Augmented Dynamic Data Physicalization: Blending Shape-changing Data Sculptures with Virtual Content for Interactive Visualization

Severin Engert, Andreas Peetz, Konstantin Klamka, Pierre Surer, Tobias Isenberg, Raimund Dachselt

Abstract—We investigate the concept of Augmented Dynamic Data Physicalization, the combination of shape-changing physical data representations with high-resolution virtual content. Tangible data sculptures, for example using mid-air shape-changing interfaces, are aesthetically appealing and persistent, but also technically and spatially limited. Blending them with Augmented Reality overlays such as scales, labels, or other contextual information opens up new possibilities. We explore the potential of this promising combination and propose a set of essential visualization components and interaction principles. They facilitate sophisticated hybrid data visualizations, for example Overview & Detail techniques or 3D view aggregations. We discuss three implemented applications that demonstrate how our approach can be used for personal information hubs, interactive exhibitions, and immersive data analytics. Based on these use cases, we conducted hands-on sessions with external experts, resulting in valuable feedback and insights. They highlight the potential of combining dynamic physicalizations with dynamic AR overlays to create rich and engaging data experiences.

Index Terms—Augmented physicalization; Augmented Dynamic Data Physicalization; hybrid visualization; physical-virtual continuum; tangible interaction; shape-changing interface; data visualization; interactive storytelling; holographic overlays; data sculptures.

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1 INTRODUCTION

The visualization of data in manifold ways is central to our modern, increasingly digital society and has therefore seen numerous research contributions over the past decades. While often still centered around classical 2D desktop environments with mouse and keyboard input, researchers have addressed novel form factors and display environments with alternative, more natural interaction approaches to support improved data analysis in modern and ubiquitous computing environments [67], [94]. Among them are mobile devices [66], large high-resolution displays [11], multi-display environments (e.g., [48]), or augmented and virtual reality setups for Immersive Analytics [17], [30]. One interesting research direction is *data physicalization*, where the geometric and material properties of physical artifacts are used to encode and embed data (e.g., [26], [55], [125]). Artistic and research-related physicalizations show the potential of making data tangible and underline its cross-disciplinary nature, as discussed in the past [9], [25], [49].

Physicalizations have been successful in conveying a physical and tangible means of visualizing data, but they remain mostly static. While this is inherent to the medium, dynamic changes may be desirable or even necessary after data updates. Dynamic physicalizations solve this issue, with only few approaches to date in the form of actuated objects [21], micro-robots that form dynamic composite data physicalizations [64], or shape-changing 2.5D pin-arrays (e.g., [35], [72], [121]).

The missing dynamics of data physicalizations can be addressed by borrowing from the research area of *shape-changing interfaces* (SCI) [1], [91], where a multitude of physically tangible, interactive devices, surfaces, or spaces has been proposed that facilitate rich and organic experiences with computational devices [112]. Among those approaches supporting shape-change under computational control is the popular category of texture-changing SCIs [91], also called 2.5D displays. These devices alter the height of the individual, often colored display elements—either as actuated pins from the bottom [35], [72] or animated by strings from the top [29], [74]. Often, they allow for rather simple, sculpture-like data visualizations with fewer details when compared to, for example, pixel-based displays [97]. Complex visualizations using physical forms or SCIs remain challenging, as state-of-the-art devices are limited in their expressivity due to their constrained physical shape and appearance. In addition, their resolution is restricted by the size and precision of internal or visible composite components [1].

Our vision is thus to overcome both the static nature of many data physicalizations and the limited space and resolution of shape-changing approaches for data visualizations by combining dynamic, interactive data physicalizations with augmented reality (AR) content. We call this concept **Augmented Dynamic Data Physicalization**, thereby extending the term *augmented physicalization* from Djavaherpour et al. [23] by merging active physicalizations with augmented reality. In contrast to prior work, this extension enables data physicalization with both parts offering dynamic input and output capabilities that work seamlessly together. Visual enhancements of rigid data physicalizations or of dynamic

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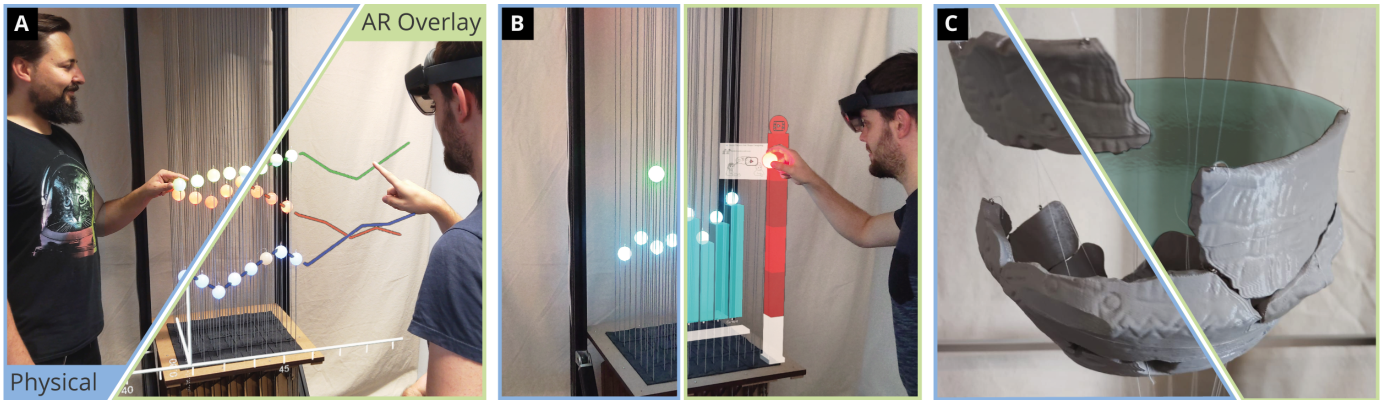

Fig. 1: With Augmented Dynamic Data Physicalization, we present concepts and implementations for combining dynamic *Data Physicalizations* with *Augmented Reality* to create interactive data visualizations, for example, for lightweight data analysis (A), personal applications (B), or physical artifacts in a storytelling museum context (C).

SCI have been proposed already, for instance by directly embedding visualizations (e.g., [81], [101]), projecting data on top (e.g., [35], [53]), or overlaying information using AR (e.g., [20], [47]). Here we explore the basic principles of Augmented Dynamic Data Physicalizationand provide a detailed account of related work (Fig. 2).

Most existing approaches, however, do not facilitate an effortless transition between persistent tangible data sculptures and hybrid data visualizations that incorporate both physical and virtual visualizations, and they lack rich means of interacting with the data. To improve on that and explore our vision of Augmented Dynamic Data Physicalization in practice, we propose to combine shape-changing interfaces for a persistent, physical, and ambient (low-fidelity) representation of data with supplementary (high-fidelity) AR overlays to provide a flexible mixed reality (MR) experience of tangible data visualizations. The recent advances in MR technology, especially in head-mounted displays (HMD), further fuel this approach.

We investigate this complex interplay of dynamic physical and virtual visualization (which has been considered only rarely [70], [75]) using a concrete type of shape-changing display: We combine mid-air, string-based shape-changing interfaces (e.g., [4], [29], [100], [124], [127]) with supplementary high-resolution AR content. In this way, we combine the specific advantages of both technologies to get the best out of them. By adding detailed information to parts of the physicalization, we show how established visualization techniques such as focus + context [19], details on demand [107], or coordinated views [93] are feasible on our device combination. We split the interaction among the involved devices, including direct input with haptic feedback with the SCI as well as mid-air gestural input of the AR HMD.

To validate our concepts, we implemented prototypes for three different scenarios. We demonstrate visualizations for data analysis in a company (Fig. 1A), a smart living room setting for private users (Fig. 1B), and an interactive exhibition for a museum (Fig. 1C). We used them for interviews with three domain experts to get in-depth external feedback about the validity and usefulness of Augmented Dynamic Data Physicalizationexemplified by our system. In summary, our main contributions are:

- a systematic **design investigation** in blending dynamic midair data physicalizations with AR exploring the concept of Augmented Dynamic Data Physicalization,
- a structured repertoire of essential **visualization components**, **interaction principles**, and **visualization concepts** with synergies between physical and virtual properties,
- three **implemented example applications** that demonstrate, how our concept can be conveniently used for personal information hubs, interactive exhibitions, and immersive data analytics scenarios, and
- promising insights and **discussion of expert feedback** from hands-on sessions with the implemented applications.

2 RELATED WORK

We draw inspiration from prior research on *non-actuated data physicalization* (Sec. 2.1) and combine *shape-changing UIs and data sculptures* (Sec. 2.2) with *immersive augmented reality overlays* (Sec. 2.3). To position our approach of *Augmented Dynamic Data Physicalization*, we discuss representative examples along an overarching classification theme (Fig. 2) that crosses the dimensions of visual enhancements (columns: E *embedded*, P *projected*, and A *AR overlay*) and their physical geometries (rows: ❶ *non-actuated* and ❷ *shape-changing*).

2.1 Non-actuated data physicalization (❶ + E P)

While a variety of passive physical visualizations—where primarily geometry or material properties encode the data—have been presented (overview: [25]), we are particularly interested in visually enhanced data physicalization.

In this regard, prior research explored how emerging display technologies could be *embedded* (E)[1] to create, for instance, interactive info-graphics using printed electronics [84], dynamic graphs based-on microfluids [81], or adjustable map visualizations made with polarized light mosaics [106]. Driven by enabling technologies and programmable materials, such data physicalization techniques offer aesthetic qualities for specific applications, but are also limited in their visual capabilities due to technically imposed constraints such as pre-defined electrodes, microtubes, or polygons.

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[1] Please note, the term *embedded* is used here in a technical sense, other than describing the connection of data and the environment [125].

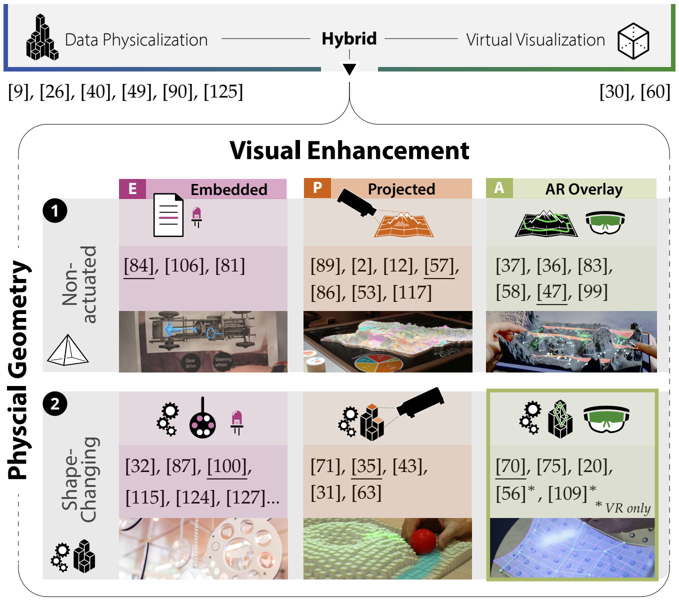


Fig. 2: We position the **Augmented Dynamic Data Physicalization** approach at the intersection of shape-changing data physicalization and virtual AR-based visualization as a dynamic hybrid form that blends the best of both worlds: Dynamic and tangible data sculptures with a physically-persistent and ambient character as well as additional virtual layers of information for more detailed on-demand content overlays. The mentioned references are examples. The images shown are from the publications with underlined references.

To facilitate more dynamic visual augmentations, *projected* (P) layers of information have been investigated. For example, augmented relief models, such as PARM [89], Cityscope [2], or Gaia [12], combine physical map artefacts with visual projection overlays to create more dynamic and interactive systems. In addition, more tangible approaches like Illuminating Clay [86], SandScape [53], and TanGeoMS [117] even allow the user to deform the surface and thereby directly receive visual feedback from the system (for example, adjusted topological representations).

We are inspired by the calm and aesthetic qualities of tangible artefacts and data physicalizations and also want to place a special emphasis on the emotional and hedonic qualities, as discussed in [123]. So we aim to retain the beauty and physical persistence of the simple and the abstract as an overarching theme to integrate Augmented Dynamic Data Physicalizations, e.g., into minimalist living and interior spaces. Besides these qualities, we also embrace other benefits of data physicalization as noted by Jansen et al. [55], including benefits related to perception, cognition, accessibility, and engagement.

2.2 Shape-changing UIs and data sculptures (❷+E P)

To extend the dynamic capabilities of interactive physicalization and data sculptures, research has been conducted into how spatial actuation and shape change can be used to physically react to users (overview: [1]).

Rasmussen et al. [91] classify *shape-changing UIs* along a number of properties that can be computationally controlled such as the orientation [118], volume [21], texture [35], viscosity [34], or spatiality [4]. The category of texture-changing SCIs (also known as 2.5D displays) is the most popular [91]. Overall, 2.5D displays (e.g., pin-actuated [32], [35], [71]) have dynamic physical affordances and constraints by controlling the height of individual elements. As an additional dimension, the approaches also often use either *embedded* (E) (e.g., LEDs [32], [115]) or *projected* (P) (e.g., [35], [71]) visual enhancements to provide additional layers of information. Representative projects are, for instance, Relief [71], inFORM [35], or ShapeCanvas [32], which together cover a range of interesting tangible visualizations for geographic maps, math equations, or weather.

In addition, interactive *data sculptures* [128]—a term being used well before data physicalization [26]—and mid-air interfaces have been proposed in art and research. These kinds of installations elevate objects in mid-air by employing string-based (e.g., [29], [100], [127]), magnetic (e.g., [68]), acoustic (e.g., [85], [105]), or air flow (e.g., [3], [39], [121]) levitation. As representatives of shape-changing data physicalizations, string-based data sculptures are of particular interest to us because these types of mid-air displays often embed visual light sources to create single or connected data points, and offer potential for visual extension. While a series of artistic installations have been presented (e.g., greyworld [42], projects by ART+COM Studios [4], [5], [6], WHITEvoid [124], TAIT [116], Hypersonic [50], and sosolimited [111]), research also explored the potential for string-acutated interactive visualizations. For instance, Econundrum [100] visualizes the climate impact of dietary choice through a shared data sculpture. More generic approaches like STRAIDE [29] or AeroRigUI [127] provide platforms for distributed and ceiling-mounted, string-based displays and enable the positioning and orientation of physical objects.

Motivated by the expressiveness in both artistic and functional qualities of shape-changing data sculptures, our approach aims to retain these characteristics and visually extend them through virtual overlays for more complex visualizations as needed, thereby leaving pure artistic ground.

2.3 Immersive augmented reality overlays (❶❷+A)

AR overlays (A) have been discussed either for the visual augmentation of *non-actuated* physicalizations or in the context of haptic proxies by rendering dynamic tangible sensations using *shape-changing* and actuated mechanisms. Examples of combining contextual tangible references with virtual visualization include opportunistic controls [46], lab devices [59], relief maps (e.g., [47], [83]), and handheld artefacts (e.g., [36], [37], [99]) and devices (e.g., [44], [62], [110]). Gillet et al. [36], [37] combined, for example, AR overlays with tangible molecular models to allow users to switch between different representations and dynamically explore additional molecular properties. For the seamless integration of touch input, Bae et al. [8] introduced a computational design pipeline that extend physicalizations with capacitive touch sensors that allow, for instance, to visualize active selection of a physical node-link artefact in mobile AR. Nittala et al. [83] introduce PlanWell, a spatial user interface for collaborative petroleum well-planning based on a physical topographical map that is augmented with an extended user interface using an iPad and stylus. Herman et al. [47] combine geographic relief maps with immersive AR to support multi-touch querying. From a visualization perspective, the dynamic AR overlays and the physical map complement each other in a meaningful way, facilitating a tangible and spatial interaction as well as dynamic in-situ visualizations. Similar but using a different form factor, Tangible Globes [99] combine virtual visualizations with a spherical earth physicalization. RealitySketch [113], e.g., embeds responsive graphics and visualizations in mobile AR through dynamic sketching. Finally, many artistic installations have been presented in which AR overlays are used to extend urban spaces or city models. Sanaeipoor & Emami, e.g., explored how cities can use AR for installing public art projects [98], while Echavarria et al. [27] discussed artwork and augmented reality maps with embedded creative narratives of the communities' cultural environment.

In contrast, Sublimate [70] investigates state-changing virtual and physical rendering to augment interaction with active shape displays. In a similar respect, Lindlbauer et al. [75] combine SCIs and Spatial AR to enable extended object appearance. Embodied Axes [20] and MADE-Axis [110] use tangible, actuated interaction for 3D augmented reality data spaces. While there is only a small body of prior research combining AR with shape displays, the focus of these works, however, has been on rendering dynamic haptic sensations. With similar goals, approaches such as Elevate [56] or Shapeshift [109] explore how shape displays can also support VR experiences.

In our work, we discuss a third overarching perspective that aims to enable users to seamlessly move from abstract dynamic data physicalizations (for instance, single illuminated data points) to more detailed and complex hybrid visualizations (e.g., an extended graph visualization). Augmented Dynamic Data Physicalization builds on the design rationale that both ambient and detailed views of a dynamic data sculpture are beneficial.

3 DESIGN CONCEPT: AUGMENTED DYNAMIC DATA PHYSICALIZATION

As mentioned above, we aim to explore the promising intersection of dynamic data physicalizations and augmented reality, which we call **Augmented Dynamic Data Physicalization**. In particular, we investigate the transitions, visual synergies, and interaction possibilities within the continuum of *physical* and *virtual* visualizations. Inspired by the methodological approach of Physecology [103], we first define the conceptual framework to systemically explore our envisioned approach. We believe that the following concept subsections can be generalized to most types of *dynamic* data physicalizations, including, for example, physical shape-changing displays like pin-arrays, levitation devices, or string-actuated mid-air displays. For illustration purposes, we use the latter class of SCI (e.g., [29], [100], [124]) with color-controllable *physical elements*, which we show as blue spheres in the schematic figures below. Regardless of the specific type, the dynamic data physicalization is combined with head-worn AR glasses to provide *high-resolution augmented content* (which we show as green overlays). We can thus exploit the advantages of both approaches (Table 1).

❒ In contrast to virtual visualizations, such as floating holograms in AR [7], the main advantage of physicalizations is their persistent character. They exist in the real world and are also able to provide additional interaction dimensions such as touching, grasping, or deforming a real surface. In addition, the casual perception of its ambient and "always-on" representation contrasts with the explicit, active usage of today's AR devices. The physical affordances of SCIs invite users to interact directly, providing them with an entry point to engage with a visualization.

▦ As the additional visual component, AR allows us to add high-resolution 3D visualizations of (theoretically) arbitrary size that extend the limited resolution of SCI. The latter, however, can physically illuminate the environment (e.g., via projection or embedded LEDs), visible to everyone.

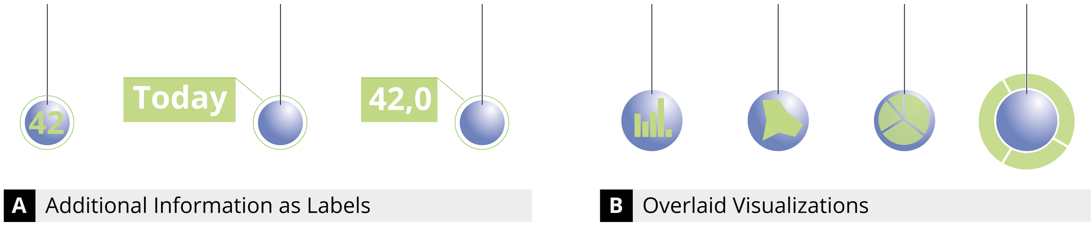
🔗 While AR visualizations can (theoretically) fill the entire room or even beyond, SCI are bound to their specific physical constraints, such as 2.5D surfaces with limited grid resolution and pin/object size. In addition, virtual content can be of any type or shape, and dynamic motion or animation is only limited by the current framerate.

👤 Data physicalizations inherently suit multi-user scenarios and facilitate collaborative analysis, while, in particular, head-mounted AR has the further benefit of individual personalized views that can show different information per user. This information could be role-dependent (e.g., presenter vs. audience, teacher vs. student) or adapted to an individual's preferences (e.g., with regard to color schemes).

Overall, in the combination of both systems, we see great potential: physical and virtual elements can be aligned to create a high-resolution view with a tangible and persistent character, counterbalancing each other's shortcomings and resulting in potential synergies. We strive for a more differentiated usage of physical and virtual content to make the best use of both worlds. In a bottom-up perspective, we derive basic components for such hybrid visualizations (Sec. 3.1) and analyze possible interaction techniques (Sec. 3.2). We

TABLE 1: Comparison of dynamic data physicalization through shape-changing displays and head-mounted Augmented Reality regarding their capabilities to create interactive data visualizations.

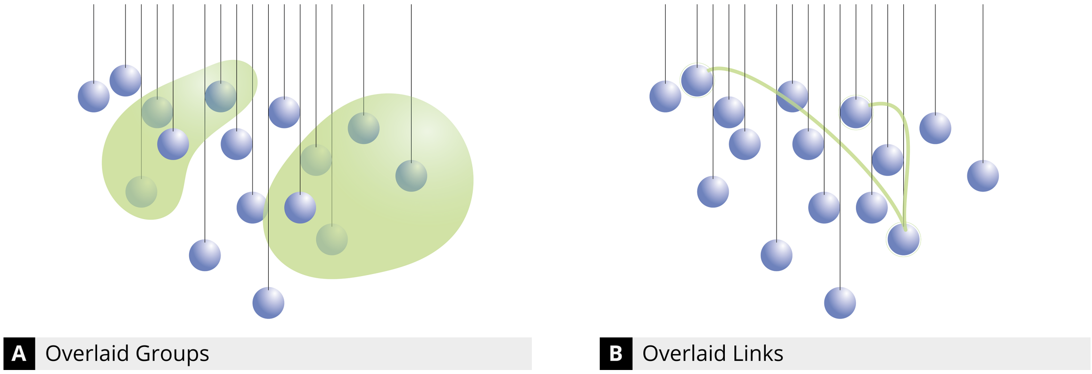
Dynamic Data Physicalization: Shape-Changing Display		**Virtual Visualization: Augmented Reality**
physical instantiation, tangible interaction persistent character, ambient representation	❒	purely virtual, gesture input requires active usage, limited FoV
limited resolution, illuminates environment	▦	high resolution, vibrant colors
physically constrained (e.g., 2.5D grid), geometric solids	🔗	any visual content, highly dynamic
inherently suits multi-user scenarios	👤	can render individual, personalized views for every user



A Additional Information as Labels

B Overlaid Visualizations

Fig. 3: In closer inspection, virtual content can show additional information about individual elements, for example, labels (A). Adding small virtual visualizations onto elements facilitates view aggregation (B). For illustrations, we use a color scheme that shows holographic overlays in **green** and physical elements in **blue**.



A Overlaid Groups

B Overlaid Links

Fig. 4: Additional attributes of elements can be visualized using a virtual overlay, e.g., shared attributes of items in a physical 3D scatterplot (A). Relations between elements can be highlighted as a virtual link connecting multiple physical elements (B).

further discuss how existing visualization concepts can make effective use of this device combination (Sec. 3.3) as well as general design aspects for Augmented Dynamic Data Physicalization (Sec. 3.4). In all these sections, we do not mean to present a definitive set of techniques, but instead a fundamental collection of possibilities that may inspire future research in this domain.

3.1 Basic visualization components

The goal of Augmented Dynamic Data Physicalization directly leads to two fundamental questions that initially may seem to lead in opposite directions. First, how can AR enhance dynamic data physicalizations? And, second, how can dynamic physical interfaces improve AR-based visualization by bringing them closer to the physical world?

AR enhancements of physical representations. As physicalizations, even when being dynamic, are bound by technical constraints, AR offers great potential to enhance their visualization of data. *Virtual overlays can be situated on or around the elements* that constitute a physical data visualization, regardless of the actual size of an element or whether it is part of a composed physical display. Virtual content can also be classified based on its relation to an *individual element, to groups of elements, or to the whole physicalization*.

AR can **provide additional data and information** besides the primary data encoded in a physical element's position, shape, or color[2]. Especially precise numerical or textual information is hard to realize in dynamic data physicalizations. They can benefit from descriptive labels [102] to present names of attributes, precise values of individual items, or further information (Fig. 3A). Despite simple labels, more sophisticated visual content can be shown on or close to each element. To do so, small dynamic AR visualizations (such as bar charts) can be overlaid to some or all physical elements (Fig. 3B). This approach allows us to show detailed, potentially multivariate information about individual data elements. All overlays should be orientation- and viewpoint-dependent and require reorganization upon change [102], which is hard to achieve in existing physicalizations without virtual overlays. Moreover, all visual overlays may not only be applied to *single elements* (like data marks), but also to *groups of elements* (e.g., by showing an average value or providing a comparison chart) or to *all elements*, i.e., the entire data physicalization (e.g., by showing time-dependent data at different time steps for comparison).

The **display of additional highlighting or relational information** is especially hard to achieve in data physicalizations that are mostly restricted to physicalize primary data. Especially for additional information such as highlights of selected data marks, connections between them, dependencies of views and their data, or groupings of elements, AR can successfully overcome this limitation. Virtual overlays can easily highlight a set of elements (e.g., according to some filter criteria) or depict dynamic links in a node-link graph visualization (Fig. 4A/B).

Regarding the overall physicalization, AR allows us to address further physical limitations of the shape-changing interface. Virtual overlays can **extend the physical display space** beyond its boundaries on all sides, effectively increasing the amount of data to be shown (Fig. 5A). Furthermore, virtual replicas of the physical elements can **increase the number of available data points** and fill gaps irrespective of

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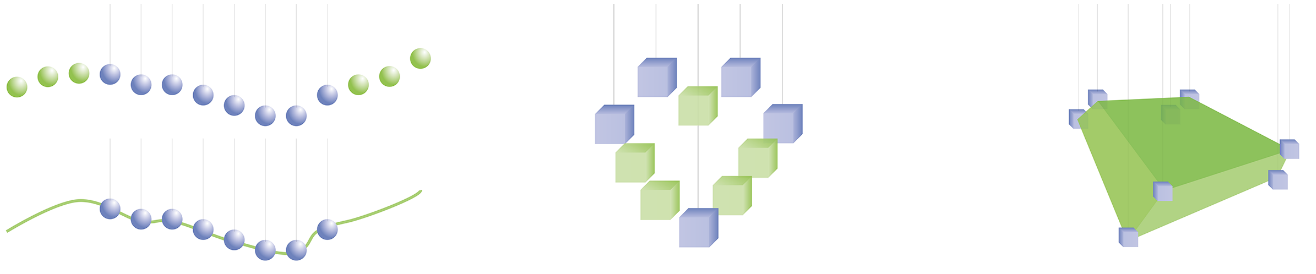
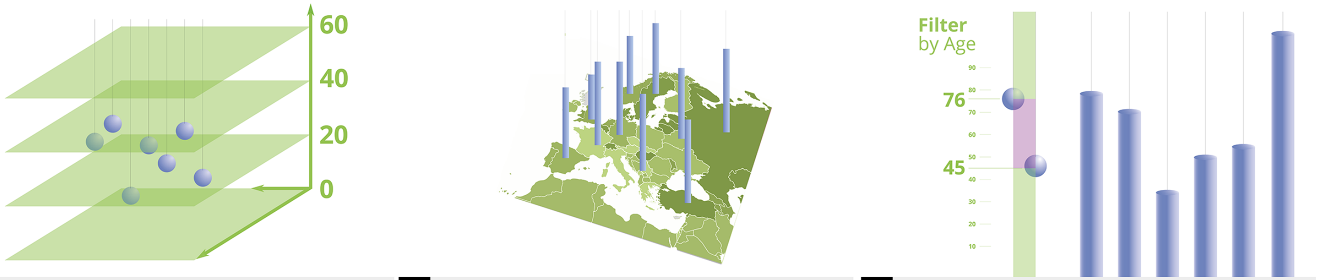
[2] Please note that the expressiveness of the data physicalization can vary and may provide interesting opportunities for the sole use. Our prototype, for example, uses built-in color change for each sphere.



A Extending beyond Display Space **B** Extending within Display Space **C** Visualizing Shapes



D 3D Grids and Axes **E** Providing Context **F** Physical Handles

Fig. 5: Augmented Reality extends visualizations beyond the technical limitations of the physical interface. Virtual elements can extend the physical visualization (A), for example, to show trends. Similarly, virtual content can fill gaps within the coarse physical visualization, extending the display space within (B). While a physicalization can only approximate a bigger shape, the AR overlay provides more details (C). To allow accurate readings of element values, a virtual grid or coordinate system can be shown (D). In addition, virtual content can be used to show the context of physically presented data (E), for example, a map. AR may also provide necessary information for physical handles that are used to control a visualization (F).

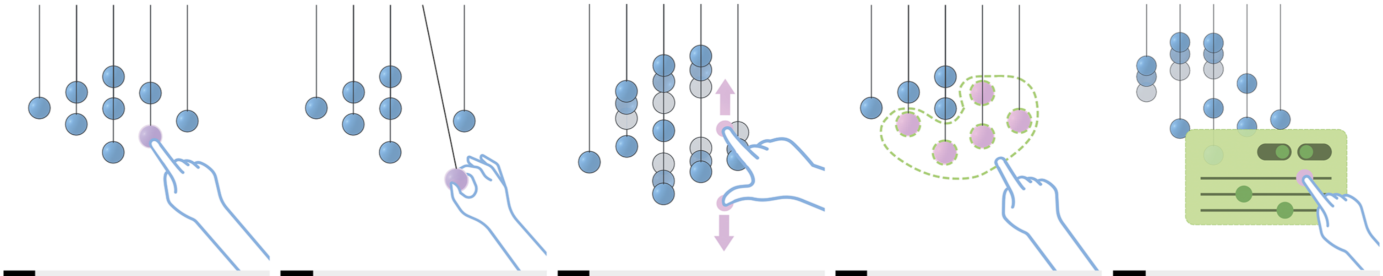
the given layout and resolution of the SCI (Fig. 5B). Similarly, detailed virtual 3D geometries can be shown in AR to compensate for the approximations of the shape inherent in many dynamic data physicalizations (Fig. 5C). For providing necessary details beyond physicalizing the primary data and for facilitating precise readings, physicalizations typically make use of printed values on bars, engraved labels on the base, or transparent back walls with scales [54]. Augmented Reality can overcome the respective limitations that even exist with dynamic physicalizations. By spatially registering the physicalization and dynamic AR information, such as axes, coordinates, scales, grids, or legends (Fig. 5D), **auxiliary information can be shown and improve the reading of accurate values**. Overlays can also be used to **provide the context of a data physicalization**, for example, by displaying a map below the associated physicalization (Fig. 5E). Some data physicalizations provide direct tangible interaction, e.g., by means of manipulating physical handles, but do not facilitate discoverability of the associated function sufficiently. Appropriate **AR overlays can help users to recall actions assigned to them** and to see their current state or value (Fig. 5F). Besides visual enhancements, AR HMDs also provide additional gestural input that can be used for interacting with virtually and also physically displayed information, as we discuss in Sec. 3.2).

Physical enhancements of AR visualizations. The other way around, AR can also benefit from the physical properties of a shape-changing interface used for dynamic data physicalizations. Especially the haptic sensation missing in AR visualizations can be provided by the physical display. In contrast to other approaches such as gloves or ultrasonic devices that create virtual touches, elements of a physicalization can be positioned to **provide physical handles** wherever required within the SCI's display space. Furthermore, virtual data visualizations or parts thereof can be **made persistent when needed**. With Augmented Dynamic Data Physicalization, a user can seamlessly drag a visualization from the virtual into the physical realm. This process creates a (likely) lower-fidelity **ambient representation** [88], [95], perhaps serving as a reminder to continue the analysis later. In multi-user scenarios, physicalizations can serve as **real-world anchors to ground discussions** about the data [77]. In conclusion, tangibility and persistence of data physicalizations (even when powered off) can enhance AR-only visualizations. Augmented Dynamic Data Physicalization thus supports both the ephemeral and persistent, and even the permanent display of data (when the physicalization remains powered off), according to Bae et al.'s [9] data duration dimension.

3.2 Interaction methods

The described basic visual components are important ingredients of a hybrid visualization—as is the support of a variety of interaction techniques. Typical interaction tasks or methods for working with a visualization (the *how?*) include selection, navigation, arrangement, change, filtering, aggregation, or annotation [14]. In Augmented Dynamic Data Physicalization, we can exploit and combine the input capabilities of both the physical and the virtual system for several interaction methods (Fig. 6).

The physical interface may facilitate direct input like touch or drag with inherent haptic feedback. It affords natural pointing and direct manipulation of elements, which suits **selection** and **arrangement** of individual data points



A Direct: Touch **B** Direct: Grab **C** Gesture: Pan & Zoom **D** Gesture: Selection **E** GUI: Menus

Fig. 6: Both a shape-changing interface and an AR devices afford a rich set of interaction techniques. Each physical element may facilitate direct input (A), for example, using touch or drag. This also affords direct manipulation such as grabbing a data object (e.g., one with an AR overlay) for closer inspection (B). Remote AR hand gestures can be used to overcome physical boundaries, for example, for horizontal navigation (C), group selection (D), or interacting with AR menus (E).

(Fig. 6A). Furthermore, depending on the degrees of freedom of the data physicalization, we envision direct tangible interaction, such as holding elements for closer inspection of data items (Fig. 6B). This is different to using external tangible controllers like in [110] that can only indirectly change aspects of the visualization. Depending on the technical realization of the dynamic data physicalization, even **changing the encoding** of a visualization is possible. Taking the example of a string-actuated mid-air display [29], [100], [124], [127], the additional ability to swap the physical elements attached to the strings facilitates this.

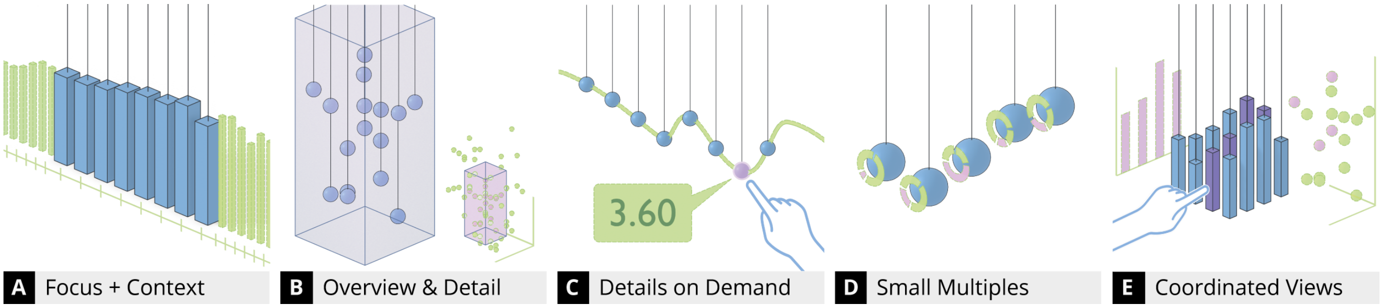
Head-mounted AR, in contrast, promotes a rich set of remote input, utilizing the user's spatial movement, gaze, and hand gestures. As these are not bound to any physical constraints of a SCI, AR mid-air hand gestures can be used to **navigate** within a visualization space. With two-point zooming and panning, users can manipulate the visualization such that points of interest are physicalized (Fig. 6C). As demonstrated by Leithinger et al. [70], [72], mid-air gestures are also useful to **select** and spatially **arrange** a group of elements (Fig. 6D). Finally, in AR, conventional GUI components such as buttons or sliders can be used to **change**, **filter**, or **aggregate** parts of a visualization (Fig. 6E). Such widgets also allow users to tag or **annotate** previously selected elements. In a combination of the physical interface with AR, sequences of interdependent inputs on both systems are feasible, for example, selecting a group of elements with two hands forming a rectangle and then dragging one physical element to adjust the group's height. Here, we only illustrated basic interaction methods; a particular use case calls for designing a consistent set of interaction techniques. We discuss examples of combined interactions in Sec. 4.1.

3.3 Visualization concepts

Based on the previously introduced visual components and interaction methods, it is now possible to create dynamic interactive visualizations. While even dynamic physicalizations are often limited in expressivity, the combination with AR facilitates advanced hybrid visualization techniques. The examples we propose and discuss in this section (see Fig. 7) can, of course, not cover the full range of possibilities but illustrate the richness of the design space Augmented Dynamic Data Physicalization offers. Visualizations can use **focus + context** techniques [19], in which either the physical or the virtual part can be the center of attention. For the first case, a physicalization can be extended beyond its hardware limits using AR (see Fig. 5A). Similar to other spatial methods, we envision that the AR context can have a different scaling or encoding than the physical part (Fig. 7A). The other way around, the physicalization can be used to provide an approximation of the information space, for example, with each element resembling a group of data items. We can then use the personal views in AR like **visualization lenses** [119], showing detailed information in the region of interest—also in the form of personalized, user-sepcific AR lenses. Closely related are **overview & detail** approaches [19], although the physicalization and AR visualization, in this case, might be spatially decoupled. For instance, we can use AR to show a minimap to highlight the section of a visualization that is shown on the physical interface (Fig. 7B). For all previous examples, 3D navigation is required, for which we suggest two-point gestural input for zooming and panning in AR.

Another common feature of visualizations is to show **details on demand** [107]. For low-resolution physicalizations, we can present additional information for individual elements, groups, rows, or the whole visualization as AR overlays (Fig. 7C). The respective demand for such additional data can be inferred not only from a direct selection but also from the user's viewpoint or distance. Details can be simple labels, numbers, elaborate texts, glyphs, or full visualizations. If the visualizations are small and overlaid onto respective physical elements (e.g., in a grid), a **small multiples** representation can be achieved (Fig. 7D). A common encoding of all overlays allows users to compare data items while looking at both the bigger physicalization and the small multiples.

Finally, as Augmented Dynamic Data Physicalizations basically constitute a hybrid multi-display environment, **multiple coordinated views** [93] can also be created that utilize brushing and linking [10], [16]. While the shape-changing interface is useful for a central physicalization, AR can present several adjacent views (Fig. 7E). Here we can depict other attributes with the same encoding [122] as well as different representations of the same data. We can link all visual representations such that they share changes in visual encoding, arrangement, selection, and annotations. Users can then employ both physical and virtual inputs to control the visualization, depending on their task. We further see necessity in a quick view rearrangement between the virtual and the physical world. An interesting virtual view could



A Focus + Context

B Overview & Detail

C Details on Demand

D Small Multiples

E Coordinated Views

Fig. 7: By combining the dynamic visual components and input capabilities provided by both a shape-changing physicalization and augmented reality overlays, advanced visualizations become feasible. They, among others, comprise focus + context techniques (A), overview & detail approaches (B), details on demand (C), small multiples (D), and multiple coordinated views (E).

thus be quickly physicalized to facilitate tangible interaction, collaboration, and persistent long-term representation.

3.4 Overarching design aspects

In the previous sections, we discussed ways of combining shape-changing data physicalizations with AR for dynamic interactive visualizations. From these conceptual considerations of Augmented Dynamic Data Physicalization and our experiences in realizing exemplary use cases (see Sec. 4), we next derive overarching aspects that can be helpful in designing specific instances of such hybrid visualizations.

First, the **properties of the physical interface** affect the suitability of different virtual overlays. Some modular shape-changing platforms [29], [45] support configuring properties such as the geometry and size of elements (e.g., small spheres, big pins), their supplementary capabilities (e.g., illumination, vibration), and the feasible interactions (e.g., touch, push). These properties of the physical interface should be fixed (if at all customizable) according to the application needs *before* adding AR overlays. For example, a string-based system can actuate extensible telescope pins for a bar chart, but virtual overlays should consequently be aligned on top to not interfere with the physicalization (cf. Fig. 10C).

We also have to consider the **interplay of physical and virtual** subsystems. Both can be employed independently, in parallel, only on demand, or in succession. The advanced visualization techniques we just described typically use the data physicalization and AR in parallel, for example, by overlaying virtual axes or trend lines onto the physicalization. The visual components, however, can instead be blended in on request only, especially in cases when detailed insights are not always needed. Furthermore, we think of cases for using both systems in succession. First, changes in the data physicalization may attract a user who then transitions to a detailed data analysis with the help of AR. Second, an interactively created AR visualization can be physicalized for a persistent ambient display in the vicinity of the user.

Making sense of the presented hybrid visualizations can depend both on visual **recognition and recall**. While AR can clearly encode data with a high level of detail and explanations thus fostering recognition, data physicalizations without contextual information often require users to recall the encoding. Applications can thus strategically employ AR to increase a user's understanding of the visualization. After seeing a virtual line chart and its axes in AR, e.g., the user can disable the overlay and still make sense of the peaks and dips within the physicalization (Fig. 1A). Furthermore, this approach can be used for different degrees of privacy on purpose. Imagine a shape-changing interface to be placed in a private living room. External invited guests would just see an engaging kinetic artwork. Closer friends, however, may be aware that it encodes data such as the number of steps per family member. The family itself, knowing about the encoding, can make immediate sense of who was the most active throughout the week. For any of these user groups, AR with its personalized views can provide adapted virtual overlays to make further sense of the encoded data.

The physicalization as a central real-world anchor facilitates **collaboration** between multiple people, each having individual AR views. Respective applications can focus on co-located as well as remote collaboration with two distant instances of the shape-changing interface (cf. [69]). Furthermore, next to a symmetric setup, asymmetric applications are feasible, which involve a teacher, parent, or expert seeing additional information (in AR) about the dynamic physicalization presented to students, children, or clients. While a detailed discussion of such collaborative scenarios using the device combination of shape-changing physicalizations and AR promises to be an interesting field of research, it is out of scope for this article.

Finally, the particular **context of a given use case** plays a major role in the development of a hybrid visualization. It must fit the available data, the user requirements, and the usage scheme (cf. [103]). In a professional context, for example, it could be necessary to display concrete values and axes with precise readings, while in a private context, it maybe more important to not overwhelm the user with visual clutter. In the private or public context (e.g., museum or lobby), drawing attention and attracting the user to the visualization are most important—especially for the physical part of the visualization. In the following section, we describe our implemented use cases, each chosen deliberately with a different context in mind, to showcase how the above-mentioned concepts and general design aspects can be instantiated and taken into consideration.

4 IMPLEMENTED EXAMPLE USE CASES

Our demonstration use cases include a dynamic data sculpture for a domestic context (Sec. 4.2), an interactive museum exhibit (Sec. 4.3), and dynamic hybrid visualizations for professional users (Sec. 4.4). Each application uses different visualization and interaction components to showcase the versatility of our approach. Next, we first detail the general implementation and specific hardware platform we use for these applications, before we discuss the individual designs.[3]

4.1 Technical implementation & setup

To investigate and evaluate the design concept of Augmented Dynamic Data Physicalization, we need a flexible, shape-changing system as a baseline that supports simple and abstract dynamic data physicalizations and simultaneously offers opportunities for more detailed and complex hybrid visualizations. Based on these design requirements, we use our open-source system STRAIDE [29] as a representative instance: the platform is accessible, extensible, and meets our requirements by driving multiple generic elements simultaneously, supporting embedded low-fidelity visualizations, and providing spaces in-between that can be extended with AR overlays. STRAIDE is a modular research platform for SCI's with string actuation from the top. Its core is an extensible actuation system, to which a variety of exchangeable elements (e.g., spheres with embedded LEDs) can be attached. Specifically, we use a versatile matrix setup, which positions up to 8×8 elements within a $0.5\,\mathrm{m} \times 0.5\,\mathrm{m} \times 1.3\,\mathrm{m}$ display space. The string placement is flexible and we can reroute them, for example, to stack elements on the z-axis (Fig. 10F). Furthermore, we also use STRAIDE's software framework and API's. In detail, our applications rely on the C# libraries to communicate between the AR HMD and SCI via WebSockets. They simplify the timed control over the position, color, and speed of each individual element.

For high-resolution AR overlays, we use Microsoft's HoloLens 2 [79] as it provides additional features such as spatial recognition and hand-tracking. The Mixed Reality Toolkit [80] we use in conjunction with Unity [120] simplifies the software control, facilitating stereoscopic rendering, gesture recognition, and QR code tracking for alignment with the physical interface. On top, we work with the open-source Universal Unity Visualization Framework u2vis [92]. Its basic functionality allows us to create generic visualizations such as line charts, bar charts, scatter plots, or parallel coordinates. We extended these libraries to work with STRAIDE, e.g., to interpolate physical element positions on a virtual line chart and added new visual components from Sec. 3.1, e.g., labels, overlays, or virtual extensions. Building on this foundation, our three application use cases demonstrate our approach in a private, public, and professional context.

4.2 Personal information hub

Kinetic interior such as the Sisyphus Table [108], which magnetically rolls a steel ball through a field of sand creating beautiful patterns under glass, are in the process of becoming commercially available. This trend has the potential to soon evolve into even more interactive interior objects and art decors. Kinetic data sculptures being placed in private living spaces as ambient displays, for example, could subtly visualize information such as personal fitness statistics or the weather forecast. However, complex contextual meanings and data relationships remain hidden due to the limited visual capabilities of such abstract kinetic art installations.

With our first use case, we demonstrate how the concept of Augmented Dynamic Data Physicalization can be applied to personal information hubs to guide and support users in exploration tasks with additional layers of information. Therefore, we focus on providing valuable casual insights for users in a domestic environment (Fig. 8A). Personally relevant data can be taken from a home automation system or from personal data tracking (e.g., a user tracking data about their own body and behavior or that of social contacts). Visualizing such data serves two goals of the user, which Li et al. [73] call Maintenance and Discovery. For the first, people want to see their current status, e.g., of their electricity consumption, daily steps, or expenses. For the latter, users aim at analyzing trends and causalities encoded within a visualization. We can support both goals in our Personal Information Hub, by providing **approximate physicalizations of common plots** (Fig. 8B). The illuminated physical elements encode the upper end of bar charts or interpolate a line plot, with color used for differentiation. Demonstrating the concept of details on demand, once the user steps closer for inspection the AR provides detailed overlays such as the charts' axes, exact values, trend lines, and legends. This combination provides the necessary information to make sense of the physicalization, but the overlay can be omitted once the user is familiar with the encoding.

Apart from the physical charts, our application provides **ambient notifications**. We assume that urgent notifications should be presented close to a user, while less urgent information will benefit from an ambient, non-distracting display. In our example, we show notifications from messaging apps, media suggestions from friends, etc. as a striped bar in AR (Fig. 8D): We illuminate and raise a physical element according to the current amount of outstanding notifications. The user can drag this element to a section of the bar to select an item, first seeing a preview (Fig. 8E) and then triggering an action like showing a video, playing back music, or answering a message. While we predetermine the data encoding, the arrangement of the whole application can be individually customized, thus fostering the user's recall of the virtual-to-physical mapping. We, for example, show available data, both for charts and notifications, as handles in AR, which can be assigned to the available physical elements of STRAIDE with a drag gesture (Fig. 8C).

With these application components we have illustrated how personal data visualizations, ambient notifications and events, or even entertainment functions can be integrated into dynamic data sculptures. Focusing on overarching interaction techniques and design principles (e.g., the drag & drop placement of virtual data to materialize it as a physical representation, the cross-device media controls or the tangible notifications), the personal information hub primarily serves as a basis for discussing visually-enhanced kinetic sculptures and representative interactions in living spaces, rather than being a fully-fledged solution.

4.3 Interactive exhibition

The approach of Augmented Dynamic Data Physicalization allows us to dynamically move, arrange, elevate physical

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[3] Our accompanying video dynamically demonstrates all use cases.

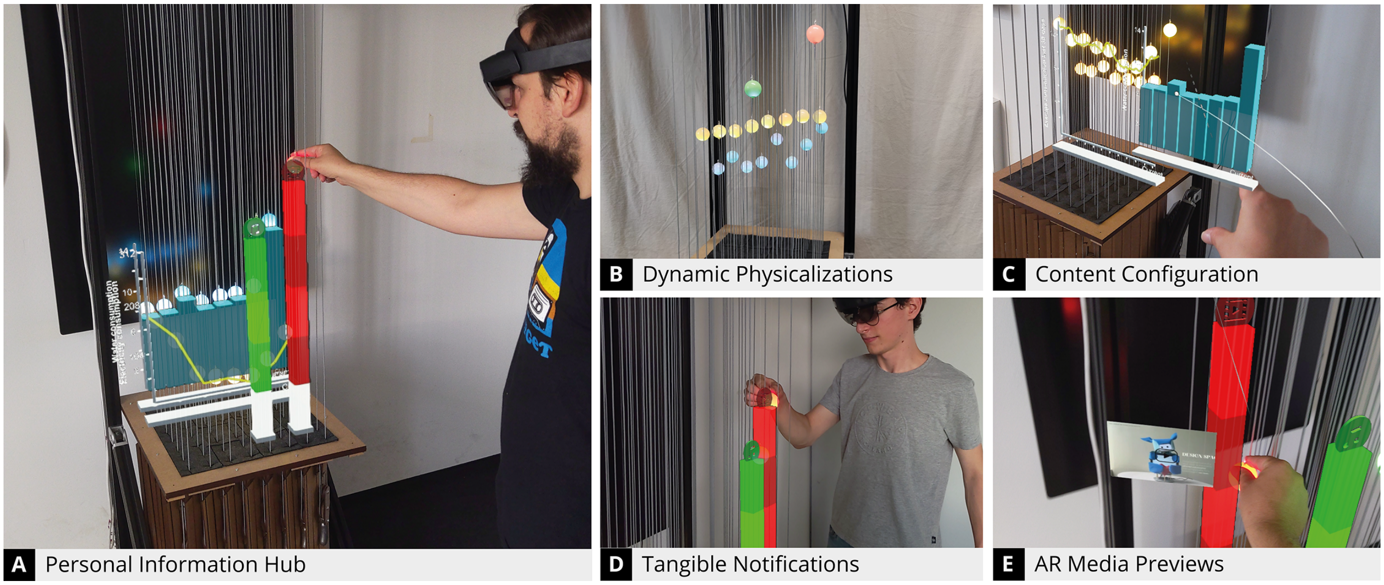

Fig. 8: The *Personal Information Hub* provides casual visualizations for domestic users (A). It uses simple charts for personally relevant data such as energy consumption (B) that can be configured according to the user's needs (C). It further provides physical notifications for messaging apps or online subscriptions (D), for which previews are provided in AR on demand (E).

artefacts, and blend them with additional information overlays to tell curated narratives in an extended and interactive way. These unique capabilities also inspired our second use case—an interactive exhibit in a museum for storytelling.

In more detail, our example use case narrates a story about the Vase from Bronocice,[4] a pot from 3637–3373 BC found in Poland (Fig. 9A) as shards of clay. We built **scaled replicas of its individual shards** and attached them to STRAIDE so that these physical parts can be individually actuated. Integrated magnets ensure that all parts seamlessly snap together in their final assembly position. For the application, the user employs an AR device that shows additional explanations, data, and 3D content. We make use of proxemic interaction [41] to guide the user along the narrative, which can be seen as an immersive adaptation of ScrollyVis [78]: Starting from afar, the AR HMD displays a **volume visualization** of the archaeological excavation site (Fig. 9B) and thus hides the STRAIDE assembly as well as the physical shards, providing the *physicalization's context*. By stepping closer to the exhibit, the virtual excavation starts from the top, progressively unveiling more and more parts of the vase. Supplementary texts and graphical elements explain

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[4] See `muzea.malopolska.pl/en/objects-list/1619`.

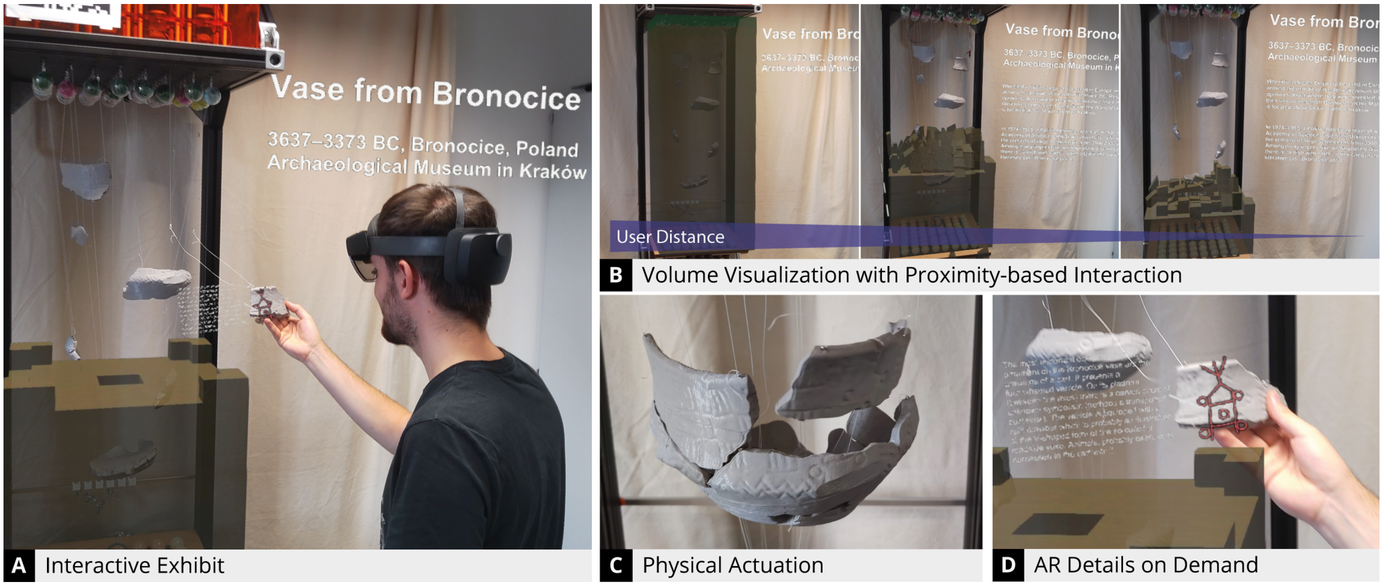

Fig. 9: Our *Interactive Exhibit* attracts users by physically actuating a replica of a historic vase as well as providing playful and informative AR overlays (A). To start, an AR volume visualization showing the excavation side hides the shards (B left). By using a scrollytelling approach, more physical parts get revealed based on the user's proximity to the exhibit (B). In the end, the historic vase is reassembled by physical actuation (C). Users can grab shards to get more details on demand (D).

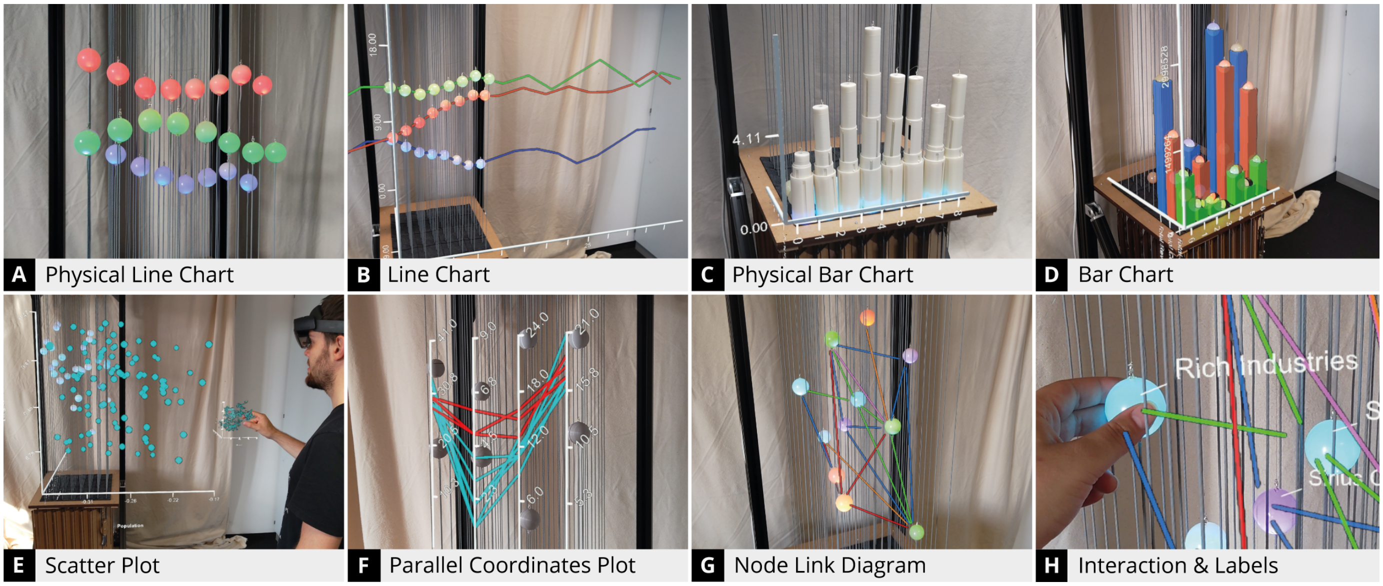

Fig. 10: Our *Company InfoVis Suite* features a variety of visualizations to whose dimensions the user can freely assign attributes of the dataset: hybrid line chart (A/B), bar chart physical (C) and hybrid (D), hybrid scatter plot (E), tangible parallel coordinate plots (F), and a physical node link diagram with AR links (G). For all, AR provides necessary supplementary information and details on demand (H).

the history, the excavation, and its value for archeology. Once the visitor stands directly in front of the exhibit, the volume is gone and all shards are clearly visible. Now the physical interface lowers the parts, scattered in the volume, to finally **form the physical reconstruction of the vase** (Fig. 9C). An AR model fills the gaps between the shards to complete the historic object (Fig. 1C). Now the visitors can walk around, focusing their gaze onto certain areas to **reveal details** about the material, the inscriptions, or the reconstruction (Fig. 9D). The physical actuation has the potential to increase people's interest in the object and its excavation, encouraging visitors to explore the additional AR content—maybe even combined with narrations on demand [61]. Overall, this interactive exhibition shows how blended data sculptures can be designed to create a predefined interaction space related to a specific theme and curated narrative using custom elements and proxemic interactions.

4.4 Company InfoVis suite

Inspired by companies who place interactive sculptures in their atriums (e.g., The Source [42] at the London Stock Exchange), our third use case reflects on how shared data sculptures can visualize business trends, foster employee discussions, and materialize overarching corporate data or projects stats—in an artistic, abstract way (e.g., for visitors) or in more depth with extended details for analytical use.

For data analysis in a rather professional context, we demonstrate a suite of basic visualizations with a workflow inspired by modern software such as Tableau [114], while not claiming our system to be a substitute for it. Data attributes can be individually mapped to dimensions of the hybrid visualization, for example, the elements' position, their color, the AR overlay color, virtual size, or labels. While the dynamic physicalization provides points of reference for multiple users, tangible input, and long-term presentation, the AR adds as many additional output dimensions as required (Fig. 10). Our suite comprises six exemplary types of visual representations for multivariate data. A physical **line chart** interpolates data depending on the selected range chosen by the user (Fig. 10A/B). The virtual lines extend past the physicalization to show a bigger portion of the available data, showcasing a focus + context approach. **Bar charts** can be either physical—with extensible, telescopic 3D-printed bars—or hybrid, with generic elements placed on top of 3D-rendered bars (Fig. 10C/D). Our **scatter plots** need to be hybrid, as some items can be physicalized, while for others no physical element is available due to the fixed grid and other hardware limitations (Fig. 10E). As an example for an overview & detail technique, we provide a head-coupled mini-map of the scatterplot in which the user can manually make a range selection using mid-air gestures. We realize **parallel coordinates plots** by making use of STRAIDE's reconfigurability and direct input capabilities (Fig. 10F). Two stacked elements on each vertical axis serve as handles to control attribute ranges of the virtual parallel coordinates. **3D node link diagrams** are feasible by arranging the physical elements and adding AR links (Fig. 10G). In all mentioned visualizations, the AR presents **supplementary information**, such as axes, legends, labels on demand, and provides remote input to control axes and encoding (Fig. 10H). We can also create multiple visualizations and arrange them around the physical interface, realizing multiple coordinated views.

With the implemented use case of the Company InfoVis Suite and its components, we have shown how the concept of Augmented Dynamic Data Physicalization can be used to create a versatile set of hybrid multivariate data visualizations that go beyond ambient applications and interactive exhibitions. In detail, we envision that a visualization suite as discussed in the use case can be convincingly used to create detailed, yet engaging information visualizations, for example for corporate presentations or customer meetings.

5 EXPERT FEEDBACK AND DISCUSSION

New post-desktop visualizations or physical systems are often challenging to study. Qualitative evaluation methods can be an appropriate and valid approach—especially for novel systems that are difficult to compare to existing ones [18], [52], [65]. Evaluations with experts are likely to cover a wide range of important aspects or issues and help determining the actual potential of design principles, concepts, and implementations. Moreover, in such feedback sessions it is common to work with few experts (e.g., [28], [76], [126]) because they can identify major issues and can provide the high-level feedback needed for conceptual research. We thus decided to use *interactive walk-through demonstrations* and to conduct *semi-structured interviews* with experts.

Invited experts. To gain insights into the approach of Augmented Dynamic Data Physicalization, we invited three independent professionals with in-depth knowledge of visualization, AR, and tangible installations. Our first expert (P1) is a professor who leads an HCI lab that focuses on visual engineering, multidimensional visualization methods and research into novel tangible displays. In addition, we recruited an expert (P2) who has many years of industrial and artistic experience in the fields of immersive media for museums, immersive art, and creative computing as well as extensive perceptual and cognitive knowledge for virtual reality technologies as a university professor. Finally, we talked to a founder and professor (P3) whose work and research interests lie in the field of trans-disciplinary new work design and information management. All recruited experts (age M=42.33, SD=4.19 years; 3 male) are independent from our team and come from three different universities.

Procedure. Our feedback sessions lasted $\approx$90 minutes each and comprised an introduction, an interactive hands-on sessions with our implemented applications (Sec. 4.2: Personal Information Hub; Sec. 4.3: Interactive Exhibition; Sec. 4.4: Company InfoVis Suite), and a follow-up interview and discussion. While this set of applications may not represent the next smartphone-like change of visual information access, it showcases a wide range of augmented dynamic data physicalizations. Made possible by modern AR headsets, we can use it to evaluate and validate different aspects (e.g., data/operation abstraction, encoding/interaction technique design [82]). All experts experienced our applications on their own following the same semi-structured presentation, free exploration, and feedback procedure, while we asked them to comment on advantages, disadvantages, and problems in a think-aloud style. During these sessions, one experimenter moderated the session and helped the participant when questions arose, a second was responsible for the technical operation of the different applications, and a third took written notes. We also audio-recorded all sessions, from which we extracted additional notes and quotations.[5] Based on the feedback we received and our notes, which we provide in Appx. A, we then used open coding [33] (done by a co-author different from the experimenter) to extract key points that the experts had noted. We discuss these key findings along five overarching schemes.

General feedback. All experts were curious to experience and evaluate the interactive prototypes and expressed overall excitement in the hybrid combination. In particular, they liked the interplay of the physical interface with the HoloLens' AR view, stating that *"it's a pretty seamless connection"* (P2), that *"the two parts complement each other very well"* (P3), and that the system *"reacted immediately"* (P1). For the physical interface, the participants appreciated the direct interaction as well as the option to actuate different types of physical elements (spheres, bars, or the vase). The shape-changing interface provides valuable persistence and *"instant zero-cost access"* (P2) to data. P1 also mentioned that *"AR helped the physical interface to go beyond its limited structures."* They also mentioned several points of criticism, including noting well-known hardware limitations of the HoloLens HMD (i.e., its limited field of view and low resolution—P2), issues with the prototypical nature of our implementation (i.e., calibration—P1, P2—and lag issues—P2—, unintentionally initiated gestures—P3), as well as some of our design decisions such as virtual and physical label placement (P1, P2) or certain overlaps (P3), most of which can easily be addressed with more modern AR HMDs and straight-forward usability adjustments.

Hybrid 3D visualizations. While the experts generally described their first impressions positively as *"charming"* (P1), *"special"* (P2), and *"cool"* (P3)[6] and we received a large number of comments about the respective benefits of the physical and virtual components of our design, P1 also expressed concerns, discussing issues with occlusion. In particular, he had difficulty comparing values within the virtual bar chart scenario. However, he continued to be motivated to explore several use cases, as he stated that the hybrid approach was more engaging than classical 3D visualizations. Compared to 2D screens, P1 and P3 rated the system as superior for 3D visualizations, but equivalent to pure AR visualizations. Interestingly, P3 also expressed a clear affinity for 3D visualizations of abstract data, in line with some discussion in the visualization community [13]. One major advantage our participants mentioned for 3D visualizations—both physical and virtual—is that they exploit proxemic interaction and spatial memory. P3 stated that moving around the physical device itself helps him to better understand the data and that its individual element can foster communication in co-located collaborative scenarios. While the experts noted issues with 3D visualizations such as that AR overlays (e.g., bar charts) can lead to visual occlusion, they also stated that the specific combination *"has more charm/[is] better suited in this form than 3D vis on typical 2D displays"* and that one *"can recognize and experience everything"* (P1) as well as that it is *"aesthetically pleasingly simple"* (P3). They also appreciated small additions such as links or labels. They thus preferred a physicalized representation of data points, while they favored AR for data sense-making as lightweight visual extensions, which can serve as inspiration and guideline for future hybrid setups.

Continuum of AR and physicalization. From the six scenes we showed to the experts, the archaeological exhibit (P1) and the node link diagram (P2, P3) received the most

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[5] The quotes here have been translated from the original German.

[6] While positive comments in a qualitative evaluation such as ours are not too surprising given demand characteristic effects [15], [22], [51], we also note that we consistently followed the same semi-structured protocol in our qualitative setup, that the positive comments by far outnumbered the negative ones, and that the negative ones generally focused on potential improvements of the system or prototype issues.

positive comments. When asked for reasons, the experts pointed to the clear differentiation of *"what is virtual and what is physical"* (P3) and how both parts are used. We noticed that feedback became less positive the less similar the physical elements and their AR counterparts were, another important insight for future work. For the line chart we combined spherical elements with an AR line, which seemed acceptable, but for the bar chart we aligned these spheres with virtual bars, which was not as well received. Those scenes also required a precise registration of the physical and virtual components, which the HoloLens does not consistently offer. *"When it is aligned, it works really well and pays off. But if the alignment fails a bit, it gets destroyed"* (P2). There is thus a need for precise tracking and alignment, a requirement currently only lab settings can fulfil. We also noticed that brightness is important for the perception of the visualization. The brightness of the physical elements as well as the AR content must be adjusted to clarify which part facilitates direct interaction. This observation shows, however, that blending the physical with the virtual world is possible in a way that the physical and virtual parts merge.

Interaction. We recorded statements such as *"it invites to interact directly"* (P1) or *"one got direct control over the data"* (P3). The experts further appreciated that this direct interaction integrates well with the remote gestures provided by the HoloLens. With AR one can create, configure, and learn about the data shown in a physicalization (P1–P3). We noticed that all participants showed interaction sequences that moved between two spatially and semantically split zones, for example, while working with the virtual bar charts. They stood in close proximity to make use of the direct input capabilities, but the limited field of view of the HoloLens did not allow them to see the whole visualizations. So the users regularly stepped back to get an overview and then used the provided remote gestures to adjust the visualization—pointing at certain general interaction needs for hybrid representations. We further observed that mixing these modes led to avoidable problems, e.g., when gestures were recognized while interacting directly with a physical element (P3). All experts also intuitively grasped the functions we had assigned to each of the separate inputs (e.g., P3 figured out the bar chart interaction without explanation). Finally, as the *"lack of touch in AR is a big deal"* (P2), all experts stated that active haptic feedback would be useful in the future.

Additional application ideas. Besides the presented use cases, our visually augmented dynamic data sculpture sparked many ideas, also with regard to novel use cases. For example, the experts highlighted other promising use cases, such as storytelling or presentations (P1) and dashboards or trend trackers (P3). In addition, P2 and P3 had similar takes on using Augmented Dynamic Data Physicalization for tangible telepresence (cf. [69]), to *"use the system to bring things to life"* (P2). Both further suggested edutainment applications as potential follow-ups to our exhibit, for example, for topics like lattice structures and bonds (P2) or force vectors affecting buildings (P3). Finally, the experts suggested looking into more dynamic scenes or even simulations, as both the AR HMD as well as the physical interface are capable of presenting dynamic content in unison. This direction is particularly promising as only a few systems can display both dynamic physical and dynamic virtual content.

6 LIMITATIONS AND FUTURE WORK

Like most research work, ours is not without its limitations. These limitations largely cover four major themes: the complexity of the setup, current hardware limitations, usability issues, and the question of generalization, as we discuss next.

First, the STRAIDE system with the extensions we proposed for visualization, such as for the museum exhibition use case, are admittedly complex—an extensive technical scaffolding is needed for the physical part (comparable to other approaches like [35], [70]). Nonetheless, our setup doubles as a technology-art installation, so the complexity is worth it for specific application scenarios such as for companies, exhibits, and museums. Also, smaller or more lightweight variants are possible [29], [127]. In addition, while we cannot foresee technological innovations like levitation displays, we consider the complexity of the setup to be addressable by advancements in technology. Next, once the setup, like in the museum use case, is finished, it may be difficult to reconfigure, but also rarely required. However, the generic visualization setup typically does not need to be reconfigured physically. After all, a precise calibration between the physical installation and the HMDs is needed. While we did this calibration manually in our experiments, it can also be embedded into the software by taking advantage of 2D visual markers placed on the physical device.

A second group is the current hardware limitations of, in particular, the used AR HMDs. It is well established that the HoloLens has problems with the field of view, spatial resolution, and color reproduction. Nonetheless, the situation is evolving quickly and better hardware is already available, such as Meta's Quest 3 and Apple's Vision Pro. These headsets are still rather unwieldy, but more lightweight devices such as RayNeo X2 Lite glasses or the spectacles by Snap are becoming available. Another hardware limitation is the relatively low physical data display resolution (8×8×x) of our setup. Here it may be possible to consider alternative setups such as shape-changing displays [1], modular self-reconfigurable building blocks (e.g., [96], [104]), or actuated objects using specific actuation mechanisms (e.g., puppeteering [127])—the latter requiring less or same amount of actuators to combine real-world artifacts with AR layers.

A third class of challenges consists in the usability of the setup. The physical part, e.g., is limited without the virtual, and the virtual part is (partially) limited without the physical. Yet our focus lies on the combination, such that a use of the individual parts (in particular the physical) falls back to an artistic exhibition piece. Rather than considering this a limitation, one could even see it as a feature: the abstraction of the physical leads to calmness and to an aesthetic reduction to the main dimensions that fit into the interior (living room, office space), and that spark curiosity and invite further exploration with AR HMDs. Then it is also not an issue that the tangible/physical part may not be understandable without "initiation"—that would be provided through the AR augmentation, and "initiated" users can understand the physical display without the virtual overlay. The question of what to show there then remains an open design issue that needs to be investigated for concrete applications—in some cases (museum) it is quite clear, in others we face the same issues as in normal visualization design. Here one would usually use the main dimensions or data of interest.

A final class of limitations affects the question of generalizability. While we believe the concepts of Augmented Dynamic Data Physicalization to generalize to different data physicalizations, the use cases we demonstrated rely on a particular setup and quite specific types of data exploration, with clear challenges in expressivity and precision of control. While our setup arguably will not replace the PC as a data exploration tool, such issues may be less important for the very classes of applications we discussed: ambient displays with the possibility for further AR-based exploration, or the combination of physical and virtual artifacts in a museum. In future work, generalizing the approach beyond the application domains we demonstrated would be interesting.

7 CONCLUSION

Our evaluations highlight that dynamic data physicalization and AR-based visualization are not only exciting research topics on their own, but that it is possible to combine them into a single promising approach: *Augmented Dynamic Data Physicalization*. With this concept, both subfields gain fundamentally new properties and possibilities: The AR side gains haptic feedback and control as well as a physically persistent character, while data physicalizations gain many additional layers of information representation as well as a rich vocabulary of interactivity. Given the current discussion about tangibility and virtuality in HCI [24], reality could be augmented with either high-resolution virtual overlays or computational matter [38]. While both approaches digitally expand our reality, both have distinct advantages that we can strategically take advantage of: A futuristic interface could physicalize data for tangible interaction wherever needed, and provides rich virtual content otherwise.

With our work, we have started to investigate this intersection of dynamic data physicalizations and augmented reality, both conceptually and practically. We anticipate that the presented implementation, the repertoire of hybrid visualizations, and the insights of our experts contribute to a better understanding of how future designers can conceptualize and create interactive hybrid visualizations. These can go beyond our presented components and leverage them for novel applications. For example, in our personal information hub use case, the requirement of an AR HMD may be considered unrealistic or too much of an additional burden, yet the use of hand-held AR instead is not much of a stretch given the prevalence of smartphones and therefore could be explored as an alternative implementation—not just for this use case. In addition, while we realized the physical setup with a shape-changing 2.5D midair display, we believe that any other type of (novel) *dynamic* data physicalization setup will also benefit from the combination with AR, suggesting promising directions for future research. Given our design concepts, one of our main goals for the future is thus to foster discussion in this new exciting avenue of research. Traditional data physicalizations, for instance, often take the form of art pieces or installations—here the additional AR information layer provides exciting new opportunities. The virtual layer can itself have an artistic character—or it can build a bridge from the artistic physicalization to detailed visualizations of the underlying data.

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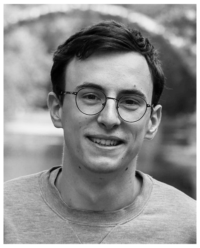

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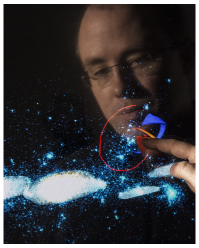

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APPENDIX

A EXPERIMENTER NOTES FROM THE EVALUATION

In this appendix we provide our notes from our interactive walk-through demonstrations and semi-structured interviews that we described in Sec. 5, which are an integration of the notes taken during the experiment and those added after consulting the audio recordings (which we used, in particular, to get precise quotations from the participants).

We had conducted the evaluation sessions in German, as both the experimenter and the participating experts were German native speakers. We, therefore, also took the notes in German, which we then automatically translated to English using the DeepL engine (`deepl.com/translator`). Below we provide these translated notes as additional material, which we used as the basis for our discussion in Sec. 5.

The three evaluation sessions took place in separate time slots, so we have one set of notes per participant. The notes below are numbered "Study 1", "Study 2", and "Study 3", which correspond to P1, P2, and P3 as mentioned in Sec. 5, respectively. The timing mentioned in the study notes are minutes:seconds after the start of the study (which is noted at the top of the document), which we extracted from the audio recordings.

We provide the notes as embedded PDF pages as we took them or extracted them from the audio recording, with the codes from our open coding process added as bold expressions in square brackets at the beginning of each point. In addition, below we list the codes used in the interview notes with their respective explanations.

quote A direct quote which we recorded from the participant.

reaction-positive Generally positive reaction from the participant.

reaction-negative Generally negative reaction from the participant.

reaction-system_impression A reaction by the participant that generally points to the subjective perception of the system by the participant, that is neither clearly positive nor clearly negative.

reaction-HCI A reaction by the participant that relates to HCI design.

reaction-integration A reaction by the participant that relates to the integration of physical with AR elements.

reaction-personal_use_reflection A reaction by the participant that relates to how they imagine to personally use our system/approach.

comparison-other_3D_vis A comparison by the participant of the tested system with another 3D visualization tool or system that they know.

comparison-other_platforms A comparison by the participant of the tested setup with another platform or system that they know.

reflection-3D_vis_benefits A reflection or realization of the participant that relates to benefits of visualization in 3D.

reflection-3D_vis_issues A reflection or realization of the participant that relates to visualization issues in 3D.

reflection-unique_feature A reflection or realization of the participant that relates to a unique features of our system/approach, as perceived by the participant.

reflection-interaction_styles A reflection or realization of the participant that relates to interaction styles required, suggested, enabled, or encouraged by our system/approach.

reflection-benefits_of_physical A reflection or realization of the participant that relates to benefits of the physical depiction or interaction with our system.

reflection-benefits_of_AR A reflection or realization of the participant that relates to benefits of the AR-based depiction or interaction with our system.

reaction-integration A reflection or realization of the participant that relates to how to integrate physical with AR elements.

reflection-alternatives_to_AR A reflection or realization of the participant that relates to how the AR part of the system could be replaced by an alternative.

reflection-classification_of_approach A reflection or realization of the participant that relates to the discussion of what is augmented reality or a physical interface, and how to classify it.

reflection-use_case A reflection or realization of the participant that relates to potential use/application cases, either generically or specifically.

reflection-usability A reflection or realization of the participant that relates to the usability of our system/environment.

reflection-design_issues A reflection or realization of the participant that relates to specific design choices we made.

reflection-remote_interaction A reflection or realization of the participant that relates to a potential remote interaction.

reflection-collaboration A reflection or realization of the participant that relates to a potential collaborative use scenario.

criticism-needs_improvement A criticism voiced by the participant that points to a needed change in the implementation; often a usability issue.

criticism-hardware_limitations A criticism voiced by the participant that relates to specific (and often well-known) hardware limitation of the used setup.

prototype_issue An observation of an issue of the realization that is likely due to the prototypical nature of the system; often would require some hardware adjustment.

specific_situation_comment A comment from the participant that relates to the specific interaction situation, can be a criticism or a positive comment or suggestion for improvement.

future_work_idea A suggestion by the participant for future work (usually not a criticism).

ranking A ranking by the participants between the three different application cases they saw.

Note:
The following protocol and notes were automatically translated (original language German) with DeepL

Study 1

Wednesday, 31 August 2022
Start at 10:24

Setup/STRAIDE

Line Chart

- **[criticism-needs_improvement]** Label positioning not ideal
- **[prototype_issue]** Calibration problems at the beginning
- **[reaction-positive][reaction-system_impression][prototype_issue]** Quite responsive - feels fluid, although the elements still need time to activate (approx. 3:40)
- **[reaction-positive][reaction-system_impression][quote]** "I have the feeling it reacts to me immediately"
- **[criticism-needs_improvement]** One would expect a zero point rather in the middle (approx. 5min) or a highlight for the origin
- **[criticism-needs_improvement]** Labels might be better fixed - there are generally even better approaches/algorithms for positioning labels - as a suggestion for improvement
- **[reaction-positive][comparison-other_3D_vis][quote]** Pure phys+AR added value? --> ca. 6:50 --> "3D visualization generally less good, but in this case it has more charm / better suited in this form than 3D vis on typical 2D displays or similar."
- **[reaction-positive][comparison-other_platforms][quote]** "But here it's cool and fancy that it's in the room like this - I actually find it a bit more charming here - it definitely has more potential than 3D Vis on 2D screens"
- **[reflection-3D_vis_issues][reaction-positive]** Typical 3D Vis problems like occlusion etc., but you can recognize and experience everything, but pleasant experience although rather critical of 3D
- **[reflection-3D_vis_issues][reaction-positive][reflection-unique_feature]** "The ability to walk around the prototype somewhat reduces the problems of 3D visualizations"
- **[reflection-interaction_styles]** To compare values, I always look at the visualization from the front - to explore, I also look around it sometimes
- **[reflection-3D_vis_issues][reaction-positive][quote]** Question: can I scale? ca. 9:45 --> "yes it works! Very nice", but the closer you bring the lines together, the more problems arise (occlusion etc.)
- **[future_work_idea]** Idea: Highlights like in 2D Vis, extend more visual variables to the individual lines
- **[ranking]** added later: favorite of the Info-Vis applications

Bar Chart: Start: 11:30

- **[reflection-3D_vis_issues]** Occlusion problem a bigger problem than with the line chart
- **[reflection-use_case][quote]** "It's more of an illustration than something I would use to solve a specific task"
- **[reflection-use_case][quote]** "But it's good for presentation / storytelling" (approx. 15:00) - good for convincing the boss or similar.
- **[comparison-other_platforms]** Looks like Relief from the MIT Media Lab with AR extension
- **[reaction-positive][reaction-system_impression]** Selection and then the element comes up again = conforms to expectations

- **[criticism-needs_improvement]** It is better to move elements into the bar and not the sphere above the element
- **[future_work_idea]** Alternative elements conceivable for the respective use case -> here e.g. cube
- **[reaction-positive][reaction-system_impression][quote][reflection-benefits_of_physical]** "I'm not such a fan of mixed reality and 3D visualization, but the physical component really reduces my resistance to 3D visualization - at least it's tangible"
- **[quote]** "Only in VR/AR would I say the topic is missed"
- **[reaction-positive][reflection-use_case][reflection-usability][quote]** "precisely because it invites interaction and you can possibly also tell a story with it, is ... already good"
- **[reaction-positive][reaction-system_impression][reflection-benefits_of_physical]** Haptics in general: tangible interaction helps a lot - especially for 3D visualization
- **[reaction-positive][reaction-system_impression][quote][reflection-benefits_of_physical]** "In general, the physical invites interaction" (ca.20:00)
- **[ranking]** --> added later: least convincing

Node-Link: Start: 22:00

- **[criticism-needs_improvement]** Interaction limitation: constant urge to move elements upwards as well
- **[criticism-needs_improvement]** Hiding labels in particular is problematic - better positioning (see comment on the line chart)
- **[reaction-positive][reaction-system_impression][quote]** Concealment: "I just tried to solve it by moving - you could also say that's the fun of it"
- Summary: 24:00
  [criticism-needs_improvement][quote] "the positioning of the labels would have to be explored again in detail - there are already many algorithms - you would have to see how this can be used here"
- **[criticism-needs_improvement]** Wish: more interaction and simulation - dynamic changes would be easy to imagine with the system and could benefit from this + dynamic highlighting and explaining/analyzing for storytelling/process chains ... Benefit --> professional pitches can benefit from this system
- **[criticism-needs_improvement]** Current prototypes still a bit too static - even more dynamic applications would be particularly interesting, because both the physical prototype and AR can display and convey dynamic changes well
- **[future_work_idea]** Legends would be an option - or tutorial for the explanation of the colors see introductory animations / First Steps / Intro ca. 27:00

Private: Start: 29:00 Introduction - Start: 30:00

- **[specific_situation_comment][quote]** "That's too low for me" - Set scaling / ground level individually
- **[criticism-needs_improvement][reflection-3D_vis_issues][quote]** "Try to get the perspective distortion out"
- **[reaction-negative][reaction-system_impression][reflection-3D_vis_issues]** Very difficult to read or compare - the two graphs are difficult to compare (3D visual problems)
- **[reaction-positive][reaction-system_impression] [quote][reflection-benefits_of_physical] [reaction-HCI]** "Interaction is very cool - you can grab a virtual object and it is then physicalized"
- **[reaction-positive][reaction-system_impression][reflection-benefits_of_AR]** Learning effect is definitely there - AR helps with creation and learning and can later also be read without AR - especially for your own data / fitness tracker etc.

- **[reaction-positive][reaction-system_impression][reflection-benefits_of_AR]** "The advantage is that other people don't know what it says"
- Notifications 37:00
    - **[criticism-needs_improvement]** Physical elements are very difficult to see - especially if they are overlaid with AR elements
    - **[criticism-needs_improvement]** I find notifications a bit complicated at first
    - **[reaction-negative]** Probably feasible and conceivable with some learning/time, but not directly convincing
    - **[reaction-negative]** Especially for music - personally very targeted - for other users who simply use 5 playlists, it is probably useful, but not suitable for the test person
    - **[future_work_idea]** Alternative: Smartphone see-through --> also conceivable and would certainly be interesting as a technically simpler variant that anyone can use without HL
    - **[criticism-needs_improvement]** Transition video from small to TV too fast - other hints

Museum: Start: 45:00

- **[specific_situation_comment][criticism-needs_improvement]** Oh, that was too quick for me - I wanted to read (excavation)
- **[specific_situation_comment]** The height problem again
- **[reaction-positive][reaction-system_impression][quote][reflection-benefits_of_AR][reflection-benefits_of_physical][reaction-integration][quote]** "That's really cool" --> Vase is extended by AR / reconstruction in AR in combination with the real thing
- **[reaction-positive][reaction-system_impression][quote]** "I find that very appealing"
- **[reflection-benefits_of_physical]** Testing the real thing would really be something else (in the sense of being able to test and touch it yourself)
- **[reflection-alternatives_to_AR][quote][reaction-HCI]** "I could actually imagine doing that very well with a tablet"
- **[reaction-negative][reflection-alternatives_to_AR][quote]** e.g. also to read the text --> 2D text and 3D extension --> 3D see-through would be a nice idea - could possibly work even better than it already does - "Text in AR eventually becomes tiring to read"
- **[ranking][reaction-positive][reaction-system_impression][quote]** "I think the general idea is very good and convinces me the most" ... of all applications (approx. 50:00) ... "because it is actually very easy to understand and you can really put yourself in the shoes of an archaeologist, for example"
- **[reaction-positive][reaction-system_impression][quote]** Worthwhile application
- **[reflection-use_case]** Story must be prepared accordingly and then it can be very nice to use

Other

- **[ranking]** Info-Vis aspect more difficult to convey
- **[reflection-benefits_of_AR][quote]** "AR helps to break the physical out of the given structures or to expand them - but that's already in the name AR"
- **[reflection-classification_of_approach]**"Whether you say augmented or enhanced reality here" --> question of where the system should be classified --> he sees it more as enhanced because it has both virtual and physical components
- **[future_work_idea]** You could combine it well with audio output
- **[future_work_idea]** Vibrotactile could be explored even more
- **[reaction-negative][reflection-alternatives_to_AR]** Text is difficult in AR --> resolution etc. --> possibly tablet application - good mix of 2D and 3D advantages
- **[reflection-use_case]** But storytelling and scrollytelling application looks very promising

- **[reflection-benefits_of_AR][reflection-alternatives_to_AR]** Use AR with caution - e.g. bar chart application was very crowded / a lot to see and overlays
- **[reflection-benefits_of_AR][reflection-benefits_of_physical][reaction-integration]** Concrete distinction between real and virtual, possibly useful as a guideline - always pay particular attention to: what is real/what is virtual/how is it combined and what do you see/perceive when? (see node link diagram - very clear here)
- **[future_work_idea]** Question: where should the balls hang, e.g. in the bar chart - above or in the bar - unsure myself: above the bar you perceive the balls as a separate element - in the bars the "but I'm unsure what is ideal in this case" becomes blurred
- **[reflection-use_case][quote]** "Proxemics works very well"
- **[prototype_issue]** Technical problem: incorrect recognition of gestures and grasping of elements
- **[reflection-benefits_of_physical]** Elements as interaction point "Grabber" element appealing
- **[reflection-use_case]** Applications: Museum and Private data sculpture with own data - simpler visualization
- **[future_work_idea][quote]** "Bringing back more comprehensibility" is a nice thought

Note:
The following protocol and notes were automatically translated (original language German) with DeepL

Study 2

Wednesday, August 31, 2022
Start at 13:13

Line Chart

- **[reaction-positive][reaction-system_impression][quote]** "Its a pretty seamless connection" - virtual and real is very much connected
- **[reaction-positive][reaction-system_impression]** Color matching works also well
- **[reaction-system_impression][quote]** "I want to touch the spheres" - first thought
- **[criticism-needs_improvement]** Scale line is a bit distracting - could be on the wall instead of the front
- **[criticism-hardware_limitations]** Field of view problems/limits of the HL
- **[reflection-use_case]** The real challenge is to find a killer app
- **[reflection-usability][quote]** "What kind of benefit should I get from the physical balls?"
- **[reflection-use_case]** If its suitable depends on the use case
- **[prototype_issue][quote]** "When it works (alignment) it really works good and it pays off but if the alignment fails a bit it gets destroyed - fragile system"

Bar Chart: Start approx. 10:00

- **[reflection-interaction_styles]** "interesting" --> direct interaction with the elements
- **[reflection-interaction_styles][future_work_idea]** Would be interesting to also include touch input with the HoloLens depth buffer
- **[future_work_idea][prototype_issue]** To touch virtual elements with that It would need to be aligned perfectly
- **[reflection-interaction_styles][quote]** "You end up with that strange effect where the real elements are feeling like virtual because the virtual elements are more bright than the real ones"
- **[reaction-positive][reaction-system_impression][quote]** "What works really well is that if you move it, you see the changes very well"
- **[reflection-benefits_of_physical][quote]** "In static the physical part don’t really add something but to engage people it is valuable"
- **[reflection-benefits_of_physical][quote]** "Instant zero cost access" --> from the physical device
- **[reflection-benefits_of_AR][future_work_idea]** HoloLens could also add more dynamic content
- **[reaction-positive][reaction-system_impression][reflection-benefits_of_physical][reflection-benefits_of_AR][reaction-integration] [quote]** "The part when it moves (AR & physical in combination) - there is something special happening here"

Node-Link start 19:00

- **[reaction-positive][reaction-system_impression][reflection-benefits_of_physical][reflection-benefits_of_AR][reaction-integration][quote]** "It’s a nice connection between the elements" of the system – AR & Physical
- **[specific_situation_comment][future_work_idea]** Also wanted to lift an element

- **[criticism-needs_improvement][reflection-design_issues]** The elements are nice to grab/interact with but sometimes is a bit difficult to reach all elements - the threads are even harder to see with the HL
- **[future_work_idea]** Idea: combine touch with an AR gesture to be also able to move it up
- **[reaction-positive][reaction-system_impression][reflection-benefits_of_physical][reflection-benefits_of_AR][reaction-integration][quote]** The blending is very good --> "here the blending of virtual and real works really good "
- **[reaction-positive][reaction-system_impression][quote]** "Despite the complexity you can clearly see the graph"
- **[reflection-usability][quote]** Other applications: "you could make something really beautiful but maybe not 100% useful" - with this setup
- **[reaction-positive][reaction-system_impression]** Convey movement very well in a multi-user setup (ca. 24:00)
- **[reaction-positive][reaction-system_impression][reflection-remote_interaction][reflection-use_case][reflection-usability][quote]** Multiuser scenario: advantage of sharing the same 3D data but would be the same with multiple HL - but it adds physicality and the haptic vibe --> "if someone else […e.g. remotely…] would move the elements this would really transmit the sense of being in the presence - quite physical feeling and connection"
- **[reaction-positive][reaction-system_impression][quote]** Collocated collab: "everyone could have this 3D data but the same magical effect can be achieved with multiple HL anyways - but the advantages of the haptic display is the fact that is haptic"
- **[future_work_idea]** Idea: capture vibrating / when you flick against it and the elements bounce back and forth as interaction

Private: Start 30:00

- **[reflection-benefits_of_physical]** The physical part is persistent - slower term data will persist and that where the physical part got is advantage
- **[reflection-benefits_of_AR]** AR allows you to see more and to control it
- **[criticism-needs_improvement]** Too much moderation tbh
- **[reflection-benefits_of_AR][quote]** "the AR part allows you to see more but it also allows you to control it"

Museum 37:00

- **[reflection-benefits_of_physical][quote]** "That's very interesting to have different physical objects"
- **[future_work_idea]** Idea: could one project onto the objects and illuminate onto it instead of illumination from the inside – cf. projector vs. HL
- **[future_work_idea]** 3D projection screen - reconfigurable with diff. phys. arrangement - large scope there
- **[reflection-benefits_of_physical][reflection-benefits_of_AR][quote]** "Use the system to bring things to live" - that could really work - physically move things and animate it with AR
- **[reflection-benefits_of_physical]** And it could also be an interface of course
- **[reflection-benefits_of_physical][quote]** Sidenote: "64 channel controller"

Other start: ca. 48:00

- **[reaction-negative][reaction-system_impression][reflection-benefits_of_AR][future_work_idea]** Struggling with resolution in Phys --> use AR to enhance this

- **[reaction-negative][prototype_issue][quote]** "Lag of touch in AR is a big deal" --> you have to invite to the touch --> focus more on the interaction part because otherwise it could be only AR
- **[reaction-positive][reaction-system_impression]** In general if STRAIDE is animated than is really present and replicated something living / something is really present
- **[reflection-benefits_of_physical]** Get physically aware of the system is a plus
- **[future_work_idea][reflection-remote_interaction]** Remote: if it would really mimic the movement of another person in detail and naturally it would be very interesting
- **[reaction-system_impression][ranking]** Most promising: all worked, node-link diagram was really visually appealing (may also because it was fitting in the field of view?) also when the bar graph was in motion these something spatial was happening
- **[reaction-negative][prototype_issue]** Liked the least: alignment in general
- **[reflection-use_case]** Other use cases: 57 - educational use cases e.g. for physics classes - simulations in general

Note:
The following protocol and notes were automatically translated (original language German) with DeepL

Study 3

Wednesday, September 1, 2022
Start at 10:30

Line Chart

- **[reaction-positive][reaction-system_impression][quote]** "The sound is cool, of course"
- **[reaction-negative][reflection-3D_vis_issues]** The spheres somewhat obscure the additional information and I'm unsure whether you need them (spheres) at all
- **[reflection-benefits_of_physical][reflection-unique_feature][quote]** "But it's nice to have a clear place for visualization"
- **[reflection-benefits_of_physical]** The spheres help with orientation in the room - lines alone would be harder to recognize from the side
- **[reaction-positive][reaction-HCI][quote]** "I really like the interaction (one-handed and two-handed - pan & zoom) because you have direct control over the data"
- **[reaction-positive][reaction-personal_use_reflection][quote]** "I would like to have this for my loan because there is never enough space in Excel"
- **[reaction-personal_use_reflection][reflection-benefits_of_AR][quote]** "I could well imagine using the system to visualize data - but I wouldn't really need the physical one for this"
- **[reaction-HCI][reflection-benefits_of_physical]** But possibly interesting as an interaction medium - especially if the user has no AR experience
- **[reflection-benefits_of_physical][reaction-HCI][quote]** "when I physically grab something, I know exactly what I'm doing" - more natural than AR freehand gestures
- **[reflection-collaboration]** Analytics and data in general as a shared experience
- **[reflection-benefits_of_physical][reflection-unique_feature][quote]** "If you have to think about the data, it's incredibly helpful to be able to walk around the room"
- **[reaction-negative][reflection-benefits_of_physical]** Accuracy: physical probably not useful
- **[reaction-positive][reflection-benefits_of_physical][reflection-use_case][quote]** General trends: "also completely conceivable in physical and of course also very cool" - example: marketing agency - live dashboard / most important KPIs passively displayed in a dynamic physicalization
- **[reflection-benefits_of_physical][reflection-use_case]** Many things fall behind in everyday life - e.g. successes - physicalization can create awareness here and also have a motivating effect - ambient sculpture e.g. in the company

Bar Chart: Start 09:30

- **[prototype_issue]** Gestures sometimes trigger unintentionally
- **[specific_situation_comment][quote]** Selects a bar: "cool"
- **[reaction-positive][reflection-3D_vis_benefits][quote]** "I always like it - 3D bar charts - it's also aesthetically pleasingly simple"
- **[reflection-benefits_of_AR][reflection-use_case][quote]** "Without AR, I wouldn't perceive it as a bar chart - more like an art installation"
- **[reflection-benefits_of_physical][reflection-use_case][quote]** "The physical is also very aesthetically pleasing and easy to imagine as a casual vis"
- **[reflection-benefits_of_physical]** The "always there" factor is very interesting with the physical sculpture

- **[reaction-positive][reaction-HCI][reflection-benefits_of_physical][reflection-remote_interaction][quote]** "I find the direct interaction very valuable" "remote is certainly very convenient because it also works from a distance, but this physical touch is exactly what is always missing and what I also miss when you are only in VR/AR - even force feedback controllers are always a crutch"
- **[reaction-positive][reaction-HCI][reflection-benefits_of_physical][quote]** "I can imagine that the physical interaction would be very helpful, at least for me"
- **[reflection-benefits_of_AR]** AR enhancements (see line chart vs. bar chart example) depend heavily on the use case and the data
- **[reflection-benefits_of_physical]** Bar Chart you want to touch directly - not necessarily with Line Chart --> Here the physical would be more important to me than with the Line Chart --> Bar Charts have more of a 'physical affordance'

Node-Link: Start 18:00

- **[reaction-positive][quote]** "Yes, that's very cool"
- **[reflection-benefits_of_AR][reflection-benefits_of_physical][reaction-positive][quote]** "Very nice symbiosis of AR and physical elements"
- **[reflection-benefits_of_AR][reflection-benefits_of_physical][reaction-positive][quote]** "The nice thing is that I can immediately see the difference between what is physical and what is virtual"
- **[ranking][reaction-negative]** In the other examples, this overlaps and can be somewhat confusing
- **[reflection-benefits_of_AR][reflection-benefits_of_physical]** The relationship between the physical element and virtual lines is clear and both parts have a clear role
- **[reflection-3D_vis_benefits]** "Spatial memory is very important with graphs and often difficult in other solutions - 2D representation is often not powerful enough and the space gives me the opportunity to locate myself"
- **[reflection-3D_vis_benefits]** Much more intuitive than in 2D/2D display with 3D vis
- **[reflection-benefits_of_physical]** Do I need the physical? --> Advantage: touch, collaborative aspect very well emphasized - you don't need extra visuals for pointing etc. but you have a common point
- **[reaction-positive][reflection-benefits_of_physical][reaction-HCI][quote]** "It's also easier for me to interact with it when I have physical handles"
- **[reaction-HCI]** Other variables may be important for reminders in Phys - but also depends on the dynamics - changes must not be too big if you only see physically / without AR
- **[reflection-alternatives_to_AR]** Also conceivable with tablet and cell phone - the advantage of this would of course be that the devices are available and within reach
- **[reaction-positive][reflection-benefits_of_physical]** Big advantage: something is directly in the room without any effort - you don't have to switch anything on etc. and additional information is then shown if required
- **[reflection-benefits_of_physical]** Generally very interesting combination with new 3D / holo technologies to bring haptic feedback into the three-dimensional world ... not just via vibration or similar.

Private: Start 31:00

- **[specific_situation_comment][quote]** "Of course, it's really cool when I know that the green one is my music" --> after the test person has raised their visor and can see without AR

- **[reaction-positive][reaction-system_impression][reflection-benefits_of_AR]** "I can well imagine that" (use case in general) - e.g. setting the heating of the individual rooms and displaying data - AR helps to see the details and general trends, you know after a certain time even without AR - approx. 35:00 - good comments
- **[reflection-benefits_of_physical][reflection-benefits_of_AR]** Interaction after learning phase also conceivable and imaginable without AR - particularly good for direct interaction, e.g. setting the next song or heating values and overview - I can well imagine details and setting up the UI with AR
- **[future_work_idea][reflection-use_case]** Visitor mode --> audio visualization --> want to decide for yourself what is displayed and when and not just always the data - can then be nicer
- **[future_work_idea]** You also don't want to see the statistics all day - have modes change or trigger them yourself - especially ambient visuals/art displays
- **[future_work_idea][reflection-remote_interaction]** Remote Parship displays - e.g. partner is at home - animation starts etc. - Telepresence
- **[future_work_idea][reflection-remote_interaction]** Creating a sense of cohesion is always difficult (with digital systems) and much is based on awareness - this is important peripheral information and such an ambient display can achieve this passively --> awareness e.g. the partner/colleague is "there" or is also currently working etc.
- **[reflection-use_case]** Can help in a private and professional context

Museum: Start 42:00

- **[reaction-positive][specific_situation_comment][quote]** "Hehe cool" --> when removing the earth
- **[reaction-positive][reflection-use_case][quote]** "Basically, this is a very nice use case for AR in museums"
- **[reflection-benefits_of_physical]** "The added value of the physical is of course that I can still move objects that I am otherwise not allowed to touch"
- **[reflection-benefits_of_physical][reflection-benefits_of_AR][quote]** "I can also do playful things" e.g. puzzle together the individual parts + AR extensions - gamification could be possible
- **[reflection-benefits_of_physical][quote]** "Physically touching it is definitely the added value here too"
- **[reflection-use_case]** I can also imagine different static things or simulation of e.g. bridge construction or similar. Simulation of bridge construction
- **[reflection-benefits_of_AR]** AR can then help with the interaction
- **[reflection-benefits_of_physical][reflection-benefits_of_AR][reaction-HCI]** You can create very good simulations that can have great added value for us humans - combine different senses/methods (direct manipulation/AR gestures and menus etc.)

Other: Start 54:00

- **[reaction-HCI][reflection-benefits_of_physical][reflection-3D_vis_issues]** Mainly the interaction brings the physical added value for AR - visual clutter avoidable with this interaction
- **[reaction-integration]** Question understood the other way round 56:00 - so the same again - interaction in particular is very good in physical terms
- **[reflection-benefits_of_physical][quote]** "I also see a big advantage in having a display that first shows something - also for a group of people - and then can react to it if necessary and get details on demand through AR"

- **[reaction-integration]** Having the transition from the physical and then details on demand is a very good way to combine the two technologies
- **[reaction-integration][quote]** "I think that the two parts (physical&AR) complement each other very well"
- **[ranking]** Complementing the technologies: Graph application worked very well and synergized
- **[ranking][quote]** Line Chart rather no phys needed - in AR sufficiently good --> "here I even found it more of a hindrance, as they obscured more in the lines than they helped me"
- **[reaction-positive][ranking]** Graphs were very good and the museum use case was also convincing
- **[reaction-positive][reaction-HCI]** Manipulation also very good with bars, but use case not quite clear / unclear what you would use it for
- **[reaction-positive][reflection-3D_vis_benefits]** Features: support spatial memory, the system can do this very well - great strength of the system - Phys offers good reference and AR the details - not easy to convey in 2D/3D on display - also the persistence in space
- **[reflection-use_case]** Other use cases: edutainment, simulations and telepresence/feeling of presence/cohesion could help with applications in this system (- e.g. see private use case end)
- **[reflection-benefits_of_physical]** Key Performance Vis Live on Phys + concrete numbers and details on demand --> make awareness and connections recognizable - because Phys is persistent and dynamic
- **[reflection-use_case][quote]** Example: a prize won is displayed, but the small daily success is quickly forgotten "life happens permanently - otherwise you only ever have this snapshot - and making the current process visible and (physically) displaying it is an interesting thought"