DataLev: Mid-air Data Physicalisation Using Acoustic Levitation

Lei Gao
Department of Computer Science, University College London, London, United Kingdom
lei.gao.20@ucl.ac.uk

Pourang Irani
Department of Computer Science, University of British Columbia (Okanagan), Kelowna, British Columbia, Canada
pourang.irani@ubc.ca

Sriram Subramanian
Department of Computer Science, University College London, London, United Kingdom
s.subramanian@ucl.ac.uk

Gowdham Prabhakar*
Department of Computer Science, University College London, London, United Kingdom
g.prabhakar@ucl.ac.uk

Diego Martinez Plasencia
Department of Computer Science, University College London, London, United Kingdom
d.plasencia@ucl.ac.uk

Ryuji Hirayama
Department of Computer Science, University College London, London, United Kingdom
r.hirayama@ucl.ac.uk

ABSTRACT

Data physicalisation is a technique that encodes data through the geometric and material properties of an artefact, allowing users to engage with data in a more immersive and multi-sensory way. However, current methods of data physicalisation are limited in terms of their reconfigurability and the types of materials that can be used. Acoustophoresis—a method of suspending and manipulating materials using sound waves—offers a promising solution to these challenges. In this paper, we present DataLev, a design space and platform for creating reconfigurable, multimodal data physicalisations with enriched materiality using acoustophoresis. We demonstrate the capabilities of DataLev through eight examples and evaluate its performance in terms of reconfigurability and materiality. Our work offers a new approach to data physicalisation, enabling designers to create more dynamic, engaging, and expressive artefacts.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interactive systems and tools.

KEYWORDS

Acoustic levitation, data physicalisation

ACM Reference Format:
Lei Gao, Pourang Irani, Sriram Subramanian, Gowdham Prabhakar, Diego Martinez Plasencia, and Ryuji Hirayama. 2023. DataLev: Mid-air Data Physicalisation Using Acoustic Levitation. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany*. ACM, New York, NY, USA, 14 pages. https://doi.org/10.1145/3544548.3581016

*The author is presently at the Department of Design, IIT Kanpur, India

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04...$15.00
https://doi.org/10.1145/3544548.3581016

1 INTRODUCTION

Data physicalisation encodes data through the geometric and material properties of an artefact [38]. Unlike conventional data visualisation that is constrained by the pixel (digital) representation on flat displays, data physicalisation brings data into the physical world to help users understand, explore, analyse, and perceive it. By directly handling or walking through a physicalisation artefact, users can actively perceive the data with not only visual but other senses (e.g., touch) and can obtain proper depth cues. Various static data physicalisation examples have been created using a variety of materials and embodiments, either by hand (e.g., clay, scale models [75]) or through computer-supported fabrication techniques (e.g., 3D printers [4], laser cutters [37]). Data physicalisation has applications in different fields such as medicine [4], geography [31], and education [76], for different purposes including self-reflection [65], storytelling [41], and decision-making [23].

One of the most difficult challenges in data physicalisation is satisfying both its reconfigurability and materiality [6],[38]. Dynamic physicalisations typically rely on approaches such as shape-changing devices [18],[25] or swarm robots [22], which still fail to provide full 3D reconfigurability and severely limit the types of materials used to create the physicalisation, to the point that current classifications [6] divide them into *electronic* (and reconfigurable) and *non-electronic* (flexible materiality, but static). Often designers have had to choose between reconfigurability of the physicalisation and material freedom for the physicalisation but cannot have both. These suggest a need for an alternative reconfigurable physicalisation platform, capable of supporting different physicalisation structures (mixing different embodiments and materials) and interaction possibilities (like combining visual, auditory, tactile, and olfactory) to build new types of data physicalisation.

Acoustophoresis—a method of suspending and manipulating materials in a medium (e.g., air) using acoustic radiation pressures exerted by sound waves—is a promising approach to realise such new data physicalisations. The suspended particles can be manipulated to create different geometries in mid-air that serve as data physicalisations. Thanks to its flexible 3D manipulation capability, acoustophoresis allows not only reconfiguration but also the animation of physicalisation artefacts (i.e., movements of artefacts can embody meaning). Additionally, acoustophoresis can handle

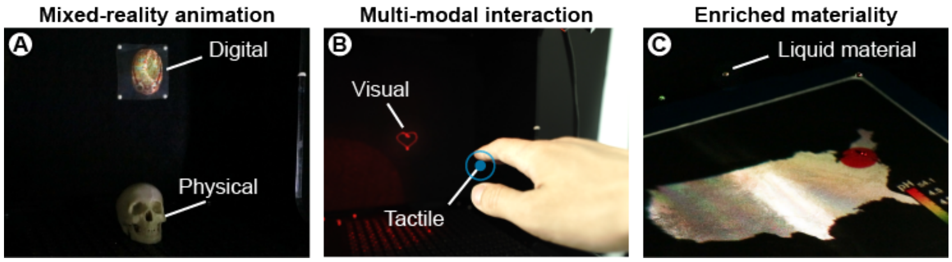

Figure 1: DataLev allows new types of animated data physicalisation. For example, (A) a mixed-reality presentation of scientific data, (B) multi-modal interaction showing the user's heart rate through visual and tactile sensations and (C) a data physicalisation with enriched materiality presenting the pH level of acid rain with actual droplets.

different kinds of material, like expanded polystyrene (EPS) particles [45], small LEDs [66], threads [17], pieces of fabric [49], liquid droplets [20], and food items [68]. This ability of acoustophoresis opens the possibility of offering enriched material support for data physicalisations.

In this work, we present DataLev, a design space and platform exploiting data physicalisation and acoustophoresis to create reconfigurable artefacts with enriched materiality, multi-modal interactions, and mixed-reality animations (see Figure 1). Our first contribution is a novel design space for acoustophoretic data physicalisations that outlines five main dimensions: *Embodiments, Materials, Multi-modal support, Mixed-reality components,* and *Animation* to enhance data physicalisation through acoustophoresis. Our second contribution is a hardware and software platform that makes use of state-of-the-art advances in acoustophoresis, together with physical props, levitated materials, digital imaging devices (e.g., the ASKA3D aerial plate [77]), and path planning techniques. We use this platform to demonstrate 8 examples of novel data physicalisations illustrating specific dimensions of our design space, but also as a reusable platform for others to explore this space. We also contribute a technical evaluation of the reconfigurability and materiality capabilities of the platform, as the two key aspects delimitating the conceptual space proposed by DataLev.

2 RELATED WORK

Data physicalisation [38] aims at enhancing humans' abilities to understand, explore, analyse, and perceive data. However, it does not explicitly focus on visual sensations nor solely relies on flat displays to convey data. Instead, data physicalisation uses physical artefacts to represent data, attempting to tap into the human's perceptual exploration skills more broadly (e.g., active perception, multiple senses, correct depth cues). Empirical studies have shown that the use of data physicalisations improve users' performance of exploring and interacting with 3D bar charts, when compared to interactions through flat screens (i.e., monoscopic or stereoscopic) [37] or VR glasses [57], thanks to visual realism and direct user touch.

We review this space according to the cross-disciplinary design space proposed by Bae et al. [6], which describes and analyses data physicalisation according to three facets: i) Structure, which focuses on how the data is physically embodied (Section 2.1) and materialised (Section 2.2); ii) interaction, which focuses on the dialogue between the user and the physicalisation (Section 2.3); and, iii) Context, which is analysed in terms of existing acoustophoretic applications (Section 2.4).

2.1 Embodiments

Advances in digital fabrication have made the process of creating physicalisation artefacts easier for many people who have access to computer-supported manufacturing machines such as 3D printers [4], laser cutters [37], and computer numerical control (CNC) milling machines. The choice of materials in digital fabrication is more limited than in the hand-crafted approach, but multi-material 3D printing technology [60] is still rapidly advancing and is expected to cover more and more materials. Reconfigurability [38] is challenging in physicalisation as updating the data entails a time-consuming process of reconstructing the physical artefacts.

A promising approach to reconfigurability is through shape-changing displays that use an array of motorised elements such as rods [64], pins [18], or clips [25] to create different height maps. Researchers have also explored the possibilities of employing other actuators, such as thermal [29], fluidic [48], pneumatic [72], biologic [73], or shape-memory alloys [58], to achieve reconfigurability, but actuation is typically limited to 1D. Self-propelled swarm robots like the Zooids-based platforms [22],[23] with wheeled micro-robots are used as physical tokens on a tabletop for data physicalisation. These robots can be manipulated collectively or individually and behave like moving physical pixels to display line charts and scatterplots on the tabletop (i.e., 2D reconfigurability). Combined with reel-based linear actuators, ShapeBots [62] allows various shapes and geometric transformations, and up to 12 robots as physical tokens have been demonstrated. The data representation capability of such platforms (even combining shape-changing and swarm robots) is limited to supporting planar or 2.5D structures and does not support any 3D transformations.

There are several approaches to suspending materials in mid-air [9] and manipulating them in 3D that have been explored by the HCI community. For example, ZeroN [42] uses magnetic levitation to suspend a metallic sphere that users can interact with and manipulate in the anti-gravity space. Air stream has also been used to levitate materials and to create mid-air tangible interfaces: Aerial Tunes [1] is composed of six devices that can control air stream to levitate EPS balls at different heights, and Floatio [74] used a similar setup but focused more on presenting lifelike movements with a single ball. Smalley et al. [61] used light to trap and scan a cellulose particle quickly to create mid-air volumetric images. However, individual 3D manipulation of multiple materials is still challenging in these approaches.

Drone shows with 100s of drones are a popular alternative to fireworks to create 3D images in the night sky [78], and they offer more flexible movements in 3D space. GridDrones [8] presented relief maps in mid-air with 15 cube-shaped drones. However, their design was limited to a 2.5D grid (e.g., $1 \times 3 \times 5$) representation because they did not allow drones to fly over the top of one another due to the downward thrust each drone creates. This suggests that drones' capabilities of 3D manipulation are still limited when space is confined.

In contrast, acoustophoresis [45] allows 3D manipulation of multiple materials at the same time inside an enclosed space, enabling data physicalisation to be highly reconfigurable. Another important advantage of acoustophoresis is that levitation is not limited by material properties, while such choice is limited in other levitation techniques (e.g., only ferro-magnetic materials are suitable for magnetic levitation). We review acoustophoresis in more detail in Section 2.4.

2.2 Materiality

One popular definition of data physicalisation suggests that data is encoded through both the geometric and material properties of an artefact [38]. A recent physicalisation review [6] classified materials in physicalisations into *electronic* and *non-electronic* materials to highlight that many reconfigurable data physicalisation platforms (aka electronic platforms) limit material choice while static physicalisations (aka non-electronic platforms) offer the most material freedom.

Non-electronic materials, like artefacts fabricated by laser cutters [37], 3D printers [4],[63], and fluidic materials [48], can often enrich the embodiments and situatedness of data to better contextualize [10] them for different data types and chart types. Meanwhile, electronic materials such as the plastic pins in the InFORM system [18] have more reconfigurable capability, but they are carefully designed and only adopted in specific interfaces and contexts. That is, electronic materials are tightly coupled with their reconfigurability with the loss of materiality choices.

Non-electronic materials (e.g., 3D-printed objects or hand-crafted artefacts) can be made to represent data in reconfigurable physicalisations by integrating them with the microcontrollers or sensors used in the platform [6]. Despite this possibility, material reconfigurability, where different materials can be used within the same physicalisation, is extremely hard to achieve. Therefore, decoupling material choices and corresponding reconfigurability (i.e., allowing both material independency and reconfigurability) is very promising to open immense data encoding channels, physicalisation structures, and interaction possibilities.

2.3 Animations and Interactions

Animations are used in data visualisations to support the interactions and transitions between different analysis tasks (e.g., select, filter, sort [64]) which can effectively attract user attention and enhance engagement or enjoyment [27]. Although animations have been proposed in physicalisation [38], they are often challenging to implement as they require fine reconfiguration or transformation of physical materials (e.g., changing positions, deformation, or smoothness) over time. Swarm robots support some physicalisation-based animations like stop-motion animation [22],[23] and animated sine waves [62], by changing their positions and shapes. However, these animations are often limited to rigid 2D motions [23]. Shape-changing displays (e.g., EMERGE [64], InFORM [18]) changed heights of actuated pins or rods to demonstrate interaction animation effects. Meanwhile, an interaction study of physical bar charts [64] has noted that some participants felt that the interaction animations interfered with their ability to comprehend the data and that they did not get much value from them.

According to a recent design space study [6], visual and haptic interaction are still the main interaction modality in most physicalisation works. For example, direct touch and tangible interaction are allowed with physical charts [23],[48],[67] where users can manipulate their physical elements (materials) and get haptic feedback. However, existing works typically design through visual modality to encode and perceive the data information and less likely to consider combining multi-sensory channels (i.e., visual, auditory, tactile, and gustatory modalities), despite the fact that such multisensory integration could make data more accessible to visually impaired people and deliver data in more intuitive ways.

In terms of interaction environments, data physicalisations have attempted to integrate both physical and digital presentation [70], to take advantage of the benefits of both physicalisation (e.g., multisensory and realism) and visualisation (e.g., high resolution, animation, and scalability). This mixture has a close relationship to immersive analytics [14], which also seeks to interact with and explore data in mixed-reality environments (i.e., situated contexts). However, the implementation of mixed-reality environments typically uses optical projection onto planes [25],[62], limiting spatial presentations. The other way is rendering digital environments through head-mounted displays [30], which also brings technical challenges for multi-user co-located collaboration [15]. Thus, a well-designed interaction environment is needed, which could help to promote the efficiency of data physicalisations.

2.4 Acoustophoretic systems

Acoustophoresis has been notably advanced over the past decade through the introduction of two fundamental techniques: phased arrays of transducers (PATs) [20],[52] and acoustic holography [45],[46]. PATs allow dynamic control of dense arrays of sound sources (e.g., 16×16 ultrasound transducers), while holography enables PATs to accurately control sound fields and manipulate multiple materials freely in 3D space [45]. High-performance computational techniques have allowed fast manipulation of materials in real-time, and speeds of up to 8.75 m/s have been demonstrated on a lightweight EPS particle [33]. The above advances assumed the space between the transducers to be always empty with no sound-scattering objects, but a recent reformulation of the boundary element method removed this limitation [32], enabling high-speed acoustic levitation in more flexible environments even with the presence of sound-scattering physical artefacts.

Threads [17] or lightweight fabric [49] with an arbitrary shape (e.g., a fish, a butterfly, or a rocket) can be levitated and manipulated in mid-air by using small particles attached to the threads or fabric as levitation anchors. Levitating sound-scattering objects larger than half of the wavelength (i.e., 4 mm) requires special vortices of high aperture [13],[35]. 3D manipulation of large-sized sound-scattering objects has not been demonstrated yet, but we believe that further technical advances will allow us to integrate such objects into the DataLev system as well.

An interesting application of acoustophoresis is to create multi-modal volumetric displays [33],[56]. In these systems, particles scan 3D content quickly enough to provide the persistence of vision (POV) effect with simultaneous full-colour illumination, revealing the 3D visual content in mid-air. Acoustophoresis can recreate tactile and audio spotlight sensations by delivering similar tactile pressure points that our bare hands can feel [11] and sound spotlights that are audible only within a defined space [51]. The interesting point is that the creation of these three modalities (i.e., visual, auditory, and tactile) relies on the single acoustophoretic principle and can be combined together to provide multi-modal experiences [33],[56]. Acoustophoresis also covers the other two senses: gustatory and olfactory. For example, TastyFloats [68] is a levitation platform on which food morsels (e.g., coffee, meat, and bread) can be levitated and transported to different locations. The system is also being setup at a restaurant in London (Park Row [79]) to provide multi-modal experiences to customers who can see, smell, and drink levitated liquor droplets.

Floating Charts [53] is the only example of using coloured EPS to represent the numerical values of tabular data using acoustophoresis. However, Floating Charts did not leverage the unique features of acoustophoresis (i.e., material independency, multi-modal capability, mixed-reality display) that could benefit the creation of novel data physicalisation.

3 DATALEV DESIGN SPACE

DataLev provides a design space to create rich physicalisation by leveraging acoustic levitation. Our design space includes 5 main dimensions (*Embodiments, Materials, Multi-modal support, Mixed-reality components*, and *Animations*, detailed below) and is summarised in Figure 2. On the left, each dimension includes various potential possibilities and features, extracted from state-of-the-art advances in acoustophoresis. On the right, we show how the prototypes presented later in the paper (E1-E8) fit within our design space, showcasing their stress on different dimensions but also how physicalisations can combine several features from each dimension, providing a huge number of potential physicalisation combinations.

3.1 Embodiments

This dimension encompasses the traditional concept of embodiment from data physicalisation, being related to the geometric properties of the artefact and including all approaches and alternatives discussed in Section 2.1 (e.g., *Object* for static parts, *Mechanical* for shape-changing parts). However, DataLev extends this concept to explicitly include and consider the transducer arrangements required to enable the levitation. Among these arrangements, the top-bottom setup provides the most levitation capabilities and is the most widely used for acoustophoretic displays [33],[45],[49]. Single-sided setups [46] offer more flexibility in designing the embodiment but more limited levitation capabilities, while V-shaped setups [46],[53] provide a trade-off between both aspects. Note that transducer arrangements can also be combined with other aspects of the embodiment. For example, they can be attached to a mechanical arm [16] or a gimbal structure [39] (i.e., *Mechanical + Transducer*) or combined with external objects (i.e., *Object + Transducer*), such as acoustically transparent objects (e.g., decorations [21] or tools [54]) or arbitrary objects reflecting ultrasound off their surfaces [32].

3.2 Materials

This dimension extends the traditional concept of materiality. Again, typical material properties for traditional physicalisation (i.e., *electronic* and *non-electronic*, as in [6]) are available, but these are extended with the materials that acoustophoresis can dynamically control. At this point, it is important to consider the raw materials that can be levitated (e.g., EPS particles, liquid, food), but also the structures that can be built using them (e.g., using threads or fabric), as they all provide designers with opportunities to enhance physicalisation materiality, which can influence data semantics and storytelling (see Figure 3).

For a solid material, the shape, size, and density of the material sample trapped are the main factors that determine its suitability (i.e., trapping stability). Most algorithms are designed to trap lightweight, spherical objects smaller than half the acoustic wavelength (i.e., 4 mm in our case), explaining the commonplace use of EPS particles [45]. Edible materials can also be used, such as meat, rice and noodles [69] (e.g., to represent nutrient data), or any other solid material providing domain-specific meaning (e.g., cubic zirconia in Figure 3 , electronic components [3] or even insects [71]). Liquid materials such as water [20], silicon, and glue [16],[24] can also be used to physically represent data, such as raindrop pollution levels or temporal evolution. For example, dynamic fabrication can be used to show how data objects change over time. This level of material freedom provides unprecedented choice not available in any other physicalisation platform, blurring the boundary between physicalisation and fabrication [34], with the content being levitated first, and then assembled to join the static (i.e., *Object*) embodiment of the DataLev physicalisation.

Following from the above, materials can also be arranged into structures using cotton thread [17] or SuperOrganza fabric [49], and such structures have been extensively used mostly for display and visualisation purposes [17],[32],[49]. Those materials are used for optimum manipulation enabled by their low weight allows, but other materials explicitly representing the domain properties of the data can be used instead. Thus, it is up to designers to exploit this *Materiality-Animation* trade-off, using general-purpose materials to improve *Animation* performance, or other materials for context or *Multi-modality*.

3.3 Multi-modal support

This dimension extends traditional physicalisation to include the potential of acoustophoresis to represent multi-modal data without

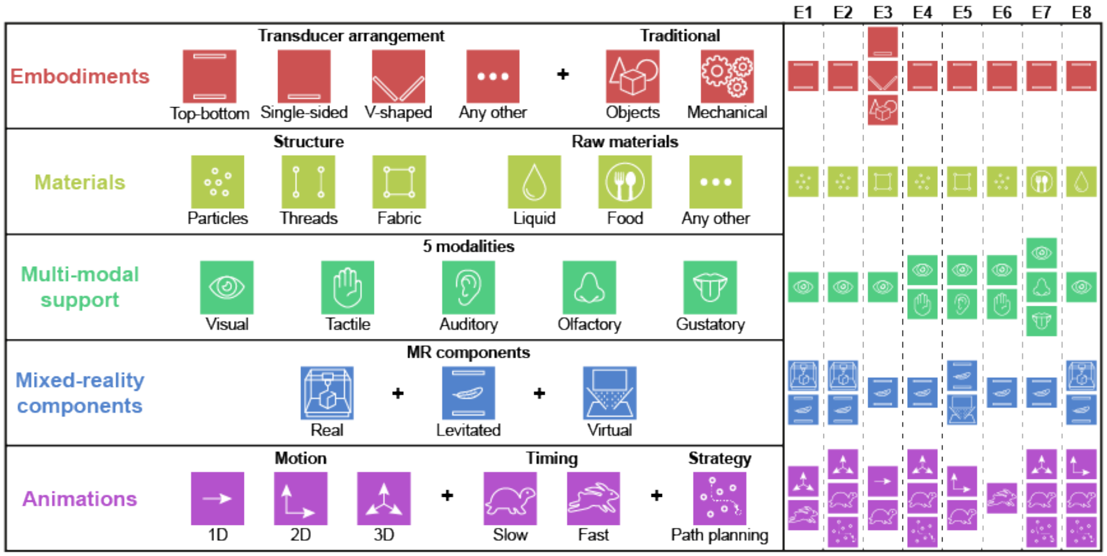

Figure 2: DataLev provides a design space with 5 main dimensions, based on state-of-the-art advances in acoustophoresis shown in the left within each dimension). On the right, breakdown of the features exploited by each of our example prototypes.

Figure 3: Different types of materials that can be used in DataLev physicalisations, and example structures.

the need for additional haptic, audio speakers, or smell delivery devices. The levitated part of the physicalisation can deliver not only visual but also tactile and auditory content all at the same time [33]. Due to its extended materiality, acoustophoresis also facilitates the stimulation of chemical senses, such as olfactory and gustatory modalities. The most trivial approach is to use smell-infused and/or edible materials to encode data. Ultrasound resonant modes [33] cause drops to vibrate, facilitating diffusion for smell delivery. Alternatively, scented aerosols can also be directed, using Bessel beams [50] or even acoustic focal points [26]. Smell and taste can help contextualise the physicalisation and improve users' situated awareness of the dataset. For instance, a multi-modal display could levitate different types of coffee, creating audio spotlights with the name of the source (e.g., Egyptian, Ethiopian) when a user points at them, directly tasting the liquid coffee, or directing its scent to the user.

On the one hand, the potential of acoustophoresis is to address all modalities while, at the same time, decoupling such modalities brings an interesting perspective to physicalisation. That is, simultaneous seeing, hearing, and feeling are possible, but it is equally possible for some parts of the data to only be seen while other parts can only be felt or heard. The modalities used or even the mapping of modalities to subsets of data also remain reconfigurable over time.

On the other hand, the benefits of physicalisation are often assumed to rest on their tangibility, letting users directly explore data simultaneously through all their senses. The visual complexity of levitated content is still limited, and tactile sensations cannot replicate the feeling of a solid object (e.g., weight, temperature). While techniques for direct manipulation of levitated content [36] exist, the content is never in direct physical contact with the user's skin, and manipulation still needs to follow the rules defined by the interaction technique, arguably not being as natural, intuitive and expressive as an unconstrained object exploration with the hand. Hence, the extended materiality and reconfigurability achieved via levitation need to be considered against its more limited support for direct interaction and exploration.

3.4 Mixed-reality Components

This dimension addresses changes in the visual appearance of (parts of) the physicalisation not related to their *embodiment* (e.g., shape change) or *materiality* (e.g., glue solidifying), which can be supported by a range of display approaches. We consider 3 elements for this dimension: *Real*, *Virtual* and *Levitated* Mixed-Reality *(MR) components*.

Real MR components refer to appearance changes to the *Embodiment* (i.e., not including the levitated content). They can be implemented using a variety of approaches, such as projection mapping or displays embedded on the surface of static objects, and they address more traditional physicalisation approaches (i.e., tangible materiality, but limited reconfigurability). *Virtual MR components* support current trends in immersive analytics and MR [14],[15] and can be created by additional display approaches such as ASKA3D aerial plates [77], autostereoscopic devices, or VR headsets, providing immersion and high reconfigurability, but no materiality. *Levitated MR components* change the appearance of levitated parts of our physicalisations (e.g., particles, threads, fabric), achievable via projection mapping [49] or LED illumination systems [33]. *Levitated MR components* are crucial to provide a more complete coverage of the *Reality-Virtuality* continuum, filling the gap between the rich materiality but reduced reconfigurability of *Real MR components*, and the high versatility but lack of materiality of *Virtual* ones.

3.5 Animations

We embrace the concept of animation over the traditional concept of reconfigurability [38] in our design space. That is, DataLev can not only spatially reconfigure, transitioning between states as to represent different datasets (or views of the same dataset), but also allow high-speed manipulation of data objects in the temporal dimension. We define this dimension as *Animation*, stressing time as an extra feature of the physicalisation in which motion, timing and other principles of animation also reflect meaning [40].

Animation can be constrained (i.e., 1D as in ShapeClips [25], 2D as in Zooids [22]) or completely free (3D)), and DataLev distinguishes two mechanisms for specifying such animations: *Manual* and *Automatic*. The *Manual* mechanism gives the designer control over where each element moves and at what speed to customise the *Animation*, increasing control and expressiveness at the expense of increasing their workload. Where the physicalisation only needs to transition between states (i.e., expressiveness is not required, and simple reconfigurability is enough), *Automatic Animation* can be implemented by using path following techniques (i.e., the geometry of transitions is known, but timing is not specified or not relevant) or path planning (i.e., only starting and end states are known) to compute both animation path and timing for reconfigurable physicalisations.

4 DATALEV PLATFORM

Our platform is based on OpenMPD [47], an open hardware and software solution for multi-modal ultrasound displays, and introduces novel components never demonstrated with acoustophoresis before, such as a hybrid imaging technique combining projection mapping with an ASKA3D aerial plate [77] and path-planning techniques [12] applied to levitation. We describe this platform[1] according to its implementation and support for each of the 5 dimensions in our design space:

Embodiments: Our *Embodiments* make use of open transducer boards [47] (16 × 16 transducers, at 40 kHz) in different arrangements (i.e., top-bottom, V-shaped, or single-sided; see Figure 4A). In most cases, we reuse OpenMPD's implementation of the GS-PAT solver [56], as it can be configured to support all these arrangements by simply specifying transducers' positions and orientations. For specific examples using *Object + Transducer* embodiments (**E3,** exploiting ultrasound reflections off static objects), we used the algorithm by Hirayama et al. [32], encapsulating it as an additional OpenMPD solver. These solvers can support up to 2048 transducers if larger-scale data physicalisations are required.

Materials: Our platform is material-agnostic (i.e., any can be used) and allows users to adjust the acoustic pressure level at each levitation trap according to the material properties, thanks to the GS-PAT solver [56]. For instance, we can adjust the pressure according to the material density to efficiently manipulate multiple different materials (i.e., dedicate more pressure to denser materials) or provide constant pressure to avoid levitated droplets atomizing [20]. Importing materials (i.e., levitating materials at the initial positions in levitation space) is achieved by a camera-based self-assembly technique [17] for solid materials (including structured fabric) and by an automatic injection method [2] for liquids.

Multi-modal Support: As per *Multi-modal support*, both of the solvers used are capable of delivering tactile, auditory, and visual modalities. We support the delivery of the gustatory and olfactory modalities through suitable materials and amplitude control for resonant modes. Switching to visual, gustatory, or olfactory modalities requires the same self-assembly or auto-injection process described in *materials*, as they involve levitating materials, while switching to tactile or auditory modalities can occur instantly. Hand-tracking devices (Leap Motion and OptiTrack) are used to support interaction with the physicalisations, either co-located [36] (see Example **E5**) or at a distance [5] (see Example **E4**).

Mixed-Reality Components: *Mixed-Reality Components* are implemented by a combination of 2 imaging solutions. First, an LC projector is used to support *Real MR Components*, via projection mapping on the surface of static, non-levitated objects. This projector is also used to project on *Levitated MR Components*, either via projection mapping on mid-air screens [17],[49] illuminating levitated materials (e.g., EPS particles, droplets, food) or even POV volumetric display by high-speed particles or quickly spinning screens [47].

Second, we use an ASKA3D aerial plate [77] to support *Virtual MR Components*, being the first to demonstrate virtual content spatially overlaid with levitated components. By integrating aerial images within DataLev, we can provide a balance between the levitated materials (true 3D), which have low resolution, and perspective-correct aerial images, which can present high-resolution 2D digital images or 3D objects. The location where the aerial images are generated is defined by the embodiment (e.g., see Figure 4B for our top-bottom examples). No calibration is thus necessary for the aerial images, and such mapping could even be dynamically modified by adding *Mechanical* embodiments (i.e., moving the display).

Animation: Finally, *Automatic Animation* is supported by a S2M2 path planning algorithm implementation [12]. We demonstrated for the first time that adaptation of path planning to acoustophoresis is important to provide feasible paths and timing for the particles to move from one state to another, avoiding collisions under user-defined maximum velocity constraints. To avoid physical collisions for animation transformation, the path

[1]Source code, hardware components and design files are available at https://github.com/Lei-Oriana/DataLev

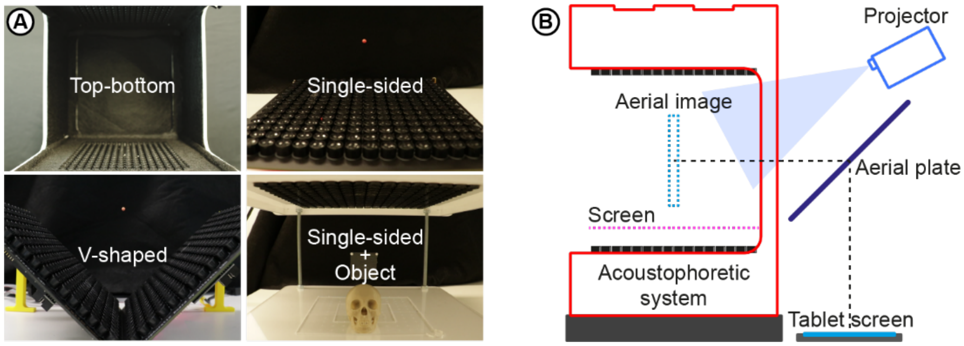

Figure 4: Details of our reference implementation. (A) Main transducer arrangements and embodiments supported. (B) Overview of the imaging solution used to support *MR Components* featuring a projector and an ASKA3D aerial plate.

planning algorithm keeps safe distances between levitated materials as it is difficult to separate levitation traps once they merge [45]. The maximum velocity constraints vary according to the number of elements and *materials* used, and thus it is important to investigate them in each case as described in Section 6. Given the planned position and timing information, our solvers can achieve reconfigurable animation using acoustophoresis.

5 EXAMPLES

Our design space can define a wide range of unique and rich physicalisations, extended via acoustic levitation. We then use our platform to demonstrate several physicalisation examples, highlighting DataLev's potential to enable mixed-reality animation, multi-modal interactions, and enriched materiality (see also our video).

5.1 Mixed-reality animation

DataLev's MR components allow physicalisations in which the dataset is presented both digitally and physically, co-located inside the working volume, with no user instrumentation (i.e., user is not expected to wear any head-mounted displays for 3D visualisation or haptic gloves for multi-modal feedback). The platform is versatile in supporting dynamic mixing of MR components, with *Levitated MR components* representing data of interest while the *Real MR* or *Virtual MR* ones can represent additional or contextual information, or vice versa. In addition, our physical representation in DataLev can be animated, allowing the embodiment of data meaning even through artefacts' movements (e.g., speeds, paths, vibrations).

Example **E1** (Figure 5) demonstrates the physicalisation of bird migration. An acoustically transparent screen is laid horizontally 3 cm above the bottom board, acting as a *Real MR* component on which a world map is projected. *Levitated MR components* are then used to represent several bird-migration routes, either as EPS particles or via a POV image of a bird flapping its wings along the route. Both are *Manual Animation*s, which the designer can tune to embody data (i.e., flying speed and time) or for expressive storytelling. The system supports multiple POV images, allowing a user to inspect the migratory patterns of multiple species at the same time.

Example **E2** (Figure 6) shows the mixed presentation of data using similar MR components (i.e., a projected map and EPS particles with different colours) to represent airport connections as a network diagram. The specific path connecting airports is not relevant, and only airport connectivity needs to be presented. Given that paths do not have meaning in this network diagram example (only the fact that they are connected is relevant), E2 uses *Automatic animation* (path planning) to define paths.

In the previous two examples, data of interest was presented by the *Levitated* content, while the contextual digital information in the form of maps was presented by the other components (i.e., projection). Example **E3** (Figure 7) demonstrates mixed-reality presentation in the opposite way, providing a neurosurgical visualisation using a *single-sided* transducer arrangement with a passive real-world *Object* [55]. A 3D-printed artefact (i.e., a skull) is physically placed by the user, defining the dataset to visualize. A projection on the structured fabric material is used to visualise the contextual data (e.g., a cross-sectional cryosection of a human head). Our video shows that the same example can be implemented using a different embodiment (i.e., V-shaped + *Object*), demonstrating how the DataLev platform supports different embodiments. Please note any of these examples can be trivially extended via *Virtual MR components* (i.e., the ASKA3D plate), such as to provide additional contextual information in mid-air (i.e., as illustrated later in **E5** and Figure 9).

5.2 Multi-modal Interaction

Example **E4** (Figure 8) uses a scatterplot to showcase the possibilities in our platform, supporting also interaction at a distance (gestures) and simultaneous visual and tactile modalities. The scatterplot is composed of 9 EPS particles levitated and represents the total investments in networks in three different countries over different years, each on a different axis. The user can inspect the data in different ways, like filtering, sorting, or updating. Using *Automatic Animation* (i.e., path planning), DataLev can translate each data point individually in 3D space and allows reconfigurability of the dataset. Unlike other reconfigurable data physicalisation platforms where physicalisation is limited to 2D or 2.5D, DataLev supports full 3D control. Using the Leap Motion camera in the DataLev system, simple user gestures can be mapped to the different tasks. During the gesture input, DataLev can also provide tactile

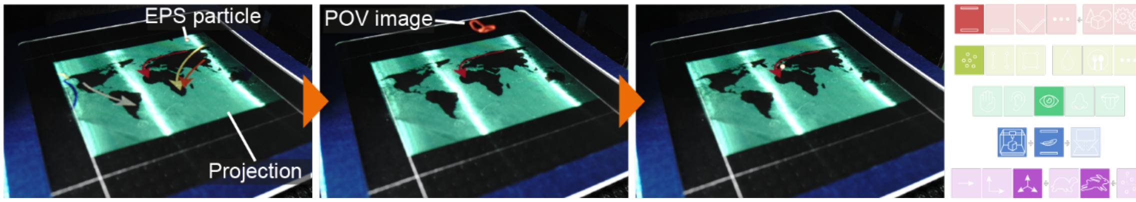

Figure 5: Example E1, embodying a 3D arc diagram representing bird migration. *Real MR* component is used to represent the world, while *Levitated MR* represents bird migrations as *Manual* animations using a single 3D particle or a POV shape to resemble birds.

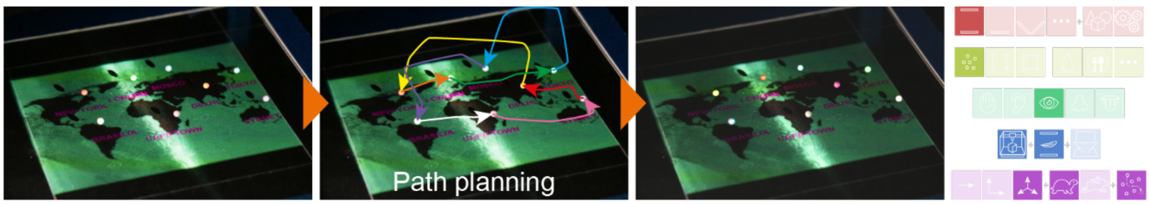

Figure 6: Example E2 combining *Real* and *Levitated* MR components to represent airport connections. *Automatic animation* (e.g., S2M2 [12]) is used to visualise existing connections in the graph.

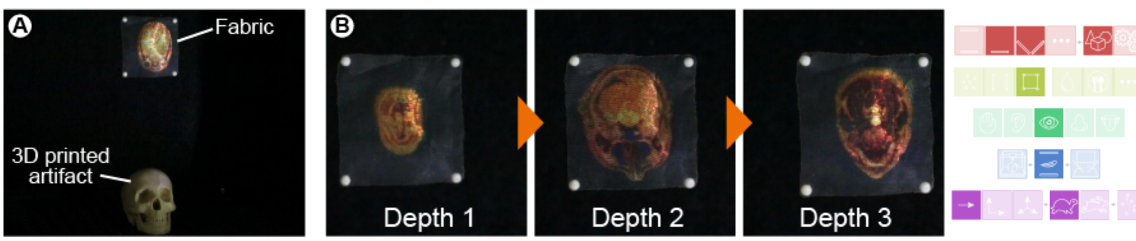

Figure 7: Example E3: Physicalisation of scientific data (i.e., the cross-section of a human male head from [80]). (A) Sections are presented on the fabric above the 3D-printed artefact; (B) Different cross-sectional images are projected when the fabric is at different depths, and the 3D skull helps the user know which part of the head is presented on the fabric.

feedback to the user according to the fingertip position obtained by the Leap Motion.

Example **E5** showcases an interactive weather report combining visual and auditory modalities, *Virtual MR content* and direct manipulation of *Levitated* content. This example used the ASKA3D plate to display the aerial imagery of the UK map (*Virtual MR*) and enabled the user to manipulate the levitated fabric with hands by using a direct manipulation technique (i.e., TipTrap [36]). When the user moves the lens displayed on the fabric to one of the cities (e.g., Newcastle, Glasgow) presented on the aerial imagery, the weather forecast in the city is visually displayed on the fabric and aurally presented by creating an audio spotlight. The audio could instead be used to physicalise other aspects of a dataset, such as urban noise levels.

While the haptic sensation was used as confirmatory feedback to support users' interaction in Example **E4**, it can also be used to embody data. Example **E6** (Figure 10A) shows a self-quantification example where a user can see and feel their heart rate at different times in the day to get a sense of their cardio fitness and appreciate the intensity of their daily workout. Here, the beating frequency of the heart is mapped to a haptic frequency and intensity and displayed on the user's finger, while the visual POV image of the heart contextualises the information.

5.3 Enriched materiality

The choice of material connects context, interaction and structure together and makes data more perceptible and interpretable [6]. These examples showcase the enriched materiality enabled by DataLev, presenting scatter plots made with materials that have meaning to the user in the specific context of that data. Example **E7** (Figure 10B) shows a scatter plot representing nutrient data of different food items (i.e., percentages of carbs, protein and fat, each on one axis). In this example, actual foods (e.g., bread, mushrooms) are used to represent their own data (i.e., instead of labels or icons, as in alternative systems), and users can even directly explore the data or see what the food tastes like. Such enriched materiality with free 3D reconfigurability (i.e., *Animation*) is only possible with acoustophoresis.

Materials that can be levitated in DataLev are not limited to solids and can be liquid droplets too. Example **E8** (Figure 11) shows a geospatial map presenting pH levels of acid rain in the US in

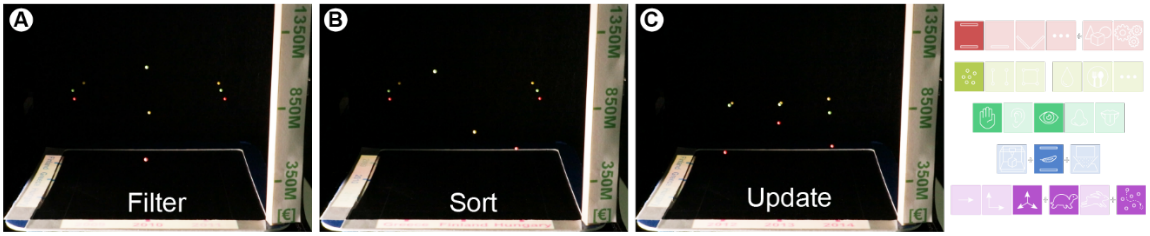

Figure 8: Example E4 showing a 3D scatter plot presenting the total investment in networks by the electronic communication sector, per country and year: The original data can be (A) filtered, (B) sorted and (C) updated.

Figure 9: Example E5 showing a geospatial map and presenting the UK weather forecast. The ASKA3D plate provides contextual information about the UK map, while users can directly manipulate the levitated fabric, which shows detailed information about the weather using both visual and auditory modalities.

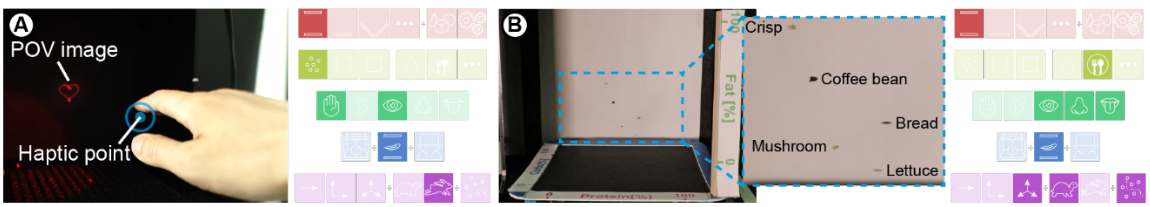

Figure 10: (A) Example E6 shows physicalisation of users' heart rates. The DataLev platform can simultaneously create a visual image (i.e., heart shape) and tactile sensation, which represents the heart rate. (B) Example E7 uses a 3D scatter plot to represent the nutrient data of different foods. DataLev can use different materials to represent the data, enhancing materiality in data physicalisations.

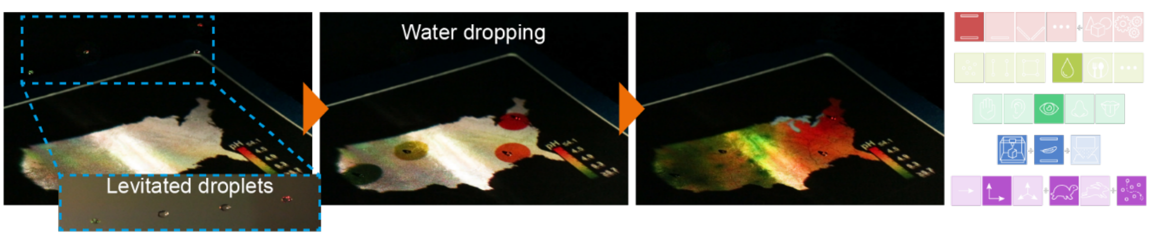

Figure 11: Example E8 shows a geospatial map presenting the pH level of acid rain in the US in 1994. We represented raindrops by dropping the levitated water droplets and updated the map with enhanced materiality.

1994. In this example, the water droplets that are levitated and illuminated by different colours represent raindrops with different pH levels. After dropping the levitated water droplets one by one at the specific positions, we update the geospatial map according to the pH level. Although we used water for all the droplets, this approach has a huge potential to embody data through different physical properties (i.e., using sourness to represent the pH level through taste or other material properties, such as viscosity and odour).

6 EVALUATION

DataLev provides a design space to help design rich physicalisations augmented with acoustic levitation, and our platform and examples illustrate its potential. However, conceptual designs resulting from

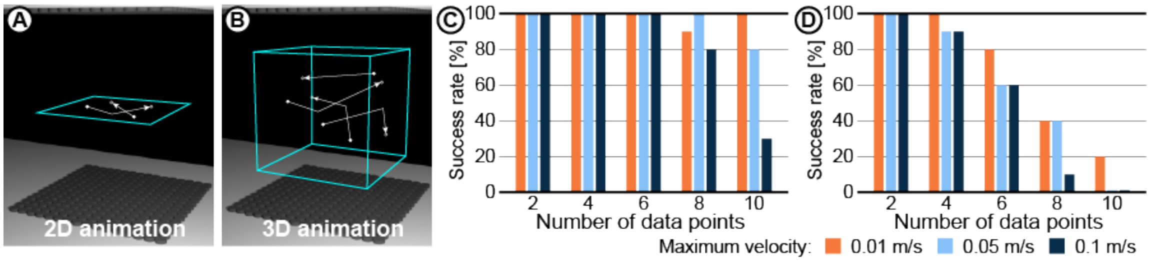

Figure 12: Animation performances under the 2D animation condition (A)(C) and the 3D animation condition (B)(D).

our design space could exceed the physical capabilities of the levitation system, and a designer needs to be aware of such limitations to make effective use of our tool at the intersection of what is desirable and what is feasible. The following 2 subsections provide a technical characterization of the capabilities of our platform, focusing on its reconfigurability (i.e., *Animation*) and materiality [6],[38], as two of the key strengths acoustophoresis brings to data physicalisation.

6.1 Animation Performance

The available movement speed is an important factor when designing animations in DataLev. Although a maximum speed of 8.75 m/s was reported in [33], this speed test was only for a single EPS particle moving along a 1D path (vertical or horizontal). In this evaluation, we examined achievable speeds in different conditions: animation dimension (2D plane or 3D volume) and the number of data points $N = \{2, 4, 6, 8, 10\}$. We used EPS particles in our animation evaluation as well because they are the most common materials used in acoustic levitation.

In this evaluation, we randomly assigned initial and target positions and used the path planning algorithm to determine the animation path for each data point. Here, the initial and target positions are constrained to a 2D plane (i.e., 12 cm × 12 cm at the centre of the system as shown in Figure 12A) or a 3D volume (i.e., 12 cm × 12 cm × 12 cm as shown in Figure 12B) according to the animation dimension, and the maximum velocity $v_{max}$was set to 0.01 m/s as a reference. We repeated this process to obtain 10 different animation patterns for each condition. Then, we played each animation at three different playing speeds (i.e., ×1, ×5, ×10) to check if all the EPS particles could successfully translate to their target positions and reported the success rate for each condition (see Figure 12). Since the reference maximum velocity v_{max} is 0.01 m/s, different playing speeds of ×1, ×5, and ×10 correspond to different maximum velocities of 0.01 m/s, 0.05 m/s, and 0.1 m/s, respectively. We do this instead of changing v_{max} to allow us to compare the same paths across different velocities because the change of v_{max} in path planning could lead to different paths for the same start and target positions.

Each condition was classified as a success if all the particles reached their destination without dropping (i.e., the system could not hold the particle in place by defying gravity, and it fell to the base of the platform). If any particle dropped, the trial was classified as a failure. The success rate was calculated by dividing the number of successful trials with the total number of attempted trials. For the 2D animations (see Figure 12C), we can always obtain high success rates (80–100%) when $N \leq 8$, even with the highest playing speed (i.e., $v_{max} = 0.1$ m/s). With 10 data points, the animation performance declined at the fastest animation velocity (i.e., 0.1 m/s), but we can still obtain high success rates at the slower animation speeds. The plot of the performance in 3D animations (see Figure 12D) indicates a tendency to decrease with the increase in the number of data points. This result agrees with the algorithmic evaluation from [56], which explains how the number of focal points influences the acoustic pressures the system can induce. Although it is possible to increase both N and v_{max} at the same time by increasing the number of transducers, we should strike a balance between them to make full use of the setup.

6.2 Materiality Performance

To evaluate the performance of materiality, we performed similar evaluations from the previous section using different four types of liquid droplets instead of EPS particles: water, milk, isopropyl alcohol, and UV resin. Manipulation of liquid droplets is usually more difficult than handling EPS particles because of their higher densities and the fact that the trapping forces need to be carefully adjusted to avoid droplet atomization. Therefore, we used less-challenging conditions, focusing on the 2D plane, smaller N (2 or 4), and lower v_{max} (0.01 or 0.03 m/s).

Figure 13A shows that there is no big difference between different materials when $N = 2$, but the materials start behaving differently when we double the number of data points ($N = 4$) as shown in Figure 13B. Droplets of isopropyl alcohol perform the best among the four materials, realising a high success rate (i.e., 70%) even with $v_{max} = 0.03$ m/s. On the other hand, the success rates with UV resin are the worst and lower than half even with the slower velocity (0.01 m/s). The material densities of the liquids used are the main factor in this result. The low density of isopropyl alcohol (about 80% of the others) makes the manipulation easier than with the others. The second possible reason is their surface tensions. When a droplet with a higher surface tension is injected from the dispenser, a stronger capillary force is applied to the droplet, making it difficult to inject a small droplet [19]. During the evaluation, we observed that the droplet size of the UV resin tends to be larger than the others, and we believe this affects the performance of the UV resin. To mitigate the effect of surface tension in the injecting process, we need an injecting approach like the one proposed in acoustophoretic printing [19].

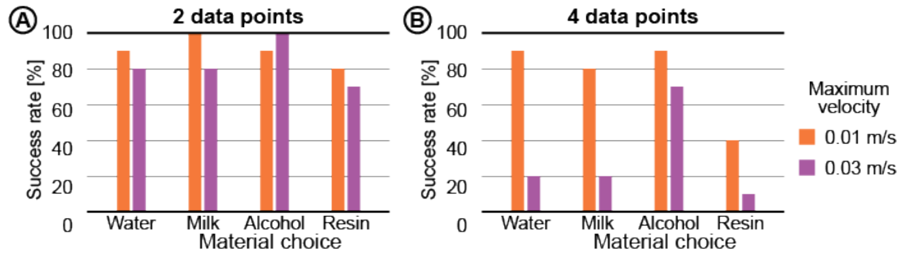

Figure 13: Different liquid materials' performances.

7 DISCUSSION

DataLev offers a new approach to data physicalisation by combining traditional methods with acoustophoresis. This creates new opportunities for creating reconfigurable physicalisations with interesting materiality and multi-modal interaction. Our design space provides a framework for exploring these physicalizations, and our reference platform offers a starting point for rapid prototyping.

Our technical evaluations show the potential of current acoustophoresis technology in terms of reconfigurability and materiality. As research into acoustophoresis continues, these capabilities are likely to improve, allowing us to explore a wider range of physicalisations within our design space. However, even with the current limitations of the platform, our evaluations can provide designers with a foundation for exploring physicalisations at the intersection of conceptual and physical. As the capabilities of the platform evolve, we would also need to extend our evaluations to consider more material properties, interactions between modalities, and dimensions within our space.

Even in the context of current technologies, DataLev's design space allows for the creation of novel physicalisations for a range of 3D chart types, including network diagrams, scatterplots, and map charts. These types of charts can be difficult to create using traditional 2.5D physicalisation methods, but with DataLev's support for 3D reconfigurability and non-electronic materiality, they become possible. Our 8 example physicalisations demonstrate the particular potential for showing data sets with a temporal component, such as airline routes or migration patterns, or those using materiality for semantic purposes, such as scatterplots of nutrition data or pH levels.

One potential benefit of using DataLev is the ability to easily add visual elements such as axes, texts, and legends without physically occluding or disturbing other data objects. This can improve the readability and understandability of the data by providing context and reference points for users [23]. In the DataLev platform, these additional elements can be added in a digital way, such as by projecting labels on a horizontal plane or levitated fabrics or by using an ASKA 3D plate to generate aerial labels in the vertical dimension. This allows the labels to be updated as the user changes the orientation or the datasets being visualized. Other auxiliary visual elements, such as a 3D grid coordinate system, measuring scale, and legends, can also be easily supported within DataLev to make the physicalisation more practical and understandable for users.

DataLev's use of acoustic levitation allows for digital and physical displays to complement each other, allowing for the best of both worlds. For instance, *Virtual MR components* can be used to show, reconfigure, and filter large datasets, while *Levitated MR components* can be used to focus on specific subsets and benefit from the enhanced materiality and 3D reconfigurability of acoustophoresis. This approach is particularly useful for physicalisations that use a focus + context approach [7], as it allows for reconfigurability and materiality to be dynamically adjusted. It can also be used to easily add visual elements such as axes, texts, and legends, which are necessary for interpretation but can be difficult to incorporate into a reconfigurable physicalisation.

The possibility of non-ephemeral *Levitated* content strengthens the case for DataLev as a bridge between the *Real* and *Virtual* components. While *Visual* POV, *Tactile* or *Auditory* elements are typically ephemeral, some of the other physicalisations we demonstrated using EPS and food particles are persistent for longer periods. The use of other materials (e.g., glue and solid elements) in acoustophoretic 3D printing and fabrication techniques [16] provides a further way for *Levitated* content to support dynamic and controlled transitions from immaterial but highly reconfigurable *Virtual* content to material-rich and permanent physicalisations, using mostly *Real* objects. We believe that this novel approach will blur the boundary between reconfigurable physicalisation and fabrication, opening up opportunities for new physical analytics.

In this work, we proposed a generic design space and illustrated it using a number of embodiments (top-bottom, single-sided, and V-shaped, with and without external objects) that used arrays of 16×16 transducers to manipulate 10 animated data objects (i.e., up to 32 static data objects according to [56]). Other embodiments can also be considered, such as top-bottom setups mounted on rotating frames [39], setups using more boards (e.g., for desktop or tabletop-sized physicalisations) or smaller setups that are wearable (e.g., GauntLev [44]). Each of these different embodiments will have its own capabilities, enabling a range of application scenarios and associated challenges. For instance, smaller setups will require the integration of acoustic board circuitry without compromising the aesthetics or functionality of other elements in the physicalisation. Larger setups (e.g., room-scale) will need more transducers, increasing the complexity for the acoustic solvers that must meet demanding performance requirements (i.e., >10K solutions computed per second). Evaluations that characterise the reconfiguration and material capabilities of each of these specific platforms would also be necessary. We believe such evaluations can help us understand some principles that can guide decisions on how different embodiments influence other parameters in our design space.

We presented co-located [36] and indirect [5] multi-modal interactions and mid-air haptic sensations. However, as discussed in Section 3.3, there is a spatial separation between the finger and the levitated contents even in the co-located case. User interactions in the DataLev platform tend to be mediated and it may not always be possible to emulate the dexterity of the interaction that is prevalent in free-hand exploration and manipulation. It can further be argued that such mediated interactions, whether purely gestural or augmented with tactile feedback, may never match the richness of physical contact that is possible with tangible materials. However, Cornelio et al. [43] showed in a study that users feel a similar sense of agency (measured using the intentional binding paradigm) using virtual knobs and mid-air haptic feedback as with physical knobs. This suggests that it is possible to create experiences like agency in the DataLev platform if the design of actions and outcomes is well thought out.

Regardless, these differences and losses in tangibility need to be understood and considered when designing DataLev physicalisations. For instance, hand-held objects that can be examined using fine motor skills and senses may require different types of interactions than levitated elements inside larger setups with reconfigurable materials. These reconfigurable materials may choose to minimise direct manipulation while offering maximum reconfigurability.

Understanding how to best design and exploit these strengths and limitations will require further efforts. Currently, the system has been set up to showcase the opportunities and possibilities enabled by DataLev, but it has not been designed to serve as a full end-to-end data physicalisation platform. Plug-ins for other visualisation packages like Excel, D3 [28], or Vega-Lite [59] would be required for converting raw data into 3D scene-graphs that are ready for physicalisation (e.g., our implementation uses the Unity 3D client in OpenMPD [47]). We believe this is an important step in exploring DataLev further, and one that we hope our open platform can facilitate. A second challenge is that we lack specific design principles for creating complex data physicalisations with DataLev. Further explorations are required, along with suitable studies that gather feedback and curate it into reusable knowledge for the future creation of levitation-enhanced data.

8 CONCLUSION

Our work presents DataLev, a design space and platform for data physicalisation that leverages the capabilities of acoustophoresis to create reconfigurable artefacts with enriched materiality and multi-modal interactions. The design space outlines the many ways in which data physicalisation can be enhanced through acoustophoresis, and the platform showcases 8 examples of novel data physicalisations that illustrate specific embodiments and chart types to exemplify the dimensions of this space. We also provide a technical evaluation of the reconfigurability and materiality capabilities of DataLev, highlighting its potential as a new platform for data physicalisation. We believe that acoustophoresis holds great promise for creating novel data physicalisations and that DataLev will inspire further research and development in this exciting field.

ACKNOWLEDGMENTS

We thank Elinor Haynes from University College London, who helped with the video creation. This work was supported by the EU-H2020 through their ERC Advanced Grant (number 787413), the Royal Academy of Engineering through their Chairs in Emerging Technology Program (CIET18/19), EPSRC through their prosperity partnership program (EP/V037846/1), UKRI Frontier Research Guarantee grant (EP/X019519/1).

REFERENCES

[1] Tobias Alrøe, Jonas Grann, Erik Grönvall, Marianne Graves Petersen, and Jesper L. Rasmussen. 2012. Aerial tunes: Exploring interaction qualities of mid-air displays. *NordiCHI 2012: Making Sense Through Design - Proceedings of the 7th Nordic Conference on Human-Computer Interaction*: 514–523. https://doi.org/10.1145/2399016.2399095
[2] Marco A.B. Andrade, Thales S.A. Camargo, and Asier Marzo. 2018. Automatic contactless injection, transportation, merging, and ejection of droplets with a multifocal point acoustic levitator. *Review of Scientific Instruments* 89, 12. https://doi.org/10.1063/1.5063715
[3] Marco A.B. Andrade, Tiago S. Ramos, Julio C. Adamowski, and Asier Marzo. 2020. Contactless pick-and-place of millimetric objects using inverted near-field acoustic levitation. Applied Physics Letters 116, 5. https://doi.org/10.1063/1.5138598
[4] Kathleen D. Ang, Faramarz F. Samavati, Samin Sabokrohiyeh, Julio Garcia, and Mohammed S. Elbaz. 2019. Physicalizing cardiac blood flow data via 3D printing. Computers and Graphics (Pergamon) 85: 42–54. https://doi.org/10.1016/j.cag.2019.09.004
[5] Myroslav Bachynskyi, Viktorija Paneva, and Jörg Müller. 2018. LeviCursor: Dexterous Interaction with a Levitating Object. In Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces (ISS '18): 253–262. https://doi.org/10.1145/3279778.3279802
[6] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. 2022. Making Data Tangible: A Cross-disciplinary Design Space for Data Physicalization. Association for Computing Machinery. https://doi.org/10.1145/3491102.3501939
[7] Patrick Baudisch, Nathaniel Good, and Paul Stewart. 2001. Focus plus context screens: Combining display technology with visualization techniques. In Proceedings of the 14th annual ACM symposium on User interface software and technology: 31–40.
[8] Sean Braley, Calvin Rubens, Timothy Merritt, and Roel Vertegaal. 2018. Griddrones: A self-levitating physical voxel lattice for interactive 3D surface deformations. UIST 2018 - Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology: 87–98. https://doi.org/10.1145/3242587.3242658
[9] E H Brandt. 1989. levitation in Physics. Science 243, 4889: 349–355.
[10] Nathalie Bressa, Henrik Korsgaard, Aurelien Tabard, Steven Houben, and Jo Vermeulen. 2021. What's the Situation with Situated Visualization? A Survey and Perspectives on Situatedness. IEEE Transactions on Visualization and Computer Graphics 28, 1: 107–117. https://doi.org/10.1109/TVCG.2021.3114835
[11] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces. UIST 2013 - Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology: 505–514. https://doi.org/10.1145/2501988.2502018
[12] Jingkai Chen, Jiaoyang Li, Chuchu Fan, and Brian Williams. 2020. Scalable and Safe Multi-Agent Motion Planning with Nonlinear Dynamics and Bounded Disturbances. In Proceedings of the AAAI Conference on Artificial Intelligence. Retrieved from http://arxiv.org/abs/2012.09052
[13] L. Cox, A. Croxford, B. W. Drinkwater, and A. Marzo. 2018. Acoustic Lock: Position and orientation trapping of non-spherical sub-wavelength particles in mid-air using a single-axis acoustic levitator. Applied Physics Letters 113, 5. https://doi.org/10.1063/1.5042518
[14] Tim Dwyer, Kim Marriott, Tobias Isenberg, Karsten Klein, Nathalie Riche, Falk Schreiber, Wolfgang Stuerzlinger, and Bruce H. Thomas. 2018. Immersive analytics. Immersive Analytics. Springer International Publishing 11190 LNCS: 1–23. https://doi.org/10.1007/978-3-030-01388-2_1
[15] Barrett Ens, Benjamin Bach, Maxime Cordeil, and Ulrich Engelke. 2021. Grand challenges in immersive analytics. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3411764.3446866
[16] Iñigo Ezcurdia;, Rafael Morales, Marco A. B. Andrade, and Asier Marzo. 2022. LeviPrint: Contactless Fabrication using Full Acoustic Trapping of Elongated Parts . ACM Transactions on Graphics 1, 1. https://doi.org/10.1145/3528233.3530752
[17] Andreas Rene Fender, Diego Martinez Plasencia, and Sriram Subramanian. 2021. ArticuLev: An Integrated Self-Assembly Pipeline for Articulated Multi-Bead Levitation Primitives. In Proceedings of 2021CHI Conference on Human Factors in Computing Systems ACM. https://doi.org/10.1145/3411764.3445342

[18] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. InFORM: Dynamic Physical Affordances and Constraints through shape and object actuation. UIST 2013 - Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology: 417–426. https://doi.org/10.1145/2501988.2502032

[19] Daniele Foresti, Katharina T. Kroll, Robert Amissah, Francesco Sillani, Kimberly A. Homan, Dimos Poulikakos, and Jennifer A. Lewis. 2018. Acoustophoretic printing. Science Advances 4, 8: 1–10. https://doi.org/10.1126/sciadv.aat1659

[20] Daniele Foresti, Majid Nabavi, Mirko Klingauf, Aldo Ferrari, and Dimos Poulikakos. 2013. Acoustophoretic contactless transport and handling of matter in air. Proceedings of the National Academy of Sciences of the United States of America 110, 31: 12549–12554. https://doi.org/10.1073/pnas.1301860110

[21] Euan Freeman, Asier Marzo, Praxitelis B. Kourtelos, Julie R. Williamson, and Stephen Brewster. 2019. Enhancing physical objects with actuated levitating particles. Proceedings - Pervasive Displays 2019 - 8th ACM International Symposium on Pervasive Displays, PerDis 2019. https://doi.org/10.1145/3321335.3324939

[22] Mathieu Le Goc, Lawrence Kim, Ali Parsaei, Jean-daniel Fekete, Sean Follmer, Mathieu Le Goc, Lawrence Kim, Ali Parsaei, Jean-daniel Fekete, Pierre Dragicevic, Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-daniel Fekete, and Pierre Dragicevic. 2016. Zooids: Building Blocks for Swarm User Interfaces. UIST 2016 - Proceedings of the 29th Annual Symposium on User Interface Software and Technology.

[23] Mathieu Le Goc, Charles Perin, Sean Follmer, Jean Daniel Fekete, and Pierre Dragicevic. 2019. Dynamic Composite Data Physicalization Using Wheeled Micro-Robots. IEEE Transactions on Visualization and Computer Graphics 25, 1: 737–747. https://doi.org/10.1109/TVCG.2018.2865159

[24] Mohsen Habibi, Shervin Foroughi, Vahid Karamzadeh, and Muthukumaran Packirisamy. 2022. Direct sound printing. Nature Communications 13, 1: 1–11. https://doi.org/10.1038/s41467-022-29395-1

[25] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. Shapeclip: Towards rapid prototyping with shape- Changing displays for designers. In Proceedings of 2015CHI Conference on Human Factors in Computing Systems 2015-April: 19–28. https://doi.org/10.1145/2702123.2702599

[26] Keisuke Hasegawa, Liwei Qiu, Akihito Noda, Seki Inoue, and Hiroyuki Shinoda. 2017. Electronically steerable ultrasound-driven long narrow air stream. Applied Physics Letters 111, 6. https://doi.org/10.1063/1.4985159

[27] Jeffrey Heer and George G. Robertson. 2007. Animated transitions in statistical data graphics. IEEE Transactions on Visualization and Computer Graphics 13, 6: 1240–1247. https://doi.org/10.1109/TVCG.2007.70539

[28] Michael Bostock; Vadim Ogievetsky; Jeffrey Heer. 2011. D3 Data-Driven Documents. IEEE Transactions on Visualization and Computer Graphics 17, 12: 2301–2309.

[29] Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. 2015. Unimorph -fabricating thin-film composites for shape-changing interfaces. UIST 2015 - Proceedings of the 28th Annual ACM Symposium on User Interface Software and Technology: 233–242. https://doi.org/10.1145/2807442.2807472

[30] Bridger Herman, Maxwell Omdal, Stephanie Zeller, Clara A. Richter, Francesca Samsel, Greg Abram, and Daniel F. Keefe. 2021. Multi-Touch Querying on Data Physicalizations in Immersive AR. Proceedings of the ACM on Human-Computer Interaction 5, ISS. https://doi.org/10.1145/3488542

[31] Hessam Djavaherpour, Mahdavi-Amiri Ali, and Faramarz F. Samavati. 2017. Physical Visualization of Geospatial Datasets. IEEE Computer Graphics and Applications: 61–69.

[32] Ryuji Hirayama, Giorgos Christopoulos, Diego Martinez Plasencia, and Sriram Subramanian. 2022. High-speed acoustic holography with arbitrary scattering objects. Science Advances 8, 24: 1–13. Retrieved from https://www.science.org/doi/10.1126/sciadv.abn7614

[33] Ryuji Hirayama, Diego Martinez Plasencia, Nobuyuki Masuda, and Sriram Subramanian. 2019. A volumetric display for visual, tactile and audio presentation using acoustic trapping. Nature 575, 7782: 320–323. https://doi.org/10.1038/s41586-019-1739-5

[34] Ryuji Hirayama and Sriram Subramanian. 2022. Magical Multi-modal Displays using Acoustophoresis. XRDS 29, 1: 54–58.

[35] Seki Inoue, Shinichi Mogami, Tomohiro Ichiyama, Akihito Noda, Yasutoshi Makino, and Hiroyuki Shinoda. 2019. Acoustical boundary hologram for macroscopic rigid-body levitation. The Journal of the Acoustical Society of America 145, 1: 328–337. https://doi.org/10.1121/1.5087130

[36] Eimontas Jankauskis, Sonia Elizondo, Roberto Antonio Montano Murillo, Asier Marzo, and Diego Martinez Plasencia. 2022. TipTrap: A Co-located Direct Manipulation Technique for Acoustically Levitated Content. UIST 2022 - Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology.

[37] Yvonne Jansen, Pierre Dragicevic, Jean-daniel Fekete, and Jean-daniel Fekete Evaluating. 2013. Evaluating the Efficiency of Physical Visualizations. In Proceedings of 2013CHI Conference on Human Factors in Computing Systems ACM.

[38] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and challenges for data physicalization. In Proceedings of 2015 CHI Conference on Human Factors in Computing Systems ACM: 3227–3236. https://doi.org/10.1145/2702123.2702180

[39] Ben Kazemi, Roberto Montano-Murillo, and Diego Martinez Plasencia. 2022. Two-Gimbal PAT: An artistic installation combining mechanical and acoustic rotation of levitated content. In CHI Conference on Human Factors in Computing Systems Extended Abstracts. https://doi.org/10.1145/3491101.3519891

[40] John Lasseter. 1987. Principles of traditional animation applied to 3D computer animation. In Proceedings of the 14th annual conference on Computer graphics and interactive techniques (SIGGRAPH '87). 21, 4: 35–44.

[41] Bongshin Lee, Nathalie Henry Riche, Petra Isenberg, and Sheelagh Carpendale. 2015. More Than Telling a Story: Transforming Data into Visually Shared Stories. IEEE Computer Graphics and Applications 35, 5: 84–90. https://doi.org/10.1109/MCG.2015.99

[42] Jinha Lee, Rehmi Post, and Hiroshi Ishii. 2011. ZeroN: Mid-air tangible interaction enabled by computer controlled magnetic levitation. UIST'11 - Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology: 327–336. https://doi.org/10.1145/2047196.2047239

[43] Patricia Cornelio Martinez, Silvana De Pirro, Chi Thanh Vi, and Sriram Subramanian. 2017. Agency in Mid-air Interfaces. 2426–2439.

[44] Asier Marzo. 2016. GauntLev: A wearable to manipulate free-floating objects. Conference on Human Factors in Computing Systems - Proceedings: 3277–3281. https://doi.org/10.1145/2858036.2858370

[45] Asier Marzo and Bruce W. Drinkwater. 2019. Holographic acoustic tweezers. Proceedings of the National Academy of Sciences of the United States of America 116, 1: 84–89. https://doi.org/10.1073/pnas.1813047115

[46] Asier Marzo, Sue Ann Seah, Bruce W. Drinkwater, Deepak Ranjan Sahoo, Benjamin Long, and Sriram Subramanian. 2015. Holographic acoustic elements for manipulation of levitated objects. Nature Communications 6: 1–7. https://doi.org/10.1038/ncomms9661

[47] Roberto Montano-Murillo, Ryuji Hirayama, and Diego Martinez Plasencia. 2022. OpenMPD: A low-level presentation engine for Multimodal Particle-based Displays (MPDs). ACM Transactions on Graphics 1, 1: 1-12(To Appear).

[48] Hila Mor, Tianyu Yu, Ken Nakagaki, Benjamin Harvey Miller, Yichen Jia, and Hiroshi Ishii. 2020. Venous Materials: Towards Interactive Fluidic Mechanisms. In Proceedings of 2020CHI Conference on Human Factors in Computing Systems: 1–14. https://doi.org/10.1145/3313831.3376129

[49] Rafael Morales, Asier Marzo, Sriram Subramanian, and Diego Martínez. 2019. LeviProps: Animating levitated optimized fabric structures using holographic acoustic tweezers. Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology: 651–661. https://doi.org/10.1145/3332165.3347882

[50] Mohd Adili Norasikin, Diego Martinez Plasencia, Gianluca Memoli, and Sriram Subramanian. 2019. SonicSpray: A technique to reconfigure permeable mid-air displays. ISS 2019 - Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces: 113–122. https://doi.org/10.1145/3343055.3359704

[51] Yoichi Ochiai, Takayuki Hoshi, and Ippei Suzuki. 2017. Holographic whisper: Rendering audible sound spots in three-dimensional space by focusing ultrasonic waves. Conference on Human Factors in Computing Systems - Proceedings 2017-May: 4314–4325. https://doi.org/10.1145/3025453.3025989

[52] Yoichi Ochiai, Takayuki Hoshit, and Jun Rekimoto. 2014. Pixie dust: Graphics generated by levitated and animated objects in computational acoustic-potential field. ACM Transactions on Graphics 33, 4. https://doi.org/10.1145/2601097.2601118

[53] Themis Omirou, Asier Marzo Perez, Sriram Subramanian, and Anne Roudaut. 2016. Floating charts: Data plotting using free-floating acoustically levitated representations. 2016 IEEE Symposium on 3D User Interfaces, 3DUI 2016 - Proceedings: 187–190. https://doi.org/10.1109/3DUI.2016.7460051

[54] Viktorija Paneva, Myroslav Bachynskyi, and Jörg Müller. 2020. Levitation Simulator: Prototyping Ultrasonic Levitation Interfaces in Virtual Reality. In Proceedings of 2020CHI Conference on Human Factors in Computing Systems: 1–12.

[55] Randy Pausch, John C Goblel, and Neal F Kassell. 1994. Passive Real-World Neurosurgical Visualization. Conference on Human Factors in Computing Systems - Proceedings: 452–458.

[56] Diego Martinez Plasencia, Ryuji Hirayama, Roberto Montano-Murillo, and Sriram Subramanian. 2020. GS-PAT: High-Speed Multi-Point Sound-Fields for Phased Arrays of Transducers. ACM Transactions on Graphics 39, 4. https://doi.org/10.1145/3386569.3392492

[57] He Ren and Eva Hornecker. 2021. Comparing Understanding and Memorization in Physicalization and VR Visualization. TEI 2021 - Proceedings of the 15th International Conference on Tangible, Embedded, and Embodied Interaction. https://doi.org/10.1145/3430524.3442446

[58] Anne Roudaut, Abhijit Karnik, Markus Löchtefeld, and Sriram Subramanian. 2013. Morphees: Toward high "shape resolution" in self-actuated flexible mobile devices. In Proceedings of 2013CHI Conference on Human Factors in Computing Systems ACM: 593–602. https://doi.org/10.1145/2470654.2470738

[59] Arvind Satyanarayan, Dominik Moritz, Kanit Wongsuphasawat, and Jeffrey Heer. 2017. Vega-Lite: A Grammar of Interactive Graphics. IEEE Transactions on Visualization and Computer Graphics 23, 1: 341–350. https://doi.org/10.1109/TVCG.2016.2599030

[60] Pitchaya E Sitthi-Amorn Javier Ramos Yuwang Wang Joyce Kwan Justin Lan Wenshou Wang Wojciech Matusik. 2015. MultiFab: A Machine Vision Assisted Platform for Multi-Material 3D Printing. ACM Trans. Graph. Article 34, August: 11. Retrieved from http://doi.acm.org/
[61] D. E. Smalley, E. Nygaard, K. Squire, J. Van Wagoner, J. Rasmussen, S. Gneiting, K. Qaderi, J. Goodsell, W. Rogers, M. Lindsey, K. Costner, A. Monk, M. Pearson, B. Haymore, and J. Peatross. 2018. A photophoretic-Trap volumetric display. Nature 553, 7689: 486–490. https://doi.org/10.1038/nature25176
[62] Ryo Suzuki, Clement Zheng, Yasuaki Kakehi, Tom Yeh, Ellen Yi Luen Do, Mark D. Gross, and Daniel Leithinger. 2019. ShapeBots: Shape-changing Swarm Robots. In Proceedings of the 32nd annual ACM symposium on user interface software and technology: 493–505.
[63] Saiganesh Swaminathan, Conglei Shi, Yvonne Jansen, Pierre Dragicevic, Lora Oehlberg, and Jean Daniel Fekete. 2014. Supporting the design and fabrication of physical visualizations. Conference on Human Factors in Computing Systems - Proceedings: 3845–3854. https://doi.org/10.1145/2556288.2557310
[64] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring interactions with physically dynamic bar charts. In Proceedings of 2015 CHI Conference on Human Factors in Computing Systems ACM: 3237–3246. https://doi.org/10.1145/2702123.2702604
[65] Alice Thudt, Uta Hinrichs, Samuel Huron, and Sheelagh Carpendale. 2018. Self-reflection and personal physicalization construction. In Proceedings of 2018 CHI Conference on Human Factors in Computing Systems ACM 2018-April: 1–13. https://doi.org/10.1145/3173574.3173728
[66] Yuki Uno, Hao Qiu, Toru Sai, Shunta Iguchi, Yota Mizutani, Takayuki Hoshi, Yoshihiro Kawahara, Yasuaki Kakehi, and Makoto Takamiya. 2018. Luciola:A Millimeter-Scale Light-Emitting Particle Moving in Mid-Air Based On Acoustic Levitation and Wireless Powering. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies 1, 4: 1–17. https://doi.org/10.1145/3161182
[67] Annemiek Veldhuis, Rong Hao Liang, and Tilde Bekker. 2020. CoDa: Collaborative data interpretation through an interactive tangible scatterplot. TEI 2020 - Proceedings of the 14th International Conference on Tangible, Embedded, and Embodied Interaction: 323–336. https://doi.org/10.1145/3374920.3374934
[68] Chi Thanh Vi, Asier Marzo, Damien Ablart, Gianluca Memoli, Sriram Subramanian, Bruce Drinkwater, and Marianna Obrist. 2017. TastyFloats:A Contactless Food Delivery System. In Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces: 161–170. Retrieved from https://doi.org/10.1145/3132272.3134123%0D
[69] Chi Thanh Vi, Asier Marzo, Gianluca Memoli, Emanuela Maggioni, Damien Ablart, Martin Yeomans, and Marianna Obrist. 2020. LeviSense: A platform for the multisensory integration in levitating food and insights into its effect on flavour perception. International Journal of Human Computer Studies 139, March: 102428. https://doi.org/10.1016/j.ijhcs.2020.102428
[70] Wesley Willett, Yvonne Jansen, and Pierre Dragicevic. 2017. Embedded Data Representations. IEEE Transactions on Visualization and Computer Graphics 23, 1: 461–470. https://doi.org/10.1109/TVCG.2016.2598608
[71] W. J. Xie, C. D. Cao, Y. J. Lü, Z. Y. Hong, and B. Wei. 2006. Acoustic method for levitation of small living animals. Applied Physics Letters 89, 21: 1–4. https://doi.org/10.1063/1.2396893
[72] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically actuated soft composite materials for shape changing interfaces. UIST 2013 - Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology: 13–22. https://doi.org/10.1145/2501988.2502037
[73] Lining Yao, Jifei Ou, Chin-Yi Cheng, Helene Steiner, Wen Wang, Guanyun Wang, and Hiroshi Ishii. 2015. bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces. In Proceedings of 2015 CHI Conference on Human Factors in Computing Systems ACM: 1–10. https://doi.org/10.1016/B978-0-12-811155-0.00004-1
[74] Toshiya Yui and Tomoko Hashida. 2016. Floatio:Floating Tangible User Interface Based on Animacy Perception. Proceedings of the 29th Annual Symposium on User Interface Software and Technology: 43–45. https://doi.org/10.1145/2984751.2985699
[75] Data Storytelling with LEGOs. Retrieved May 25, 2021 from http://dataphys.org/list/data-storytelling-with-lego/
[76] Steven Pinker explains Global Life Expectancy with Physical Line Charts. Retrieved May 28, 2021 from http://dataphys.org/list/steven-pinker-explains-global-life-expectancy-with-physical-line-charts/
[77] ASKA3D. Retrieved July 4, 2022 from https://aska3d.com/en/
[78] Drone 100: A World Record with 100 Points – Ars Electronica Blog. Retrieved September 16, 2022 from https://ars.electronica.art/aeblog/en/2016/01/12/drone100/
[79] Park Row London & Monarch Theatre – Wonderland Restaurants. Retrieved July 5, 2022 from https://parkrowlondon.co.uk/
[80] The National Library of Medicine's Visible Human Project. Retrieved July 4, 2022 from https://www.nlm.nih.gov/research/visible/visible_human.html