SONARIOS: A Design Futuring-Driven Exploration of Acoustophoresis

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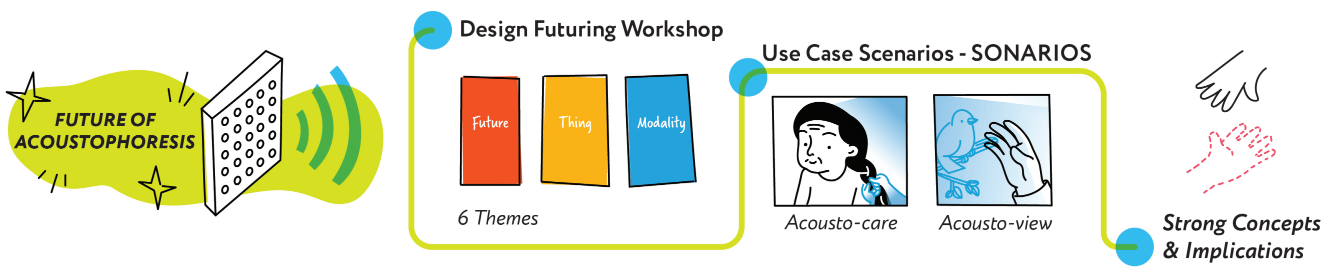

Figure 1: The research involved: (i) a design futuring workshop on acoustophoresis, (ii) the development and feasibility assessment of two SONARIOS (i.e., scenarios), and (iii) the synthesis of three strong concepts, along with key tensions and responsibilities in shaping the future of acoustophoresis applications.

Abstract

Sound waves shape not only our ability to hear but also offer new ways to interact with and experience our environment. Acoustophoresis, a method of manipulating objects using the mechanical energy of sound, enables multimodal displays incorporating touch, taste, vision, and more. While current research has focused on technical advancements, we explore acoustophoresis and its applications through a design-driven lens. We conducted a design futuring workshop, speculating on possible applications, and identified six key themes. Based on these insights, we developed two speculative scenarios, SONARIOS, that illustrate future experiences shaped by acoustophoresis. We abstracted the insights into three strong design concepts that bridge speculative exploration with practical design. We emphasize the importance of balancing desirability, feasibility, and responsibility in acoustophoresis development, advocating for a design approach that integrates technical innovation with user-centred considerations.

CCS Concepts

• **Human-centered computing → Interaction design**; *Interaction paradigms*; *Interaction design process and methods*; **Interaction design process and methods**.

Keywords

Acoustophoresis, Acoustic Levitation, Speculative Design, Design Futuring, Sound waves, Multisensory Experiences

ACM Reference Format:

Ceylan Beşevli, Lei Gao, Narsimlu Kemsaram, Giada Brianza, Orestis Georgiou, Sriram Subramanian, and Marianna Obrist. 2025. SONARIOS: A Design Futuring-Driven Exploration of Acoustophoresis. In *Designing Interactive*

DIS '25, Funchal, Portugal

ACM ISBN 979-8-4007-1485-6/25/07
https://doi.org/10.1145/3715336.3735775

Systems Conference (DIS '25), July 05–09, 2025, Funchal, Portugal. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3715336.3735775

1 Introduction

Imagine a future where interactions with your loved ones transcend traditional technology. Instead of communicating through a flat screen or wearing a VR/XR (Virtual Reality/Extended Reality) headset, picture their 3D images floating beside you. These holographic projections, enriched with touch, audio, and scent, would allow you to experience their presence as if they were physically there. Once a concept of science fiction, this vision is approaching reality with technological advancements like acoustophoresis.

Acoustophoresis, also known as acoustic levitation, allows the manipulation of objects in mid-air using sound waves, with a single setup rather than multiple elements [31]. The potential applications of acoustophoresis are vast (See Figure 2), from interactive displays to novel human-food interactions. For instance, ultrasonic waves can levitate particles to deliver flavour morsels directly to the user's tongue, an innovation capturing the attention of molecular gastronomy chefs and researchers alike [81]. Beyond gastronomy, acoustophoresis creates mid-air volumetric displays where coloured particles form visible 3D images [39], transforming how we perceive and interact with information through data physicalisation [31]. These applications highlight how acoustophoresis could redefine multimodal interactions, blurring the boundaries between physical and digital realities [41].

While these advances are exciting, acoustophoresis research is still primarily focused on technical realisation. While these applications hint at transformative possibilities, realising these visions requires moving beyond the initial spectacle to address practical design considerations and associated societal and ethical challenges [77]. We propose a design-led perspective to identify practical use cases that maintain engagement and excitement beyond initial technical demonstrations [37] and create inspiration for a wider research and practice audience.

We employed a design futuring approach [45] to explore how acoustophoresis can evolve from a captivating concept into meaningful applications. We organised a futuring workshop with 13 experts from diverse fields, including acoustophoresis, design, psychology, philosophy, and neuroscience, by adapting The Thing from The Future [10] ideation card deck. During the workshop, we focused on ideating how the sensations (e.g., visual, auditory, tactile) generated by acoustophoresis could be applied for various future use cases. From the workshop, six recurring themes emerged, representing distinct areas where acoustophoresis could grow: Social Interaction, Content Creation, Safety Nudges, Human Wellbeing, Beyond-human Interaction, and Playful Interaction. We then developed two scenarios, which we call SONARIOS, "Acousto-care" and "Acousto-view," to exemplify the technical considerations and future speculative scenarios. Each Sonario is linked back to the themes identified in the workshops, iteratively discussed and improved by the interdisciplinary team, bridging technical, social and design expertise (see Figure 1).

Building on these scenarios, we introduce three strong concepts, Multisensory Harmony, Cross-Modal Transfer, and Embodied Proxemic Choreography, that abstract insights from our two use case examples to broader future applications. These concepts, situated within the intermediate knowledge space [40], offer actionable principles for integrating acoustophoresis into diverse contexts, with a focus on interaction-driven possibilities rather than isolated speculative ideas.

This paper contributes in two ways: (1) demonstrating how design futuring can inform emerging technologies and (2) offering design knowledge (strong concepts) that bridge technical feasibility and user-centred interaction. Beyond technical advancements, we reflect on the societal impacts, both positive and negative, that acoustophoresis may have in future contexts, fostering a dialogue on its opportunities and risks to ensure responsible design [44].

2 Background

2.1 Acoustophoresis/Acoustic Levitation

Acoustophoresis leverages acoustic radiation pressure from sound waves to suspend and manipulate objects within a medium, a phenomenon initially demonstrated over a century ago [76]. By employing acoustic transducers (small speakers), objects can be levitated at the low-pressure nodes formed between two opposing transducers. These acoustic traps effectively counteract gravity, facilitating the levitation of diverse materials in air, water, or biological tissues.

Advancements in transducer technology have led to the development of modular and open platforms for phased arrays that typically operate at 40 kHz [49], enabling the arbitrary placement of local standing wave patterns and thus allowing precise positioning and manipulation of small objects in three dimensions [39] (see Figure 2a). The challenge lies in identifying the optimal transducer amplitudes and phases to generate the desired sound fields.

For instance, the LeviPath system [62] uses a modular arrangement of two opposing transducer arrays to achieve controlled positioning and manipulation of suspended particles in three dimensions. This is achieved by adjusting the phase and amplitude of transducer groups based on specific patterns, directing particles in predetermined directions. Marzo et al. [51] demonstrated a method to simplify the computation of transducer amplitudes and phases by encoding them as the combination of a holographic acoustic lens creating focal points and a fixed levitation signature (Figure 2b). These signatures are fixed phase modifiers applied to the transducer phases, transforming any focal point into a levitation trap.

This methodological advancement enables the integration of phase-algorithms such as the Gerchberg-Saxton (GS) [33], Iterative Backpropagation (IBP) [50] algorithms into acoustophoresis. These algorithms iteratively compute transducer phases to generate patterns and apply the fixed signatures required for levitation. GS-PAT (Gerchberg Saxton-Phased Arrays of Transducers) [65] represents an adaptation of the GS algorithm tailored for acoustophoresis, enabling high-speed computation of transducer phases to create volumetric Persistence of Vision (PoV) images using multiple particles. This technique supports both haptics and directional audio.

Finally, OpenMPD (Open-source Multimodal Particle-based Display) [54] served as a low-level presentation engine that standardises the pipeline for content delivery on these levitation platforms, thereby simplifying the development of rich and innovative applications utilising acoustophoresis (see Figure 2c). This enhancement

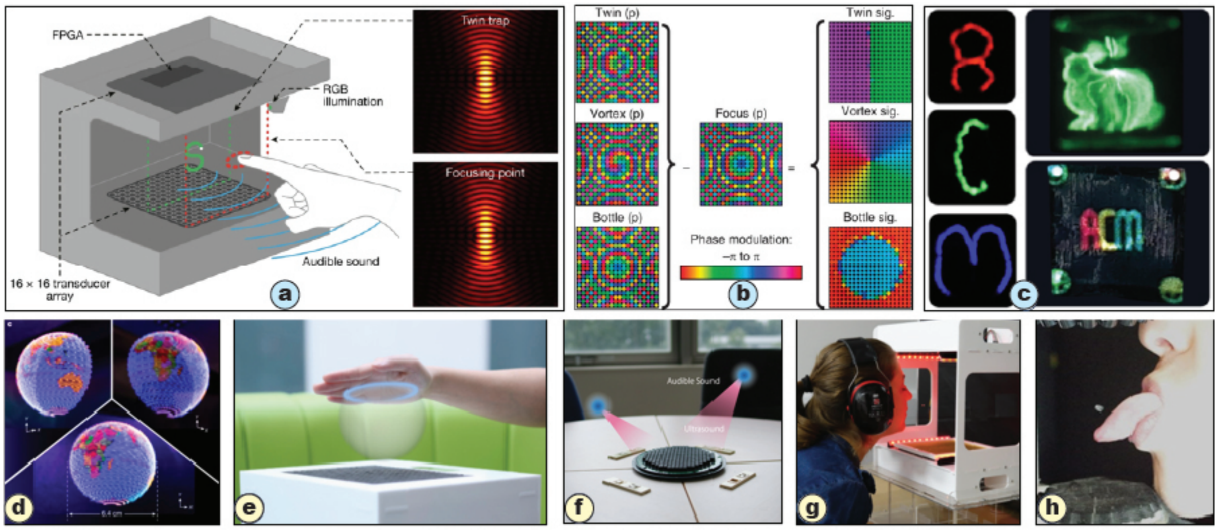

Figure 2: Advancements in transducer technology: a) modular platforms for precise object manipulation [39], b) computation via holographic acoustic lenses [51], c) multimodal content integration with OpenMPD [54]. Acoustophoresis applications - d) Vision: volumetric display [39], e) Touch: volumetric haptic [47], f) Hearing: directional audio [60], g) Smell: smell-based interactions [82], and h) Taste: taste-based interactions [81].

in platform and technology underscores the growing practical applications of acoustophoresis.

2.2 Explorations of Acoustophoresis

Improvements in infrastructure and methodology for mid-air object manipulation with sound waves highlight the expanding scope of acoustophoresis applications. This technology facilitates multimodal interactions across diverse contexts, engaging senses like vision (e.g., volumetric displays, data physicalization), touch (e.g., mid-air haptic interaction), hearing (e.g., directional audio feedback), and even smell and taste (e.g., contactless odour and food delivery). See an overview of application contexts in Figure 2.

By swiftly moving levitated particles, it's possible to exploit the principle of PoV, allowing our brains to perceive continuous motion from a rapid succession of still images [29, 39, 54, 65] (see Figure 2d). This technique extends beyond threads and fabrics, also projecting digital visual content [25, 55]. Furthermore, acoustophoretic data physicalization [31] encodes data using the rich geometric and material properties of levitated artefacts, allowing users to interact with data objects in a more immersive and multi-sensory manner. As tangible voxels [27, 48], these objects offer interaction methods such as mid-air gesture selection [3, 26] and co-located direct interaction [42], enhancing user engagement and experience.

Beyond levitating and manipulating objects in mid-air, the same principle of adjusting sound waves was extended to create contactless haptic feedback on human skin [11, 47] (see Figure 2e). Through different modulation methods [28, 71], high-intensity impinging waves can create different haptic patterns, providing a sense of agency [17], emotional responses [13, 58], and textures [5].

Similarly, Acoustophoresis can generate audible sound points from the focused ultrasound waves, facilitating as directional loudspeakers in interaction space [60] (see Figure 2f). This is achieved by modulating the audible signal into the ultrasonic carrier [66]. Initially, this was confined to a single steerable audio column [61] and then extended to multiple independent ones emanating from the same transducer array system [72].

Finally, acoustophoresis has been proposed for levitating morsels of food or droplets encapsulating taste and smell, offering computational gastronomy experiences. For example, Vi et al. [81] introduced TastyFloats, a contactless system that uses acoustic levitation to deliver food morsels and tastes to the users' tongues automatically. This technology has been extended to synchronise the integration of levitated food with visual, olfactory, auditory, and tactile stimuli [82], enabling systematic investigations of multimodal signals around levitated food and eating experiences (see Figure 2g and 2h). Combined with haptic stimulus on the tongue using ultrasound [70], it holds promise for exploring the influence of haptics on taste perception.

In summary, acoustophoresis revolutionises interactions across all five senses, reshaping multimodal experiences in various domains. Steady progress in hardware, software, and Human-Computer Interaction (HCI) paradigms underscores its potential. Looking ahead, collaborations with industry partners and advancements in computing, such as AI and 6G, promise further enhancements. Taking a design futuring approach, this paper strategically and responsibly charts the future trajectory of acoustophoresis. This ensures its full potential is realised, inspiring technical progress and addressing societal needs sustainably and effectively.

2.3 Design Futuring Relevance

Departing from conventional design methodologies, design futuring approaches refrain from presenting solutions or predetermined objectives [78]. Rather, they seek to cultivate critique, dialogue, deliberation, and inquiry surrounding potential futures. Drawing

Figure 3: 'The Thing from the Future' Ideation Cards: Comprising three card types: Future, Thing, and Theme. In our version, we provided descriptions for the Future cards, while the Theme cards were exclusively dedicated to 'Modality.' On the right is an example card drawn by a group along with their description of the world.

from Kozubaev et al. [45], we adopt the term 'design futuring' to encompass a spectrum of methodologies leveraging design as a vehicle for envisioning future scenarios, thereby offering commentary on, and potentially influencing, the present.

As outlined in the previous sections, the rapid evolution of applications and advancements in acoustophoresis underscores the importance of reexamining its future trajectory. Design futuring can facilitate the exploration of diverse scenarios for acoustic levitation's future by considering technological advancements, societal values, environmental concerns, and economic systems, thereby offering nuanced perspectives on its evolution [24, 46]. Moreover, design futuring encourages the interrogation of dominant assumptions [45] regarding the trajectory of acoustic levitation, enabling the uncovering of new possibilities and the disruption of established norms within the field. For example, early research [73] suggested that acoustic levitation was too coarse to rival holography for 3D displays, concluding that it was not feasible for such uses. However, subsequent studies [39] demonstrated that acoustic trapping could produce larger and faster holographic 3D images with additional multimodal capabilities, challenging these initial conclusions. This research sequence highlights how initial limitations perceived through a narrow lens can be overturned by subsequent work pushing the boundaries of what is considered possible, where design futuring can provoke and potentially advance acoustophoresis research.

Lastly, design futuring can explore the ethical, social, and cultural implications [8] of future developments, identifying potential risks and opportunities, and fostering responsible innovation [44] aligned with societal values. Recent advancements in acoustic levitation have focused heavily on demonstrating technical feasibility, often without user evaluations. For instance, earlier work showcased various data physicalizations [31] but lacked user feedback due to prototype instability. Later research [30] addressed these stability issues, making strides toward practical applications. While some studies [38] explored the potential of acoustic levitation in 3D printing, they often presented carefully curated examples rather than practical, user-ready solutions. To that end, a design futuring approach offers such critique by suspending disbelief and looks at the implications of this emerging technology.

3 Design Futuring for Acoustophoresis

Design futuring can take various forms, including the use of prototypes [22] and written formats such as fictional narratives [6]. Our design futuring process began with workshops aimed at exploring ideas. We engaged professionals from diverse fields (e.g., design, psychology, philosophy, neuroscience) who are involved in acoustophoresis research. Their expertise allowed us to examine acoustophoresis from an experiential, user-centred perspective. By involving researchers rather than end-users, we ensured that our exploration remained both imaginative and grounded, tempering the 'magic' often associated with current acoustophoresis research.

3.1 Workshop Method and Participants

We adapted *'The Thing from the Future'* ideation card deck for acoustophoresis, which originally comprises three types of cards: *Future, Thing,* and *Theme* [10] (see overview in Figure 3). *Future* cards represent possible futures (e.g., "recovering," "feminist"), while *Thing* cards describe tangible objects or entities such as monuments, ceremonies, or devices. We modified the third card type, *Theme*, to *Modality*, focusing on the visual, auditory, and tactile sensations that acoustophoresis can create. This adaptation was aimed at helping participants move past the 'wow' effect, where acoustophoresis is seen as capable of anything, and instead concentrates on its specific interaction capabilities. Also, this card-based approach encouraged participants to set aside biases and think beyond technological limitations.

Participants were pre-assigned to one of three groups to ensure a balanced mix of technical expertise, academic backgrounds, and industry experience. Groups were not divided by specific expertise but organised to create diverse, well-rounded teams. Each group was guided by a facilitator who moderated the brainstorming process.

Groups drew random card combinations and addressed questions such as "What is the Thing?", "How is it used in that Future in relation to the Modality?", and "Why does it exist?", with guidance from moderators. Initially, groups picked only one Modality card to familiarise themselves with the process. From the second draw onwards, they increased the number of Modality cards to explore acoustophoresis's multi-modal capabilities. Groups were

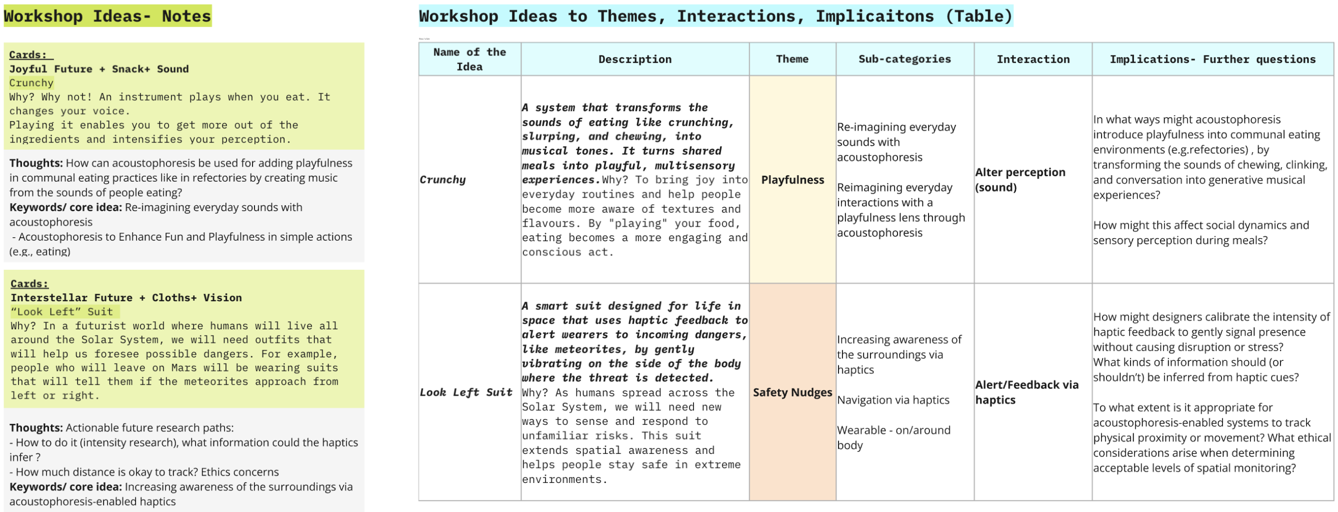

Figure 4: A snippet from the Miro board capturing workshop analysis. Left: Workshop ideas are presented with annotations highlighting precursors to key themes and related discussion points. Right: A table categorises these ideas into themes, with additional columns detailing the relevant interactions and exploring broader questions and implications associated with each theme.

encouraged to use up to three Modality cards only when their concepts developed, helping to focus their ideas rather than blending disparate concepts.

Overall, the workshop included a 45-minute brainstorming session followed by 30 minutes of reflection on the novelty, implications, feasibility, and timelines of the ideas. During the plenary session, each group presented their most exciting ideas and summarised their discussions. The entire workshop lasted 2.5 hours, with breaks as needed.

Thirteen researchers and practitioners (5 female, 8 male) with diverse backgrounds participated in the workshop, including engineering, computer science, design, psychology, philosophy, and neuroscience. Half of the participants had technical expertise in acoustophoresis, from both academic and industry backgrounds. This workshop was carried out as part of a larger collaboration between academia and industry. Participants were informed about the workshop's purpose and assured that no personal data or recordings would be used. They were not compensated, contributing as experts in a collaborative effort.

3.2 Workshop Analysis and Findings

The workshop produced 20 ideas, which the first author documented by collecting and synthesising the notes from all sessions. This was followed by collaborative annotation of ideas and discussions on the emerging commonalities, precursors to the themes as well as the broader implications of acoustophoresis in Figure 4. Following an iterative analysis approach [7], we identified six main themes, each presenting avenues for future acoustophoresis research. Also, we analysed each idea through an interaction lens, looking at the actions, the dynamic gestalt enabled by acoustophoresis. This approach aimed to disentangle the specific contributions of acoustophoresis within the proposed concepts, moving beyond specific applications/ideas [40].

The six themes are Social Interaction, Content Creation, Safety Nudges, Human Wellbeing, Beyond-human Interaction, and Playful Interaction (see themes in Figure 5). The presentation order reflects the frequency of ideas within each theme, with Social Interaction being the most prevalent.

3.2.1 ***Social Interaction***. This theme explores Acoustophoresis in modulating personal features and facilitating affective touch transfer between people. For instance, it could project outfits onto the body for different social occasions or modify voices to match preferences. It was discussed how the haptic capabilities could enable emotional connections across distances, particularly in caregiving settings for the elderly. Additionally, it could be used for non-verbal communication, like developing a haptics-based language, which could aid visually or hearing-impaired individuals. These concepts envision small modular acoustophoresis units dynamically configuring themselves for different use cases.

3.2.2 ***Content Creation***. One of the commonly seen applications for acoustophoresis is in data visualisation, artistic installations, and interactive media experiences, as outlined in Section 2. Content creation here entails a multimodal perspective, such as recreating spaces or historical artefacts like the Seven Wonders using visual projections and haptic rendering of objects and surrounding sounds. While we use the term "content creation" to describe these experiences, it risks reinforcing the distinction between medium and message; in reality, form, sensory affect, and participation are often deeply entangled. The workshop discussion highlighted the potential for these multimodal experiences to be highly immersive and emotionally impactful, suggesting applications such as raising awareness about issues like climate change. In these content

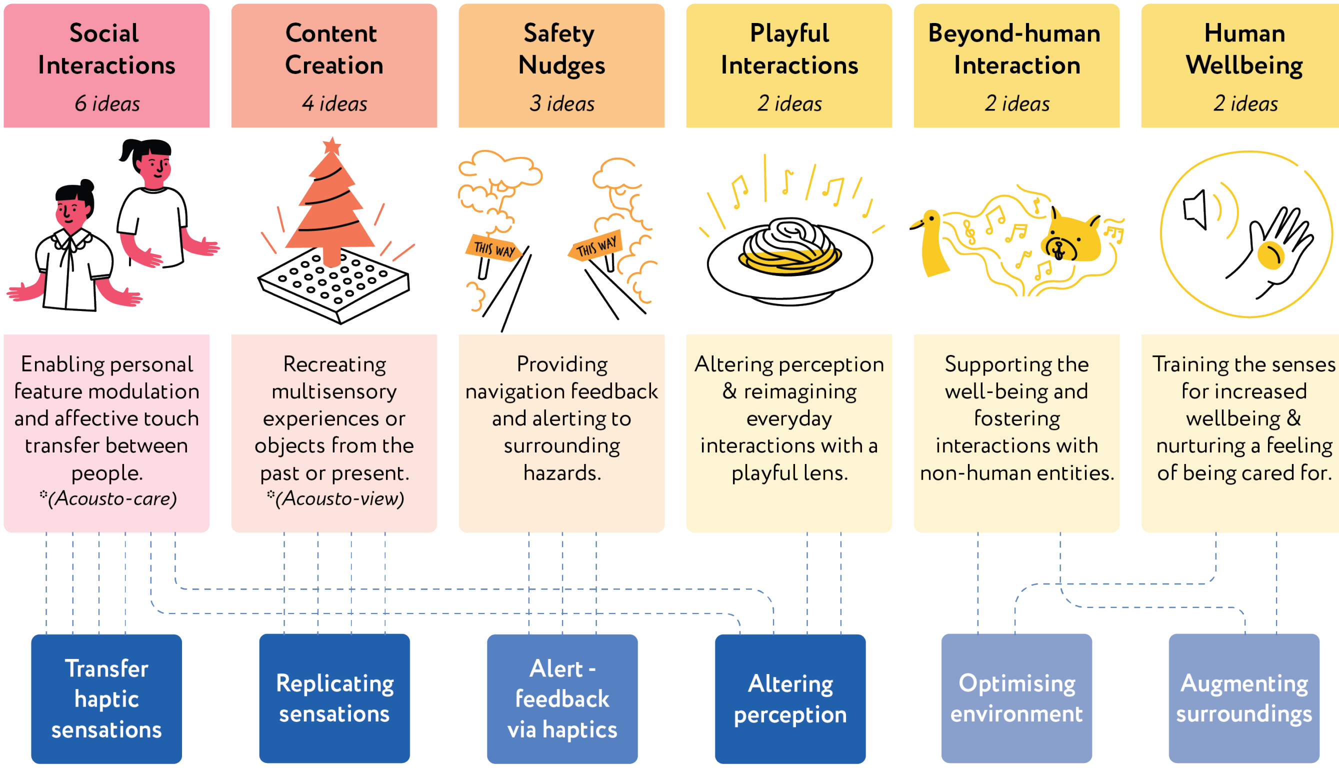

Figure 5: Six identified themes from the workshop. The top part shows themes arranged by idea density from left to right, with darker pink indicating higher density. The themes *Social Interaction* and *Content Creation* form the basis for SONARIOS. The bottom half maps interaction categories to themes, with the number of lines representing how often each interaction is associated with a theme. Multiple lines or categories suggest that ideas within a theme involve various types of interactions.

creation concepts, we imagined acoustophoresis units dispersed throughout a space, adjusting their positions in response to spectators' movements.

3.2.3 ***Safety Nudges****.* This theme envisions acoustophoresis units sensing the environment for potential hazards, such as when a car driver is unaware of speeding vehicles behind them and alerting them accordingly. The feedback can be delivered in the preferred sensory form. An example is alerting drivers through haptic 'nudges', offering an alternative to current audio and visual alert systems. These concepts involved wearables or in-vehicle integration of acoustophoresis for the driving context.

3.2.4 ***Human Wellbeing****.* This theme involves caring for and training the senses through the multimodal capabilities of acoustophoresis units. For instance, by presenting visual stimuli that move across space and around a user, acoustophoresis can aid in exercising the eyes. Similar applications can be imagined for training other senses, such as hearing and touch. In these wellbeing concepts, acoustophoresis units are dispersed around a space, dynamically adjusting their positions in response to users' movements.

3.2.5 ***Beyond-Human Interaction****.* This theme places beyond-human interactions at the centre of engagement with acoustophoresis. Leveraging its multimodal capabilities, we envisioned acoustophoresis units optimizing environments for animals to enhance their well-being. Another concept explored the augmentation of our surroundings by acoustophoresis to reveal "imperceptible" signals from non-human beings, such as amplifying their sounds or enhancing their presence to make them more discernible. In these concepts, acoustophoresis units are spread throughout a space, dynamically altering their positions in response to movements.

3.2.6 ***Playful Interaction****.* This theme explores using acoustophoresis to introduce playfulness into daily experiences by transforming our perception. For instance, acoustophoresis could modify eating sounds in a cafeteria, turning an ordinary environment into a symphony of sounds. Another scenario involves enhancing food enjoyment by altering its sensory attributes, such as adding crunchiness to bland food with directional audio or adjusting mouthfeel through haptic feedback. Acoustophoresis units in these concepts dynamically respond to users' movements by adjusting their positions around the area.

3.2.7 ***Interaction categories****.* Next, we analysed workshop ideas to identify key *interaction categories* enabled by acoustophoresis.

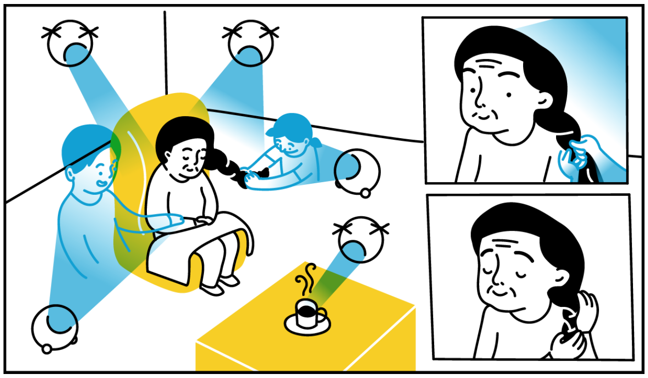

Figure 6: Illustration of Acousto-care. Mrs. Luna participates in a multimodal call with her family, during which she experiences the sensation of their embrace and feels their hands on her hair.

These categories were derived from the common patterns of interaction that we identified, each reflecting different ways the technology could alter or enhance user experiences. Common interactions included altering perception (e.g., turning cafeteria noise into music), simulating real or imagined experiences, and transmitting haptic sensations like remote hugs, mainly linked to the "social interaction," "content creation," and "playful interaction" themes. Another common interaction was using haptic feedback for alerts and notifications, which was linked to the "safety nudges" theme. Additionally, interactions aimed at augmenting environments by adding interactive layers, such as making the invisible visible or optimising ambient conditions for comfort and usability, were present in the "beyond human interaction" and "human wellbeing" themes. Figure 5 maps these categories to the corresponding themes.

4 SONARIOS - use case scenarios

We focused on two main themes with the highest volume of ideas, *Social Interaction* and *Content Creation*, driven primarily by the density of contributions rather than factors such as timeframe, technical feasibility, or conceptual radicalness. From these, we collaboratively formulated two example Sonarios (i.e., scenarios). Then, we extracted the core technical details to realise them. The tone of these Sonarios were intentionally positive, as these visions of the future, including our scenarios, can influence *anticipatory regimes*, influencing which futures are prioritised and how resources are allocated [2]. By adopting an optimistic lens, we aimed to promote the use of multisensory technologies for positive societal impact [80]. While the Sonarios suggest hopeful futures, the Discussion offers a critical view of possible unintended consequences.

4.1 SONARIO 1: Acousto-care

Imagine a future of social care: *"Mrs. Luna, an elderly resident in a care facility with family living far away, typically eagerly awaits the arrival of her designated Acousto-care each morning. She is in a fragile state that prevents her from getting into close contact with people, so Acousto-care is there to help her. While looking out the window and lost in thoughts, she's pleasantly surprised by a gentle touch simulated by Acousto-care on her forearm. Acoust-care then draws her attention to the levitated pill in front of her with a touch on her hand. As Mrs. Luna opens her hand, Acousto-care deliberately moves the pill around, urging her to catch it in a playful way. She feels a little more invigorated now. Not feeling like having breakfast today, she asks for a cup of tea. While Acousto-care prepares her tea, a napkin and a cookie are sent in her direction, floating through the room. Mrs. Luna grabs the napkin and starts nibbling on the cookie, watching as the invisible waves from the Acousto-care create bubbles in her mug to heat water. Acousto-care then initiates a calming sequence. A gentle breeze brushes against her skin and the room's colour changes to a nice sunset-pink. Mrs. Luna reflects that she feels much calmer now. Before leaving, Acousto-care ensures her comfort, nudging the mug forward to be within her reach.*

In the evening, Mrs Luna returns to her bedroom, Acousto-care reappears and puts her in touch with her family. As the call connects, she sees her son, and they share an embrace, bringing her immediate comfort (see Figure 6). With enthusiasm, Kira, the granddaughter, joins the call, positioning herself next to Mrs. Luna, their bond evident despite the distance. Kira excitedly mentions learning how to braid hair and, with a gentle tug, begins practising on Mrs Luna's locks. As the call ends, Mrs. Luna feels a renewed connection with her family, cherishing the memory of Kira's gentle tugs on her scalp."

4.1.1 *Realising Acousto-care.*

In this scenario, we envision seamlessly integrating the multimodal capability of acoustophoresis into our daily interactions with environments and people in a social care context. Here, we assess the feasibility of each technical feature involved in Acousto-care and provide an overall review.

Object delivery and processing: Acoustophoresis is primarily used in laboratory settings for manipulating lightweight objects for particles, fabrics, droplets, and food units [29, 39, 54, 65]. Thus, it is technically feasible for object delivery like medication. Meanwhile, functioning in a dynamic environment like a care home requires more customised technical solutions, like maximising the acoustic energy to hold different shapes of objects [23] and improving the system robustness [30] to meet usability in real scenarios.

Stimulated touch: In recent years, the HCI community has pioneered the use of acoustophoresis to create mid-air haptics through focused ultrasound. Robust theoretical and technical foundations support this field [11, 47], facilitating the generation of rich tactile sensations and exploring their emotional and psychological impacts. Commercially, companies like UltraLeap [32, 56] have developed products that bring these haptic technologies to the public. However, despite the well-established technology for contactless touch interactions, there remains a significant opportunity to expand the range of application tools and scenarios.

Autonomous navigation and interaction: To seamlessly integrate into dynamic interactive environments, acoustophoretic units need the capability to navigate autonomously and discern both the surroundings and the intended interactions. While current prototypes primarily operate within static interaction spaces designed for laboratory studies [62], it is technically feasible to leverage advanced techniques from modern robotics and machine vision, such as guidance, navigation, control, and image recognition. These fields provide mature solutions that can be effectively adapted to enhance the functionality of acoustophoretic systems.

Hologram display and telepresence: High-performance computing has enabled the rendering of volumetric display in the last five years by fastly moving levitated objects without wearing any instruments [29, 39, 63, 65], which makes this "Ultimate display" into reality and not just exist in the science-fiction movie. To enhance realism, further investment in computing resources and high-resolution visual content is essential, along with improved networking communication to ensure seamless, real-time data transmission for a more immersive and responsive experience.

Remote physical interaction: Delivering multi-modal interactions just with the manipulation of ultrasound waves is one of the biggest advantages of acoustophoresis [31, 39, 65]. Apart from vision, delivering other modalities of sensations brings truly intuitive and natural interactions. This is still at an early stage but is leading to the futuristic convergence of physical and digital realms, potentially revolutionising how we interact across human-human, human-computer, and human-environment interfaces by blending advanced sensory feedback with everyday experiences.

4.2 SONARIO 2: Acousto-view

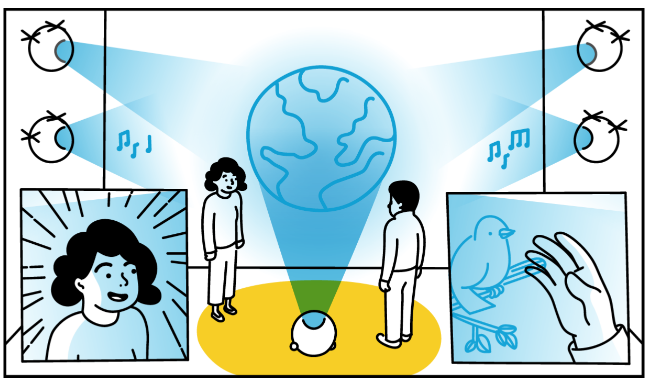

Figure 7: Illustration of Acousto-view. Through acoustophoresis units positioned around the space, Alex experiences a multisensory interaction with the Earth at various scales, including a close-up encounter with a bird.

Now imagine this scenario: "*In the corridors of the Science Museum, Alex notices a glowing blue sphere, no larger than an apple, floating in the air. With curiosity, he inches closer, only to realise it's our very own planet Earth. Alex approaches the tiny globe, and it grows to the size of a beach ball. As he marvels at the sight, another visitor joins him, and they walk around the globe. With each lean, the Earth enlarges, stretching beyond the span of their arms (see Figure 7). This scale reveals vibrant forests side by side with barren lands scarred by human hands. The sight of felled tree trunks weighs heavily on him, contrasting starkly with the lush Amazon rainforest. The other visitor shares his sentiment with a deep sigh.*

As he leans forward to the greenery, squinting, he finds himself in the heart of the forest, surrounded by majestic trees towering above him. He senses the temperature change around him and hears a sweet birdsong coming from his right. As he edges closer, he discovers a small purple-feathered bird. With hesitant fingers, he reaches out and is astonished by the softness of its head against his skin. The other visitor is also exploring the surroundings; he is touching the tree trunk in awe. However, his moment of solace is shattered by the unwelcome intrusion of mechanical noises, announcing the intrusion of human activity. The bird flees in the blink of an eye. He feels the rumble of engines and hears the crash of falling trees. Instinctively, Alex takes a step back in fear. The surroundings disappear, and he sees the globe, now back to the size of a beach ball once again. In that moment, while Alex finds a deep connection with the natural world, a twinge of anxiety and fear lingers. Contemplating his experience, he ponders how he can contribute to preserving our planet and its precious inhabitants, like the tiny bird with purple feathers."

4.2.1 *Realising Acousto-view.*

In this scenario, acoustophoresis enriches content creation, blending digital and physical displays in a mixed-reality format. Implementing diverse multimodal content (especially for physical display) requires advanced acoustophoresis with great reconfigurability, mobility, modularity, and reliability. We list typical functionalities and discuss technical feasibility.

Touch: Simulated touch as discussed in the Acousto-care scenario, demonstrates the potential of acoustophoresis for contactless tactile sensations, however, there are still some spaces to render more discernible and high-resolution simulated touch. Next, implementing a realistic touch on different materials in the ultrasound field would be more desirable, but would require algorithm development to compute the sound field.

Directional audio: Recent advancements [60, 72] affirm that directional hearing through acoustophoresis is feasible and has the potential for further refinement. More efforts should concentrate on improving the precision and range of loudness and sound directionality to support more complex and interactive applications, enhancing immersive auditory experiences.

Mixed-reality display: Mixed-reality merges tangible materials and virtual imaging to create immersive experiences, effectively blending physical and digital realms. Acoustophoresis plays a pivotal role in this integration, already demonstrated in recent systems [25, 31, 55]. To enhance these displays, it is crucial to achieve a balanced integration of physical and virtual elements. This involves designing interfaces that are intuitive and fully leveraging the tangible materials to maximise the system's capabilities. The goal is to enrich the realism and interactivity of mixed-reality environments, making them more engaging and lifelike.

Collective transformation: To realise the Acousto-view scenario, it's essential to develop multiple acoustophoretic units that seamlessly integrate and are highly reconfigurable to suit various content and interactions. These units must be modular to facilitate customisation and scalable for different settings to display virtual and physical content. Additionally, advanced AI integration is crucial for coordinating these units and dynamically adapting the content in response to user interactions.

Large-scale distribution: Developing a robust infrastructure is crucial to efficiently organise and allocate computational resources across multiple acoustophoretic units. This system will require advanced algorithms for real-time data management and task distribution to minimise latency and enhance responsiveness. Further development in hardware and fabrication is essential to ensure that acoustophoretic units operate reliably across diverse conditions.

Overall, the Acousto-care and Acousto-view SONARIOS not only demonstrate potential applications of acoustophoresis but also serve as foundational examples for understanding the unique interaction paradigms this technology affords, serving as the foundation for the strong concepts illustrated in the Discussion section.

5 Discussion

We aimed to explore the potential of acoustophoresis beyond its technical advancements and towards practical design opportunities. By adopting a design-driven approach, we illustrate possible use case examples, their technical feasibility, and desirable scenarios. Beyond the two examples of Acousto-view and Acousto-care, here, we provide the design community with more actionable, interaction-focused insights that complement technical feasibility.

In this context, *strong concepts* play a crucial role in advancing acoustophoresis research and design. Strong concepts are design elements or principles that are generative, meaning they can be adapted by other designers and researchers to develop applications in various design contexts [40]. Acting as intermediate-level knowledge, strong concepts bridge specific prototypes (in our case, scenarios) and theoretical frameworks. By isolating core components of a given design, strong concepts allow designers to translate specific instances into broader, more versatile design principles applicable across a range of applications, use cases, and genres [40].

For a technology like acoustophoresis, which is both novel and versatile, strong concepts provide direction for exploring interaction-driven possibilities and prioritise areas for development, ensuring that the technology is integrated into cohesive, synchronised user experiences, distinct from those offered by existing systems that rely on isolated sensory inputs.

To create these strong concepts, we followed an iterative process of co-author discussions, guided by a horizontal and vertical grounding approach [40]. Horizontal grounding involved examining the existing body of work to identify gaps and opportunities for novelty, ensuring that our ideas were distinct and not merely reiterations of prior concepts. Vertical grounding, on the other hand, focused on connecting emerging ideas to established theories and frameworks. This step ensured that our concepts were rigorously supported by existing knowledge, enhancing their validity and relevance. This process resulted in three strong concepts—Multisensory Harmony, Embodied Proxemic Choreography, and Cross-Modal Transfer—into well-supported ideas, grounded in our design futuring workshop findings, with clear pathways for integrating acoustophoresis into future scenarios. In the following sections, we also reflect on the broader design responsibilities associated with acoustophoresis.

5.1 Strong Concept 1: Multisensory Harmony

Multisensory Harmony integrates auditory, visual, and haptic modalities to create cohesive and harmonious user experiences [80]. Two principles underpin this concept: *temporal alignment* and *dynamic adaptation*. Temporal alignment ensures coherence within each modality (e.g., smooth visual textures or distinct tactile feedback patterns) and synchronises cues across modalities. For example, in the Acousto-care scenario, the visual elements of hair braiding, texture, colour, and motion are aligned with tactile sensations simulated by ultrasound-generated haptics, creating a seamless experience. Dynamic adaptation adds real-time responsiveness, as demonstrated in Acousto-view, where the Earth model's size and tactile engagement adjust based on user proximity, enhancing agency.

Acoustophoresis enables such multisensory interactions by producing haptic, auditory, and visual effects through a unified mechanism. Unlike traditional technologies that layer sensory inputs, acoustophoresis inherently integrates them, requiring designers to adopt holistic approaches. While tools like audio-video editors enable layered designs, there is a clear need for workflows tailored to acoustophoresis' distinct capabilities. Tools like xSense Design Cards [79] can support this process by helping designers map narrative contexts (e.g., who, where, what) to multisensory goals.

However, synchrony is not always straightforward or desirable. Studies show that sensory dominance varies: vision often overrides audition, yet auditory cues can also lead perception depending on context [68]. For instance, animators frequently play footstep sounds just before visual contact to create a stronger illusion of realism [14]. Designers need to be mindful of these nuances to create intended effects.

Acoustophoresis also invites exploration of intentional *misalignment*. For instance, mismatching cues could also evoke surprise or tension, deepening engagement and encouraging users to attend more closely to sensory details [59]. Fixed cause-effect patterns may constrain perception, biasing users toward familiar interpretations [69]. Therefore, rather than always aiming for seamless integration, designers might strategically disrupt harmony to foreground sensory textures or challenge habitual perceptions.

This concept is particularly impactful in immersive storytelling, such as Acousto-view, and in themes like Beyond-Human Interaction (Section 4.2). For example, acoustophoresis could amplify subtle animal sounds, like ultrasonic bat communications, pairing them with synchronised tactile feedback to foster a deeper connection with non-human entities [36]. In such contexts, blending modalities in time-sensitive ways can enable more embodied, expressive, and affective experiences.

5.2 Strong Concept 2: Embodied Proxemic Choreography

Embodied Proxemic Choreography (EPC) highlights users' ability to actively shape multisensory experiences through movement and spatial behaviour. Building on proxemic interaction principles [4], EPC highlights how physical distance and orientation modulate the intensity and quality of sensory feedback [34]. In Acousto-view, for instance, approaching a bird amplifies auditory cues and introduces haptics that mimic the texture of feathers. These spatial dynamics invite users to choreograph interactions through embodied gestures, like Alex, whose distance from the Earth model affects its scale and tactile presence.

Acoustophoresis introduces a unique design affordance for EPC by generating haptic, auditory, and visual feedback from a shared physical source: ultrasound. Rather than separately controlling each sensory channel, as is common in XR systems with headsets, gloves, and headphones, acoustophoresis inherently aligns sensory outputs through the same acoustic field. This reduces the need for artificial synchronisation and supports more cohesive interactions. For example, a levitated object's position, vibration, and sound are all shaped by the same wave field, creating a tightly coupled sensory experience.

This coherence simplifies implementation but invites complexity in design. Designers can explore how subtle changes in proximity shape multiple sensory dimensions at once through proxemic layering. In this approach, physical distance from an object or stimulus not only influences individual sensory channels (e.g., olfactory, haptic, gustatory) but also modulates them in layered ways, creating richer interactions. For instance, standing closer might not just increase the volume of sound but also shift its texture, change the intensity of haptic feedback, and alter visual aspects like scale or clarity. This layering of sensory cues enhances spatial interactions, creating a more immersive and adaptive experience as users navigate the space. To achieve this, designers should also consider user proxemic sensitivities, such as personal space, social context [34], and movement patterns within the application domain.

While EPC assumes a degree of system control over spatial feedback, designers should also consider how users may subvert or resist proxemic expectations. Someone might deliberately hover at a threshold to delay system response, or reposition themselves to elicit unintended combinations of cues. Such gestures complicate assumptions of smooth adaptation, instead opening up space for critical or playful forms of engagement.

This concept is particularly suited for contexts where spatial exploration and manipulation are integral to the experience, such as installations, education, or therapy. Drawing from our workshop themes on Safety Nudges, EPC could help cyclists adjust sensory cues—like haptic vibrations and auditory alerts—based on proximity to hazards, enhancing safety and reducing cognitive load [52]. Similar strategies have been explored in driving contexts [83].

5.3 Strong Concept 3: Cross-Modal Transfer

While Multisensory Harmony and EPC focus on temporally and spatially shaping sensory experiences, leveraging acoustophoresis, Cross-Modal Transfer (CMT) offers a different approach. CMT involves transferring sensory information from one modality to another [74], enhancing experiences by providing additional sensory input. Key elements include *Sensory Translation* and *Sensory Enrichment.*

Sensory Translation involves expressing information from one sense through another [75]. For example, in Acousto-care, calmness is conveyed not through direct tactile input but via ambient colour shifts and a soft breeze, evoking relaxation without replicating the source sensation. Sensory Enrichment goes further by adding cues from other modalities to deepen the primary experience. In Acousto-view, a subtle drop in temperature complements forest imagery and sound, enriching the moment without requiring perfect synchrony between senses [16].

Acoustophoresis uniquely enables such experiences through acoustic holography, where spatially structured sound waves interact with matter and air to produce tactile, auditory, and visual phenomena [38]. Unlike traditional systems that rely on separate devices (e.g., haptic gloves, VR headsets), acoustophoresis ensures sensory information is co-located and accessible in real-time, allowing users to engage with the same sensory data through their preferred modalities in a shared, tangible experience.

However, meaningful cross-modal interactions require careful design. Designers must manage coherence across modalities [74], ensure intuitive mappings, and balance against overwhelming or underwhelming enrichment. The latter can occur due to the dominance of the modality, for example, when visual input overshadows subtle haptic or auditory cues unless designed to stand out [68]. Equally important is considering user needs, especially for those with sensory impairments, to apply cross-modal techniques in accessible and inclusive ways [75].

While CMT is conceptualised to deepen immersion, it also holds potential for productive tension. *What happens when sensory inputs contradict, when tactile feedback disrupts visual serenity, or auditory cues introduce ambiguity?* These moments can prompt reflection, playful misalignment, or resistance to dominant design logics. Acoustophoresis, then, could support not only seamlessness but also forms of sensory disruption that foster awareness and agency.

Beyond the Social Interaction and Content Creation themes, CMT is especially relevant to Playful Interaction. For example, tactile feedback could simulate crunchiness in bland food, enhancing human-food interactions [57]. This may be especially beneficial for older adults with diminished smell or taste [21], where cross-modal stimulation could help restore appetite and promote enjoyable, multisensory engagement.

5.4 Tensions of (Im)materiality and Agency

A central tension across our scenarios and strong concepts that warrants further discussion is the paradox of materiality and immateriality. Acoustophoresis is a profoundly physical phenomenon rooted in sound pressure and spatial vibration. Yet, many envisioned applications (including the sonarios presented in this paper) aim to simulate immaterial experiences: remote presence, intangible touch, and floating visuals. This raises questions about how such technologies mediate our sensory relationship with the physical world. *Do they risk detaching us from unmediated sensory engagement, or might they instead offer new ways to surface and revalue the material conditions of perception?*

We see this not as a flaw, but as a provocation: to design with acoustophoresis not only for seamless multisensory integration, but also for moments that reveal, disrupt, or even re-materialise sensory experience in ways that challenge dominant paradigms of immersion.

Related to this is the question of user agency. While our strong concepts emphasise coherence, harmony, and choreography, they may also suggest compliance with system logics. As highlighted in our strong concept discussions, users might intentionally resist these patterns by disrupting interaction flow or engaging outside intended sensory zones. Designing for such divergent use aligns with seamfulness [18, 40]: the idea that systems should expose their inner workings and allow users to appropriate or play with the "seams." In acoustophoresis, this could mean making perceptual boundaries, feedback delays, or spatial interaction rules visible and modifiable. Exploring these seams through Wizard of Oz studies [20] or speculative probes could reveal how people may engage with the "seams" and how such interactions can inform design evolution of acoustophoresis.

5.5 Navigating Desirable and Responsible Futures

The SONARIOS presented in this paper offer deliberately optimistic applications of acoustophoresis, envisioning multisensory technologies that enhance societal well-being. Yet imagining futures involves a responsibility [45] to engage with the sociotechnical imaginaries that influence collective priorities and resource allocation [2, 43]. Even without modelling institutional decisions, scenarios participate in anticipatory regimes and carry rhetorical force, with the potential to steer design and research trajectories. In the context of acoustophoresis, engaging policy stakeholders and publics directly can surface the sociopolitical assumptions that may shape how such technologies are imagined, developed, and deployed [44].

Our ethical orientation was shaped through co-author discussions, iterative scenario development, and a dedicated Responsible Research and Innovation (RRI) workshop with our interdisciplinary team, using RRI Prompts [67]. While the outcomes of this workshop lie beyond the scope of this paper, they informed how we engaged with broader questions of care, agency, and responsibility.

In the *Acousto-care* scenario, acoustophoresis offers significant promise to foster emotional connections and alleviate loneliness, particularly among elderly and isolated populations [9]. However, these benefits are not without risks. Over-reliance on technology could dehumanise caregiving, substituting meaningful human interactions with mediated solutions [1]. There is also the danger of encouraging passivity, as automated systems replace tasks that maintain physical and mental engagement [64]. In addition, care-oriented systems that rely on sensory or affective sensing raise concerns around unintended monitoring or privacy intrusions [1, 15]. Designers must carefully navigate these challenges, ensuring technology supports, not replaces, human care, avoids intrusive monitoring, and empowers active participation in care routines.

Similarly, the *Acousto-view* scenario demonstrates how acoustophoresis can unlock novel opportunities for immersive storytelling, education, and environmental awareness. However, the desirability of such futures hinges on inclusive design and the mitigation of risks associated with multisensory realism. These include the potential for perceptual manipulation, immersive attacks [12], and threats to autonomy or mental wellbeing [35, 53]. As multisensory media become increasingly convincing, emotional realism must be balanced against risks of dependency, disorientation, or psychological harm [15, 19]. Safeguards that protect user autonomy, consent, and emotional safety are essential.

Across both scenarios, the transformative potential of acoustophoresis brings with it a *dual imperative:* to explore what such technology could make possible, while remaining attentive to what it might displace, obscure, or endanger. Alongside our optimistic visions, we also identified futures to resist: those involving sensory commodification, surveillance, behavioural control, or the erosion of human agency. These outcomes may be technologically plausible, but they conflict with commitments to inclusive, responsible design.

Our work highlights the need for continued dialogue between designers, researchers, and society to ensure that emerging technologies such as acoustophoresis are developed in ways that align with sustainable, equitable goals, and that critically examine both their promise and their potential harms [15, 44].

5.6 Limitations and Future Work

While this paper offers design-oriented visions for the future of acoustophoresis interaction, several limitations should be acknowledged. The scenarios adopt a deliberately optimistic tone, which, while useful for speculative exploration, must be balanced with empirical research into their real-world complexities and consequences.

Future work should prioritise user-centred studies to evaluate the experiential and ethical dimensions of these technologies. Given the technical challenges of acoustophoresis, early exploration can be supported through Wizard of Oz methods [20], speculative probes and video prototypes that simulate dynamic sensory interactions. These approaches would allow for early feedback on how users perceive agency, immersion, and interaction logic in different contexts.

Further refinement of the strong concepts is also needed—both to test their resonance with users and to understand how they translate across diverse cultural and situational settings. While real-world deployment is still emerging, these concepts offer a foundation for iterative, interdisciplinary development. This includes engaging with engineers, policymakers, and artists to shape how acoustophoresis systems might evolve toward meaningful, responsible applications.

Although significant technical and market challenges remain for acoustophoresis to achieve widespread adoption (i.e., to cross the "valley of death" [37]), this research contributes by offering a design-driven perspective that complements technical development. The speculative scenarios and strong concepts developed here provide actionable, interaction-focused insights that can inform future research and development. By focusing on these foundational aspects, we aim to support a more holistic understanding of how acoustophoresis might evolve toward meaningful applications.

6 Conclusion

As acoustophoresis advances and its technical feasibility continues to be explored, it is essential to focus not only on technical achievements but also on shaping its future directions thoughtfully [15, 77]. This paper presents a design-driven exploration of acoustophoresis, a technology with the potential to transform multisensory interactions. By synthesising insights from a design futuring workshop, we identified key themes and interaction categories that can guide the speculative development of this technology. Moreover, the three strong concepts of Multisensory Harmony, Embodied Proxemic Choreography, and Cross-Modal Transfer abstract key insights from the workshops and scenarios we created, offering overarching themes to pursue and experiment with. From a technical standpoint, these concepts provide a roadmap for developing technologies that prioritise these principles, towards interactions that are both meaningful and engaging. While it is challenging to predict the future of emerging technologies like acoustophoresis, this work contributes to the ongoing dialogue about their possibilities and desirability. We aim to engage and inspire the design community to shape thoughtful and desirable directions for this technology. By exploring speculative futures, we hope to spark collaboration and encourage collective efforts toward responsible and innovative design.

Acknowledgments

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) as part of the Swarm Social Sound Modulators project (EP/V037846/1). We are grateful to all our workshop participants for their valuable input and reflections on the futures of acoustophoresis. Special thanks to Ana Marques for her scribing during the workshops, which helped capture the essence of the discussions and informed the figures presented in this paper.

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