Exploring Co-located Interactions with a Shape-Changing Bar Chart

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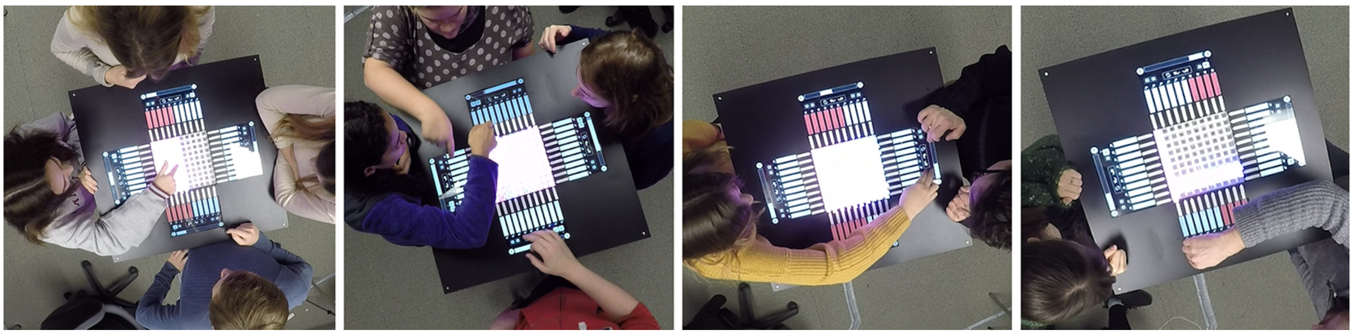

Figure 1: Co-located groups and pairs interacting with a shape-changing bar chart

ABSTRACT

Data-physicalizations encode data and meaning through geometry or material properties, providing a non-planar view of data, offering novel opportunities for interrogation, discovery and presentation. This field has explored how single users interact with complex 3D data, but the challenges in the application of this technology to collaborative situations have not been addressed. We describe a study exploring interactions and preferences among co-located individuals using a dynamic data-physicalization in the form of a shape-changing bar chart, and compare this to previous work with single participants. Results suggest that co-located interactions with physical data prompt non-interactive hand gestures, a mirroring of physicalizations, and novel hand gestures in comparison to single participant studies. We also note that behavioural similarities in participants between interactive tabletop studies and data-physicalizations may be capitalised upon for further development of these dynamic representations. Finally, we consider the implications and challenges for the adoption of these types of platforms.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in visualization**; **Visualization systems and tools**; **Empirical studies in collaborative and social computing**.

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KEYWORDS

Data-physicalization, Co-Location, Shape-changing interfaces, Bar-Graph, Tangible Interaction

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1 INTRODUCTION

Planar representations of data are commonly used to identify trends and communicate findings. These representations often take the form of numerically accurate and relational spreadsheets, graphs and charts [46]. Bar charts in particular are used to show the relationship between data points by using numerical data converted into visuals relating to height or width, and are common in presentations and reports [76]. One issue with these representations however, is that it is difficult to show multiple axes alongside each other so that direct comparisons can be made, or continuous data for small sample sizes in an accurate manner [74], instead, data might be shown on subsequent pages, screens or at a scale too small to make accurate inferences. A solution to this might be to create 3D representations on screen, or as physical models which can be interrogated and rotated to allow for multiple viewpoints — however, physical representations have been suggested to be preferable to their onscreen 3D counterparts, possibly because the extra sensory information allows for enhanced cognition (extra sensory modality confirming visual data) [30]. Additionally, tangible interfaces have also been shown to have benefits for collaborative learning and interaction [56]. This has given rise to the study of Data Physicalization [31], where data is made into physical, 3D, tangible representations which can be viewed at multiple angles, interrogated with touch, and even animated.

Further support for additional dimensions in data visualisation comes from multi-modal data output, which has previously been shown to provide novel insights into existing data, e.g. data in acoustic form allowed for the identification of coronal mass ejections [6], and using haptics allows for enhancement of user experience with data [43]. Another method of enhancing experiences with data is to animate the information to show relationships across time, or between groups [23]. Dynamic transitions for physical data therefore combine the benefits of physicalization with those of animation, but present additional challenges in terms of the availability of technology [31].

Actuation capabilities and level of manipulability must also be considered when designing for physical data [36]. Platforms such as *inFORM* [19] and *EMERGE* [63] have begun to explore the potential of data visualisation using shape-changing interfaces, which offer new insights into dynamic data-physicalization [64], however these studies do not take advantage of the platform's size and availability of 360° viewpoints – which make shape-changing interfaces of this type ideal for multi-user interactions with data-physicalization.

As technology advances, so do the ways in which computational support can assist with a multitude of tasks: in the field of shape-changing interfaces, this can be demonstrated by concepts such as *physical telepresence* [38] where a user can share a physical manifestation of their movements in a remote location; or with reconfigurable tabletops and other furniture to support co-located user scenarios [20, 65]. Although large-scale shape-changing installations and how they support multiple users have already been documented, there is appears to be no existing work looking at analysing co-located interactions with tabletop sized dynamic physicalizations [4, 31]. Given the potential benefits of presenting information in this way, we therefore aim to examine the ways in which users interact together – and with – tabletop-sized interactive data-physicalizations.

We seek to understand how the principles of co-located interaction with data-physicalizations compare to existing work with 2D tabletop interfaces. Therefore we present: An investigation and exploration of co-located interactions with a dynamic, tabletop sized data-physicalization of a bar-chart; an analysis of co-located user interactions and techniques for working with dynamic data-physicalizations; and, recommendations and discussion around the challenges and potential for dynamic data-physicalizations of bar charts.

2 RELATED WORK

Data-physicalization is a relatively new description for the presentation of datasets in a tangible, 3D format, although physical representations of information have been used for thousands of years (e.g. the abacus) [31]. In HCI, it is directly related to tangible computing, where users can both physically and visually interact with data, and especially in the study of shape-changing interfaces where animation between data points is possible, as well as direct interrogation of the data by users. For example, volumetric medical data [39] or water usage in design for behaviour change [70]. The additional dimension offered by data-physicalization has been shown to offer opportunities for enhanced cognition [30], and can allow for the simultaneous representation of information on multiple axes [64].

2.1 Data-Physicalization in HCI

The investigation of data-physicalization can be combined with the study of tangible user interfaces (TUIs) [28] to produce meaningful, tangible artefacts [30]. However, static data representations [30] cannot alter their data, and therefore are limited to certain forms of analysis and interaction (manually moving components). These sculptural formats nevertheless play an important role in validating the use of the physical form in presenting data [26], providing historical or personal references [33], as well as fulfilling roles as artworks and installations [53], or even reminders of the frailty of our environment [27]. Data-physicalization is also swiftly becoming a field within HCI in its own right, and continues to attract researchers interested in investigating how it might be explored and applied [2, 25]. Jansen et al. [31] identify a number of challenges and opportunities for data-physicalization as a field — notably, supporting animated transitions, combining physical and synthetic interactions, self-actuating surfaces, and application specific challenges such as collaborative use.

Work on data-physicalization has also focused on judgements of size and shape, or interactions with physical data platforms. For example, participants were seen to be better at judging bars (cuboid) than sphere sizes [32], which suggests that a physical bar chart might allow for the judgement of values with some degree of accuracy. Further work has examined the effect of user orientation on the perception of physical data [54], the perception of size across different physical shapes [30], and the strategies applied when organising physical information [55]. Physical data can also be interactive, such as *CoDa* who examined scatter plots with tangible tiles on reactive screens [72]; or Perovich's *Big Bar Chart* that allows room size interactions with bar-chart data [44]. Perception of information in a graphical format might also be improved when animated transitions between data points are supported [23] – therefore combining animated transitions with physical bars should have benefits when making value judgements for datasets. This suggests that shape-changing interfaces could be a suitable vehicle for data-physicalization and user interaction.

2.2 Shape-Changing Interfaces

The exploration of data readily lends itself to the shape-changing paradigm, with these interfaces having advantages over simpler, static, displays by allowing for additional user interaction and visual display of information in addition to that of form. One of the first of such platforms was used to explore terrain from a military perspective [16], and subsequent iterations of prototypes in this area have returned again and again to maps, elevation data and other geographic information systems (GIS) [3, 14, 17, 40]. However, shape-changing interfaces are not limited to this type of data, *Relief* [40], *inFORM* [19] and *EMERGE* [63] all have the potential to show quantitative data in the form of physically animated bars. These types of interfaces typically have a 2.5D output and utilise a form of linear actuator (e.g. stepper or servo motor) to animate points on a surface, though have the potential for vastly different data representations. Dand and Hemsley [14] point out that there remains a gap in the research to explore more varied datasets on shape-changing interfaces (in addition to GIS), but also to investigate collaborative interactions with physically dynamic interfaces. Current shape-changing interfaces for data-physicalization already lend themselves to the support of more than one user due to their size, or tabletop presentation format [19, 29, 63, 69], but have additional features that may also prove valuable in investigating collaborative use such as remote collaboration [38]. Given the parallels in format, the most relatable resource for exploring collaborative use in shape-changing interfaces is likely to be that of tabletop interfaces and planar vertical displays (although there are interesting developments with swarm interfaces [37]), where existing social and technical interactions has already been mapped and can be compared and contrasted to co-located interactions with data-physicalization. At present technology levels, physical data lends itself readily to co-located interaction, where it can be shared easily [62].

2.3 Planar Vertical Displays

Planar vertical displays can accommodate larger groups more easily [52], as tabletop surfaces mean multiple users may have different viewpoints [50]. Tong et al. [71] suggests orientation of an interactive surface creates different effects, e.g. horizontal displays may be better than vertical for collaborative work (also seen in [50]) but they result in less structured output. The vertical condition was found to support one main user as the interaction focus, but also resulted in more structured outcomes.

Viewing angle and perception with multiple users may be problematic with shape-change where the combined physical and visual output is dependent on a single viewpoint [12, 54], but readability for acutely angled outputs on planar surfaces can present issues [75]—although this is less likely with new screen technology. The advantage of shape-changing interfaces for displaying data is that the output is dynamic, so unreadable text might be tilted, altered or dynamically re-presented to ensure legibility. The tabletop style set-up of *EMERGE* was found to elicit body movements to alter/fix the perceptual angle [64], and other movements—using the hands—can have non-verbal communication properties when collaborating around tabletop surfaces, and support group interaction [49]. Hand gestures may also support interactions with tabletop styled data-physicalizations, hence Taher et al. [64] question whether the hand gestures observed around the *EMERGE* platform would also relate to 2D, planar displays of bar charts.

Finally, one of the challenges of utilising platforms supporting data-physicalization is that users typically need to be occupying the same space in order to collaborate [31, 62], however, it is likely that this barrier will be overcome at some point [24], with advances in 3D printing or physical telepresence [38]. Currently, the opportunity to utilise data-physicalization in a co-located group setting has been under-explored however, so it is this we intend to address with this research. The similarities between the *EMERGE* platform and existing studies with tabletop and planar vertical displays makes it an ideal starting point.

3 CO-LOCATED OBSERVATIONAL STUDY

Using the *EMERGE* platform [5, 63, 64], we aimed to explore co-located behaviours and interactions with a dynamic bar chart [1]. This section briefly describes the physicalization platform, participants, and user study design.

3.1 The EMERGE Platform

EMERGE [5, 63, 64] is a pin-actuated shape-changing interface and display comprised of 100 physical bars in a 10×10 grid. Each bar extends to a maximum distance from baseline of 100mm, and is internally lit using an RGB LED. EMERGE is designed to navigate much larger datasets than its 100 physical bars; this is supported through various physicalization interactions.

Interaction is supported by both direct interaction with the bars, and by connected planar tablet devices on each side of the grid (Figure 2). Direct interaction involves pulling (highlight) and tapping single (hide bar) or multiple bars (isolate rows), whereas the indirect tablet interaction allows users to swap rows, scroll through large data sets, lock rows, and, take and remove snapshots. The command structure is paired, so that both x-axis, and both y-axis, tablet displays always update together (otherwise the data-view would not make sense from the opposite side of EMERGE); however users can control EMERGE from any side. This results in turn-taking between paired tablets. An extended description of the platform can be found in Taher's original paper [63] and Taher's video of the capabilities at: https://youtu.be/xA4jOwCHO8I. This work builds on previous studies of EMERGE [64], where *single* users successfully explored a dataset and produced a summarative presentation; key findings included frequent physical movements around EMERGE and extensive use of hand-gestures while inspecting data. In contrast to previous studies, this work looks at pairs and groups of users around EMERGE.

3.2 Participants

We recruited 24 participants aged 21–58 (8M/16F). Participants were assigned to either condition #1 (interactions in pairs—8 participants) or condition #2 (interaction in a team of 4—16 participants). None of the participants had previously used *EMERGE* and all were unfamiliar with shape-changing displays. Participants were required to be previously acquainted from the workplace, where they were already likely to discuss or interact with data in groups, and so that unfamiliarity did not affect the interactions [49].

3.3 Study Design

The co-location study follows the design of previous work using the platform [64], which we adapted for group situations. Three cameras were set up to capture participant interactions (one above the interaction area, two diagonally to the sides to capture participant movements around the platform). The study took place in three phases, *Demonstration & Training*, *Exploration*, and *Presentation*. The datasets used were chosen specifically for their complexity and number of data points—they would be extremely difficult to represent in a single (interactive) 2D visualisation.

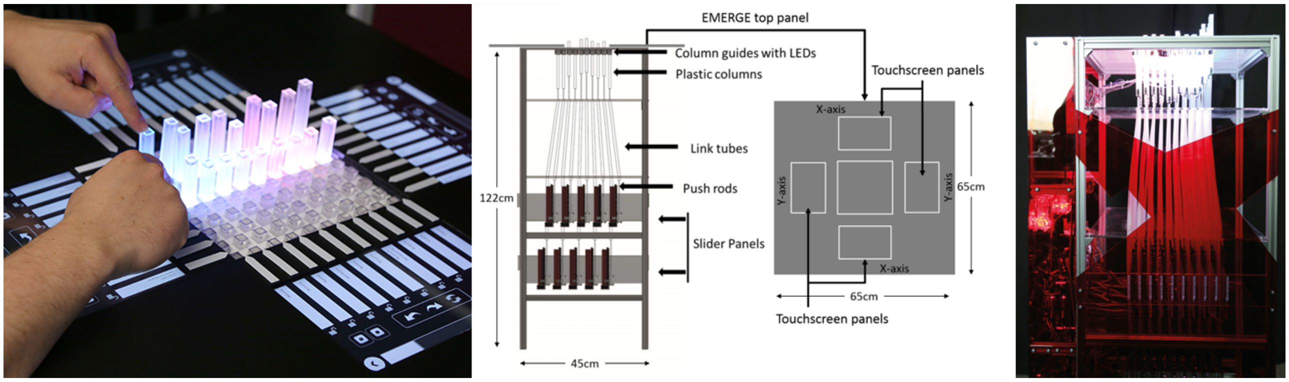

Figure 2: The *EMERGE* platform, comprising of 100 interactive, actuated bars, with four tablets for additional control. Left, a user interacts with the bars; Middle, a technical diagram of the platform [63]; Right, a side view photograph.

3.3.1 Demonstration & Training Phase. Participants (in groups of four or in pairs) were given 30 minute demonstration and training on *EMERGE*. First, they were shown six prescribed interactions/task types, which were verbally described by the researcher, then physically demonstrated using an initial dataset. Each individual participant was given the chance to try the interaction. Second, the participant pair or group was tasked with exploring a second dataset and preparing a short, informal presentation. The second dataset exploration was open-ended, to give participants a chance to practice the actions they had learned on the first dataset. They were also asked to give a demonstrative presentation of any data that seemed interesting, to prepare them for the next phase of the study.

The first dataset used was the average rainfall data in the UK over 103 years for 11 regions ([1]). The X/Y axis showed years/regions, with the height of the bars representing the rainfall in millimetres. Rows for both datasets were colour-coded in order to provide visual cues to differentiate between years and regions. The second dataset, utilising student ratings of appropriate behaviours from 1974 [48] (15 actions/15 situations) was then used to check participants' understanding of the platform over the six task types: a) Selecting or grouping interesting categories; b) Scrolling, grouping with locked categories and taking a snapshot; c) Hiding the remaining data points, and taking a snapshot; d) Comparing situations/actions, highlighting points of interest and taking a snapshot; e) Explaining highlighting and showing all three snapshots, explaining what they show; f) Repeating for remaining categories. Interaction data was not recorded for the demonstration and training phase.

3.3.2 Exploration & Presentation Phase. A third dataset —also consisting of peoples' ratings— and taken from the *European Value Survey* was used for the exploration phase. The information covers 46 European countries on popular topics (e.g. politics, healthcare) [18] – and contains 31×46 data points[2]). Participants were invited to explore the data using the skills learned in the previous phase – and specifically encouraged to explore more data than was seen in the default view (initial 10×10 start point, indicated by the black outline in Fig 4). This phase lasted for ten minutes. They were also asked to work together to discover points of interest and discuss these with each other, before preparing a short informal presentation for the researcher, and were given five minutes for this task. This open-ended approach was designed to foster collaboration and communication in order to allow for the study of dynamics between groups and pairs.

3.4 Post-Study

Participants were asked to spend a few minutes to give feedback about their experiences using the *EMERGE* system after the *Presentation* phase, and complete a post-study questionnaire about their experiences with both 2D bar charts and shape-changing displays. The questionnaire also asked about the ease of interaction, and data interrogation. Likert responses were recorded, and can be seen in Figure 3.

4 DATA ANALYSIS

In this section we present our exploration of expected and novel interactions, and themes inherent in the application of data physicalization to group or pair setting.

4.1 Video Coding

The video recordings were split into *Exploration* and *Presentation* phases. Taher et al.'s [64] codebook was used to generate results for consistency, e.g. hand/arm gestures that do not trigger the device; hand/arm gestures that *do* trigger the device; body/head movements that change a users' view. We also recorded failed or impossible actions, and unusual actions, these two categories were not reported in Taher et al., but were of particular interest for our co-located study. All videos were coded for physical interactions, 15% of the data was interpreted by both coders, giving a Cohen's Kappa [13] of 0.58, indicating moderate agreement. Vocalisations and interpersonal reactions were recorded via field notes taken during the sessions [67], and these were used alongside the video coding for

[1]Rainfall data source: www.metoffice.gov.uk/pub/data/weather/uk/climate/datasets/Rainfall/date/UK.txt
[2]The European Values dataset is available via www.europeanvaluesstudy.eu/methodology-data-documentation/previous-surveys-1981-2008/survey-2008/ and specifically search.gesis.org/research_data/ZA4800

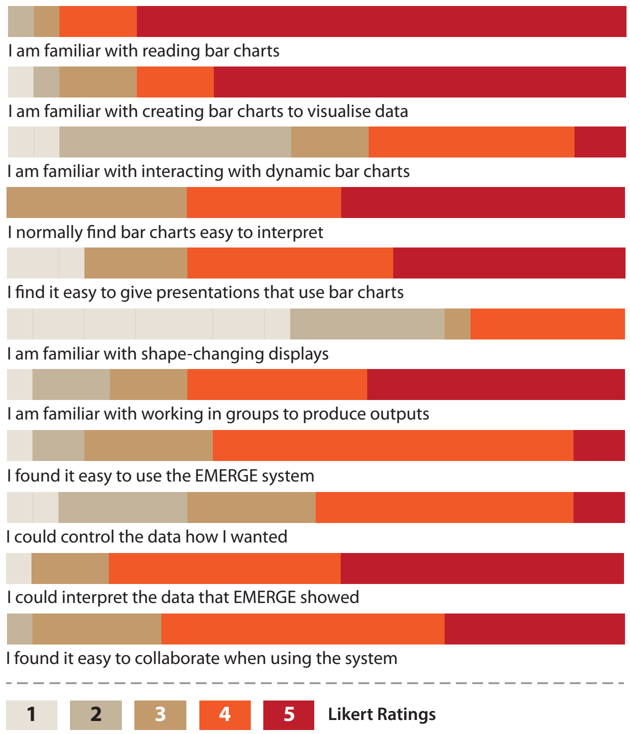

Figure 3: Participant Likert responses from pre & post questionnaires. 1 = strongly disagree, 5 = strongly agree

full analysis. The vocalisation data was used to compare and contrast the co-located study to related work on tabletop surfaces [49, 67].

4.2 Log Data

The *EMERGE* system logs were analysed to identify which bars and areas of the dataset were interacted with during the session. Each tablet produced a separate record so that interactions could be connected to specific individuals (Figure 6).

5 RESULTS

We start with a comparative overview of high-level findings, before looking at the *Exploration* and *Presentation* phases in turn. The average times for both phases can be seen in Table 1.

5.1 General Findings

Participants were offered an open-ended session for both phases: *Exploration* was consistent at around 18.5 minutes across both session types, but the pair setting resulted in a slightly longer *Presentation* time (around 3/4 of a minute longer). It was expected that during the *Presentation* phase that our participants would use hand gestures to communicate concepts to the researcher, which was observed, but it was also observed that participants made use of these in non-communicative settings, although not extensively, or consistently.

Table 1: Average session times in minutes.

	Combined	Group	Pair
Exploration	18.61	18.56	18.66
Presentation	3.67	3.25	4.09

To look at content navigation between studies we analysed the logs to create comparative visuals (more than the visible 10×10 data points were available) see Figure 4. We used a logarithmic colour scale to show time spent on areas of the dataset within the 10×10 grid (threshold of less than 3 seconds). The black square outline in the top left of the images reflects the start/reset point for the data. Blue represents the *Exploration* phase, and purple, the *Presentation* phase, with the darker shading relating to a longer time on the display. For example, you can see that group four (G4) only explored a third of the dataset, in comparison to groups one and two (G1/G2), who covered nearly all of total dataset. Whereas Taher et al. [64] stated that during their study there was a considerable variance in terms of the amount of the dataset explored, the coverage patterns for exploring the dataset within the co-located settings appeared to relatively similar to each other. The difference in the total area explored is down to the freedom of navigation the groups and pairs were given – the task was open ended and focused on items of interest to the participants, who took different approaches to exploration and discussion. No participant groups or pairs stayed on the initial view, which is evidenced by coloured areas outside of the black starting point outline in Figure 4.

5.2 System Interaction Behaviours

Overall, co-located participants were found to make sustained use of the interactive qualities of the *EMERGE* system, for example, locking rows and continuing to scroll, reorganisation in order to group items of interest, hiding irrelevant data, and taking snapshots before resetting, or starting a new investigation (Figure 5.2 & 5.3). Also of interest is the *between-participant* interaction, and corresponding dialogue — participants had to communicate to take turns or to highlight points of interest.

5.2.1 Movement Behaviour. Within our co-located study, movements were subject to group dynamics: e.g. examining user incursions into space that is already in use, such as reaching over to another tablet, or the far side of the platform (more than 2 actions per minute for pairs, around 1.5 per minute for groups, Figure 5.4). Although participants did not often reach over to the far side of the platform, they still covered a lot of the dataset – there were not many "cold" spots (areas of non interaction) on the bars over the session despite some participants being less active than others. Most participants tended to interact with those sections that were directly in front of them, producing a complete coverage of the physical bars – meaning no participants appeared compelled to walk around the platform. We noted that some participants utilised another participant's tablet which was interesting as it appears to contradict findings that participants around tabletop displays prefer to have discrete "ownership" of a section [52, 57].

User placement was of particular interest. In the group and pair conditions, verbal explanations and pointers were given to elucidate

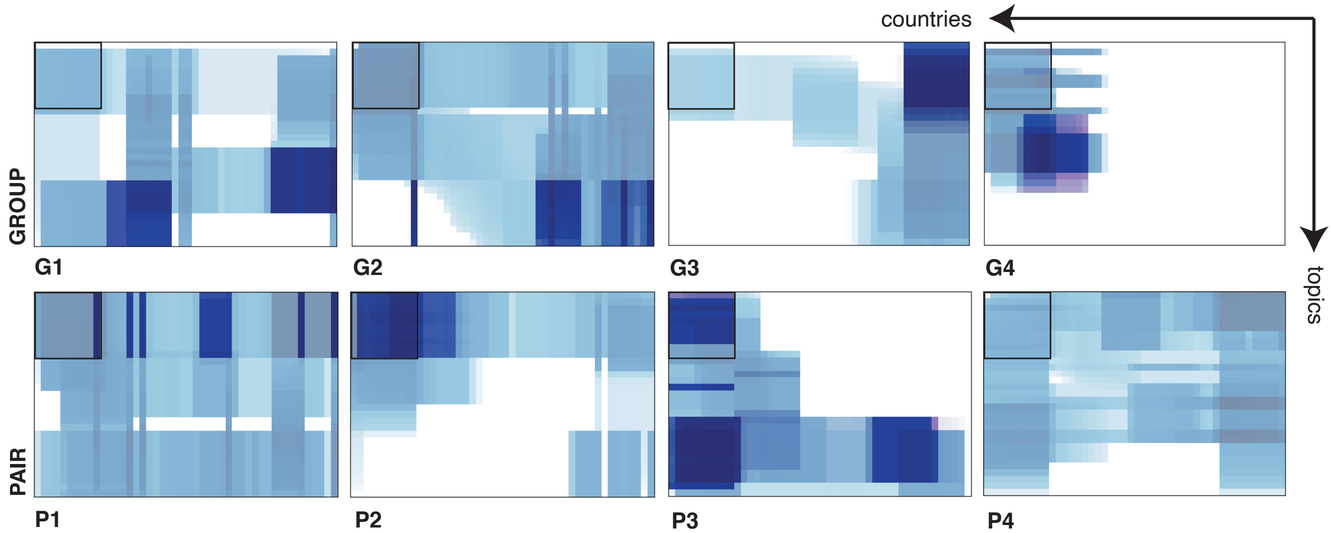

Figure 4: Participant navigation across the dataset in groups/pairs (aggregated). Blue indicates the *Exploration* phase, and purple (displayed as overlay) indicates the *Presentation* phase. The darker the colour, the more times that particular area of the dataset was viewed. The purple, when overlaid on the lighter blue exploration, appears as a richer, darker blue – a 'hot spot'. White areas indicate parts of the data set that were not explored.

information that was occluded from view for others. Participants rarely swapped position in the groups of four, (only two groups made an effort to change places to allow a change of perspective) and then only moved to the adjacent side so as to view the dataset from an alternate axis. Pairs, in comparison, always started opposite each other, and tended to reach across to the adjacent axis whilst maintaining a static position instead of physically moving. This is similar to *settled formations* observed in Azad et al.'s territoriality study conducted with a vertical display [8], and in contrast to the pair position changes witnessed by Klinkhammer et al. in their tabletop study [34]. – however, the area in front of a participant became their 'territory' during that placement (see also Section 5.5.2).

For body movement from a fixed position, leaning over the surface was completely absent for both group and pair conditions, though head tilting was frequent, and participants also made use of crouching to change view. Participants did not lean and or tilt their heads much, perhaps due to the close proximity of other participants, and the risk of connecting heads, or blocking the view of others — one of the interesting interactions seen during the sessions was *collisions*, e.g. accidentally knocking hands. It is also possible that there was no need for these types of movements to gather different viewpoints of the data, because another participant could relay that information. Finally, in some cases, participants appeared to actively "disengage" from the platform by folding their arms (similar to Klinkhammer et al.'s *passive observers* [34]. This happened only in the group condition (rather than the pair), and could be attributed to the fact that only one person at a time can actively engage with the platform, and even with turn taking there was waiting time between participants.

5.2.2 Gesturing, Pointing, and Physical Interactions. The range of hand gestures and interactions during the study largely tracked those seen in Taher et al. [64], with the exception of those we present in Figure 5.4. Most of the novel actions (those that the earlier study did not elicit) we discovered involved two hands simultaneously rather than one hand to complete an action or make a gesture. The only two-handed gesture seen in the previous study was the "two hand consecutive bar press". The prevalence of two-handed gestures and interactions in both conditions could have been due to increased confidence in using the platform over the duration of the session. With a solo participant there is obviously no external encouragement to complete an action, whereas having peers to guide and assist may have meant that participants felt able to be "hands on" by way of peer support. Of particular note is the incidence of using hand movements to demonstrate, e.g. showing a wave motion, or comparing heights using both hands. Although using the hands to emphasise points during speech is a common occurrence during general conversation, the nature of those used here directly related to the physical data. This makes sense from the perspective that the hands are already required to make physical movement to interact with the platform (above and beyond that used for planar displays), so further information about physicality can also be conveyed using *shape*, *height* and *movement*—mirroring attributes of the shape-changing interface. Figure 5.1, top-left, shows the number of all non-interactive hand movements in the group and pair condition. The most pronounced finding for gestures is pointing with a single finger. This not only served to communicate to other participants, or interrogate data, but also may have been used to focus other participants on a particular point, and/or halting interactions momentarily. The groups and

Figure 5: Average actions per minute for co-located groups and pairs, for direct interactions with physical data. Longer bars indicate an increased length of time taken on those actions. Where no expected interactions occurred the rows are blank—there was no data ('expected' referring to actions that were observed in Taher et al. but were absent from this study). [64]. Bottom-left graph has an adjusted x-axis in order to show a larger number of interactions.

pairs used the reset and undo functions extensively, which could be due to conflicting interactions and multiple users attempting to interact at the same time, leading to mistakes or unwanted changes to the data.

5.3 Presentation Phase

All participants were able to gather and make inferences about the data in the *European Values Survey*. Participants were allowed to present their thoughts in an unstructured way, but the experimenter occasionally asked questions or asked for elaboration on points. In the group setting, one participant usually led the presentation, with others interjecting with minor points, or waiting until the first presenter had finished talking to add their part. In the pair condition the presentations took a more conversational style, and there was more turn taking.

5.3.1 Presentation Style & Strategies. Taher et al. [64] identified four key presentation styles — although not all of these were mirrored in our study: 1) Snapshot-centric presentation; 2) Single-view presentation; 3) Interactive presentation (participants interacted with the data); 4) Non-interactive presentation without data. Snapshot-centric presentations were seen in 3 cases (2 group/1 pair) whilst the rest of the presentations were interactive (involving scrolling, highlighting, filtering and so on), although one started with snapshots before extending the discussion and utilising the platform to do so. Being co-located appeared to produce high levels of engagement within presenting style.

5.3.2 Themes of Presentations. Participants were able to identify and discuss high level and complex issues from the data. Complex themes such as attendance of demonstrations in Eastern block countries and high national pride, or views on abortion and attitudes toward single unmarried mothers were discovered. Participants seemed to focus on themes where there were results which went against expectation. Choices of data to discuss either emerged organically when participants identified particularly prominent points, or because of existing relationships toward particular countries, or interests (e.g. one participant was from Cyprus and wished to look at Greek values). This relationship between participant and data was also found in the previous work [64]. Another similarity was that participants were able to make high level inferences about the relationship between data points, several of whom stated that having the extra axis enabled them to "see more at the same time" and make judgements.

5.3.3 Difficulties. Participants had trouble remembering what data was in each snapshot. The suggestion was made that the UI should have the snapshots numbered to ease recall. This lapse in memory led to some participants cycling through several snapshots to find the one they wanted. A further difficulty was remembering the interesting points in the presentations where no snapshots had been saved, this sometimes led to several minutes of scrolling action (as indicated by the logs) to try and reproduce findings or jog the memories of the participants.

5.4 Comparison to Prior EMERGE Study

Our work used an almost identical procedure to the work by Taher et al. [64], and as such we have utilised the same analysis techniques. This enables us to suggest comparisons to a single participant condition, for example, the earlier work recorded average times of 16 minutes and 5 minutes across phases, although comparatively the combination times for both phases is similar for our study. Regarding non-interactive hand gestures, in comparison to the single person study, the group and pair setting elicited many more of these gestures during *Exploration* (e.g. single finger pointing at bars/labels) – except in the case of *multiple* finger gestures, where there is less difference (Figure 5.1). One reason for this might be that there is less physical space for multiple participants to reach over the system, or perhaps that double handed gestures may relate to "thinking through" and using both hands to create reference points or comparative heights.

A point of similarity between the two studies is that participants rarely made use of the interactive features of *EMERGE* during the presentation phase (e.g. scrolling, highlighting bars), instead relying on the *snapshot* feature to create a succinct overview of points of interest – except in a couple of cases where no snapshots were used, even if they had been prepared previously. What is markedly different is the comparison between dataset exploration: co-located participants explored much less of the dataset, and spent longer on single 10×10 views than single participants. This could be attributed to the addition of verbal reasoning and negotiation—participants having to take turns, discuss, and make decisions as a group or pair. In the *Presentation* phase, a longer time was spent on smaller areas of the dataset to describe findings of interest, in comparison to the previous study.

In terms of position change, in the single participant study by Taher et al. [64] individuals were more likely to walk around to the other side rather than reaching, spending time moving around the platform to view the data from different perspectives (walking around the platform was not observed in our study – Figure 5.1). By comparing our study data, we also note that tilting of the head was more common with single participants. The digitally logged interactions also show some differences between the studies: Single participants spent more time swapping labels (8 actions per minute compared to less than 0.5 per minute), and highlighting bars (over 1.5 actions per minute compared to less than 0.5 per minute).

5.5 Comparison to Tabletop Studies

This work generated some interesting comparisons with existing research on collaboration over tabletop displays or interfaces. There are possible comparisons to tabletop interfaces as they are an environment conducive to cohesive group interactions with data [50]. When multiple users interact with the same interface, there becomes a dichotomy between personal and shared group spaces, sometimes with *territoriality* for objects and files [10, 57]. Some tabletop interfaces allow for this need to separate personal and group space, by making discrete workspaces on which users can conduct data transfers [66], by providing tablets for individual interactions [71], or even additional "tangible views" [61]. In public settings, the need for privacy alongside multiple user support becomes important [73], creating personal and private spaces simultaneously. Further work has explored the ways in which pairs interact around tabletop displays and across tasks, describing discrete states and positions, and making recommendations for the development of these devices [67]. Tabletop studies often focus on a specific problem or task (grouping data [52]), whereas the task here was open ended — i.e. identify and describe *interesting trends* in the data. However, many of the interpersonal interactions can be seen in both this work and existing tabletops studies: this relation means that we may be able to use tabletop work to further inform the design of data-physicalizations.

5.5.1 Planar Vertical & Horizontal Displays. Rogers and Lindley documented that users interacting with a large vertical display for group work found having to stand all the time "unnatural and socially awkward" [50], however, we did not find any similar effects

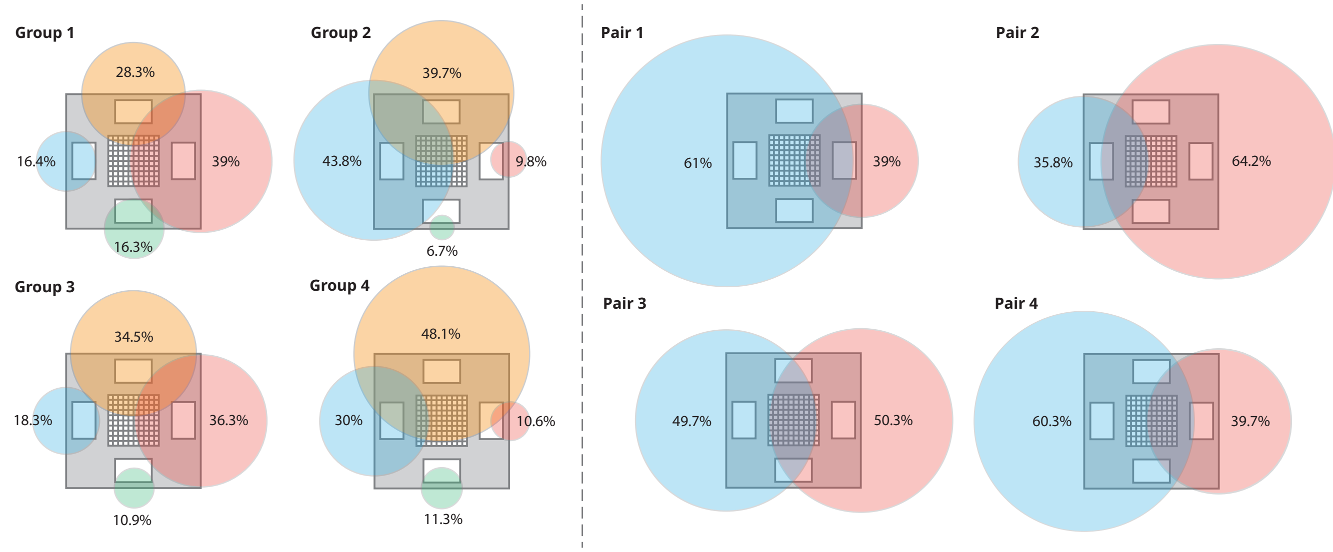

Figure 6: Percentage participant actions per group/pair, against relative positions. Participant placement was organic (self-selected). Diameter of circle (pixels) represents percentage and all are relative to each other, exact percentage figures added for clarity.

with participants standing around *EMERGE*. This is possibly because the platform allowed for participants to support themselves on the non-interactive areas whilst taking part in the study, or because the platform surface was small enough to focus on and work on with minimal exertion – similar to tailoring a display to the 'average group height' and ensuring interaction always occurs above the waist [8]. The relatively short length of the study may also mean that participants were less fatigued, although Rogers and Lindley's study took place over a similar timescale (20 minutes). Due to *EMERGE* having dynamic data height, it could be seen as encompassing both horizontal and vertical display attributes, thus combining the advantages of both [50, 52, 71].

5.5.2 Territoriality. Preferences for maintaining personal space and individual access to data can be seen in group work with tabletop surfaces [57], and in other group-compatible interfaces, such as *spherical* displays [10]. Scott et al. [57] discovered three types of territorial attitudes toward tabletop displays: *personal, group* and *storage*. It is not possible to store individual representations on *EMERGE*, but we can look at *personal* and *group* strategies. Research suggests participants usually see the area directly in front of them as their *personal* space [35, 57, 68], and in this case, the tablet UIs in front of the participants fulfil this role, with the dynamic bars comprising the *group* space. However, due to the paired UIs by axis, this prescribed personal area is already being shared by one other in the groups of four, and the observed behaviour of reaching across to another participants tablet could be seen as an acknowledgement of that fact – this 'reaching' behaviour is also seen in vertical displays [8]. Additionally, the axis controls being shared meant that one or more participants had to assume a passive role whilst another was operating the controls, which is similar to observations by Piper and Hollan in their tabletop study using physical and digital materials [47]. This also reflects a lack of data *ownership*, so the lack of territoriality may be a remnant of this [67]. Another tabletop study of note suggests that this turn-taking is part of the flow-and-ebb of tabletop interaction and territoriality, and that whilst having personal tablets [34] is useful for group communication (and ideation), it does not assist with group coordination. This connects with our findings, as participants enjoyed shared and personal space, yet also had to negotiate the flow of the main tabletop.

In both the pair and group condition, participants were generally seen to interact with those bars closest to them, but would reach across when invited to do so, or if they needed to make a point. The small size of the *EMERGE* platform also may more readily invite this sharing of space, as if all of the platform is "at arm's length" [21], then the nature of the activity may become automatically shared. Ryall et al. identified territorial behaviours in two sizes of tabletop, but noted that where a task is focused on co-design, and is not divisible, this effect may be confounded [11, 52]. Further discussion by Ryall et al. also points out that close proximity may support group work and coordination [52, 60], and as *EMERGE* only supported single physical or UI interactions at a time, coordination is essential in order to produce meaningful output. Despite this reasoning around the perceived lack of territorial behaviour, the novel nature of the platform, and the concept of data physicalization, may also be responsible for breaking down the boundaries between personal and group space. In the related work, we mention a possible issue in lack of privacy when using physical data — conversely, it may be that physical data invites sharing and openness.

5.5.3 "Fingertalk". Participant interaction with the platform highlighted similarities in behaviour with Rogers et al. [49] who found that fingertip interactions with a tabletop display were supported by speech — *fingertalk*. This *fingertalk* is expanded by the physical nature of our display, and also involves *handtalk*, both in direct interaction with qualifying speech acts, but also in explanation and mirroring of the dynamic data visualisations. The gestural support of the finger movements was seen to support sequential interaction (Roger et al. platform allowed for both simultaneous and sequential interaction) except when participants were initially exploring the capabilities of the platform. The difference between our study and the *Fingertalk* study however is that our platform does not support dual interaction, although Rogers findings suggest that the group did not make use of this feature. *Fingertalk* was also seen to be integral to decision-making during table interactions, and supporting turn-taking, usually in conjunction with speech acts.

This mirrors our findings, as we found groups and pairs actively used paired speech and gesture, the following are taken from Rogers et al. and presented alongside examples: 1) Ask a question (*"Can you see anything interesting on your side?"*; 2) Instructing another (*"I can't reach that bit, could you do it?"*; 3) Making a suggestion and inviting (*"How about we look at Slovenia? You could highlight it"*; 4) Requesting confirmation and inviting (*"Did that label swap work? could you try again?"*); 5) Offering and inviting (*"Would you like to have a go? You haven't had a turn yet"*); and, 6) Encouragement of contributions (*"Can anyone else see anything interesting in that section?"*). Additional *hand* and *fingertalk* also occurred when making statements about the data-physicalization, for example, participants used terminology consistent with physical descriptions, *"look, this one is the highest"*.

5.5.4 "Collaborative Coupling". Collaborative coupling suggests that participants carrying out a task using a tabletop display actively and fluidly engage/disengage during the session [67]. Figure 6 shows that distinct "couples" emerged during our study. In the group condition, pairs on adjacent axes took either a lead or passive role, whereas in the paired condition coupling occurred over one axis, although interaction still occurred on the adjacent axis via a sharing strategy. This pattern was also observed by Ryall et al. [52] who found that pairs tended to distribute tasks more evenly, whereas groups were more likely to have "leader" roles. In our study, the pairs had a "leader" in 3/4 cases. Uneven distribution of interaction can be partially attributed to the duplication of tablet UIs, and competition for interaction—as the platform only supports sequential interaction. As above, participants frequently invited and encouraged others to actively take part in the data interrogation. Further, some participants quickly became familiar and confident in their interactions, whereas other did not feel they could get the platform to work how they wished. Tang et al. identified several styles of working, which are partially reflected here—due to the sequential nature of the platform interactions there were always participants taking the passive role, hence we identified *SPSA* (Same Problem Same Area) which meant that two participants were working together on the same problem in a collaborative manner, or *VE* (View Engaged) where one participant was working but the others were actively watching. Occasionally, we also saw *D* (Disengaged), which was usually accompanied by folded arms.

6 DISCUSSION

Data-physicalizations lend themselves readily to co-located interactions due to their physical nature—it is easier to share data with a group where screen angle is not an inhibiting factor in understanding [75] – although this is less of an issue with more recent planar displays. This type of data representation may also elicit novel findings: representing data in alternative formats has been proven to offer alternative perspectives [7]. The tabletop size of *EMERGE* also promotes sharing behaviours, although it is also small enough to encourage collaboration rather than discrete ownership of space or tasks. There is also the possibility that by making data physical, we encourage the "fluidity" of collaborating around a table using traditional media [58]. We also found that the novelty of the platform meant that participants enjoyed the experience, although many said they could see the potential of physical data for business and research use, where interrogation is a dynamic process, rather than looking at a screen while another person presents. The study was seen as a positive experience by all participants, which is encouraging for the continued development of this type of shape-changing data-physicalization.

The disadvantages of data-physicalizations must also be considered however: whereas there are methods to create personal space in public ambient displays [73], it is more difficult to produce discrete *physical* data. Planar displays can be made private by user proximity (such as when a person uses a cashpoint and shields their information), but physical data is multi-directional, which lends itself to multiple users — in order to make physical data private, one must *contain* it within a shell, or use it in a solitary setting. Another disadvantage is that physical data can be occluded, and viewing angles can distort or hide parts of the data from the user. With *EMERGE* this was solved by individual participants moving around the data, but the grouped and paired did not have this advantage. Even though it was possible to gain information and perspective from co-located participants, some individuals expressed a preference to view the data for themselves. Despite this, there is the potential for dynamic data-physicalizations to be reconfigured to support other viewpoints, which would not occur with static representations.

6.1 Platform Improvements & Limitations

Using multiple participants had an unexpected benefit in that it encouraged inter-participant discussion and critical reflection of the platform itself and resulted in a number of helpful suggestions for improvements that would enhance the user experience. For example, two groups questioned the lack of a baseline and absolute top value, which they said would allow them to make more precise judgements about the values displayed by the physicalization. Two solutions were proposed: the first was to incorporate a *physical* indicator in the form of a static bar scale with the top and bottom values labelled; the second was to add a simple visual display to the sides of the rods to show textual data (numbers/labels). Another participant felt that the pairs condition meant that it would be more useful to have a rotated view of the tablet on the other axis, although they conceded it would be more difficult to label the data points. Additional suggestions match current thought in data-physicalization, such as the ability to "save" a snapshot and print a

3D static representation of that interpretation of the data to take away and share. Several groups also expressed that it would be more intuitive to have an entire dataset on display at the same time (making comparisons whilst scrolling over large sets became time-consuming), so future iterations of physical, animated bar charts could consider a larger base of actuators — or adopt the methodology of a reconfigurable base (such as with *ShapeClip* [22]. In terms of collaborative improvements, participants proposed to have an indication of participant interaction on the other tablets so as to prevent dual-purpose interactions, though others felt that the physical components of the platform should support multiple interactions at the same time. Another limitation of the study design itself, was that the final part (exploration and presentation) was open ended, so it was more difficult to make direct comparisons between findings in that phase, although the open-ended choice was interesting in itself. A subsequent study might give participants a specific task in order to mitigate this, or make use of other forms of measurement such as physiological response to collaboration (e.g. as was used to evaluate collaborative gameplay in [41]). Finally, we should also consider that although these findings may be mirrored by future work, at present they are based on a single platform – although they offer a starting point for other work looking at shape-changing bar charts and tabletop physicalizations.

6.2 Future Work

To better consolidate the findings in this work, it would be helpful to reproduce the findings with additional groups and on different physicalization platforms—this would help in understanding the generalisability of the presented study results. It would also be beneficial to create new platforms which support larger datasets in a single view, as participants felt it would be more intuitive, with an additional option to have a rotating display to support all viewpoints. To support varying datasets it may also be helpful to have a reconfigurable grid, which could be supported by a modular platform such as *ShapeClips* [22]. Support for simultaneous interaction would be beneficial, so there would be no "interrupted" interactions, an also open up the potential for manipulation to occur on different parts of the grid at the same time. As work progresses in this area, it may also be beneficial to apply evaluative techniques to data-physicalization, following guidelines from Collaborative Usability Analysis (CUI) [45, 57].

Data-physicalization has the potential to support collaborative work and enhance interaction by expanding the modality of data interrogation – that is, by adding the component of physical interaction, we support additional cognitive processes between individuals [31]. The technology is at a stage where it can be developed toward a groupware model, drawing on current work in data-physicalization. We found that pairs and groups could draw detailed insights from comparison of the physical data, even without numerical data, showing the capacity of data-physicalization to support complex processing. We also find looking at data in this way provokes discussion, suggesting that further benefits to data-physicalization might be evidenced as work continues. Finally, there are recent advances in data-physicalization not from a standalone perspective, but as a tool within a set which also includes Virtual Reality (VR) and Augmented Reality (AR) [15, 51]. Both of these technologies have the potential to support multiple views, collaboration with remote participants, and the way forward for seamless, blended experiences [9]. Such blends might make use of gestural and acoustic interactions [42] to replace the "solid" physical experiences, or even replace physical interactions with alternate objects [59].

7 CONCLUSION

Over the course of our analysis we have provided novel and comparative findings which we can leverage to further develop data-physicalization. Overarching themes such as shared and direct *access* to the platform, gestural behaviours for communication and role-forming, role allocation and understanding and communicating high-level data relationships emerged. Data-physicalizations on shape-changing interfaces benefit from the advantages of tabletop displays, which support collaborative behaviours and support more dynamic data-interactions than planar equivalents. This work forms the basis for future investigations into collaborative interaction with shape-changing data-physicalizations.

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REFERENCES

[1] Jason Alexander. 2022. Data as Action: Constructing Dynamic Data Physicalizations. In *Making Data: Materializing Digital Information*, Ian Gwilt (Ed.). Bloomsbury Visual Arts, 223–225. https://doi.org/10.5040/9781350133266

[2] Jason Alexander, Yvonne Jansen, Kasper Hornbæk, Johan Kildal, and Abhijit Karnik. 2015. Exploring the challenges of making data physical. In *CHI EA '15*. ACM, 2417–2420.

[3] Jason Alexander, Andrés Lucero, and Sriram Subramanian. 2012. Tilt displays: designing display surfaces with multi-axis tilting and actuation. In *MobileHCI '12*. ACM, 161–170.

[4] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbaek, Miguel Bruns Alonso, Sean Follmer, and Tim Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *CHI '18*. ACM.

[5] Jason Alexander, Faisal Taher, John Hardy, and John Vidler. 2022. EMERGE. In *Making with Data: Physical Design and Craft in a Data-Driven World*, Samuel Huron, Till Nagel, Lora Oehlberg, and Wesley Willett (Eds.). A K Peters/CRC Press, 286–297. https://doi.org/10.1201/9781003264903

[6] Robert L Alexander, Jason A Gilbert, Enrico Landi, Mary Simoni, Thomas H Zurbuchen, and D Aaron Roberts. 2011. Audification as a diagnostic tool for exploratory heliospheric data analysis. International Community for Auditory Display.

[7] Robert L Alexander, Sile O'Modhrain, D Aaron Roberts, Jason A Gilbert, and Thomas H Zurbuchen. 2014. The bird's ear view of space physics: Audification as a tool for the spectral analysis of time series data. *Journal of Geophysical Research: Space Physics* 119, 7 (2014), 5259–5271.

[8] Alec Azad, Jaime Ruiz, Daniel Vogel, Mark Hancock, and Edward Lank. 2012. Territoriality and behaviour on and around large vertical publicly-shared displays. In *Proceedings of the Designing Interactive Systems Conference*. 468–477.

[9] Benjamin Bach, Ronell Sicat, Johanna Beyer, Maxime Cordeil, and Hanspeter Pfister. 2017. The hologram in my hand: How effective is interactive exploration of 3d visualizations in immersive tangible augmented reality? *IEEE TVCG* 24, 1 (2017), 457–467.

[10] Hrvoje Benko, Andrew D Wilson, and Ravin Balakrishnan. 2008. Sphere: multi-touch interactions on a spherical display. In *UIST '08*. ACM, 77–86.

[11] Sara A Bly. 1988. A use of drawing surfaces in different collaborative settings. In *CSCW '88*. ACM, 250–256.

[12] Marcelo Coelho and Jamie Zigelbaum. 2011. Shape-changing interfaces. *Personal and Ubiquitous Computing* 15, 2 (2011), 161–173.

[13] Jacob Cohen. 1968. Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. *Psychological bulletin* 70, 4 (1968), 213.

[14] Dhairya Dand and Robert Hemsley. 2013. Obake: interactions on a 2.5 D elastic display. In *UIST '13*. ACM, 109–110.

[15] Kurtis Danyluk, Teoman Tomo Ulusoy, Wei Wei, and Wesley Willett. 2020. Touch and Beyond: Comparing Physical and Virtual Reality Visualizations. *IEEE TVCG* (2020).
[16] ESRI. 2005. Northrop Grumman and Applied Minds case study - Esri, Touch-Screen Mapping for Intel and Defense. In *www.esri.com/library/casestudies/northrop-grumman.pdf.*
[17] Aluna Everitt and Jason Alexander. 2017. PolySurface: A Design Approach for Rapid Prototyping of Shape-Changing Displays Using Semi-Solid Surfaces. In *DIS '17*. ACM, 1283–1294.
[18] EVS. 2011. European Values Study 2008: Integrated Dataset (EVS 2008). In *GESIS Data Archive, Cologne. ZA4800 Data file version 3.0.0*. EVS.
[19] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation.. In *UIST '13*, Vol. 13. 417–426.
[20] Jens Emil Grønbæk, Henrik Korsgaard, Marianne Graves Petersen, Morten Henriksen Birk, and Peter Gall Krogh. 2017. Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings. In *CHI '17*. ACM, 7029–7041.
[21] Edward Twitchell Hall. 1966. The hidden dimension. (1966).
[22] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. Shapeclip: towards rapid prototyping with shape-changing displays for designers. In *CHI '15*. ACM, 19–28.
[23] Jeffrey Heer and George Robertson. 2007. Animated transitions in statistical data graphics. *IEEE TVCG* 13, 6 (2007), 1240–1247.
[24] Jeffrey Heer, Frank Van Ham, Sheelagh Carpendale, Chris Weaver, and Petra Isenberg. 2008. Creation and collaboration: Engaging new audiences for information visualization. In *Information Visualization*. Springer, 92–133.
[25] Trevor Hogan, Uta Hinrichs, Yvonne Jansen, Samuel Huron, Pauline Gourlet, Eva Hornecker, and Bettina Nissen. 2017. Pedagogy & Physicalization: Designing Learning Activities around Physical Data Representations. In *DIS EA '17*. ACM, 345–347.
[26] Carmen Hull and Wesley Willett. 2017. Building with Data: Architectural Models as Inspiration for Data Physicalization. In *CHI '17*. ACM, 1217–1264.
[27] Elle Hunt. 2017. Popsicles of pollution: ice lollies highlight Taiwan's contaminated waterways. In *The Guardian*.
[28] Hiroshi Ishii. 2007. *Tangible user interfaces*. CRC Press.
[29] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. *interactions* 19, 1 (2012), 38–51.
[30] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2013. Evaluating the efficiency of physical visualizations. In *CHI'13*. ACM, 2593–2602.
[31] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and challenges for data physicalization. In *CHI '15*. ACM, 3227–3236.
[32] Yvonne Jansen and Kasper Hornbæk. 2016. A psychophysical investigation of size as a physical variable. *IEEE TVCG* 22, 1 (2016), 479–488.
[33] Maria Karyda. 2017. Crafting collocated interactions: exploring physical representations of personal data. In *MobileHCI '17*. ACM, 74.
[34] Daniel Klinkhammer, Magdalena Mateescu, Carmen Zahn, and Harald Reiterer. 2018. Mine, yours, ours: coordination through workspace arrangements and territoriality in tabletop interaction. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*. 171–182.
[35] Russell Kruger, Sheelagh Carpendale, Stacey D Scott, and Saul Greenberg. 2003. How people use orientation on tables: comprehension, coordination and communication. In *SIGGROUP '03*. ACM, 369–378.
[36] Mathieu Le Goc, Pierre Dragicevic, Samuel Huron, and Jean-Daniel Fekete. 2015. Design considerations for composite physical visualizations. In *CHI Workshop on Exploring the Challenges of Making Data Physical*.
[37] Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. 2016. Zooids: Building blocks for swarm user interfaces. In *UIST '16*. ACM, 97–109.
[38] Daniel Leithinger, Sean Follmer, Alex Olwal, and Hiroshi Ishii. 2014. Physical telepresence: shape capture and display for embodied, computer-mediated remote collaboration. In *UIST '14*. ACM, 461–470.
[39] Daniel Leithinger, Sean Follmer, Alex Olwal, Samuel Luescher, Akimitsu Hogge, Jinha Lee, and Hiroshi Ishii. 2013. Sublimate: state-changing virtual and physical rendering to augment interaction with shape displays. In *CHI '13*. ACM, 1441–1450.
[40] Daniel Leithinger and Hiroshi Ishii. 2010. Relief: a scalable actuated shape display. In *TEI '10*. ACM, 221–222.
[41] Regan L Mandryk and Kori M Inkpen. 2004. Physiological indicators for the evaluation of co-located collaborative play. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*. 102–111.
[42] Asier Marzo, Oscar Ardaiz, Steven Kockaya, Julie Williamson, and Euan Freeman. 2019. Tangible Interactions with Acoustically Levitated Voxels. In *Interacción '19*. 1–2.
[43] Sabrina Paneels and Jonathan C Roberts. 2010. Review of designs for haptic data visualization. *IEEE Trans. Haptics* 3, 2 (2010), 119–137.
[44] Laura Perovich, Phoebe Cai, Amber Guo, Kristin Zimmerman, Katherine Paseman, Dayanna Espinoza Silva, and Julia Brody. 2020. Data Clothing and BigBarChart: designing physical data reports on indoor pollutants for individuals and communities. *IEEE Computer Graphics and Applications* (2020).
[45] David Pinelle, Carl Gutwin, and Saul Greenberg. 2003. Task analysis for groupware usability evaluation: Modeling shared-workspace tasks with the mechanics of collaboration. *ACM ToCHI* 10, 4 (2003), 281–311.
[46] Steven Pinker. 1990. A theory of graph comprehension. *Artificial intelligence and the future of testing* (1990), 73–126.
[47] Anne Marie Piper and James D Hollan. 2009. Tabletop displays for small group study: affordances of paper and digital materials. In *CHI '09*. ACM, 1227–1236.
[48] Richard H Price and Dennis L Bouffard. 1974. Behavioral appropriateness and situational constraint as dimensions of social behavior. *Journal of Personality and Social Psychology* 30, 4 (1974), 579.
[49] Yvonne Rogers, William Hazlewood, Eli Blevis, and Youn-Kyung Lim. 2004. Finger talk: collaborative decision-making using talk and fingertip interaction around a tabletop display. In *CHI EA '04*. ACM, 1271–1274.
[50] Yvonne Rogers and Siân Lindley. 2004. Collaborating around vertical and horizontal large interactive displays: which way is best? *Interacting with Computers* 16, 6 (2004), 1133–1152.
[51] Joan Sol Roo and Martin Hachet. 2017. Towards a hybrid space combining Spatial Augmented Reality and virtual reality. In *3DUI '17*. IEEE, 195–198.
[52] Kathy Ryall, Clifton Forlines, Chia Shen, and Meredith Ringel Morris. 2004. Exploring the effects of group size and table size on interactions with tabletop shared-display groupware. In *CSCW '04*. ACM, 284–293.
[53] Francesca Samsel. 2013. Art-science-visualization collaborations; Examining the spectrum. *Proceedings of the IEEE VIS Arts Program (VISAP)* (2013).
[54] Kim Sauvé, Dominic Potts, Jason Alexander, and Steven Houben. 2020. A Change of Perspective: How User Orientation Influences the Perception of Physicalizations. In *CHI '20* (Honolulu, HI, USA). 1–12.
[55] Kim Sauvé, David Verweij, Jason Alexander, and Steven Houben. 2021. Reconfiguration Strategies with Composite Data Physicalizations. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 471, 18 pages. https://doi.org/10.1145/3411764.3445746
[56] Bertrand Schneider, Patrick Jermann, Guillaume Zufferey, and Pierre Dillenbourg. 2011. Benefits of a tangible interface for collaborative learning and interaction. *IEEE TLT* 4, 3 (2011), 222–232.
[57] Stacey D Scott, M Sheelagh T Carpendale, and Kori M Inkpen. 2004. Territoriality in collaborative tabletop workspaces. In *CSCW '04*. ACM, 294–303.
[58] Stacey D Scott, Karen D Grant, and Regan L Mandryk. 2003. System guidelines for co-located, collaborative work on a tabletop display. In *ECSCW 2003*. Springer, 159–178.
[59] Adalberto L Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional reality: Using the physical environment to design virtual reality experiences. In *CHI '15*. 3307–3316.
[60] Robert Sommer. 1969. Personal Space. The Behavioral Basis of Design. (1969).
[61] Martin Spindler, Christian Tominski, Heidrun Schumann, and Raimund Dachselt. 2010. Tangible views for information visualization. In *ITS '10*. ACM, 157–166.
[62] Simon Stusak, Aurélien Tabard, Franziska Sauka, Rohit Ashok Khot, and Andreas Butz. 2014. Activity sculptures: Exploring the impact of physical visualizations on running activity. *IEEE TVCG* 20, 12 (2014), 2201–2210.
[63] Faisal Taher, John Hardy, Abhijit Karnik, Christian Weichel, Yvonne Jansen, Kasper Hornbæk, and Jason Alexander. 2015. Exploring interactions with physically dynamic bar charts. In *CHI '15*. ACM, 3237–3246.
[64] Faisal Taher, Yvonne Jansen, Jonathan Woodruff, John Hardy, Kasper Hornbæk, and Jason Alexander. 2017. Investigating the use of a dynamic physical bar chart for data exploration and presentation. *IEEE TVCG* 23, 1 (2017), 451–460.
[65] Kazuki Takashima, Naohiro Aida, Hitomi Yokoyama, and Yoshifumi Kitamura. 2013. TransformTable: a self-actuated shape-changing digital table. In *ITS '13*. ACM, 179–188.
[66] Peter Tandler, Thorsten Prante, Christian Müller-Tomfelde, Norbert Streitz, and Ralf Steinmetz. 2001. Connectables: dynamic coupling of displays for the flexible creation of shared workspaces. In *UIST '01*. ACM, 11–20.
[67] Anthony Tang, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. 2006. Collaborative coupling over tabletop displays. In *CHI '06*. ACM, 1181–1190.
[68] John C Tang. 1991. Findings from observational studies of collaborative work. *International Journal of Man-machine studies* 34, 2 (1991), 143–160.
[69] Sheng Kai Tang, Yusuke Sekikawa, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. 2013. Tangible CityScape. http://tinyurl.com/tcityscape.
[70] Jonas Togler, Fabian Hemmert, and Reto Wettach. 2009. Living interfaces: the thrifty faucet. In *TEI '09*. ACM, 43–44.
[71] Lili Tong, Aurélien Tabard, Sébastien George, and Audrey Serna. 2017. Horizontal vs. Vertical: How the Orientation of a Large Interactive Surface Impacts Collaboration in Multi-surface Environments. In *IFIP Conference on Human-Computer Interaction*. Springer, 202–222.
[72] Annemiek Veldhuis, Rong-Hao Liang, and Tilde Bekker. 2020. CoDa: Collaborative Data Interpretation Through an Interactive Tangible Scatterplot. In *TEI '20*.

323–336.
[73] Daniel Vogel and Ravin Balakrishnan. 2004. Interactive public ambient displays: transitioning from implicit to explicit, public to personal, interaction with multiple users. In *UIST '04*. ACM, 137–146.
[74] Tracey L Weissgerber, Natasa M Milic, Stacey J Winham, and Vesna D Garovic. 2015. Beyond bar and line graphs: time for a new data presentation paradigm. *PLoS biology* 13, 4 (2015), e1002128.
[75] Daniel Wigdor and Ravin Balakrishnan. 2005. Empirical investigation into the effect of orientation on text readability in tabletop displays. In *ECSCW 2005*. Springer, 205–224.
[76] Jeff Zacks and Barbara Tversky. 1999. Bars and lines: A study of graphic communication. *Memory & Cognition* 27, 6 (1999), 1073–1079.