AR versus Physical Data Representations: A Comparison of User Engagement and Spatial Exploration Patterns

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Abstract

Immersive visualisations, that enable spatial, embodied exploration (e.g., XR and physicalisations), have the potential to increase user engagement with data representations. However, which mode of representation offers a higher engagement, and how does the user experience differ? Our work compares a physicalisation to a mobile AR representation of energy consumption sources and CO_2 emissions. In a counter-balanced study with 16 participants, we found no significant differences in perceived user engagement, except for higher scores in *"perceived usability"*. The physicalisation was considered 'real' and intuitive, the AR representation technical and precise. Most participants preferred the physicalisation and felt more 'connected' with it. We also analysed patterns of how people moved around the representations, and found no differences between conditions. Despite people being able to touch the physicalisation, this was barely made use of—thereby turning both conditions into visual exploration. We discuss what rationale participants provided for barely touching and discuss implications.

CCS Concepts

• **Human-centered computing → Empirical studies in HCI**; Visualization techniques.

Keywords

immersive analytics, user experience, touch, spatial interaction

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1 Introduction

In today's world, people regularly encounter data and data visualisations in their lives, leading to an increased societal expectation regarding data literacy among citizens. However, understanding data is a difficult task, as it requires a mix of skills and knowledge [14, 45]. To help people understand data, the field of Data Visualisation (DataVis) concerns itself with visually representing data, e.g., in graphs and diagrams [61]. Despite visualisations improving the understandability of data [45], they also have drawbacks. Data visualisations still require literacy to read (visualisation literacy [6]), and traditional visualisations (such as line graphs) can be seen as *"just a graph"* [67], meaning they are perceived as detached from the user. For topics that require the viewer to be engaged and relate to the data, such as data on climate change, this could be a disadvantage, as then the chances of them acting upon the data are low.

The field of *Immersive Analytics* (IA) [42] promises to improve the viewer's experience of data. Rather than visualising data on a flat canvas (such as a screen or a sheet of paper), IA brings data into a three-dimensional (often virtual) world, using technologies such as augmented and virtual reality (AR and VR) –combined referred to as Extended Reality (XR)– or physical visualisations (also known as *"data physicalisations"* [32]), to create immersive data experiences that can be perceived spatially. As a result, IA have shown to result in a higher engagement with the data, improved understandability, and more emotional responses compared to 2D visualisations [25, 32, 42, 64, 70].

Although XR and physicalisations can be combined (i.e., [43]), they are more commonly used on their own. The biggest difference between XR visualisations and physicalisations is the tangibility of the data representation. While XR cannot be touched (unless considerable effort is put into creating artificial haptic feedback), physicalisations can be. Given that touching artefacts can lead to higher engagement and improved understandability, as well as enhanced emotional connection and attachment [9, 25, 37], the physical nature and 'touchability' of physicalisations stands out as a key difference from XR that deserves deeper investigation. Nonetheless, direct comparisons between physicalisations and XR visualisations have received little attention, with –to our knowledge– only one prior study. This study compared memorability and task completion time of a VR data representation and a physicalisation [56]. Here, participants had a faster response rate with the physicalisation. The VR setup seemed to hinder participants' interactions with the data, possibly due to its novelty and because the viewing experience was not as smooth.

Whereas VR requires the user to be fully immersed in the virtual world, AR only requires partial immersion, with the user still experiencing the real-world environment [44]. Compared to VR, the use of mobile (or hand held device, HHD) AR is very accessible, as it only requires a smartphone or tablet –rather than a specialised device, such as a head mounted display– to access the AR experience. Consequently, mobile AR is commonly deployed in museums [69], popular games (cf. [46]), and public displays. Due to the popularity and accessibility of mobile AR [41], and that the user still experiences the real-world environment, we used mobile AR to evaluate the effect of physicality on user engagement and experience with a data representation.

Sixteen participants took part in a lab-study where they experienced a data physicalisation and an AR data representation (using an iPad Air). Participants answered questions about the represented data, filled out the User Engagement Scale (short form) [49] for each condition, and were subsequently interviewed about their experience. Given earlier research indicates differences in how participants move about and spatially explore a representation (in VR versus a physicalisation) [56], we further observed and tracked participants' spatial movements and actions. Our findings indicate no significant differences in the overall user engagement score, nor its subscales, with the only exception of a just significantly higher *"perceived usability"* score for the physicalation. Furthermore, the interview data shows that participants preferred the physicalisation, and considered different strengths and weaknesses for both types of data representations. For example, the physicalisation was perceived as more 'real' and intuitive, whereas the AR representation was considered to be exciting and precise. We further found little differences between the conditions in overall spatial exploration movement patterns, but great differences between individuals within a condition. Moreover, participants barely touched the physicalisation, even though they were allowed to. This was especially the case if participants first encountered the AR condition. Besides an order effect, the size of the physicalisation could have prevented touch (cf. [39]) or the fact that touch was not required to undertsand the data.

The contribution of this work is threefold. First, we show no differences in the user engagement of two types of immersive visualisation: mobile AR and physicalisation. Second, we document that people refrain from touching a physicalisation during user studies, identify individual differences in this behaviour, and provide reasons for the absence of physical interaction. Third, based on our findings, we give insights into when to use which type of immersive data representation.

2 Background

2.1 Immersive Data Representations

Although efficient and well-established, data visualisations do not make use of people's three-dimensional perception of the world. Even when we create 3D visualisations [1], people cannot walk around the data representation or analyse it from different positions—limiting us in our embodied analysis and perception of the data [42]. Therefore, IA explores *"the use of engaging, embodied analysis tools to support data understanding and decision-making"* [17]. This includes extended reality technologies, tangible and audio displays, and data physicalisations [42]. Although IA is a comparatively new field compared to DataVis (cf. [17, 32]), research has started to uncover the strengths and weaknesses.

Compared to visualisations, IA allows for collaboration, spatial data analysis, and situating data representations in contexts that are meaningful to the data [28, 36]. Despite the progress made, there are still significant research gaps. For example, both physicalisations and immersive visualisations are said to have an increased user engagement with the data. However, the increased engagement of physicalisations has, to our knowledge, not received a dedicated study, with it mostly being mentioned in an overview paper on the opportunities and challenges of physicalisation [32]. As immersive visualisations using XR result in an increased user engagement over other visualisations as well [36, 42], it is unclear whether increased engagement is the effect of physicality or related to something else, such as a more embodied data experience.

Therefore, to explore the user engagement of a data physicalisation and to assess how it compares to a virtual, immersive visualisation, this work looks into the user engagement resulting from people experiencing a data physicalisation and an AR data representation. We further explore how people engage in 'embodied analysis': their spatial (and embodied) movements around the data representations, to determine whether people interact differently with different types of immersive data representation [56].

2.2 AR Data Representations

AR can usually be experienced through either hand-held (HHD) or head-mounted devices (HMD). Previous work has found that usage of HHDs is considered more 'natural', with HMDs lacking familiarity and therefore, user acceptance [41]. Moreover, HMDs require a longer setup time and calibration process, and are less commonly used in daily life [5]. Consequently, this work compares a physicalisation to a hand-held AR representation, using a tablet. One effect of this is a difference in how the representation is accessed, with participants being able to look directly at the data representation or via a frame (the hand-held device).

Within visualisation research, AR has been used in various contexts, such as learning environments, health care, and big data [18, 22, 54]. It was found that AR visualisations work well to foster collaborative learning [12], improve people's understanding of data (including large data sets that are normally difficult to visualise [54, 60]), and increase the motivation to engage with learning material [4]. Another benefit of AR is that it is relatively easy to create interactive visualisations. In a study comparing an HHD AR learning environment and its physical counterpart, the AR environment even led to partially better skill development, motivated continued use, and led to more collaboration; additionally, participants valued flexibility of the representation [11].

[1]This form of data representation is criticised in Information Visualisation (InfoVis) [45]

Despite these advantages, research within tangible interaction and data physicalisation has found benefits for physical models, such as improved memorisation and task performance [27, 31, 56, 62]. There may even be a general preference to physically interact with an object [11, 31]. As the benefits of AR visualisations and physicalisation both overlap and differ, our work compares the two. Besides that, we will look into the biggest differences between these representations—the ability to physically touch the data representation and explore it directly, or mediated through a hand-held device.

2.3 The Role of Touch

Data physicalisation and XR visualisations both leverage the spatial understanding of humans. Despite this common aim, these approaches differ in the focus they place on physicality. For physicalisations, the physical nature of the representation is essential, whereas in XR it is not a focus. While physicalisations can be integrated into multisensory IA [43], typically, the physicality of the visualisation does not play a significant role in IA. Therefore, we consider the ability to touch the data representation a distinct difference between IA and physicalisation.

Previous work on physicalisation indicates that people use hand interactions, such as pointing, marking, and manipulating tokens, to make sense of the data [29, 31]. In addition, research on multisensory data representations (data representations that use at least two sensory modalities to represent data, such as haptics and sound [26]) shows that people respond positively to haptic feedback provided by physical data representations, because it allows them to connect the data to their body and feel the data [16, 25]. Similarly, some creators of physicalisations see value in haptics to represent the feeling of the data (e.g., if it was a rough day, the surface of the physicalisation could feel rough [66]). Despite indications that touch and haptics can have a positive impact, little work in data physicalisation has explored the role of touch more systematically (cf. [28]).

Although immersive visualisations can often not be touched (relying on XR technologies or wall-sized displays), it has been observed that people have the inclination to reach out and want to touch virtual objects in XR [43]. Adding haptics to XR has been an active research field for years, as the addition of haptics improves user's immersion [20, 34]. However, for improved user engagement, it appears that active touch is not necessarily needed. Marketing research has found that having customers virtually touch products using AR and VR results in higher feelings of perceived ownership and satisfaction [8, 21]. The work of Kim and Park indicates that even without virtual touch, AR improves immersion [35]. Nonetheless, 'real' touch appears to have a stronger positive effect on the user experience than virtual and no touch [38].

Because of people's desire to touch, the beneficial effect of touch on the user experience, and the difference between real, virtual, and no touch, our work looks into whether participants touch the physicalisation and how this affects their user engagement compared to not being able to touch the AR representation.

2.4 User Engagement

As the strengths of IA go beyond traditional usability evaluations of data visualisations (cf. [70]), research advises assessing and looking into the user experience (UX) of data representations [32, 42, 70]. Part of UX is user engagement. User engagement (UE) refers to the degree of attention, interest, and interaction that users have with a product, service, content, or platform [48]. It is a measure of how effectively a user is captivated by and involved with a particular experience, often leading to deeper and more meaningful interactions. According to Perry, there are four types of engagement: emotional, physical, intellectual, and social [53]. This distinction was taken up by Wang et al. in their suggestions for what constitutes the experience of data representations [70]. Thus, UE goes beyond user satisfaction: it is affective, cognitive, and behavioural in nature and encompasses both short-term and long-term effects.

Previous work in IA found that physicalisations and multi-sensorial data representations can trigger more emotional repsonses to data than visualisations [16, 25, 70], potentially enhancing the user's emotional engagement [32]. Moreover, Marriott et al. suggest that the spatial immersiveness and interaction opportunities of immersive visualisations can increase the UE [42]. However, to our knowledge, no direct studies exploring the UE of mobile AR and data physicalisation has been conducted.

There are various ways of assessing the UE of a product or service, such as measuring the time the user spends with the artefact under evaluation, how often they use it, and for how long they continue using it. Although useful, these methods give a one-sided understanding of the UE. As UE is composed of numerous factors (e.g., the user's motivation and interest, the artefact's aesthetics, etc.) [48, 53, 63], O'Brien et al. developed the *User Experience Survey* (UES) and a short version of this survey (UES-sf) [49]. Whereas the previously mentioned methods look at one aspect only, these surveys assess both psychological and behavioural patterns of UE, such as pleasure, aesthetic appeal, challenge, and endurability [48, 49]. Thus, providing a broader understanding of the UE. While currently being the most complete UE questionnaire available, the UES-sf does not capture all aspects of UE [53]. Given it currently is the best option, our study uses the UES-sf to evaluate user engagement.

3 Study Design

This research aimed to explore whether the physical nature of physicalisations (them being material and touchable) influences User Engagement (UE). To investigate this, we opted for a within-subject study in a controlled setting, comparing the same type of representation in two versions (see Figure 1): one that is physical and could be touched, and one that is only available visually, presented in AR.

As material for the two conditions, a physicalisation and an exact AR copy were made. Having an exact copy was important to ensure that the visual details of both representations have the same quality and detail. Given our research question only concerns the physical nature of the data representation, an AR version is adequate for the comparison study, and allowed us to explore the most commonly encountered type of XR [41]. Furthermore, having an AR condition (instead of VR) ensures that the surrounding environment is identical and avoids any potential risk of VR-induced motion sickness.

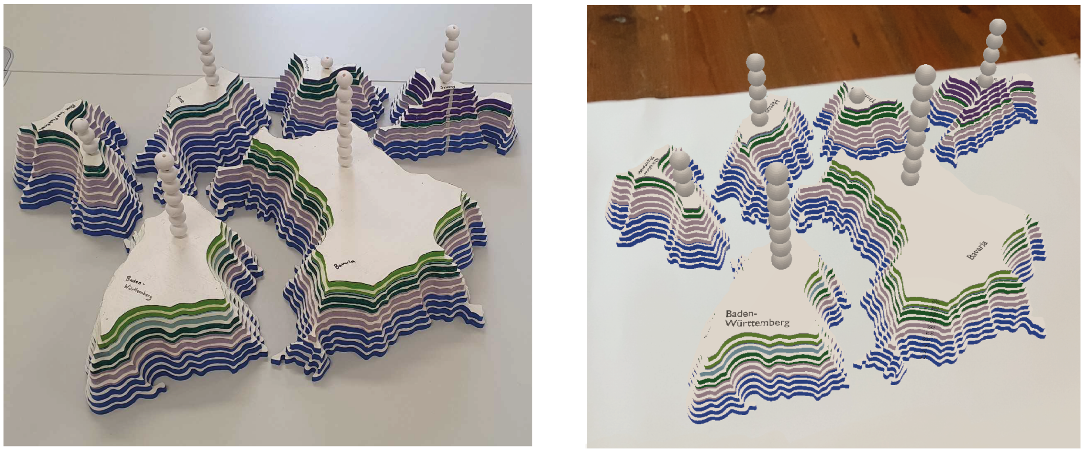

Figure 1: Left: The physicalisation of energy consumption and CO_2 emissions of South Germany. Right: the corresponding AR data representation of South Germany.

A counterbalanced study design (2 conditions: AR versus physicalisation) requires that participants encounter new data in each condition. Similar to other studies comparing data representation types (e.g., [39]), we decided to use two subsets from the same data source, so that the conditions would be comparable. Thus, after selecting the data source, it was split into two data segments, which were then represented using the same mapping/encoding mechanism. Then, for each data segment, both a physicalisation and an AR version were created, resulting in four representations in total. Based on the advice of Ren and Hornecker [56], the physicalisation was created first, to ensure the physical design could be realised, and only then an exact copy was made for AR.

We first discuss the choice of data source and representation, and then describe the details of the study design and process.

3.1 Choice of Data Source

To identify and select a suitable data source, we followed criteria similar to those outlined by Ren and Hornecker [56], but adjusted them to fit the needs of our study. The chosen data needed to be complex enough for non-trivial tasks, interesting to participants, and not widely known. We aimed for a data source that was neither too mundane nor overly exciting to avoid ceiling or ground effects, as a boring or overly simplistic topic might quickly lose participants' interest, complicating the measurement of user engagement (UE). Additionally, the data set had to be divisible into two segments to facilitate comparison without causing user fatigue.

Based on these criteria, data on the energy consumption of Germany's federal states were chosen [2]. Specifically, the energy balance (mixture of energy sources used) and carbon dioxide emissions of the federal states provided by the *LAK Energiebilanzen* [3] was chosen. The latest complete dataset dates to 2018, and was used for our data representations. Data about Germany were chosen, as the study was conducted in Weimar, Germany, with participants who reside there. We assumed that participants would feel a connection to these data, and that this would help them to understand the context of the data. The topic of energy consumption was selected for multiple reasons. Firstly, environmental data are frequently used for physicalisations [51]. Secondly, the topic is complex enough to require participants to take their time in making sense of the data and –even though it concerns everyone living in Germany– most people do not engage with these data on a daily basis. Thirdly, at the time of preparing this study, energy consumption was a major concern in Germany, not only due to the impact of climate change but also due to the gas shortage caused by Russia's war against Ukraine [10]. Thus, we concluded that the data was interesting enough for our study, but not too emotional, making it possible to evaluate the UE. Furthermore, the data are complex enough to mimic real-world data sense-making processes.

Next, this data had to be split into two segments of similar size and complexity (with resulting representations). For this, Germany was divided into a northern and southern part, each containing six states. For simplicity, the state of Saarland and the (tiny) city-states Berlin, Hamburg, and Bremen were excluded from the data representation.

3.2 Design of the Data Representations

Based on the data, various representational options were explored in brainstorming sessions (pie charts, stacked bar charts, distributed bar charts, etc.). All were based on a map of Germany, displaying the shape and geographical location of each federal state. This map-based structure and the use of familiar chart types were chosen to help participants more easily understand and interact with the unconventional medium of data physicalisation and AR representation. The map was divided into two halves, with each half containing six states, to represent North and South Germany.

While we wanted to provide a familiar reference frame for the underlying representation, we also needed to ensure the representations were not too similar to traditional visualisations (such as

[2]The datasets can be found on the following webpages: http://www.lak-energiebilanzen.de/CO2-bilanzen and http://www.lak-energiebilanzen.de/energiebilanzen/

[3]The German Länderarbeitskreis für Energiebilanzen is a governmental body responsible for the energy and carbon dioxide (CO_2) balances calculations used by the German government. LAK Energiebilanzen relies on data from the federal states for its calculations.

Figure 2: Left: Close-up of the federal state Rhineland-Palatinate. On the side, the black-and-white lines are the 1 mm rules, helping viewers to read off the percentage of energy consumption per energy source. An exact copy was also available as a training representation for the AR condition. Right: The practice data physicalisation of the federal state of Bremen.

line and bar graphs), given previous research found that people rationalise their experiences with these graph types post-hoc [67], making it difficult to evaluate their user experience (including user engagement). Thus, our design needed to include both familiar and new elements. Based on the initial ideas, the decision was made to create 3D topographic maps of each federal state. Each state consisted of stacked layers (see Figure 2). The overall height (identical for all states and representing 100% of the state's energy use) is split into ten layers. Each layer represents 10% of the energy mix. Energy resources (mineral oils, gas, renewables, coal, etc.) are distinguished by colour. The representation thus uses *colour* and *height* as explicit variables to encode energy consumption per resource [28], allowing the viewer to, e.g., compare the number of dark green layers (renewables) of the different states or to discuss the relation of pink (gas) versus blue layers (mineral oil).

The CO_2 emissions of each federal state are represented through 'bubble' bar charts on top of each state (see Figure 3). Similar to energy consumption, this representation combines familiar and less familiar representational elements (the bubbles). Since physicalisations require data curation to avoid visual clutter and maintain understandability, they cannot represent as much data as visualisations can [68]. Therefore, to prevent visual overload and ensure readability, the CO_2 emissions are represented separately from energy consumption, rather than combined in one data representation.

For the study, a legend (see Figure 3) was attached to a flat surface for both data representations. For the physicalisation, the legend was printed on DINA4 paper and placed on the table next to the physicalisation. The same document was loaded into the AR scene and the proportions were adjusted to match those of the physicalisation condition.

For the overall size of the data representations, we relied on previous work on the role of scale. This found that large physicalisations are better suited for a 'wow effect', and small and medium scale physicalisations allow getting an overview of the data without losing track when exploring details [39]. We chose a medium size for our study to avoid the 'wow effect' overshadowing any other user experience effects. A medium scale also offered a more equal comparison concerning the type of interaction afforded. A small-scale representation can easily be picked up in the physical condition, which is not possible in AR. A medium-scale representation further allows the participants to walk around the object in both representational conditions.

3.2.1 Building the Data Physicalisation. Once the representational design was determined, the physicalisations for North and South Germany were made. Figure 1 shows South Germany. Ren and Hornecker [56] suggest first constructing the physicalisation to ensure that the design can be produced, rather than discovering that a virtual representation cannot be replicated in physical form. For similar reasons, the physicalisation was made from MDF, which was painted using acrylic paint: a texture that can be easily replicated in virtual representations. The physicalisation was constructed with laser-cut layers of 10 mm MDF glued together. Each federal state consisted of ten layers, resulting in a height of 10 cm. Layers were then painted to represent the energy mixes, and each state was labelled with its name. Moreover, each state received scale marks on the side of 1 mm (Figure 2—left), to enable viewers to read the energy mix visualisation. The overall size of the representation of North and South Germany was roughly equal: 0.48 square meters (71 cm x 67 cm). Cotton balls with a diameter of 10 mm (used in architecture and available in art supply stores) were stacked on a wooden stick to create the CO_2 emission charts. Similar to MDF, the cotton texture was easy to replicate in AR.

3.2.2 Developing the AR Data Representation. An exact copy of the physicalisation was rendered in Blender to achieve an equivalent appearance (see Figure 1). This approach was chosen over photogrammetry due to performance reasons. An initial photogrammetry attempt with 300 images had created a model that was too large to easily deploy on a tablet. Reducing the model quality resulted in fuzzy edges and layers, thus being unsuitable for our study. Therefore, the data representation was modelled in Blender, based

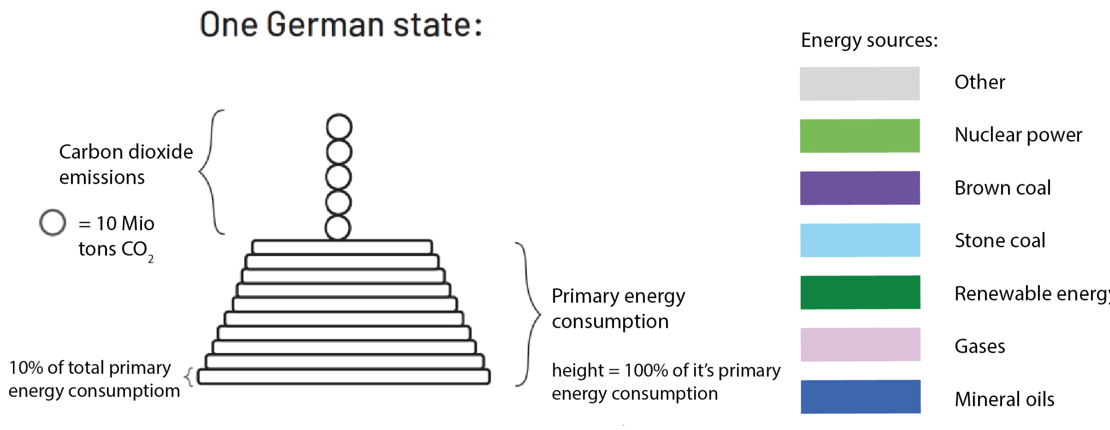

Figure 3: Legend/data encoding of the AR and physical data representation.

on the laser-cut files from the physicalisation. These then were extruded to real-world dimensions, i.e. 10 mm per layer, and coloured according to the energy mix using Blender's Texture Paint mode.

During the study, Adobe Aero was used to display the AR data representation on an iPad Air 4th generation. It was possible to perform common AR manipulations, such as rotating, scaling, and translating the AR visualisation.

3.3 Study Approach

In order to systematically evaluate and compare user experience and engagement, a within-subject study design was chosen. Participants encountered both types of data representation (one physicalisation and one mobile AR representation) in a counterbalanced order. After interacting with one of the data representations, participants had to fill out the User Engagement Scale (short form) (UES-sf) [49], to evaluate the user engagement with the data representation. Upon completion, participants were orally asked to answer some questions about the data and the encoding (e.g., *"what colour represents stone coal?"*), to assess whether they could understand the data representation. These questions spanned four levels of depth, from descriptive (easy questions) to interpretive (questions that require data understanding). Then, participants experienced the second data representation, after which they filled out the UES-sf again and were asked the same questions regarding the data. Upon completion, participants took part in a semi-structured interview to gain deeper insights in how they experienced the data representations and how they differed. The entire study was video recorded, so interaction patterns could be analysed. In the next sections, the procedure is explained in more depth.

The study was run at Bauhaus-Universität Weimar, Germany. It was conducted in a large room that could host the physicalisation as well as the AR model, to ensure that the AR model could be explored in its 'own' space within the room. As advised by Büschel et al. [9], the data representations were placed on a table in the middle of the room. Both were presented in equal size relative to the table. The table ensured that the AR representation could easily be connected to the physical surroundings and served as orientation.

3.3.1 Participants. Sixteen participants took part, seven women and nine men. Participants were aged between 18–34 years. In the USA (a Global North country, just as Germany) this age population has the most prior experience with AR [1], making this a suited age group for our study and minimising any novelty effect concerning the use of AR. Participants were recruited using convenience and snowball sampling. The average age of participants was twenty-six years (mean = 26.25, SD = 3.5). Their educational status was a general high school diploma or higher. All participants had prior AR experience. The level of experience could be grouped into: low (three participants, using AR in social media or games like Pokémon Go), medium (nine participants, with VR or AR outside entertainment), and high (four participants, developing AR environments).

3.3.2 Study Conditions. There were two conditions: (1) physicalisation and (2) AR representation. The conditions were counterbalanced using a latin square study design, where participants would first encounter the representation of one half of Germany (North or South) and then see the other half in the other condition. Half the participants started with the representation of North Germany and the other half with South Germany.

3.3.3 Procedure. The study process began with informed consent, an introduction to the study, and a training (familiarisation) phase, followed by the actual study, with questionnaires and a follow-up interview. Each participant's session lasted approximately one hour. The entire study was video-recorded to facilitate later analysis of interaction behaviours.

After acquiring informed consent, participants were asked about their previous experiences with AR. Then, the topic was introduced and participants were informed that they would explore the data for both North and South Germany, with two different types of representation. Finally, it was explained that the study does not focus on how quickly or correctly questions regarding the data are answered. Participants were encouraged to follow their normal behaviour and decision-making processes and to engage in all interactions that they felt to be beneficial for exploring and understanding the data. This was phrased very general and open-ended, as we wanted to see how participants would interact with the representations, but did not want to indicate that touching was desired. In phrasing this, we thus had to walk a fine line between signalling that any kind of interaction was allowed, and not explicitly mentioning touch.

To minimise novelty effects, a brief training phase was included [13]. Participants were provided the small state of Bremen in both data representation formats (not part of the data in the main study, see Figure 2). The presentation order was adapted to the assigned order for the participant (i.e. AR or physicalisation first). After the legend was explained, participants were free to examine the data representation and then answered a test question, to ensure they understood the data encoding and did not have problems with it in subsequent explorations.

Then, the actual study started. Based on the assigned counterbalancing order, participants explored the data and data representations sequentially. For each condition, participants were asked to first familiarise themselves with the data representation. This process took around ten minutes and ended with participants indicating that they were done and understood the data representation. Once they felt ready, participants had to answer ten short questions that assessed their understanding of the data and data encoding. These questions were asked to check whether the data representations were understandable (and thus fulfil an important aim of data representations [45]).

The questions were staggered into four levels of complexity. The first two (easier) questions related to the correct assignment of energy sources to colours. The second set of questions concerned simple queries of values, for example, *"What percentage of Thuringia's primary energy consumption is gas?"* or identifying extreme values. For the third level, the values of federal states had to be compared to each other and ranked. Two such tasks were: *"Which state has the lowest percentage of stone coal consumption?"* and *"Name the states in order of their carbon dioxide emissions, start with the highest"*. Lastly, participants were asked interpretation questions, such as *"Which state do you think is the most ecological?"* and *"Which state has the lowest carbon dioxide emissions compared to its size?"*. Participants were asked these questions in an interview setting rather than having to fill them out as a questionnaire, to reduce the feeling of sitting an exam. During these questions, participants had access to the data representation and were allowed to look at it, as the aim was to check whether they could understand the data representation, and not to assess its memorability.

After answering these questions, participants filled out the UES-sf [49]. As recommended by its creators, the order of statements within the UES-sf questionnaire was randomised [49]. This process was then repeated for the other condition.

Once participants had completed both conditions (and answered the questions and UES-sf), a semi-structured interview was conducted, which took fifteen minutes on average. Questions concerned: what their interaction behaviour and impressions of the data representations were, what they thought the differences between both representational forms were regarding their experience of the data, which of the representations they prefer and why, whether they touched the physicalisation and why (not), and to think of adjectives that either differentiate or unify the data representation forms.

3.3.4 *Data Analysis.*

The results of the UES-sf questionnaire were analysed as instructed by its creators [49]. The interviews were transcribed and analysed using Reflexive Thematic Analysis (RTA), which uses inductive coding [7]. This process was started by the first author of this paper, who started with familiarising themselves with the data over a duration of two weeks, in which the author re-read the interviews multiple times and wrote down initial thoughts (e.g., *"participants keep mentioning that the physicalisation feels more real"*). The initial familiarisation phase was discussed with the other authors, after which the first author started developing the first latent and semantic codes (e.g., *"intuitive interaction"* and *"people feel connected to the physicalisation"*). The codes were discussed with the second author, after which they were refined over a duration of a week. Then, the first author constructed the themes and subthemes. These were discussed with the other authors and refined over a duration of two weeks. In total, two themes and six subthemes were constructed.

Finally, the video data was analysed. Similar to the interviews, the videos were reviewed several times by the first author to identify patterns. The first author noted down recurring interactions across participants. For example, P2 and P14 would walk around, crouch, and bend forward to analyse the AR representation—thus, these participants were assigned to the same behaviour pattern. Contrary, for P5, P10, and P16, only changes in the upper part of their body (leaning forward and backward) were registered, constituting another behaviour pattern. Furthermore, the amount and types of touches and pointing (e.g., touching the legend or pointing at the representation) were written down. By going through the data and noting down repeating interactions, six behaviour patterns for both the physicalisation and AR representation could be constructed.

4 Findings

During the study, participants were asked questions about basic data understanding, to verify whether they could read and understand the representations. For both conditions, these questions were all answered correctly, showing that both types of data representation were understandable to participants. Furthermore, participants reported that it was easy to respond to the comparison and detail questions in both conditions, and mentioned that the illusion of the presence of the data representation in AR was satisfactory.

In the next sections, we first describe the results of the user engagement ratings. Then, we introduce the interview findings, including the reasons for why participants touched or did not touch the physicalisation. Finally, interaction patterns for both representations are discussed, where we identify an order effect of the conditions on the amount of touch.

4.1 Subjective User Engagement Ratings

To assess the representational modality's impact on participants' engagement, the UES-sf was used. UES-sf scores pertain to four factors of user engagement: focused attention, perceived usability, aesthetic appeal, and reward [49]. Figure 4 shows the results of the UES-sf for the physicalisation and AR representations of North and South Germany combined.

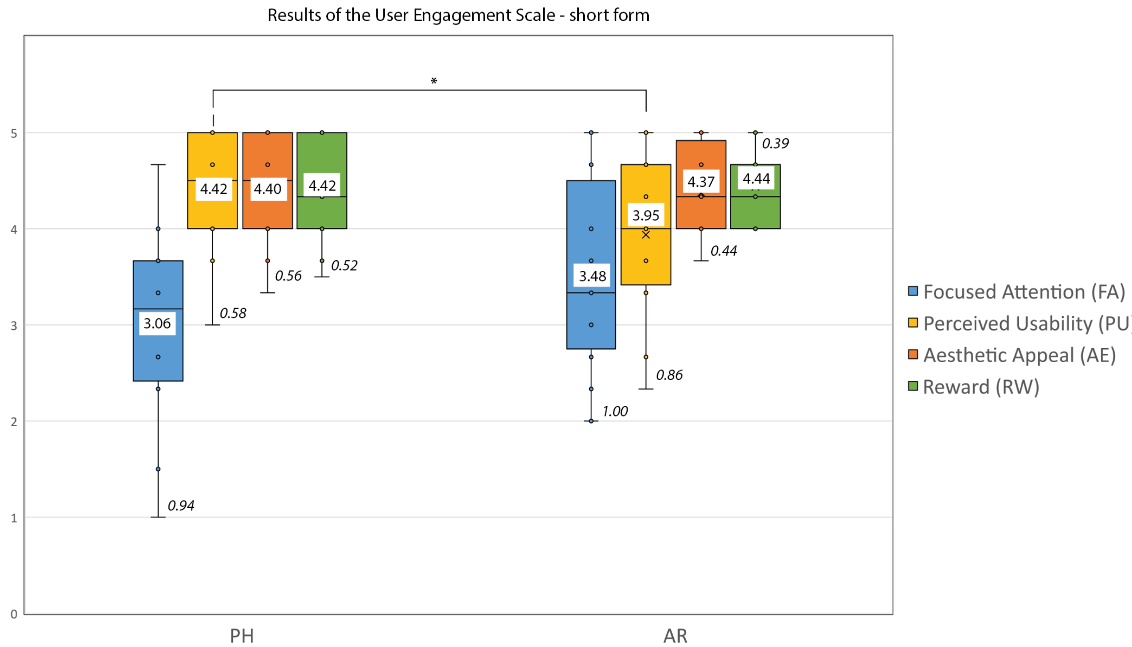

Figure 4: Results of the UES-sf, left for the physicalisation, on the right for AR.

To test if there were significant differences in the UES-sf subscales between the two representations, we performed two-tailed Wilcoxon signed-rank tests ($\alpha = 0.05$) using JASP `0.17.1.0`. Test assumptions, such as normality, were confirmed using Shapiro-Wilks Tests ($p >= .141$) and through inspecting QQ plots. Despite data being normally distributed and likert data often being treated as interval scale [72], we opted for the more conservative non-parametric Wilcoxon signed-rank tests to avoid issues around violated assumptions. P-values were posthoc corrected using Benjamini-Hochberg [23], a method more appropriate for small samples such as our study.

We found that the physicalisation had significantly higher *"perceived usability"* scores compared to AR, with a medium-large effect size ($W = 79.000, p = .050, z = 2.341^*$). For all other subscales, there were no significant differences: *"focused attention"* scores ($W = 6.000, p > .050, z = -2.401$), *"aesthetic appeal"* scores ($W = 37.000, p > .050, z = 0.356$), nor *"reward"* ($W = 29.000, p > .050, z = -0.356$). Likewise, despite the physicalisation having higher average total engagement scores ($M = 3.828, SD = .438$) than AR ($M = 3.807, SD = .338$), this result was insignificant ($W = 60.000, p > .050, z = 0.471$).

4.2 Interview Findings: Physicalisation versus AR

In the interview, sixteen participants stated that there were no differences between the two forms of data representation: *"in their appearance and everything, they seem very similar"* (P1). Despite this, participants did have a clear preference for one type over the other: twelve participants preferred the physicalisation and four participants the AR representation. One of the reasons for this was the limitations of using a tablet to see the AR representation (rather than an HMD). With the physicalisation, participants did not need to move a lot for a good overview: *"you have the advantage of having everything in your view and then just select what you are interested in"* (P10). This was more difficult with the AR representations: *"you can only see a section on the tablet"* (P14).

However, this was not the only reason. The physicalisation was also perceived as intuitive and more 'real'. Thus, leaving a bigger impact and connection to the data. On the other hand, the AR representation was described as exciting, and was valued for its sharpness and precision, making it the preferred representational modality for four participants. Below, we discuss the strengths (and perceived limitations) of the physical and mobile AR data representation in more depth.

4.2.1 Physicalisation is Intuitive, AR Exciting. Despite there being no difference in understandability (based on the ability of participants to answer questions about the data correctly), nine participants stated that reading the data and making sense of it were easier with the physicalisation: *"I also found it easier here with the physical model, because I could simply grasp it faster [...] because it is so low-threshold and easy [...] and also that it is so tangible"* (P2). In particular, counting and verifying the data was easier with the physicalisation: *"I also had the impression, because I saw it in front of me, that I could simply grasp it faster that way. For example, counting with the balls, that was somehow easier for me"* (P16). In addition, solving tasks felt more intuitive with the physicalisation, as described by P1 and P2: *"it felt more natural"* (P1), and *"somehow it was easier for me, because it was a bit more intuitive with the physical model"* (P2). This was more difficult with the AR representation: *"It wasn't so intuitive for me to take another step back and have the* *whole overview, but to stay close to it and then rather move back and forth or walk around"* (P14).

Despite being less intuitive, the AR data representation was considered more exciting: *"I found it naturally exciting, perhaps also because of the novelty factor"* (P14). In contrast, the physicalisation was deemed traditional: *"the real one is more… yeah, traditional"* (P8). A reason for this could be that participants are used to physical data representations: *"because you are more used to it"* (P15). Both novelty effect and familiarity thus influenced participants' reactions.

4.2.2 Physicality and Perceived Connection. Seven participants described feeling closer to the physicalisation than the mobile AR representation: *"the physical one like, I felt like, you know, I was closer to the object, I could feel it"* (P7). As indicated by the last part of P7's sentence, the physicality and the idea of being able to touch the object, contributed to this feeling of connection: *"It's just the like physicality of like touching the data that's made the difference"* (P5) and *"The model [physicalisation] can make the user or participants feel more close to your project, your data because the model is really there, you can sense the model. You can look at the model. You can touch the model. You can feel, okay, the data exists in the real world"* (P8). This also resulted in bigger perceived impact of the representation: *"because of its physicality. It made a bigger impression on me"* (P1).

In contrast, this perceived 'realness' and connection were absent for the AR visualisation, which reminded participants of other digital technologies, limiting a connection: *"but in the virtual one it is like it's just an app. Like I couldn't relate to it that much"* (P7). A reason for the lack of connection could be that in the AR condition, participants looked at the data through a mediating layer, as expressed by P10 and P9: *"moving around the physicalisations made it feel a bit more real somehow, whereas like moving around with iPad [...] it felt somewhat like you're looking through it rather than seeing it for yourself"* (P10), and *"I was looking through the display, so I had an external resource with me to go to view the data. So, it was like a barrier. I couldn't like, have the complete access towards the data"* (P9).

The perceived disconnect with the AR representation was not only emotional, but related to participants' experience of the data representation as well, making it difficult to get a sense of the volume of the federal states: *"in the real model, on the other hand, you somehow have a better feeling for the volume. Or the volume makes more of an impression. And in the AR model you didn't have this feeling of volume, I thought, because it was more projected"* (P15). Furthermore, P1 mentioned that the physicalisation: *"had attributes that I [. . .] did not perceive in the virtual model. Like, I didn't think about, like, how heavy it is"* (P1).

4.2.3 Hand-Crafted Nature adds Value. The lack of connection resulted in participants speaking differently about the data representations. The physicalisation made participants reflect on the creation process: *"I found it somehow quite exciting, because it didn't feel like wood, and it didn't look like wood, and I was somehow a little bit... I was asking myself the whole time: Huh, how exactly was this built, how exactly did it become such a model?"* (P2). Participants imagined the effort in construction and pointed out that this contributes to the overall value: *"I could tell that that's handmade. And it kind of added value to the, because it's art [. . .] and the fact that it's a craft. It's a handmade thing and I appreciate that"* (P6). Because of this perceived effort, participants mentioned that the physicalisation reminded them of art: *"this data is not statistics for me. This data is art. You know, like a message"* (P6), and resulted in speculations of scaling the physicalisation up to a public installation: *"in a larger scale like you know, just bam. Like look at this, this is what you're doing [...] showing the public, like, making them aware of something"* (P12).

These reflections were absent for the mobile AR representation, which was digitally crafted by the first author and could, in theory, be easier deployed as a digital artwork in various museums at the same time.

4.2.4 AR's Precision and Technical Nature. Although it appears that connecting to the data was more difficult with the mobile AR representation, participants did appreciate the precision of the AR visualisation, which made it easier to read the data: *"I had the feeling that I could read off the distribution precisely with the digital model because I could get closer to it, and it simply has even more precise, sharper lines that are [...] easier to read off more precisely."* (P13). To some, this precision came as a surprise: *"What surprised me was actually the AR model that was generated was far more accurate. [. . .] it seems to be perfectly functional, and it looks perfectly alright"* (P9).

As the AR representation was seen as 'perfect': *"You can just see it, it's just perfect. It's all rendered like that, the edges are all very sharp, and with the physical model you can just see that it's been done"* (P13), it did increase the immersion of the experience: *"the AR thing was easier to use and more immersive for me"* (P6).

Because of the AR representation's precision, participants saw the potential of using it in technical exhibitions: *"I see it more [...] in such laboratories or in such technical museums"* (P2), to represent quantitative data: *"if it has more numbers [. . .] more stats"* (P6), and when it is important to show changing data values: *"with AR, I could imagine that if you want to show [...] dynamic data, so to speak, you would have the development over time"* (P14).

4.3 Do People Touch the Physicalisation?

Various participants expressed the feeling of being able to interact with the physicalisation, as exemplified by the following quotes: *"I felt that they are always there, and I can interact with them somehow"* (P3), *"I was closer to the object, I could feel it"* (P7), and *"You can look at the model. You can touch the model. You can feel, okay, the data exists in the real world"* (P8). Despite this, most participants did not make much use of the ability to touch it. In total, seven participants (out of sixteen) touched the physicalisation: three touched it once, three did so twice, and only one participant touched the physicalisation more than four times (usually mainly for counting the bubble bar chart of CO_2 emissions). Except for the latter person, touch did not play a large role in participants' interaction with the physicalisation.

4.3.1 Reasons to Not Touch. Twelve participants stated that there was no need for touching the physicalisation: *"I didn't feel like I need to do it because I was able to read it correctly and then like understand it"* (P5) and *"I've already seen everything well, so it wasn't necessary"* (P16). Based on participants' feedback, it appears there needs to be a reason for touching a physicalisation: *"If, of course, there is* *still some information hidden somewhere or underneath, or you want to know something"* (P16), such as with *data sensification*, where the user only gets the data insights when interacting with the data representation [24]. Without a reason to touch, no extra value is gained: *"No value [...] I could have touched it, no added value"* (P13) and *"personally wouldn't attach any importance to it"* (P15).

Besides there being 'no reasons' and 'no added value' to touching the physicalisation, other factors played a role. Firstly, the weight and size of the physicalisation did not invite touching it: *"they appeared to be kind of heavy and like perfectly in place. So, I didn't feel like [. . .], something in my head that said, like: 'no, no, let's not lift it up"'* (P1). This aligns with the work of López García and Hornecker [39], who found that people are more likely to pick up small physicalisations. However, not even or barely touching the physicalisation to make sense of it and to compare and count, remains surprising; findings from constructive visualisation show that touch helps people to make sense of their data [29], and research into multi-sensorial data representations that showed that people enjoy haptic interaction with the data representation [16].

Secondly, the order in which participants explored the data representations could have had an impact, with prior experiences dictating the touching behaviour: *"Maybe also because I had seen the digital model before that I somehow didn't have the urge any more, because I [...] knew from the experience before that I could find out all the information without touching it. Maybe that's why I didn't touch it"* (P13). Lastly, it could be due to the perceived value of the physicalisation: *"I wouldn't touch it like because it's like, oh, it's art. You made it. [. . .] It's nice, so I wouldn't touch it"* (P6) which made them anxious that they would break it: *"maybe I'll drop it, or I won't be able to grip it well and then something will happen. I think that's what kept me away the most"* (P2), and reminded them of art exhibitions: *"Nothing should be touched in museums. And that's why I don't do it here either"* (P11). Some participants had thought they were not allowed to touch the physicalisation given that this had not been explicitly mentioned in the introduction of the study:*"I wasn't quite sure, so I didn't even ask"* (P14).

Noteworthy, given participants were not afraid of breaking the AR representation, this made the interaction more playful for some, as stated by P6: *"It can be more audacious with the digital version. Poke at it, you know, I tried to zoom in [...] Play with it and do whatever you want"*.

4.3.2 Reasons to Touch. Four participants saw benefits to touching the physicalisation. The most important benefit was making counting easier: *"I did a lot of like counting with my fingers. I pointed at it like a kid, like 1, 2, 3. [...] I just have to touch it and understand"* (P6) and *"If you count like normally without touching it, you can just [...] miss-value it. But when you touch it, you can easily differentiate and, like, count properly"* (P5). This behaviour aligns with findings from constructive data visualisation [29]. The inability to physically count the data was also seen as a drawback of the AR representation: *"it took much more time through the air for me to calculate the carbon emission structure"* (P9). Besides making counting easier, touch helped P5 to make sense of the data: *"It helps to process the data faster [...] I was able to answer like very quick [...] it's intuitive for me to touch it and understand it"*. Lastly, touching helped to grasp the size of the physicalisation: *"I was able to touch the model and I could actually feel the structure of the model [...] understand the size of the model itself"* (P9).

4.4 Interaction Behaviours

Each study session was video recorded, for the purpose of analysing participants' interaction behaviours with both data representations. Six behavioural patterns were identified for both conditions from the video analysis through repeated viewing, counting of touch events, and sketching the movements of each individual around the table.

4.4.1 Movement and Interaction Patterns with the Physicalisation. Figure 5 shows six patterns of participants' behaviour around the physicalisation, where pattern 1, 2 and 3 do not involve touch. Patterns range from participants remaining stationary at one position –solely viewing one side of the data representation– and only leaning forward or backward to change their view, and not engaging in any touch attempts (five participants, interaction pattern 1), to participants walking around the model, kneeling down, and leaning forward and backward to get a full view of the data, and touching both model and legend (three participants, interaction pattern 4). With Pattern 2 and 3 (four participants), people moved around the model freely, and also (pattern 3, 1 person) kneeled down and pointed at the model repeatedly. While six people (pattern 4 and 5) combined moving around the model, touching and pointing at it (pattern 5 is similar but has more varied movement around the table), one person remained at one side of the table (similar to pattern 1), but crouched down as well, and repeatedly touched and pointed at the representation.

People who touched the representation also moved around it (pattern 4 and 5), except for one person (pattern 6): P6 touched the physicalisation more than four times but remained stationary. Furthermore, apart for P1 (pattern 3), participants who pointed, also touched the physicalisation (or vice versa).

Besides changing their posture and viewing height/angle, eight participants used their arms and hands to point at or touch the physicalisation and/or legend. These interaction patterns overlap with interactions observed in earlier research, which compared a data physicalisation to an VR data representation [56].

4.4.2 Movement Patterns around the AR model. The movements in AR were also summarised in six patterns (see Figure 6). Here, touch was not possible, and thus not part of the patterns. These patterns (minus touch) are similar to those found with the physicalisation. But, within the observed postures (leaning forward or back, kneeling down), the tablet was often moved as well. This was partly due to the resolution of the tablet, which required participants to get closer to view details: *"I had to go very close to actually get the grade"* (P3). This resulted in increased movement effort for the AR condition, as described by P1 when discussing the physicalisation: *"I was still like, moving my head a bit, but definitely not as much as I was moving the tablet to try different perspectives"*, and P2: *"with the tablet I felt I had to move more, turn more"*. The increased movement effort lead to a greater perceived overall effort: *"I had to move more and had a greater effort to get to the data"* (P16).

In pattern 1 (three participants), participants hardly moved and stayed on one side of the table. They also moved the tablet in front of

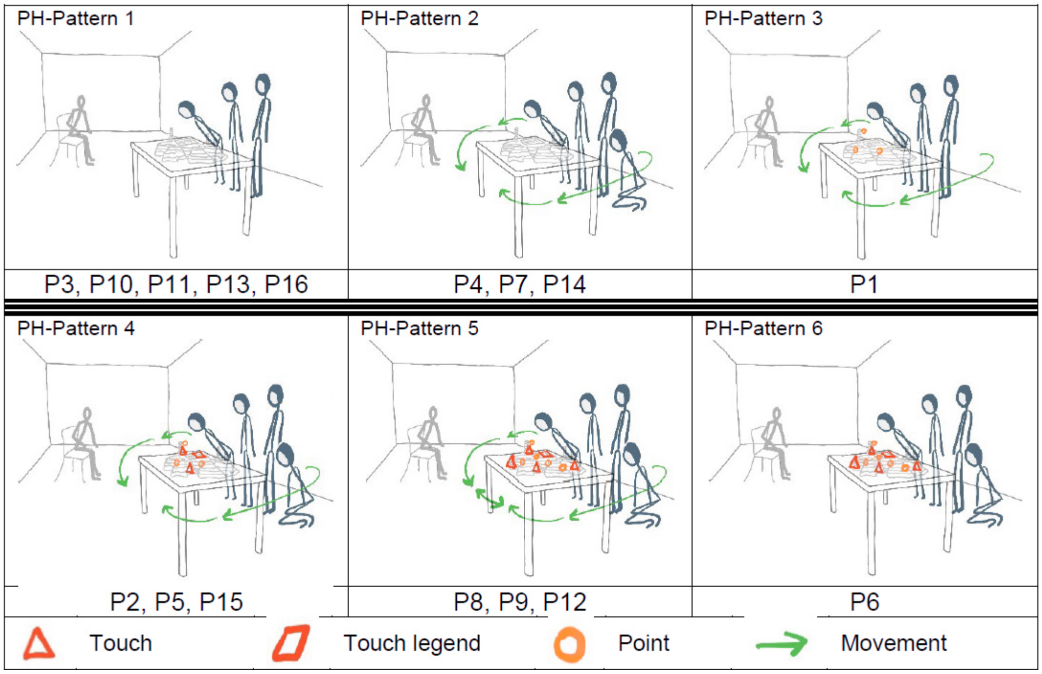

Figure 5: Behaviour patterns (touch, pointing, and movement) with the physicalisation. The person sitting in the back shows the observing researcher.

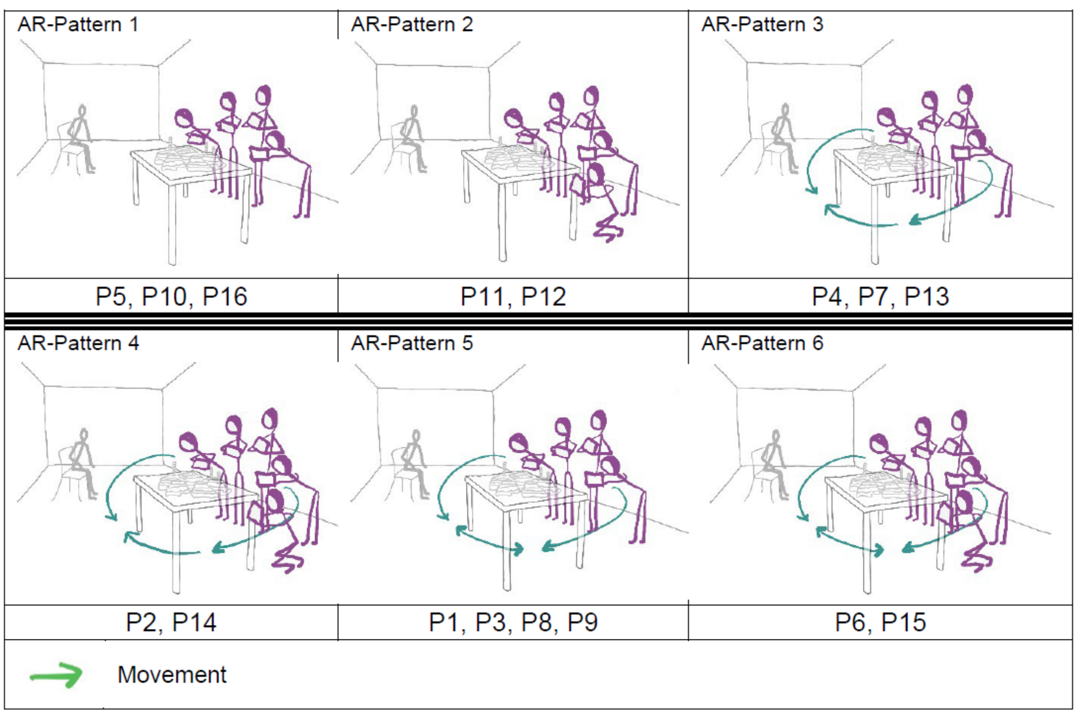

Figure 6: Behaviour patterns (pointing and movement) with the AR representations. The person sitting in the back shows the observing researcher.

their head while leaning forward. Pattern 2 includes kneeling down (two participants). In pattern 3 (three participants), the participants additionally moved around the table at least once, but in contrast to P2 and P14 from pattern 4, did not kneel down. P1, P3, P8 and P9 moved around the table the most (pattern 5). But unlike P6 and P15 (pattern 6), they did not kneel.

4.4.3 Amount of Movement and Order Effects of the Conditions. Despite the perceived increased overall movement effort in AR, participants moved approximately the same amount for both data representations (P1, P2, P4, P7, P8, P9, P10, P11, P14, P15, and P16). Thus, the condition did not appear to have an effect on spatial exploration. P3 and P6 moved slightly more in the AR condition, but P5 and P12 showed more movement with the physicalisation. Similar to observations in earlier work, for both conditions, participants changed their body height (e.g., by kneeling) to gain a better view of the data representation [56].

When taking into account the experimental counterbalanced setup, there appears to be an effect of order, with people who started with the AR condition touching less (P1, P3, P6, P8, P10, P11, P13, P14). Only P6 and P8 from the AR-first group touched the physicalisation. From the nine participants who did not touch, six had started in the AR condition, whereas from the seven participants touching the physicalisation, five started with this condition. From the pattern 1 group (standing still, no touch), only one (P16) started with the physicalisation. The six out of eight participants who did not touch, started with the AR condition. In contrast, the majority of participants exhibiting interaction pattern 4 and 5 (the most movement and interaction) started with the physicalisation, except for P8.

For the interactions around the AR version, no such order effect could be observed. AR-first and physicalisation-first participants distribute evenly across all six patterns. Noticeable, though, is that three participants chose to remain on one side of the representation in both conditions, and not move around it (P10, P16, P11). Furthermore, two people who, in the first-encountered physicalisation condition had moved around the model and touched it (P5 and P12), did not move around the AR representation.

5 Discussion

This study aimed to explore whether it makes any difference if representations are virtual and just visually available (mobile AR condition), or present in physical form (physicalisation) for the user engagement with data representations. The results from the UES-sf indicate no significant difference in the user engagement of the mobile AR representation and the physicalisation (apart from 'perceived usability' where the mobile AR version fared worse). Besides insights into user engagement, we found no impact of condition on spatial exploration (how much participants moved around the table). Despite telling participants they could explore the representations in any way they wanted, only about half touched the physicalisation—*often only once*. Part of this could be due to an order effect, with participants who started in the AR condition being less likely to touch the physicalisation, than those who started with the physicalisation. Yet, twelve out of 16 participants expressed a preference for the physicalisation. Next, we discuss reasons for this lack of touch, present use cases for physical and virtual data representations in immersive data analytics, and reflect on the apparent influence of data physicality on the user's connection with the underlying data and the creator behind the representation.

5.1 Physicality Creates More Connection—Including with the Maker

In our study, the physicalisation triggered reflection on its making process. This was notably absent for the mobile AR data representation, even though creating smooth and realistic-looking renders requires a lot of time and digital craftsmanship. As explained by Hornecker et al. [28], this can largely be explained by the material nature of physicalisation, as materials contain traces of the craftsmanship and effort someone went through. As AR visualisations lack this materiality, and in our study had a perceived 'perfection', this could be a reason for why participants did not perceive the same connection. Furthermore, most people have experience crafting an object; fewer people have experience creating digital renders. Modern digital products are often known for their ease of use, effortlessness, and instantness, which could be a reason why people do not think about the creator or creative process behind digital artefacts.

Besides lacking physical materiality, the AR representation has a level of ephemerality: it can simply be transported to other locations and when closing, turning off, or putting down the iPad, one can no longer see it. On the other hand, the physicalisation remains visible, perhaps from the viewer's periphery [3]. Therefore, the connection that participants felt may be due to the more permanent nature of the physicalisation.

Finally, in this study, participants interacted with the AR through an HHD. This brought limitations for viewing the representation (screen size) and required more physical effort to move the device. It also resulted in the feeling of looking at the data through a mediating layer, which could have prevented a connection to the representation. Thus, to compare whether our findings hold up when users experience HMD AR rather than AR on a mobile handheld device, future studies are needed. Moreover, future work should investigate the causes of the felt disconnect with the AR representation.

5.2 Use Cases for Physicalisations and AR Representations

Since the physicalisation raised questions about how it was created, it appears that data physicalisations inherently embody the data feminist principle of making labour visible [14]. Previous research found that physicalisations can show the messiness of data [67], and trigger emotional and critical thinking about the data [50, 70]. The latter, combined with our finding that participants related their bodies to the physicalisation (e.g., by discussing its size and potential weight), aligns with the data feminism principle of elevating emotions and embodiment [14]. Furthermore, the physicalisation left a bigger impression on participants than the AR data representation. Thus, it appears advisable to employ physicalisations when the creator's aim is to: (1) convey a message or story (e.g., [33]), (2) affect the user with the data (e.g., [57]), (3) make the viewer think about the data (e.g. [40]), or (4) represent data in a way that aligns with data feminist principles. Physicalisation's ability to affect people could be one of the reasons why data physicalisations are often used for critical and emotional topics, such as environmental data [51].

Contrary, as the AR representation was considered more precise, our advice is to use AR representations when the creator's aim is to communicate precise data values to its audience (such as in lab settings or science museums, per our participants). Thus, aligning the common aim of data visualisation of providing clear data insight [45]. This could be beneficial for making numerical and big data more engaging [47]. However, it is important to note that despite AR's perceived precision, participants mentioned the AR condition required more movement effort to read the data: for some data, participants had to move closer to see the numbers than with the physicalisation. This could be due to technical limitation of the display utilised for the AR condition. Yet, it is interesting that despite this increased effort and (at places) reduced readability, the AR visualisation was described as more accurate. Future studies could explore what exactly contributes to the perceived precision of AR.

Besides precision, it seems from the interviews that the AR representation was more immersive than the physicalisation. According to Ermi and Mäyrä [19], there are three types of immersive experience: imaginary, challenge-based, and sensory. Here, sensory immersion relates to disassociation for the real-world through the usage of XR technologies, and challenged-based immersion to cognitive involvement. Imaginary immersion refers to emotional involvement. Considering that participants did not perceive the same connection to the mobile AR representation as with the physicalisation, it seems that the immersion mostly was imaginary and sensory—not emotionally. Therefore, it could be that the perceived extra movement effort and interactions (from holding up the display and looking at the visualisation through it) played a role in the perceived immersion. To better understand whether this is the case and how the immersion differs between HHD and HMD AR visualisations, future studies are needed.

5.3 Data Physicalisations and Touch

The use of touch is only rarely described in survey papers on data physicalisation (cf. [2, 15, 58])—indicating that touch and haptics are still little explored fields within data physicalisation. Many physicalisations do not require touch, as the core information is encoded through shape and colour [28], which can be perceived visually. Despite this, on a tactile level, we know that haptically represented data enhance the user's emotional connection to the data and make them relate the data to their body [16, 25]. Furthermore, recent work in data physicalisation emphasises the potential of *haptic variables* for physicalisation [28, 55].

Regardless of the rare use of haptics in data physicalisation, other research fields have shown that people enjoy interfaces and representations that can be touched and physically manipulated [59, 65]. Moreover, research indicates that touching objects makes a difference: the use of touchable 3D replicas in museums enhances the museum experience and leads to higher intentions to visit [71]. Furthermore, touch increases emotional responses to products, enhancing hedonic value and emotional attachment [37], and supporting perceived ownership and endowment effect (valuing items more highly).

Yet, even though physicalisations are physical artefacts that can –in theory– be touched, in our study, touch did not play a large role in the interaction of participants. A reason could be the size of the physicalisation. Previous work has shown that people are more likely to pick up (and hence touch) small physicalisations [39] that can easily be held in one's hand. To ensure comparable conditions, we decided for a medium physicalisation, so there would not be an issue with participants not being able to pick-up the AR visualisation. However, it is worthwhile to replicate our study with small scale, hand-held data representations to see if this alters touch rates. Nonetheless, besides the size of the physicalisations, the interview data shows two other reasons for a lack of touch interaction. On the one hand, participants explained that touching was not needed; the visual sense was enough to decode the data. Especially if they started with the AR condition and had experienced that visual inspection was sufficient, participants did not touch. On the other hand, the resemblance of the physicalisation to an art object made participants hesitant to touch the data representation. Thus, there seems to be a legacy effect from prior experiences, where often at exhibitions, visitors are not allowed to touch objects. Besides these two reasons, the lack of touch could stem from people not being accustomed to touchable data representations, with not data representation being solely visual.

In effect, people not touching the physicalisation might have prevented any of the effects known from tangible interaction literature that relate to higher engagement to occur (e.g., increased emotional response, perceived ownership, support of tangible thinking, etc. [37, 59]). Participants not touching (or not touching much) equalised the conditions, but also equalised user engagement. In retrospect, the attempt to create a fair comparison between a mobile AR representation and physicalisation, and to not explicitly encourage and provoke touch, might have prevented a stronger impact of the physicalisation to arise.

This means that physicalisation creators need to actively design for haptic interaction if they want users to physically interact with the data representations. To do so, they can either use the haptic variables [28, 55], or create data sensifications [24, 30, 40]. Alternatively, they could create setups where people need to touch the objects at the start (e.g., to move it, to put it together), to enforce touch and to lower inhibitions. Future work needs to take these insights into account when attempting to identify potential benefits of physicalisations over purely visual representational forms. A difficulty then is, that it becomes hard to create equitable conditions for a comparative study, as the physical (needs to be touched) and the virtual condition would differ along not just one but several variables (including interaction mechanisms).

5.4 Future Work

Our study was conducted at the Computer Science (CS) faculty of the Bauhaus-Universität Weimar, with participants who mostly study or work in HCI and CS. While this ensured that AR was sufficiently familiar as a concept, reducing the novelty effect, this is a rather homogenous sample. In particular, compared to fields such as art and design, touch and touching materials play only a minor role in HCI and CS. Therefore, it could be that our sample consisted mostly of people with a low 'need for touch' (some people have a stronger desire and rely more on tactile sensory stimuli than others) [52], which might have predisposed them as less inclined to touch. We advise that future studies should explore whether people with a low and high need for touch differ in how they interact with and react to a data physicalisation, and to include participants from diverse fields of work or study. Moreover, studies could investigate whether there are individual differences in how much people benefit from touching physicalisations. If this is the case, then physicalisations might have more utility and appeal to some segments of the general population. We recommend for future studies to compare participants with low and high ratings on the 'need for touch' scale [52].

Furthermore, we see the need for replicating our experiment with an HMD. For our study, we chose an HHD, due to its accessibility and it being the type of AR most commonly encountered [41]. Furthermore, we assumed that the novelty of an HMD would impact our study results more than using a tablet. However, we found that using a tablet influenced our findings. For example, some participants expressed that the tablet felt like a boundary between them and the data representation, and many commented on the higher bodily effort, due to having to move the tablet around because of its limited resolution and field of view. The necessity of holding the tablet up throughout the study may also lead to physical strain, thus, potentially reducing engagement. This is reflected in the lower 'perceived usability' score of the AR condition. An HMD condition would create a more equal comparison of detailed movement patterns, including micro-level navigational movements.

Lastly, our study utilised the UES-sf to evaluate the UE. However, given UE encompasses numerous elements and types of engagement [49, 53, 63], more studies using other measurements would be useful. Although the UES-sf was chosen since it evaluates a broad scale of engagement factors (such as pleasure and challenge) [48, 49], it does not explicitly focus on emotional impact and social engagement. Therefore, it would be beneficial to have dedicated studies that, in more detail explore the intellectual, social, emotional, or physical engagement of different types of immersive visualisations.

6 Conclusion

To evaluate the effect of physicality on the user engagement (UE) of immersive data representations, this work compared a data physicalisation and a mobile AR data representation of climate data. Sixteen participants interacted with both data representations in counterbalanced order. During the study, participants filled out the User Engagement Scale – short form (UES-sf) for both data representations and took part in a semi-structured interview. Participants' interactions with the representation were recorded, to analyse spatial interactions. Our findings show no significant differences in the UE of the physicalisation and AR data representation, apart from lower 'perceived usability' for the AR version, where the latter is likely to result from the need to hold the HHD up. However, differences between the types of data representation were expressed during the interview, with the physicalisation being described as intuitive and more 'real'. Furthermore, participants discussed the effort behind the physicalisation and compared it to art works. The AR representation did not trigger these connections, but was seen as precise, exciting, and innovative.

Although people were allowed to touch the physicalisation, this was barely done—in particular if people had previously encountered the AR representation. Thus, both the AR data representation and physicalisation were mostly visually interacted with. There were also no big differences in movement patterns between these conditions.

Our work contributes to a better understanding of the user engagement of immersive data representations, highlights the lack of touch interaction in physicalisation and provides reasons for this absence, and gives insights into when to use which type of data representation (physicalisation or (mobile) AR).

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