Employing Tangible Visualisations in Augmented Reality with Mobile Devices

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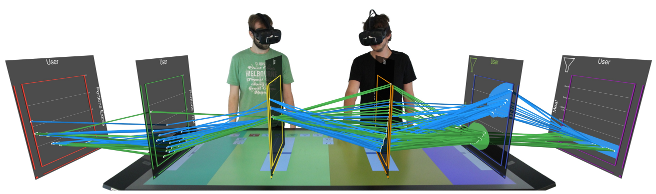

Figure 1: Augmented **R**eality above the **T**abletop (ART) [3] is designed to facilitate the collaborative analysis of multidimensional data. A 3D parallel coordinates visualisation in augmented reality is anchored to a touch-sensitive tabletop, enabling familiar operation.

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Abstract
Recent research has demonstrated the benefits of mixed realities for information visualisation. Often the focus lies on the visualisation itself, leaving interaction opportunities through different modalities largely unexplored. Yet, mixed reality in particular can benefit from a combination of different modalities. This work examines an existing mixed reality visualisation which is combined with a large tabletop for touch interaction. Although this allows for familiar operation, the approach comes with some limitations which we address by employing mobile devices, thus adding tangibility and proxemics as input modalities.

Author Keywords
Immersive Analytics; augmented reality; collaboration; multimodal interaction; mobile device; data analysis

ACM Classification Keywords
H.5.2 [Information interfaces and presentation (e.g., HCI)]: Input devices and strategies (e.g., mouse, touchscreen)

Introduction
Hardware for mixed reality systems has now become widely available, paving the way for widespread adoption of augmented reality (AR) and virtual reality (VR). Especially information visualisations can benefit from this development, as mixed reality systems can, for example, facilitate com-

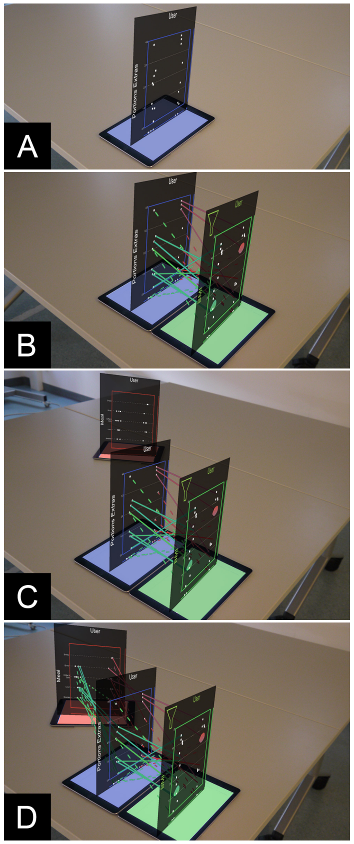

Figure 2: Mock-ups for linking scatter plots. (a) Each mobile device represents a single scatter plot. (b) Links appear when scatter plots are close together. (c) If a scatter plot is too far away, no links are established. (d) Links are thus based on the proxemic distance between mobile devices.

prehension of 3D visualisations and offer a large space for visualisations. Yet, existing systems are often more concerned with exploring new visualisation possibilities, so interaction opportunities are largely ignored. Interaction in current systems is often restricted to a combination of spatial movement with either touch or 3D controllers, while other modalities, such as proxemics or tangibility, are left unexplored. This restriction often leads to several shortcomings concerning the interaction and collaboration of these systems. In this work we therefore explore the addition of such modalities to an existing mixed reality visualisation system and show how this multimodal approach can address key shortcomings.

ART – Augmented Reality above the Tabletop

Augmented **R**eality above the **T**abletop (ART) [3] is a data visualisation system that combines an immersive AR environment[1] with touch input on an interactive tabletop to control a 3D visualisation (see Figure 1). The visualisation is composed of linked 2D scatter plots, creating a 3D parallel coordinates visualisation that hovers directly above the tabletop. A control panel on the tabletop allows users to interact with the visualisation and individual scatter plots.

The ART system offers both touch input and spatial navigation in AR for performing different tasks. For *plot arrangement* tasks (adding, reordering, removing scatter plots) and *scatter plot configuration* tasks (assign dimensions, define clusters and filters) the touch input provides a familiar interface. *Navigation* is performed through a combination of touch input (scrolling on the table) and spatial movement around the tabletop. Additionally, *collaboration* is supported through the independent spatial movement of each user.

[1] The AR environment is realised in Unity3D, using a HTC Vive headset with front-mounted stereoscopic cameras.

In a preliminary evaluation, the touch input for *scatter plot configuration* tasks was beneficial due to its preciseness when defining clusters. Although spatial movement allowed participants to *navigate* the visualisation intuitively, the fixed setup and large size of the tabletop made it difficult to move around the visualisation, forcing users to limit themselves to view the visualisation from the front. Still, spatial movement was appreciated for *collaborative* tasks, as users were able to view the visualisation from different angles. Because the visualisation is shared between users, changes made by one user also affect all other users – which may not always be intended. Users also wanted to interact more directly with the visualisation (e.g. grabbing the visualisation), especially for *navigation* and *plot arrangement* tasks. Although gesture interaction was considered, current technological limitations (e.g. detection, accuracy, occlusion with virtual objects) made gestures too error prone for use within ART.

ARts – Augmented Reality with Tablets

Augmented **R**eality with **t**ablet**s** (ARts) aims to move away from a monolithic tabletop towards multiple location-aware[2] mobile devices (e.g. tablets). This is a similar approach as applied for VisTiles [8]. We thus open up the design space through tangibility and proxemics, while keeping touch input for suitable tasks. Instead of concentrating the entire visualisation on a single device, each mobile device represents a single scatter plot (see Figure 2). Guided by the proxemic dimensions [6], we are able to support several individual and collaborative tasks: *Distance* as a measure for linking scatter plots, *orientation* and *location* for adjusting the visualisation (e.g. flipping the visualisation through rotation), and *movement* for indicating possible collaboration opportunities. The following sections describe the shift in modalities regarding *plot arrangement*, *spatial linking*, *scatter plot configuration*, *navigation*, and *collaboration* tasks.

[2] For example, by attaching HTC Vive Trackers to each mobile device.

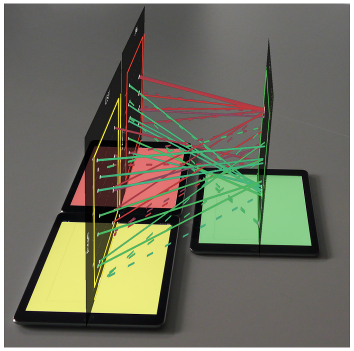

Figure 3: Mock-up for arranging scatter plots. Mobile devices allow for a flexible arrangement of scatter plots, such as a two-to-one layout.

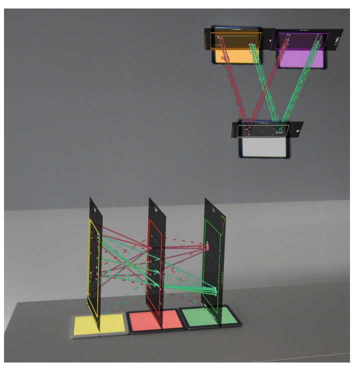

Figure 4: Mock-up for room usage. Mobile devices can be arranged in any location in the room, for example placed on a table or attached to a magnetic wall.

Plot Arrangement

By distributing individual scatter plots onto different mobile devices, the modality for plot arrangement shifts towards tangibility. The physical affordance of mobile devices also avoids some of the inherent difficulties with gesture interaction, such as the *touching the void* [2] issue. Users can therefore arrange plots by physically arranging mobile devices, allowing for flexible linked visualisation layouts (see Figure 3) similar to systems such as VisLink [4] or ImAxes [5]. This also enables users to fully utilise their surroundings, for example by mounting visualisations onto a wall (see Figure 4).

Spatial Linking

Links between scatter plots are automatically established based on the proxemic distance between mobile devices (see Figure 2). This allows for dynamic linking of scatter plots similar to ImAxes [5] and enables us to explore cross-device interaction similar to VisTiles [8].

Scatter Plot Configuration

Configuration of individual scatter plots can be performed through a familiar touch interface on the mobile device itself. This approach allows us to focus the control panel UI mainly on interaction with the scatter plot (e.g. see Sadana and Stasko [9] for scatter plot interaction on a tablet).

Navigation

The small size of the mobile devices allows users to easily navigate the entire visualisation through spatial movement. Users can also simply move or rotate their arrangement of mobile devices, allowing for navigation through tangibility.

Collaboration

Previous research [1] suggests that co-located collaboration is more efficient when each participant has control over parts of the data. By distributing the visualisation onto different mobile devices, users can either work on different plots of the same visualisation simultaneously, or work on entirely independent visualisations (see Figure 5). Especially in the latter case proxemics can be useful to indicate when two collaborators want to share their results (e.g. distance or movement of collaborators), thus supporting different collaboration styles (e.g. as classified by Isenberg et al. [7]).

Challenges

Our design space of a multimodal, mobile-devices-based visualisation system in AR brings up several *technical* and *interaction design* challenges that still need to be solved.

Technical Challenges

One of the main technical challenges with this approach is to correctly model the linking behaviour between scatter plots. Systems like VisTiles [8] show that distance-based linking can be prone to accidental activation or suffer from hidden functionality. Even though ImAxes [5] already provides a rule set for linking visualisations in VR, the physical surroundings (e.g. tables, walls) may influence spatial linking. While users can freely position scatter plots in VR, in AR mobile devices must be placed on a physical surface, thus limiting freedom for spatial linking significantly. Furthermore, linking mechanisms should ideally avoid unintentional line overlap (e.g. when inserting a new scatter plot in between two linked scatter plots), while still allowing for enough flexibility to not restrict users.

Another challenge is that the size of the visualisation is inherently limited by the number of available mobile devices. Although users can be provided with a reasonable number of devices, it may be beneficial to provide methods for freeing up devices: For example, users could decouple visualisations from their devices, thus keeping a static version of the visualisation in the AR environment, which may be

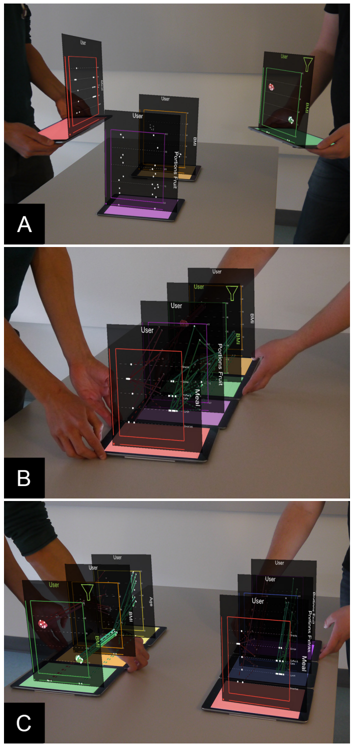

Figure 5: Mock-ups for collaboration. (a) Users working concurrently on different scatter plots. (b) Users combining their results into a shared visualisation. (c) Users working concurrently on individual visualisations.

recoupled with a device later on. Another option is to condense the visualisation onto a single device, thus freeing up the other devices.

Interaction Design Challenges

The physical position of mobile devices in the AR environment may influence the user's perception of the visualisation. Especially when comparing correlations between two neighbouring scatter plots, differing heights may lead to false conclusions if the user is unaware of the height differences. An indication may be essential to make users aware in such cases. Furthermore, while links between two scatter plots can be determined through proxemics, the links themselves may lack interactivity. For this, gesture interaction may be necessary, but exceeds the scope of this work.

Conclusion

We employ mobile devices to create a tangible visualisation system in AR. The initial system applied a combination of touch input with spatial movement in AR, which allowed for precise and familiar interaction. However, this narrow focus on touch interaction with a single device led to several shortcomings in terms of plot arrangement and collaboration. Our proposed approach of replacing the tabletop with multiple mobile devices opens up the design space by introducing tangibility and proxemics. This could result in a more flexible and collaboration-friendly visualisation system.

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