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Clusters, Trends, and Outliers: How Immersive Technologies Can Facilitate the Collaborative Analysis of Multidimensional Data

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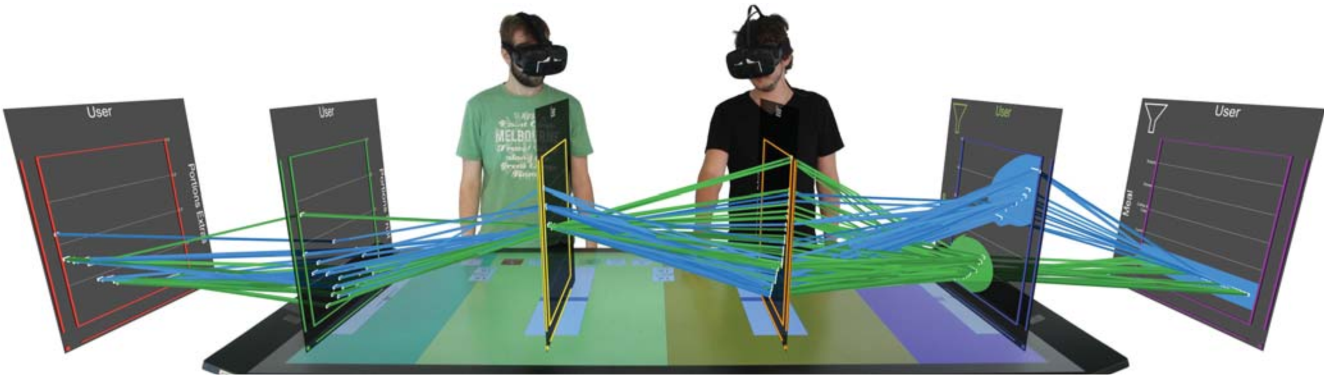

Figure 1. Augmented Reality above the Tabletop (ART) is designed to facilitate the collaborative analysis of multidimensional data. A 3D parallel coordinates visualization in augmented reality is anchored to a touch-sensitive tabletop, enabling familiar operation.

ABSTRACT

Immersive technologies such as augmented reality devices are opening up a new design space for the visual analysis of data. This paper studies the potential of an augmented reality environment for the purpose of collaborative analysis of multidimensional, abstract data. We present ART, a collaborative analysis tool to visualize multidimensional data in augmented reality using an interactive, 3D parallel coordinates visualization. The visualization is anchored to a touch-sensitive tabletop, benefiting from well-established interaction techniques. The results of group-based expert walkthroughs show that ART can facilitate immersion in the data, a fluid analysis process, and collaboration. Based on the results, we provide a set of guidelines and discuss future research areas to foster the development of immersive technologies as tools for the collaborative analysis of multidimensional data.

Author Keywords

Immersive Analytics; augmented reality; 3D parallel coordinates; multi-touch table; collaboration

INTRODUCTION

A large amount of research and productive systems (e.g., Tableau or Spotfire) alike show the value of interactive visualizations for analyzing complex data. In terms of interaction style, corresponding systems follow different approaches ranging from classical desktop systems, to touch interfaces for small screens supporting support mobile applications, to large, interactive screens that facilitate co-located collaboration. With the rapid development of new, immersive display, and input technologies and the recent commodification of virtual reality (VR) and augmented reality (AR) head-mounted displays (HMDs), the already broad design space for interactive visualizations has been extended once more. Recent research focused on how VR and AR technologies can be instrumental in supporting complex data analysis scenarios [12]. Unlike traditional desktop systems, these technologies provide the means to visualize complex information in a physical space, allowing a large amount of data to be investigated simultaneously [19]. In addition, immersive technologies “can facilitate the visual perception of users in a natural way, which, in turn, helps them quickly identify areas of interest, meaningful patterns, anomalies, and structures between artifacts” [38].

The strength of immersive technologies are especially able to leverage the analysis of information in complex scenarios like the collaborative analysis of multidimensional, abstract data. Consider the following real-world scenario:[1] *A team of behavioral and nutritional scientists intends to collaboratively analyze data collected through a mobile intervention study. The data consists of records from several hundred participants who tracked their food intake and contextual information over the course of several weeks. Based on the collected data, the scientists seek to understand what people do (behavioral patterns), why people do what they do (psychosocial and contextual behavioral triggers), and when people do what they do (timing of behavior and triggers) [24, 30]. These three aspects form a participant’s high-dimensional behavior signature. A central goal of the scientists is to understand such behavior signatures. As part of their analysis they seek to identify relations between the integrated dimensions, how an individual signature changes over time, and if there are correlations and similarities between behavior signatures of groups of people.*

The described analysis aims can be transferred to many other domains in which high-dimensional, abstract data has to be analyzed. On a more general level, the aims of the analysis can be summarized as follows:

- Identification of high-dimensional clusters (e.g., persons with similar behavior signatures) and their correlation to related outcomes (e.g., body mass index (BMI), blood level);
- Investigation of high-dimensional data on multiple aggregation levels (e.g., participant, day, meal);
- Analysis of chronological trends within the multidimensional data (e.g., change of BMI over time);
- Identification of outliers in the data (e.g., behavior signature that differs from all others).

Solving these analysis aims requires tools that are capable of visualizing not only the high-dimensional data, but also the relationships between the dimensions. Some previous work for desktop computers combined several 2D visualizations to create high-dimensional 3D representations [15, 23, 33] or provided animated 3D transitions between the 2D visualizations [21]. For these visualizations to be effective, corresponding tools had to provide certain key functionalities such as filtering and clustering the data [21], or adding, removing, and rearranging the dimensions [15, 23].

Using AR interfaces for visual data analysis, both the data and the key functionalities can be realized as 3D representations, supporting stereoscopic vision and egocentric navigation.[2] In addition, visualizations are not restricted to display boundaries but to the physical space available. Moreover, because interaction is grounded in the physical world, AR-based visual analysis tools facilitate natural communication and coordination between collaborators. While the benefits of AR have been established and the technology has matured, it is still an open challenge to provide fluid interaction for immersive data analysis scenarios[3] with complex and feature-rich visualizations in AR environments. In this paper we present **A**ugmented **R**eality above the **T**abletop (ART), a system designed for the fluid analysis of multidimensional, abstract data sets. The contribution of the paper is twofold:

1. We present the *ART system including its underlying technical setting*. ART visualizes multidimensional data in AR using multiple scatter plots with linked data points, creating a 3D parallel coordinates visualization. The visualization is anchored to a touch-sensitive tabletop, enabling familiar and fluid operation.
2. We contribute *design guidelines and future research directions* to foster the development of tools that support collaborative analysis of multidimensional data. Findings result from two group-based expert walkthroughs, within which experts from the domains of behavioral and nutritional science evaluated the ability of ART to collaboratively analyze clusters, trends, and outliers.

RELATED WORK

This work investigates the potential of immersive technologies for the purpose of collaborative analysis of multidimensional data and refers to the following research areas: (1) approaches to the *visualization of high-dimensional data*, (2) *immersive visualizations* and how they deal with high-dimensional, abstract data, (3) *interaction with immersive environments*, and (4) *collaborative, immersive data analysis*.

High-dimensional Visualizations

Elmqvist et al. presented ScatterDice [21], a desktop visualization tool for the interactive exploration of multidimensional data based on a large 2D scatter plot. The dimensions in the plot can be changed by navigating a scatter plot matrix which displays all dimensions in the data set. ScatterDice additionally allows for query sculpting where a selection of data items in one plot are reflected and can be manipulated in other plots the user navigates to. GraphDice [7] is based on the same mechanism but uses node-link diagrams instead of scatter plots. VisLink [15] is a multi-relationship visualization and supports the display of multiple 2D visualizations which can be freely arranged in a 3D environment on a desktop computer. Adjacent visualizations are connected by bundled edges which allow for cross visualization comparisons. The main contribution of VisLink refers to its capability for displaying inter-representational queries. The propagation of edges over multiple visualizations can reveal patterns based on the 2D spatial structure of the single visualizations. Vlaming et al. [49]

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[1] Associated use cases were identified within a workshop with health and biological psychologists as domain experts [36].

[2] Egocentric navigation refers to moving one’s body to navigate in a fixed information space, whereas non-egocentric navigation refers to moving the information space itself.

[3] “Fluidity in information visualization is an elusive and intangible concept characterized by smooth, seamless, and powerful interaction; responsive, interactive and rapidly updated graphics; and careful, conscientious, and comprehensive user experiences.” [22]

extended VisLink with a multi-touch virtual mouse to provide fine grained interaction for using interactive visualizations on a multi-touch table. Caleydo [33] applies a similar concept of linking 2D visualizations with each other, but reduces complexity by using a metaphor for a view arrangement where related views are rendered on the inner sides of a square bucket. The abandonment of free navigation limits the perspectives that can be taken on the visualizations but also reduces the cognitive load during navigation. Fanea et al. [23] presented Parallel Glyphs, an interactive integration of a parallel coordinates visualization and star glyphs. Parallel Glyphs therefore provide the means to display multiple attributes for each data item.

In summary, previous work for desktop computers showed that linked 2D visualizations provide the means to visualize high-dimensional data in a 3D space. The interactive visualizations often allow for changing the perspective on the data by navigating the 3D scene. But the navigation of a 3D information space with an interface that is optimized for 2D interaction is also one of the big challenges, because the input device at hand offers only 2 degrees of freedom (DOF) where 6 DOF are required [9].

Immersive Visualizations

Several kinds of visualizations have been investigated for VR and AR environments. A large body of work studied scientific visualizations[4] and showed that immersive environments can improve the effectiveness of these visualizations [32]. Examples can be found in domains such as brain tumor analysis [51], diagnostic radiology [44], archeology [3, 27, 42, 43, 46], meteorology [52], and geographic information systems [5]. These visualizations, however, are domain-specific and their applicability to other domains is limited. Other researchers investigated less domain-specific visualizations like 3D scatter plots [19, 35, 39, 41], link graphs [1, 6, 17, 20], and parallel coordinates [41]. These works report on several benefits of immersive environments for information visualizations. Raja et al. [39] developed a 3D scatter plot visualization for a Cave Automatic Virtual Environment (CAVE)[5] environment and identified benefits of higher immersion when analyzing distances, trends, clusters, and outliers. Belcher et al. [1] revealed that a tangible AR interface is well suited to link analysis. Ware and Franck [50] showed that depth and motion cues provide large gains in spatial comprehension and accuracy when analyzing 3D graph links in VR. Cordeil et al. [16] introduced ImAxes, a VR system for exploring multivariate data. The user can manipulate and position single axes like physical objects in a VR environment. Depending on the proximity and relative orientation, the axes are automatically linked to multidimensional visualizations. The linked axes correspond to well-established visualization types, such as 3D scatter plots and parallel coordinates, but can also result in complex emergent graphs like 3D parallel coordinates or 3D scatter matrices. This allows for a high degree of flexibility in terms of the visualizations that can be created, but at the same time requires the user to have knowledge about suitable visualizations and the corresponding arrangements of axes. Another work by Cordeil et al. [17] took a more technical point of view and compared a CAVE environment with HMDs in terms of the collaborative analysis of network graphs. Whereas the accuracy of the analysis and the affordances for the communication did not differ between the two technologies, the HMDs lead to a lower task completion time.

In summary, previous work showed the suitability of immersive environments for information visualization and demonstrated that HMDs can provide similar benefits as extensive CAVE setups. In terms of visualizing abstract data in immersive environments, research is mainly limited to three graph types: 3D scatter plots, link graphs, and parallel coordinates. Recent research [16] showed the potential of immersive environments to making emergent 3D graphs or combinations of known graph types experienceable.

Interaction with Immersive Environments

The interaction with visualizations in immersive environments is still an issue, in particular given that "exploration and analysis are most strongly supported when combining the best possible visual representations with the best possible interaction techniques." [34] Most commonly, spatially aware input controllers (e.g., HTC Vive Controller) or freehand gestures (e.g., with Leap Motion) are used. However, these input techniques suffer from the "touching the void" issue [10]. More recent research in the field of immersive visualizations considered the combination of immersive display technologies like HMDs or CAVEs with touch interaction as an input style. Multi-touch devices can provide haptic feedback to the user which is of high importance for both real and virtual environments [40]. Whereas HMDs and stereoscopic displays facilitate depth perception and thus offer a high level of visual immersion, touch-based interaction provides high immersion due to it immediacy of interaction [34]. Several research projects investigated the combination of AR devices with multi-touch tables to perform object positioning tasks [2, 4, 28, 45]. Hachet et al. [28] presented Toucheo, a system which used a mirror-based display to visualize 3D objects above a multi-touch table. In a user study, the interaction through well-known 2D metaphors on the multi-touch table received positive feedback in terms of user experience. However, the system limits users' freedom to move around. Sousa et al. [44] applied a similar approach for the analysis of medical images. Their VR setting combined a HMD with a touch-sensitive table. To manipulate the medical image, virtual controls were mapped to the table in VR. Unlike midair controls, this setting provides the advantage that mapping controls to physical objects provides somesthesis[6] feedback. López et al. [34] combined 3D visualizations on a stereoscopic wall display with touch-based navigation on a tablet device. They identified a set of interaction modes and a workflow that helps users transition between these interaction

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[4] Scientific visualizations can be defined as being "primarily concerned with the visualization of three-dimensional phenomena, where the emphasis is on realistic renderings of volumes, surfaces, illumination sources, and so forth, perhaps with a dynamic (time) component" [25].

[5] We refer to CAVE as the generic type of Virtual Environment systems described in [18].

[6] Somesthesis envelopes the cutaneous (skin) sensation and the capability to sense the movement and position of our limbs (proprioception) [40].

modes. Coffey et al. [13, 14] proposed Slice WIM, a combination of a vertical stereoscopic wall display to visualize medical volumetric data and a monoscopic horizontal multi-touch display which provides interaction widgets. This setup creates the impression that the 3D object is hovering above the table. In a first evaluation, users quickly learned the relation between the tabletop and the 3D content hovering above.

In summary, previous research has combined multi-touch interaction with immersive technologies and showed that interaction benefits from somesthesis feedback and familiar touch operation. However, previous work either focused on the combination of immersive technologies with touch to position objects or to navigate 3D scenes. The linking between a feature-rich interactive graph visualization on a touch table and a visualization in AR may support fluid interaction, but has not been not investigated yet.

Collaborative Immersive Data Analysis

Decision-making based on data analysis is often the result of a collaborative effort [29, 31, 38]. VR and AR environments seem to naturally support collaboration [17] as they provide the means to create a shared environment where collaborators have a sense of each other's presence. Some research has investigated the influence of immersive environments on collaboration [3, 8, 17, 19, 20, 27, 37, 42, 46]. Billinghurst and Kato [8] pointed out that collaboration can especially benefit from AR environments, because they can decrease the cognitive and functional load on the user. The project Studierstube [27, 42, 46] provides an AR environment in which users can collaboratively explore virtual objects situated in the space between them. The advantages of this AR setting are that users can interact with the real world and the virtual world simultaneously, that spatial cues are provided, and that natural collaboration is facilitated. In a manner similar to this project Benko et al. [3] developed a collaborative mixed reality system for an off-site visualization of an archaeological dig. Domain experts appreciated the provided combination of a 3D visualization of objects visible through HMDs with additional contextual information visualized in 2D, as well as the multi-modal interaction in terms of touch-input on a multi-touch table, speech, and 3D hand gestures.

In summary, previous work showed great potential for immersive environments for collaboration, whereby in particular AR environments can provide the means to facilitate the natural communication and coordination between users.

ART — AUGMENTED REALITY ABOVE THE TABLETOP

ART was designed to address the above-mentioned analysis aims that occur during the investigation of multidimensional, abstract data. Based on findings from previous research that showed ways to facilitate immersion and collaboration, ART uses AR HMDs to visualize a 3D parallel coordinates plot in physical space. The visualization in AR is combined with a touch-sensitive tabletop allowing for familiar operation. We first introduce here the conceptual components (visualization and interaction) and then present the technical setting.

Figure 2. The detailed mode on the tabletop allows for the configuration of a scatter plot in terms of setting the dimensions and defining clusters.

Visualization

Similar to previous approaches [15, 16, 23, 33, 48], ART links individual plots to each other to create a multidimensional visualization. ART consists of 2D scatter plots which are visualized in line and linked to each other to create a 3D parallel coordinates visualization (see Figure 1). Each data record is represented by a single line cutting through the 2D scatter plots at the corresponding positions. NULL values are represented by dashed lines which cut through a dedicated area below the respective axis in the scatter plot (see Figure 3). Visualizing 3D parallel coordinates in AR provides three advantages: (1) the AR environment provides a large space to visualize the information, (2) the AR environments provides better depth cues and thus simplifies the interpretation of distances, and (3) the visualization benefits from less occlusion (especially during navigation) and therefore facilitates line tracing across multiple scatter plots.

Each scatter plot has a representation in AR and a representation on the tabletop. Both representations are spatially linked to each other so that the AR representation hovers directly above the table representation. The number of visible table representations is limited by the table's size, but the representations in AR can exceed the size of the table and therefore provides a preview to all created scatter plots.

Interaction

Interactivity is an important part of viewing both 2D and 3D parallel coordinates, particularly for adding and rearranging dimensions. Thereby users can compare two dimensions, filter the data sets to avoid clutter, and sort or highlight data records to reveal correlations. In addition to these general operations, ART supports both an egocentric and a non-egocentric navigation style. During egocentric navigation the experts moved in space to change their points of view. The non-egocentric style allows for navigating the visualization by scrolling through the list of scatter plots on the table or by using the slider under a scatter plot to move the AR visualization towards or away from the user.

The table representations of the scatter plots provide two modes: an overview mode for exploring the visualization (see Figure 1), and a detailed mode for configuring the plot (see Figure 2). In the overview mode, users can add, reorder, flip, sort, and colorize scatter plots through several buttons at the bottom of the interface.

- **Add:** New scatter plots are created (plus sign located at either side of the tabletop) and can be directly dragged to the intended position.
- **Move:** Scatter plots can be moved to another location to facilitate the analysis of relations between neighboring plots.
- **Sort based on absolute values:** The X-axis of each individual plot is sorted by the respective values of its Y-axis. This essentially disregards the X-dimension in favor of an easy to interpret and detailed visualization of the distribution of the Y-values (see Figure 3). In this mode the visualization also shows the rank of the value of a record within the data set (position on the X-axis). Neighboring lines with the same Y-values appear as one line with a higher width on the X-axis.
- **Sort based on relative differences:** The X-axes of two neighboring plots are sorted based on their horizontal inclination (differences between the dimensions on the Y-axis). This allows for an easy interpretation of correlations between two neighboring plots even when the distribution of Y-values in both plots is large (see Figure 4).
- **Colorize based on absolute values:** One plot is selected to colorize the lines in the entire 3D visualization. This makes tracing individual lines or the identification of correlations over longer distances and multiple scatter plots easier. The color of the lines is either set to a predefined gradient based on the Y-axis value or set depending on the clusters defined in the detailed mode of the scatter plot configuration.
- **Colorize based on relative differences:** The color of the lines in the visualization is set by the relative difference of the Y-values between two neighboring plots. Similar to sorting based on relative differences, this allows for an easy interpretation of correlations, or more specifically clusters of records with similar correlations but different absolute values (see Figure 4).
- **Flip:** Because certain perspectives (e.g., looking from above) are difficult, users can flip individual plots (swapping the X- and Y-axis), similar to the rotation of visualizations in VisLink [15]. This is equivalent to rotating the visualization by 90°, making a side view equivalent to a top-down view.

Each scatter plot can be selected to open a detailed mode containing an interactive representation of the plot. VisLink [15] has already shown that providing 2D representation can be beneficial as interaction techniques developed for 2D visualizations can be used. The AR representation of the plot turns by 90° to provide an orthogonal view on the data and makes it easier to mentally link the AR representation to the table representation (see Figure 2). The detailed mode provides two additional functionalities: selecting the dimensions of the plot, and filtering or clustering the data set.

- **Dimensions:** The data set dimensions which should be assigned to the X- and Y-axis can be selected separately from a simple scroll list. The scroll list can be filtered depending on the aggregation level of the dimensions (e.g., calories per meal, day, week). The lines in the 3D graph visualization split up or combine between scatter plots depending on the individual aggregation level (see Figure 5).

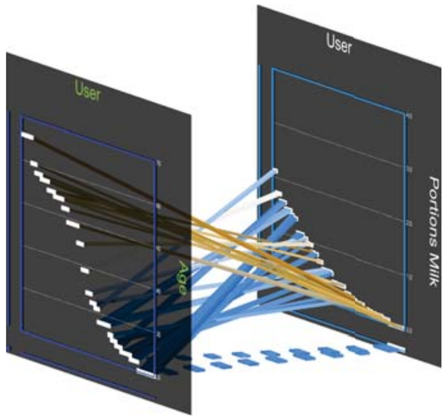

Figure 3. Scatter plots can be sorted based on their absolute values on the Y-axis. Data records with NULL values for the dimension are visualized as dashed lines cutting through the lower end of the scatter plots.

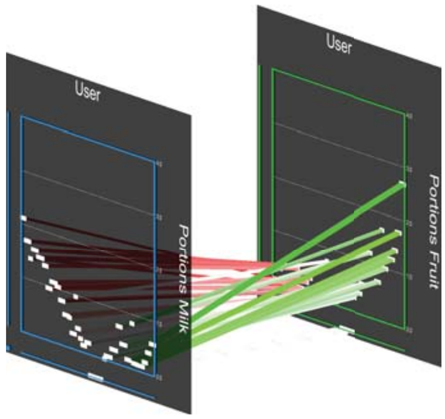

Figure 4. Lines are sorted and colored by their relative differences of the Y-values between two scatter plots.

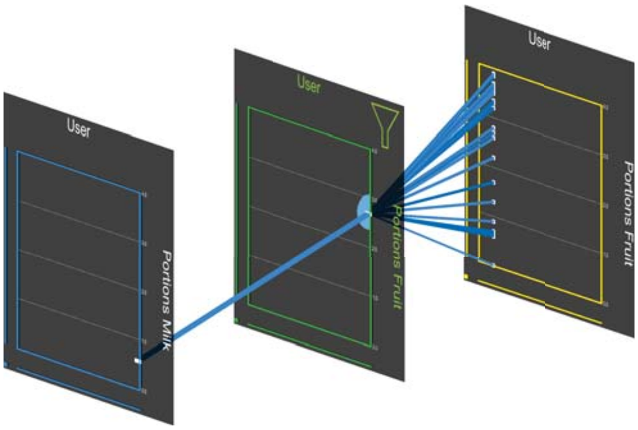

Figure 5. Lines split from the calculated average value to their individual values when the aggregation level changes between scatter plots.

- **Clusters:** Clusters based on combinations of X- and Y-values can be directly drawn into the scatter plot on the table. Clusters also act as filters. Thus, data records that do not belong to a cluster are removed from the AR representation but are still visible in the table representation. A default color is automatically assigned to each cluster. By tapping on a cluster, a menu will appear which allows for changing the color. One can either assign a solid color or a color gradient based on the X- or Y-values in the cluster. In a manner similar to ScatterDice [21] and GraphDice, [7] this allows for propagating and manipulating clusters and filters to other plots.

Technical Setting

ART is based on video see-through AR devices consisting of VR HMD (HTC Vive) and stereo cameras (Ovrvision Pro) mounted to the headset. Although these video see-through devices come with some limitations (e.g., they are tethered) they have the advantage of a considerably larger field of view than current optical see-through devices (e.g., Microsoft HoloLens). The HMDs provide a diagonal field of view of 110° and a resolution of 2160 × 1200 pixels. The Ovrvision cameras provide a resolution 960 × 950 pixels per camera (1920 × 950 pixels in total) at 60 frames per second (fps). We use the HTC Vive's built-in tracking to align the real and the virtual world, as well as to calibrate the table's position. The trackable area has a size of 15' × 15'. For an input device we used a 84" multi-touch display with a resolution of 3840 × 2140 pixels (Microsoft Surface Hub). The display has an built-in PC (Intel i7, 8 GB RAM, NVIDIA Quadro K2200). The HMDs are controlled by two external PCs (Intel i7, 32 GB RAM, NVIDIA GTX 1080). The interface running on the touch-display is web-based and the AR visualization was built with Unity3D [47].

GROUP-BASED EXPERT WALKTHROUGH

We evaluated ART as a novel approach for combining a powerful visualization in AR with the familiar touch interaction of a tabletop. We also aimed for an investigation that goes beyond the analysis of the usability and focuses on the applicability of the approach to the real-world analysis scenario described in the introduction. Therefore, we conducted two group-based expert walkthroughs with domain experts who have an understanding of the data and its context and can judge the system with respect to their real-world analysis aims.

Data Set

The data set used for the evaluation was collected during an intervention study which investigated eating behavior (e.g., food intake), psychological aspects (e.g., eating motives and emotional states), and context-related aspects such as the eating location and the social context. This data is combined with demographic information and clinical measures. Thus, the data set (1) is large, because it contains information of several hundreds of participants who tracked data over the course of several weeks, (2) is high-dimensional, because the intervention study tries to collect a holistic picture of the participants, and (3) contains mainly abstract information in terms of numerical or categorical values.[7]

Participants

The participants are domain experts in terms of nutritional and behavioral science (health psychologists and biological psychologists). The domain experts stated that they validate hypotheses using statistical methods but also apply explorative data analysis approaches to unveil unexpected effects and patterns. The explorative analysis, especially, is sometimes conducted collaboratively. They typically use spreadsheets (e.g., Microsoft Excel) or statistical applications (e.g., IBM SPSS) and only have basic knowledge in using visualization suites (e.g., Tableau). Therefore, the researchers are experts in terms of domain knowledge and statistical methods but are non-experts in terms of visual data analysis. Ten domain experts participated in the walkthroughs (five per session).

Procedure & Task

Each session lasted approximately two hours. The sessions started with a discussion about the data set and the analysis aims from the domain experts (15 min) followed by an introduction to ART (15 min). In the subsequent session (60 min) three real-world analysis aims were performed using ART. In a first use case, domain experts explored the relation between food consumption (e.g., portions of milk, meat, grains) and clinical measures like BMI. They further investigated different aggregation levels (e.g., meal, day, user level) and tried to identify clusters of people with similar behavior signatures. In a second use case, domain experts analyzed the change of different dimensions over the duration of the study. Domain experts created a timeline visualization with which they were able to track different measures over several weeks, with each week as a single scatter plot. During the session domain experts rotated from observers to actors approximately every 10 min. While two experts analyzed the data, the others observed the analysis process on two large screens situated in the same room and showing the augmented view of the actors. This actual analysis walkthrough was concluded with a group discussion in which specific characteristics of ART were discussed (30 min). The discussion focused on the fluidity of the analysis process, the readability of the 3D visualization, the influence of representing information in space, and the usefulness of the setting for collaboration.

Results

We applied qualitative content analysis with an inductive category development to analyze the transcribed data (videos and notes from two observers) from the two sessions. The high level themes identified refer to the *Analysis Process*, the *Visualization Readability*, *Space & Immersion*, and *Collaboration*.

Analysis Process

The domain experts mentioned that it was easy to familiarize oneself with ART as well as to quickly identify the operations required to follow their analysis approach. "*I found it stunningly easy to get into the workflow [...] somehow, everything was totally plausible.*" [G1/P6] To limit complexity scatter plots were configured most often with the *UserId* dimension on the X-axis. This allowed for the creation of a visualization in which each depth value represents a single user. Domain experts constantly added scatter plots either to investigate relations between dimension or solely to filter the data set (e.g.,

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[7] The data set contains information of 200 participants who tracked their food intake during five weeks. This results in 20,000 data records where each record represents one meal. Each data record has about 80 dimensions.

plot with gender on the X-axis and age on the Y-axis). To organize the visualization, plots that were intended to filter the data set were placed at the leftmost of the AR visualization (see Figure 6). Plots which did not reveal any findings were instantly reconfigured or removed.

Domain experts further changed aggregation levels during the analysis. If interesting effects were identified in a higher aggregation level (e.g., participant level), they added plots with a lower aggregation level (e.g., day level) to conduct a detailed analysis. For example, this type of detailed analysis was performed to decide if a data record is an outlier. The plots were removed afterwards to continue with the higher aggregation level. During the analysis, domain experts dynamically created clusters, colorized, and sorted the data records. They deemed these functionalities as being essential for efficiently analyzing the data set.

Domain experts agreed that ART supports an explorative analysis workflow in which findings can be fluidly investigated in more detail without discarding the previous analysis. They stated that "*The tool allows performing quick and easy actions. Thus the dynamic somehow remains in the workflow.*" [G1/P5] Or that "*If you see something interesting you can directly investigate it in more detail.* [G2/P2]" and "*If you have a look at relationships between multiple variables with other tools it instantly gets very complicated.*" [G2/P1] However, ART only supports a linear analysis workflow. Domain experts wanted to be able to save snapshots of the analysis state at hand. This would allow opening up new analysis branches without loosing previous ones. AR seems to be well-suited for this, because snapshots could be laid out in physical space, relationships between the snapshots could be visualized, and they could be easily accessed to continue the analysis at a previous state.

Design recommendations

Support fluid workflows: Extensible visualizations in combination with an easy to learn and fluid way for configuring the visualizations can provide the means to dynamically analyze data.

Future work

Support of non-linear analysis workflows
(e.g., snapshots allowing for new analysis branches).

Visualization Readability

Domain experts gave positive feedback about the readability of the visualization. They mentioned that the 3D parallel coordinates are well suited to identify multidimensional trends and relations and to visualize timelines. One participant said: "*A pretty cool thing, because I can look at the data in a different way. [...] You get a better understanding of trends, and you can see more than one relation at the same time.*" [G2/P4] Domain experts also mentioned that ART allowed them to identify multidimensional clusters of persons with similar behavior signatures. Another benefit identified by the domain experts is that multidimensional outliers are easy to detect. Outliers are not only visible if their value is quite different from the rest of the distribution, but also if the relationship to other dimensions is different (different inclination).

Domain experts made frequent use of the sort, colorize, and cluster functionalities (see Figure 6 and 7). The experts sorted most of the scatter plots to reduce the complexity. Without sorting, the lines create a lot of clutter which makes interpretation difficult. The colorize functionality was used especially to compare relationships over multiple, but not necessarily neighboring, scatter plots and to highlight created clusters. Also, the visualization of relative differences between data points on two scatter plots in terms of sorting or coloring by difference was assumed to be an important feature to the analysis.

One problem that the experts mentioned was related to the fixed scales of the scatter plot axes. The fixed scales facilitate the comparisons between plots, but to some extent the distribution of the data records span only a small part of the scale. An additional function to either automatically apply a suitable scaling based on the currently filtered data over multiple scatter plots, or to manually adapt the scales (either global for all scatter plots or local for individual scatter plots) is required.

Another difficulty occurred during the comparison of clusters with different numbers of data records. The domain experts therefore recommended the integration of visual representations for descriptive statistics. "*Would it be possible to summarize [the clusters] as average? [...] [The lines in a cluster] could become one line, the more people are contained within [the cluster], the thicker the line becomes.*" [G1/P3] In contrast to this more abstract information the domain experts also recommended integrating non-abstract information like images of the single meals. This would allow the analysts to get a better understanding of the data.

Design recommendations

Provide sort and colorize functionalities: Sorting 3D visualizations can reduce clutter and therefore complexity. Colorizing data records is essential to compare values over larger distances or to trace individual records.

Highlight relative differences: For the analysis of multidimensional relationships, absolute values but also relative differences between dimensions have to be investigated.

Future work

Automatic or manual (see e.g., [16]) scaling of axes based on the filtered data set.

Integration of descriptive statistics for clusters
(e.g., clusters' average line).

Integration of additional non-abstract information
(e.g., pictures of meals).

Space & Immersion

The domain experts perceived the immersive technology as valuable for data analysis. They reported getting a better feeling for the data than they had using traditional desktop tools. "*I think this gives you a different feel for the data. [. . .] One has a faster feeling of what is in there and how they behave.*" [G1/P4] The experts further appreciated the large space that was available to visualize information. This allowed them to visualize a large amount of data simultaneously. "*I think it's really great that you can actually see all the data at once for each person, I think that's a great advantage, because otherwise we are not able to.*" [G1/P3] Participants did not actually see all of the information at once, but perceived it as laying in physical space and therefore being available all the time. In terms of the used AR devices the domain experts stated that although the see-though functionality lowers the immersion compared to a VR environment, they would prefer an AR environment for three reasons: orientation is facilitated, co-located collaboration is supported, and the analysis could be better integrated into their holistic workflow and daily working routine.

The domain experts further reported that not only the visualization but also the familiar and fluid interaction, which allows for a dynamic adoption of the visualized information, increased their feeling of being immersed in the data. "*You can change things so easily, so you can really just move [the visualization] back and forth, or somehow choose another type of aggregation, and thereby you can immediately solve [the question you have]; otherwise it takes an eternity and one is out of the actual process already, here it is somehow done quickly and then one can continue with what you actually aim for.*" [G1/P4] The mapping between the table and the AR visualization was perceived as being easy. Some difficulties occurred during the creation of filters or clusters. To create a cluster users open the detailed view on the table. During that time the AR scatter plot rotated to match the orientation of the detailed view. As users focused on the table they did not observe this rotation and therefore had difficulties identifying the areas of interest in the rotated scatter plot.

In terms of navigation, the domain experts stated that egocentric navigation facilitates the interpretation of the multidimensional information. However, due to the immersion, users had the urge to additionally navigate the 3D visualization through gestures. "*When moving [the visualization] [. . .] you somehow have the urge to do it directly, whereas selecting [dimensions] and filtering [. . .] is fine [on the table].*" [G1/P4]

Design recommendations

Combine visualizations in AR and interaction on touch-enabled devices: AR environments provide depth cues and large spaces to visualize information. Touch displays provide a familiar and fluid interaction required for dynamic operation. Special attention has to be put to guiding users' attention between the visualization in AR and the configuration work on the touch device.

Future work

Allow for navigating the AR space through gestures (see e.g., [11] for a combination of input styles in AR environments).

Experimental comparison of AR and VR environments for collaborative data analysis scenarios.

Collaboration

The domain experts perceived ART as being suitable for collaboration. They mentioned that with classic desktop applications one collaborator performs the actions while the other collaborator only observes. The possibility for both collaborators to access the tabletop as well as the possibility to select the individual points of view gave the domain experts the feeling of being an active part of the analysis process. They further mentioned that the collaboration fostered discussions and is helpful for explaining findings to others and thus facilitates a shared understanding for the data.

We were able to observe phases of tightly-coupled collaboration and phases of loosely-coupled collaboration. During tightly-coupled collaboration the domain experts configured the visualization and discussed findings or next steps. In phases of loosely-coupled collaboration participants mainly tried to get an initial understanding of the currently visualized information. However, the support of loosely-coupled collaboration was limited, as reconfiguring the visualization would also change the collaborator's view. This hindered users from digging deeper into the data. Further support for loosely-coupled collaboration is required to overcome this limitation. AR environments allow visualizing distinct information by the collaborators if required. Still, the operation on the table also has to be adapted to the collaboration style.

In terms of navigation styles, non-egocentric navigation was applied more often during tightly-coupled collaboration. It was preferred, because it guides users' attention to the same part of the visualization (see Figure 7). For a loosely-coupled collaboration, the egocentric navigation was preferred, because the points of view can be chosen individually (see Figure 6). During the evaluation the experts often applied these two methods in the corresponding situations, because they were aware of the social protocols, and tried not to negatively influence the collaborators' environment.

During tightly-coupled collaboration, participants applied two strategies: either they tried to take similar points of view to the visualization to discuss the information, or they took different points of view (e.g., one collaborator on each side of the table) to combine their individual findings. In both situations they frequently applied deictic gestures to make spatial references, but faced difficulties, because of virtual content occluding the hand. Therefore, precise pointing was hindered and it was difficult to see exactly at what the collaborator was pointing. A 3D registration of the hand or a virtual pointing and highlighting functionality was requested by the experts and could help overcome this limitation.

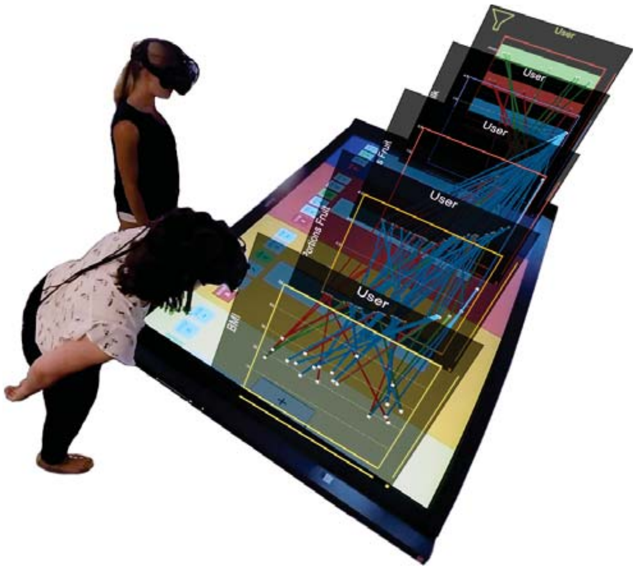

Figure 6. A phase of loosely-coupled collaboration during the group-based expert walkthrough. Domain experts navigated egocentrically to select their individual points of view.

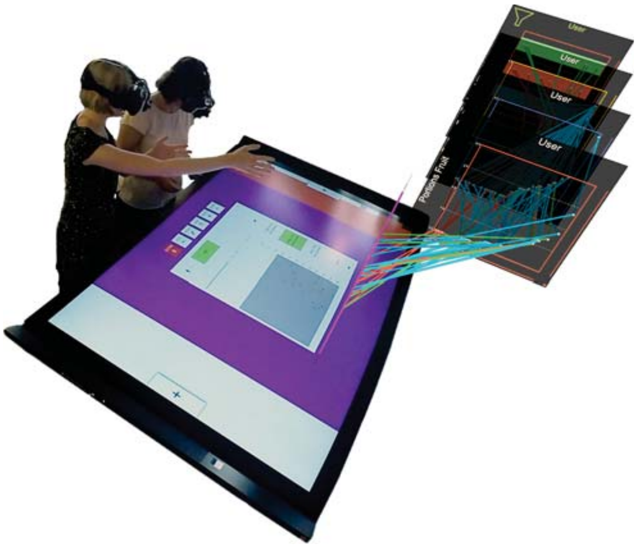

Figure 7. A phase of tightly-coupled collaboration during the group-based expert walkthrough. The domain experts selected a similar point of view and discussed the next analysis steps. Deictic gestures were used frequently during discussions.

Design recommendations

Combine navigation styles: Egocentric navigation has benefits during loosely-coupled collaboration as it allows collaborators to select individual points of view. Non-egocentric navigation has benefits during tightly-coupled collaboration as it helps to set the same focus to the collaborators.

Future work

Extended support for loosely-coupled collaboration (e.g., individual AR visualizations that allow for reconfiguration and navigation).

Extended support for tightly-coupled collaboration (3D registration [26] and pointing).

TECHNICAL LIMITATIONS

A limitation of the ART setting is the reduced quality of the video see-through functionality (e.g., resolution, contrast). As a result, the domain experts reported some uncertainty especially in terms of navigating the physical space at the beginning of the study. This effect subsided quickly, but did not vanish completely. The experts also reported that if the camera visual quality were better they would probably forget about the fact that it is a video see-through device. Further, the video see-through setting causes some latency which can cause motion sickness for sensitive people. However, although the vision was negatively influenced by the cameras, the domain experts did not report on motion sickness. One reason could be that the table served as an anchor point. Another limitation is that the HMDs were tethered. During the evaluation a long cable allowed users to walk around the table. Still, the wired connection negatively influenced users' perception of being able to move freely in space. The technical setting also had an influence on collaboration as the HMDs hindered the domain experts from seeing the others' faces. This caused them to focus on the visualization and not on the collaborator during discussions.

CONCLUSION

In this work we address the challenge of collaboratively analyzing multidimensional, abstract data. We present ART, a system that leverages the strengths of AR environments. The stereoscopic presentation in large-scale space allows for egocentric navigation and can therefore reduce the effects of overplotting when large data sets are visualized. The AR environments further allow for natural communication and coordination between collaborators. ART combines the interaction on a touch-sensitive tabletop with a 3D visualization in AR above the tabletop. This combination of AR with touch input potentially enhances interaction over a gesture-based system due to its familiar, precise, physically undemanding, and fluid interaction. The results of group-based expert walkthroughs show that ART can facilitate immersion in the data, a fluid analysis process, and collaboration. The interaction based on touch input allowed participants to fluidly operate the feature-rich systems, from which the integrated features provided the means to analyze multidimensional clusters, trends, and outliers. Based on these findings, we provide guidelines for the design of interactive visualizations using immersive technologies. In addition, we identify research directions to further facilitate the collaborative analysis of multidimensional data in AR environments.

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