinds. The result is that, in contemporary environments such as the home or car, we request and obtain services by voice, but still rely on undesigned mechanical noises or poorly-designed beeps to steer our actions. When we need precise and timely information, visual displays are the main resource, often enriched with animation and alarms. In this contribution we focus on the role that sound has played in HCI research so far, and point to the possibilities that sonic interaction and information may bring in the future. The first section provides a historical overview of research in auditory display and sonification, followed by more recent research into areas of sonic interaction design and sonic information design that have appeared in this HCI journal. In section 2, we reflect on the design process for sound-based interactions and, in particular, on vocal and gestural methods for sketching sonic interaction designs that we have been developing. Section 3 provides our speculations on how the sounds of interactive artefacts may be conceived, designed, and evaluated in the future.

1.1. A compressed history of sound in HCI

The term Auditory Display was introduced in the 1950s when the clutter of visual displays in aircraft cockpits became a problem for pilots. This term was taken up by HCI researchers in the 1980s when the accessibility of the computer drove further interest in sound, and these researchers then went on to coin the more contemporary term sonification as an sonic equivalent of visualisation. The increasing interest in Auditory Display, Sonification and Auditory Interfaces led to the founding of The International Community on Auditory Display (ICAD) in 1992 [1]. The close link between HCI and ICAD is evident in the flow-on of the three waves of research paradigms in HCI: Auditory Displays are classified as first wave human factors; work on earcons [2] is framed in terms of second wave cognitive science HCI [3]; and the sonic studies of Gaver [4, 5] anticipated the third wave phenomenological paradigm that considers sound in computation as a dimension of everyday life, with aesthetic, emotional, and cultural connotations [6]. Auditory icons were introduced as meaningful elements of ecologically inspired soundscapes, and design began to be invoked as the means to improve our (sonic) technological environment [7]. At the same time, some researchers in sound synthesis and audio signal processing understood that their algorithms and techniques could be exploited beyond the musical realm, in ecologies of computational artifacts, where interactions are more naturally multisensory [8].

At the turn of the 21st century HCI researchers began to consider interaction in terms of embodiment [9]. Increasingly since then, digital artifacts reveal affordances through the actions we perform on and with them, and the manipulation of these objects demands multiple senses, so that sound is now becoming an inescapable component of interaction design. In interaction and sound discourses, the acousmatic notion of a sound object is replaced by the embodied notion of a sounding object [10], something concrete that can be manipulated and responds to human actions. However, design methods remain focussed on the bottom-up process of building distal direct representations and affordances [11].

1.2. Designing sonic interaction and sonic information

Interaction Design has been emerging as a discipline founded on design pedagogy and methods of enquiry. While overlapping HCI, it is specifically described as a design discipline, with the purpose to "create new [artifacts] and change existing interactive systems for the better" [12]. Central to this proposal is a design process of evaluation that advances knowledge through rapid prototyping and iterative improvement, rather than one-off controlled laboratory experiments, based on the criticism that traditional HCI approaches to evaluation hamper creativity [13]. Interaction design is intrinsically participatory, and the artifact enables design knowledge to develop and emerge through expert critique which is a form of experimental phenomenology [14, 15]. These activities are based on interobservation, which is a group activity, leading to intersubjectivity as a form of experimental evidence. In the words of Bozzi [16]:"Interobservation comes before experimentation and its related computation, and it has been like this since time immemorial: an unknowing but perfect method of investigation".

The intentional introduction of sound in the human-artifact loop is called sonic interaction design [17, 18]. In this research niche, artifacts are often developed just to understand how sound and action intertwine to shape a dynamic relationship between humans and objects. Such objects can be abstract [19], metaphoric [20], or re-interpreted [21] in relation to practical use, and help focus discussion to create a consensus around sonic interaction phenomena. Possibly, at a later stage of scientific enquiry, such objects could also become instruments for controlled experiments on an interaction primitive. From this perspective computational sonic artifacts can be considered as tools to mediate or evoke behaviors, stimulate reflection, and support the development of intersubjectivity [22], and in this respect sonic interaction design anticipates the recent introduction of postphenomenology as theory in HCI research [23, 24].

As well as the interaction-centred perspective, research on sound can be viewed from an information-centered perspective. Ample demonstration has been given to the fact that many people (e.g., visually impaired or blind people, children, older adults, and people involved in visually complex and distracting tasks) can benefit from sound as a conveyor of information of many kinds. Well-designed auditory displays and sonifications may supplement or replace visual displays and enhance user experience and accessibility to digital data. In the early days of computing systems, the presence of sound itself was appreciated because it was fairly rare. Since then, a number of mapping strategies between sound and functionality have been introduced and studied [25, 26]. However the technical definition of sonification as a mapping of data into sound does not distinguish any mapping as better than any others. The lack of a unified theoretical framework, which makes scientific hypothesis testing difficult, suggests that design research is better aligned with the pragmatic nature of sonification. Sonic information design [27] aims at meaning making in situated contexts, through divergent ideation, explorative evaluation, and convergent iteration [28]. A designerly kind of knowledge is accumulated through sensible examples, and distilled through practice and critical reflection. This anniversary issue of the International Journal of Human-Computer Studies provides the opportunity to present the intersection of research into human-computer interaction and research into sonic interfaces, identify the flow-on effects of HCI research paradigms into sonic design, and differentiate between interaction and information-centered perspectives. In the rest of this section we start from the most recent sound-related articles of the present journal and proceed backwards, aiming to highlight the most relevant research streams.

1.3. A run-through of sound in IJHCS

One of the main objectives of design research is to abstract from specific objects, configurations, and contexts, to derive facts and principles of general validity. In research practices of sonic interaction design [17], abstract interactive objects have been developed to design and evaluate specific interaction gestalts [19], thus gaining understanding on how sound and action affect each other in interactive contexts. In product design, even in those cases where sound does not affect the perceived usability, it does affect the overall aesthetics [29] and, in turn, it may change behaviors. Of particular interest is the case of objects designed to encode and display information. Humans have made information available and tangible through physical objects for thousands of years, but digital fabrication processes have made these activities of data physicalisation easier and more generally useful. An object encoding information in its own shape can be touched, manipulated, hit and scraped. If it emits sounds it becomes a sounding object, and data can be heard both through its structural properties (shape and material) and its transformational properties (how it bounces, rolls, or breaks). One notable example is that of reading blood pressure, an action that is traditionally performed through interactive hearing, but that can also be made emotional through object manipulation [30].

Sound and music have been increasingly included in therapeutic practices. In particular, the continuous interaction by manipulation of sounding artifacts is proving its effectiveness with autistic children [31, 32]. Enhancing tangible visual representations, such as paper photos, with recorded audio has also proved to be beneficial for emotional wellbeing [33]. In biofeedback and self-monitoring, real-time sonification of physiological signals has a measurable impact on performance, emotional engagement [34], and mindfulness [35]. An embodied strategy to designing audio feedback for physical training, based on vocal prosody applied to non-speech audio, proved to be effective to attribute meaningful qualities to sonic interactions [36]. Phonetic auditory feedback, if properly designed, allows to create input devices that require no visual feedback, or makes touch screen keyboards faster and more precise [37]. Such requirements are particularly relevant for interactions that may not assume focused attention by the user, as in sports or driving.

A well-designed soundscape can inform about processes and events at the periphery of attention [38] without being as annoying as auditory alerts tend to be. Designing such soundscapes requires competence and sensibility that can be developed through design exercises. Tools for sound design are much demanded, which can make the composition of interactive soundscapes a direct and intuitive act. In many contexts, sound design would be more effective if embodied, through the exploitation of voice and gesture [39]. In particular, the prosody of human speech, that affects impressions and behaviors in human-human interaction, can be effectively exploited to design interactions that are socially effective [40]. In terms of creative engagement, designers dealing with interactive soundscape composition can often be considered as music novices, and musician-oriented tools and interfaces are probably not suitable [41]. On the other hand, music making is a specialized activity, whose interactive systems require specific evaluation approaches [42]. A design-pattern approach to the design of auditory displays facilitates the knowledge transfer from experts to novices [43].

At the interface between humans and technological artefacts, sound is often just one of multiple sensory interactions channels. In multisensory interaction [44], audio feedback tends to elicit the shortest response time [45]. Especially when it is combined with touch stimulation, sound increases the sense of immersion [46]. In a flipped perspective, auditory stimuli can be used to measure immersion objectively through event-related potentials [47, 48]. In complex and attention-demanding tasks, such as driving, continuous process sonification informs about the driver–machine behavior in a way that is more effective and gentler than simple alerts, especially in contexts of partial automation such as adaptive cruise control [49]. A trend in both research and applications is to combine audio with vibratory or haptic feedback both in the design of musical instruments [50], as well as in input-output devices. It has been shown that surface texture exploration and path following are equally possible by continuous auditory or vibro-tactile feedback in touch screens and drawing tablets, even with no visual information [51]. However, such path-following tasks, as well as tasks of object selection in cluttered environments, do not seem to benefit from audio-haptic feedback if visual feedback is available and properly designed [52]. When considering collaborative interfaces, where sighted persons collaborate with visually-impaired persons, auditory and haptic feedback allows participants to get a common understanding of the workspace, while being mutually aware of each other actions [53]. Conversely, if the purpose of collaborative interfaces is music and sound making, it is the design of shared visual representations that can increase mutual engagement and awareness [54]. An area where feedback is most effective when audio-haptic is that of walking interfaces [55, 56], where the user may be invited to synchronize at a given pace or, conversely, will determine the pace of an exploration by rhythmic interaction.

Wayfinding and orientation are important application areas of sonic interaction design, especially for visually-impaired persons, where some form of sensory substitution is needed. Continuous ecological sonic feedback proved to be effective and pleasant in this application area [57], and data sonification is often preferred to speech messages [58]. For locating virtual objects and creating mental spatial maps of virtual environments, systems inspired by bat echolocation and time-of-flight delays have been proposed and proved to be viable [59]. In exploration of non-visual maps, proximal active haptics has been shown to combine well with audio beacons spatialized over headphones [60]. Tactile and auditory cues are similarly effective as interruptions for operators of busy visual environments [61]. Hence, when properly combined, touch and audition offer increased reliability by redundant coding. For effective web navigation within and between pages by visually-impaired persons, dynamical changes of web content can be auditorilly provided via screen readers [62].

Museums and exhibitions have been exploiting audio guides for many years. What is relatively new is the development of sound as a design dimension that may have a central role to evoke experiences and convey emotions, to create engaging sensorial experiences [63, 46]. A semiotic approach to designing sequences of non-speech sound for educational content, to be interactively accessed by blind persons, has shown its effectiveness [64].

Spatial audio has been a topic of active research for decades, driven by the industry of entertainment. The most accurate spatial audio systems over loudspeakers are those based on Wave Field Synthesis, which allows to locate virtual sound sources effectively in three-dimensional space, arbitrarily close to the listener. How accurate should the sound positioning be, as compared to visual object positioning in 3D displays is a question that has been addressed [65]. Auditory virtual reality is based on spatial rendering of acoustic cues, that help creating a mental map of an environment that can be navigated [66]. In sonification, there is one strong spatial metaphor that can be more effective than actual vertical displacement of sound sources: Musical pitch [67]. Structured musical stimuli can even be designed to communicate diagrams non-visually [68]. It is tempting to exploit spatial sound localization for the concurrent presentation of auditory menu items, but the actual testing of such possibility in word processing tasks did not show an advantage for spatially arranged auditory hierarchical menus [69]. Conversely, in a car driving context, spatialized auditory cues representing items of a hierarchical menu were shown to be efficient and non-distracting for the primary task [70].

With data growing bigger and bigger, scientists look for new and more effective ways to make information perceivable by the limited human senses. Sound is certainly an important channel, especially for those data that have inherent temporal unfolding as in seismology [71], but it becomes particularly effective when data sonification is combined with interactive exploration [72, 73]. It has been noted that, in complex immersive environments for data exploration [74], it is the process of making the artificial world that elicits the deeper exploration and understanding of large data sets. As compared to information visualization, a few attempts have been made to systematize sonification tasks and solutions in a reference system that information designers can look at [75]. Similarly sparse, though effective, are the attempts to develop auditory representations of computer programs, that can help program comprehension and debugging [76].

2. Sketching sonic experiences

A result of the embodied perspective on human-computer interaction and design is the renovated interest towards sketch-thinking as significant means of doing research and generate knowledge. Almost a decade after the two seminal "Sketching user experiences" books [77, 78], the HCI community is looking at sketching, with and without computation, as a formal way of approaching HCI research and design [79, 80].

Sketching is that cognitive activity of articulating reasoning and discovery by means of quick, evocative, disposable, and ambiguous representations [81, 82]. What sketching denotes, either as a product or a process, a technique or a way of knowing, is a peculiar form of knowledge emerging in the continuous interplay between imagery and intermediate embodied representations, whether a drawing, a picture, a sound, a paper model, a piece of code, a physical prop or any other kind of responsive media.

By putting embodied cognition in the foreground, research on sketching HCI is likely to represent a significant and fertile field of study, in the same way research on ecological perception and affordances put in the foreground the relevance of human perceptual and motor abilities, when designing invitation to interaction with computational artifacts [83].

A proper literacy in sketch-thinking and interaction design research implies fluency and mastery of appropriate shaping tools and materials [84]. In the early stage of most design processes, the designers set the design space, by exploring product metaphors and inventive analogies through sketches [85]. The emerging abstract associations and physical properties are mapped, transformed and transferred to the design entity under scrutiny. The designers can use diverse modes to explore and project these mappings onto the design target, that is the form, material/texture, interaction, movement, and sound [86]. For example, the oscillatory regimes (higher modes, good tone, raucous sound) in bow-string interaction have been successfully exploited as driving analogy in the sound design of a continuous feedback for mechanical connections [21].

Sound design has been defined as the reverse process of listening, that is making intentions audible [87]. Audiolization is the aural sketching mode of quickly representing concepts conveyed through sound [88]. Techniques and methods to explore conceptual associations in sonic interaction are much needed [89], in a professional field in which both the creation process and available tools are largely disembodied and still conditioned by the legacy of early computer music [90]. In this respect, the availability of disposable, quick and evocative sonic interactive sketches calls for the more general need of designing and developing embodied tools for sound creation [91] rather than tools for performance, which find their home at NIME (New Interfaces for Musical Expression), and are trivially called musical instruments [92].

`SEeD` (Sonic Embodied Design) is one example of embodied tool for sound creation, grounded in vocal motor skills and control. One main advantage of embodied tools for aural creativity is that they facilitate communication and cooperation. `SEeD` is a software that affords to produce, with a certain degree of reliability, tamed and predictable synthetic representations, starting from input vocalizations: Sound designers were able to reproduce, in few minutes with `SEeD`, target examples previously created by a third sound artist-designer, with the same tool, thus showing how an embodied tool facilitates the sharing of mental models [39]. `miMic` is the physical counterpart of `SEeD`, a system architecture for voice-driven sound synthesis, based on a microphone augmented with buttons and embedded inertial measurement unit, making the whole vocal sketching activity in the digital domain potentially WIMP-free [93].

Gestures are significant means of visuospatial communication. Designers largely rely on performative actions as cognitive artifacts through which representing structural and functional information, thinking and collaborating. In the realm of sonic interaction and information design, body-centric strategies to co-explore instantaneous, temporal and metaphorical mappings through interaction, in motion-sound embodied associations, have been proposed [94]. Cooperation in sound design activities currently represents the real missing link with the human innate practice of collaborative sharing and communication through sound, called music.

The rationale of sound design tools is to support a sonic sketching mindset in explorative making, especially when the sound design inquiry falls out of the established informative, functional, interactive sonification and auditory display cases [95]. What is proposed is a new account of sound as a computational material, no more considered in the aural dimension *per se*, but rather in the same way other seemingly more apparent sensorial dimensions, particularly sight and touch, are approached by design in the creation of the product experience [96]. What we are advocating is to take control on a design dimension, which has typically been the by-product of design choices of form, configuration, style, mechanics, ergonomics, etc., in the embodiment of affect and meaning in designs [97].

3. The future sound of sonic interfaces

In computer graphics and virtual reality, many studies have been published on how to increase realism by reproducing the resonant and radiation properties of objects, while keeping computation manageable. Finite difference schemes and modal analysis derived from finite-element modeling are the most successful techniques for producing high-quality sound synthesis. It has become clear that nonlinearities in object excitation and in wave propagation in solids [98, 99] are responsible for much of the acoustic character of mechanically excited objects, and the distribution of micro-events makes composite actions such as crumpling [100] or rolling [101] acoustically salient. While the effort of deriving physics-based models that are accurate, stable, and efficient is important and laudable, for human-computer interaction it is equally important to have simple models that capture the most relevant sonic phenomena in everyday interactions. The Sound Design Toolkit is a collection of physically based models that are simple to access, describe, and parameterize, while maintaining good accuracy in modeling fine-grained interactions such as impacts, friction, or air jets [102]. In everyday activities performed in non-visual mode, the objecthood of things emerges from manipulation, exploration, and dynamic interaction, rather than from acoustic signatures derived from static sound spectra. The perception of structural properties of objects from simple impact sounds is fragile, while the perception of actions that such objects afford is strikingly robust [103], which leads us to propose that interactivity should be the focus of future research into sound-synthesis.

The two principal approaches to the digital synthesis of natural soundscapes are physics-based modeling and concatenative sample-based synthesis [39]. Physics-based modeling produces sound by solving differential equations that describe physical phenomena, such as air turbulence or fluid flow. Concatenative synthesis arranges large numbers of sonic particles or samples according to statistical and spectro-temporal descriptors. Humans have innate capabilities for imitating sounds as they occur in everyday soundscapes [104], and this can and should be exploited when interacting with and through sound, as well as to design artificial soundscapes through sound synthesis. Indeed, the human non-speech voice is increasingly being used to query large audio databases [105], to sketch new sonic concepts [91], and to control sound synthesis for performative purpose [106]. The increasing awareness among designers, artists and scientists that the human voice is an embodied tool for sketching with sound will lead to further studies and applications of the voice for sonic interaction design. We envisage that sketching by voice will become as easy and commonplace as sketching by hand with the development of sound-sketching tools that are as affordable and immediate as pencil and paper. Beyond research prototypes [93], it is promising that commercial products are starting to appear in this direction[1].

It is interesting that artistic practices such as live coding (or on-the-fly programming) have been making sound creation and manipulation more similar to iterative design processes, with initial sketches being shared and gradually evolved to complex refined objects. The specialized programming languages and environments for computer music are evolving in the direction of coding as sketching, possibly with direct export of results to larger software frameworks where a variety of sound models can be hosted and made to interact with each other [107].

The increasing awareness of the connections between body gestures, everyday sounds and human vocalizations is likely to produce new forms of interaction and new tools for designing multisensory objects. In particular, sketching is an expression of biological motion, which can be described by laws that produce visible as well as audible effects [108], with the senses affecting each other for the construction of consistent audio-visual objects. Understanding hand and vocal gestures opens up a truly multisensory domain of sketching. The sensory convergence of visual and physical metaphors may be key to successful discoveries, and to a designerly form of knowledge that can be just as important as scientific understanding [109]. For example the sound design of the moka screw conveys movement and displacement through friction sounds while also highlighting critical points (loose, tight, too-tight connection) [21].

Sound is relevant in sport and motor sciences, as its role in short-time action planning and anticipation is increasingly evident, both when sounds are produced by the player's actions [110] and when they are produced by

[1] For example, `https://www.vochlea.co.uk/`

opponents [111]. In self-monitoring and self-regulated training, rhythmic interactions through music and sound have proved to be effective to improve individual performance and increase motivation [112], and voice-based sound design can also be fruitful in this context [36]. Many everyday human activities are repetitive and regulated by some kind of beat or pace, and research into rhythmic interaction [55, 113] points to new opportunities for technological augmentation.

Sound is already an important component in virtual and augmented reality [114]. Sound in VR is often experienced through headphones or earplugs, and localization of sound sources in space require accurate recreation of head-related transfer functions (HRTF), which are signal-processing systems that can be parameterized by the individual biometric shape of the pinnae, or outer ear. Research on making HRTFs more readily individualized and more general is ongoing and likely to continue. The development of virtual audio technologies has lead to recognition of the potential of hearing aids as computational devices to augment listening and sound-based interaction for both hearing impaired and normally hearing persons [115]. For example, microphone arrays arranged on the temples of eyeglasses can be used to increase audio sensitivity in the frontal direction, making human-human or human-machine interaction more effective in noisy environments. Furthermore, audio content can be superimposed over the environmental soundscape through a tiny acoustic prosthesis, opening a wide spectrum of possibilities for sound-mediated interactions, where sound design will become critical for wide acceptance and appreciation.

Tasks of navigation can be mediated by sound, and made feasible for the visually impaired or in contexts where vision is not available. For navigation in small areas, such as a touchscreen, sonic feedback that is tightly coupled to action can make path steering possible [51], even without a spatial auditory display. If interaction occurs in room-sized or urban environments the spatial component of sonic information becomes more important, especially to steer attention in a certain direction [58]. However, space is not an indispensable attribute of sound, as it is not a prerequisite for perceptual numerosity and does not contribute directly to auditory objecthood [116]. So, we expect the attention of researchers and practitioners in functional sound to crossover between spatial audio and the design of sounding objects, with all the aesthetic and emotional nuances that have to be considered in complex environments. In particular, ubiquitous and pervasive displays will increasingly have a multisensory character, with both sound and haptic stimuli being used to steer visual attention, or to enable peripheral monitoring of processes [117].

In product design, the introduction of new sounds is often unnecessary. On the contrary, computing technologies can be exploited to enrich aesthetic, reality-based interaction. The sonic space of everyday noises can be expanded or shrunk through active design, for instance by combining physical, environmental interaction sounds with digitally altered versions, either for product quality and appraisal, or for peripheral information and awareness [118]. Future sonic artifacts may embody dynamic objecthoods through the physically based synthesis of sounds (e.g., turbulent, electromechanical, liquids) that carry information as a consequence of the operation of the product [119, 120]. Designing with sound in this way may act as a driver for conceptual blending and reflective behaviors [121, 122]. Sonic objecthoods contribute to the overall affective quality of the product experience. It has been shown that the auditory aspect of a product, distinct from and integrated with the visual aspect, is an essential component in the evaluation of the product which also evokes memory associations [123].

A seemingly paradoxical kind of dynamic sonic objecthood is that obtained through data physicalisation, which is the 3D rendering of a dataset in the form of a solid physical object. Although there is a long history of physicalisation, this area of research has become increasingly interesting through the facilitation of 3D printing technology. Physicalisations allow the user to hold and manipulate a dataset in their hands, providing an embodied experience that allows rich naturalistic and intuitive interactions such as multi-finger touch, tapping, pressing, squeezing, scraping, and rotating. Physical manipulation produces acoustic effects that are influenced by the material properties, shape, forces, modes of interaction and events over time. The idea that sound could be a way to augment data physicalisation has been explored through acoustic sonifications in which the 3D printed dataset is super-imposed on the form of a sounding object, such as a bell or a singing bowl [30]. Since acoustic vibrations are strongly influenced by 3D form, the sound that is produced is influenced by the dataset that is used to shape the sounding object. Striking, tapping or rubbing the Chemo Singing Bowl (portrayed in figure 1) produces a range of different sounds that reflect the force and mode of interaction, as well as the resonance of the shape and stainless steel material it is made of. The choice of the singing bowl has cultural and historic associations with the use of sound in healing and well-being, and provides a sonic metaphor for interpreting the health data used to shape it. Sounds can also be added to a data physicalisation by embedding a small digital sound synthesiser inside the object, such as the Mozzi sonification synth [124]. Sensors can be used to synthesise sounds in real time response to interactions such as stroking or striking the object. For example, Zizi the Affectionate Couch responds to petting, sitting and stroking with sounds such as whining, yipping and purring that convey an emotional sonic character [125].

Figure 1: A singing bowl incorporating time-series data about a chemoterapy treatment. The sound this object produces when manipulated is both informative and strongly emotional.

These experiments with data physicalisation and augmented sounding objects resonate with the recent discourse on post-phenomenological theory in HCI. The concept of a technological *quasi-other* is considered a matter of presence and engagement, rather than dialogue and interface, both in sonic interaction design and in post-phenomenological studies [24]. In their exploration of post-phenomenology in HCI, Wakkary et al. [23] use a tilting bowl as a catalyst for philosophical enquiry into the way human actors and technological actors co-shape reality through embodiment, alterity, background and hermeneutic relations. Sonic interaction design offers examples of such structures: *Embodiment* facilitates access to a wide space of synthetic sound by voice [39]; *Alterity* intervenes, for example, when a person experiences a couch as if it was a pet [126]; *Background* is what we design for peripheral interaction [38, 117]; *Hermeneutic* affordances naturally emerge as interpretive acts of the inherent ambiguity of the schizophonic artifacts we live with [127, 128].

Co-speculation defined as "participation of study participants who are well positioned to actively and knowingly speculate with us in our inquiry in ways that we cannot alone" [23], is similar to interobservation in experimental phenomenology. Sonic interaction design has extensively employed workshops with well-positioned participants to develop knowledge of the sound design process and methods [129], computing technologies for sonic interaction [130], and cognition in conceptual sound design [131]. Design workshops involving sound practitioners and researchers collaborating in sonic sketching activities lead to thought-provoking speculations around the embodied nature of designing sound, and the value of design representations through sound as provisional means to capture ideas, discuss and elaborate on them, cooperatively [89]. Through these explorations we demonstrate that sonic sketching is an effective tool to empower access to imagery while enabling timely sound production [39]. We have also found that design ontologies provide valuable frameworks to analyze and reflect on emerging cooperative behaviors in aural creativity [132].

Another key concept in post-phenomenological design thinking is the *counterfactual artifact*, which is defined as "a fully realized functioning product or system that intentionally contradicts what would normally be considered logical to create given the norms of design and design products" [23]. Again, if we extend this definition to include early prototypes of sonically-augmented found objects [133], this has been done in sonic interaction design through experiments with sounds that respond dynamically to actions in ways that contradict what is normally expected as a sonic side effect [21]. These counterfactual, or contradictory sonic artifacts, have been explored through basic design exercises in workshop contexts [134].

The difference between sonic interaction design and post-phenomenological approaches is, perhaps, in the ultimate goal of speculation. If it is oriented towards the development of improved products, then it is better done during the early stages of a design exercise, around sketchy artifacts and draft prototypes. If, on the other hand, the goal is philosophical reflection on the implications of technologies for human environments, then such speculation is better done around refined prototypes in actual use over an extended period of time. In either case, the intention is to move beyond, and against, usability and retrospective socio-technical studies of *intelligent* interactive objects. These kinds of speculative experiments with tilting and singing bowls may help designing *wise* interactive sounding objects for future multisensory interactions.

In conclusion, based on our experiments and observations, the design of future sonic artifacts will be grounded in embodied cognition, concept design, collaboration and creativity. We expect that the sonic interfaces will consist of sounding objects that naturalistically convey information and meaning through embodied and continuous gestural manipulation, rather than the dis-embodied, acousmatically abstract, triggered samples and musical motifs we find in the sound design of contemporary products.

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