Challenges and Opportunities for Collaborative Immersive Analytics with Hybrid User Interfaces

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Figure 1: An illustrative example of our envisioned collaborative hybrid user interface for the joint analysis and exploration of mixed reality user study data. Here, one analyst studies aggregated interaction data using a 2D representation in a non-immersive desktop view (left) and another analyst is looking at the same time at the same data, visualized as 3D trajectories in an immersive environment. Their views are synchronized and linked, allowing for tightly and loosely coupled collaborative activities, as well as switches and transitions between and across environments. This figure is based on our previous work on RELIVE [11] and asynchronous hybrid user interfaces [12] and combined using Adobe Photoshop (beta)'s generative fill function.

Abstract

Over the past years, we have seen an increase in the number of user studies involving mixed reality interfaces. As these environments usually exceed standardized user study settings that only measure time and error, we developed, designed, and evaluated a mixed-immersion evaluation framework called RELIVE. Its combination of in-situ and ex-situ analysis approaches allows for the holistic and malleable analysis and exploration of mixed reality user study data of an individual analyst in a step-by-step approach that we previously described as an asynchronous hybrid user interface. Yet, collaboration was coined as a key aspect for visual and immersive analytics – potentially allowing multiple analysts to synchronously explore mixed reality user study data from different but complementary angles of evaluation using hybrid user interfaces. This leads to a variety of fundamental challenges and opportunities for research and design of hybrid user interfaces regarding e.g., allocation of tasks, the interplay between views, user representations, and collaborative coupling that are outlined in this position paper.

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1 Introduction

Interaction plays a central role in visualization as it is the catalyst for a user's dialogue with the data and, ultimately, for attaining insights and understanding. The fewer resources users spend for operating tools (e.g., cognitive load [18]), the more resources are left to interpret the visual representation and to gain insight. Therefore, we consider measuring and improving the quality of interaction with visual and immersive data analysis tools as our core motivation. In the last few years, we developed a variety of research prototypes in immersive and non-immersive environments, and we placed a particular focus on evaluation settings to assess their quality of interaction in user studies. While solely quantitative methods are especially helpful to evaluate the performance of simple interaction techniques (e.g., Fitts' Law [9, 19]), they are usually insufficient to characterize more complex tasks in post-WIMP environments (e.g., mixed reality or ubiquitous computing). Today's applications in visual and immersive analytics often allow for multi-modal interaction, multi-user interaction, and multi-device settings, resulting in an elaborate interaction leading to sophisticated evaluation settings that combine quantitative and qualitative approaches [2, 11].

For the analysis of such user study settings, we designed, developed, and evaluated an initial prototype of an evaluation framework (RELIVE [11]) for the exploration and analysis of mixed reality user studies. A user study with experts in the field of visual and immersive analytics did not only prove the feasibility of the combination of in-situ and ex-situ approaches but also emphasized the need for a holistic evaluation environment. Interestingly, experts highlighted the potential for a collaborative evaluation framework – this is in line with recent research that has described the benefits of collaboration for analyzing, interpreting, and understanding visualizations [14] and defined collaborative analytics as well as the

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establishment of an evaluation framework as grand challenges for immersive analytics [6].

In this paper, we present a set of challenges for future research and design of a collaborative evaluation framework for mixed reality user studies using hybrid user interfaces – based on our previous work on the evaluation framework RELIVE [11] and insights from related work – as illustrated in Figure 1.

2 BACKGROUND

Recent research has shown the suitability of immersive (e.g., [4,17,21,23]) and non-immersive (e.g., [1]) tools for the visual analysis of mixed reality user studies. Here, previous work has shown the benefits of using immersive environments to simulate actual user study sessions (e.g., as spatial recordings) and non-immersive environments to analyze aggregated data representations. However, previous work often either focused on immersive or on non-immersive environments (i.e., and not on their combination). In contrast to them, with RELIVE [11] we aimed to place particular emphasis on the meaningful combination of immersive and non-immersive environments using hybrid user interfaces, taking *"advantage of the strong points of each [environment]"* [7]. By distributing interaction and parts of the analysis workflow across devices and modalities, we establish a *symbiosis of interfaces* [29], where each component purposefully increases the quality of interaction and further supports users in the exploration and analysis of mixed reality user study data. Rather than compensating technological limitations with additional devices, Zagermann et al. show how meaningful combinations of homogeneous (e.g., cross-device interaction) and heterogeneous (e.g., hybrid user interfaces) device classes, but also input (e.g., interaction techniques) and output modalities (e.g., visually or auditory) can complement each other to assist users in their current task at hand.

In RELIVE, the immersive VR environment allows users to relive an interactive recording of a replica of the original study, providing the possibility for in-situ analysis of the data. In contrast, the non-immersive desktop view facilitates the analysis of aggregated study data and provides a holistic overview over the available study data. In our concept, users can program components to calculate metrics and create visualizations in an interface akin to a computational notebook. RELIVE also supports the transition between the VR and desktop environment, for example by synchronizing both environments in real-time and offering a glimpse of the VR environment on the desktop and vice versa – thus representing an asynchronous hybrid user interface [13].

Our own and related research have shown the general applicability of this approach [11,12,15,24,29] – however, the combination of synchronized immersive and non-immersive components that allow for dynamic and fluid transitions within and across levels of immersion comes with fundamental challenges and opportunities regarding the **CO1 – Task Allocation** (exploring and analyzing mixed reality user study data includes several subtasks), and **CO2 – Interplay between immersive and non-immersive Analysis** (e.g., transitions and coordination between environments). CO1 and CO2 are not only relevant for collaborative scenarios, but also for individuals that e.g., use the different views asynchronously [13]. CO1 and CO2 are further described below.

Collaboration was described as one of the grand challenges for visual analytics [5], immersive analytics [6], and Isenberg et al. defined a research agenda for collaborative visualization [14]. From our own work, we gained experiences in designing, developing, and evaluating collaborative scenarios for co-located (e.g., [28,31]) and remote collaboration (e.g., [8,20]). Traditionally, collaboration can be classified according to Johansen's Space-Time Matrix [16]: Here, collaboration either happens at the same or different place (i.e., co-located or remote) and at the same or different time (i.e., synchronous or asynchronous). However, having a mixed-immersion environment, we have to add another dimension to this classification: level of immersion. This additional dimension comes with fundamental challenges and opportunities regarding **CO3 – Transitional User Representations** (e.g., from blinking cursors in shared documents to highly-realistic 3D user representations) and **CO4 – Collaborative Coupling Styles and Symmetry of Collaboration** (e.g., different views might lead to differences in roles). CO3 and CO4 are further described below.

3 CHALLENGES AND OPPORTUNITIES

The following sections describe a set of challenges and opportunities for the use case of a collaborative mixed-immersion evaluation framework (CO1 – CO4) – building on our previous work on RELIVE [11]. CO1 – CO4 serve as pointers for future research and design of collaborative complementary interfaces with a focus on immersive analytics. Although the challenges and opportunities are focused on collaborative aspects, they may also be suitable for distributing components using hybrid user interfaces in general (e.g., user representations or allocation of tasks between devices). We intentionally do not limit the following sections to a specific type of collaboration (e.g., by specifying time, place, level of immersion, or roles) as the envisioned collaborative mixed-immersion tool might allow for highly dynamic transitions between these attributes.

3.1 CO1 – Task Allocation

Exploring and analyzing mixed reality user study data includes several subtasks (e.g., gaining overview, reasoning, or compare data across sessions). However, it is unclear, which subtask is more suitable to be performed in an immersive or non-immersive environment. Both provide equal analysis opportunities and a synchronized data access. However, at least two aspects might shape the way analysts will use the framework: (1) the device-specific affordances and constraints of each individual input and output modality can influence interaction and workflows (as shown by recent research [30, 32]); and (2) the view-specific capabilities of e.g., ego-centric navigation in 3D visualizations of spatial recordings (i.e., immersive view) and aggregated 2D visualizations (i.e., non-immersive view).

The immersive view might be beneficial to gain an overview of the situation and the non-immersive view with its 2D visualizations might be more suited for an in-detail analysis. However, it might also be the other way around: Analysts might be interested to gain an overview regarding e.g., task completion times and continue their analysis in the immersive view to find reasons for differences in the data. Additionally, transitions between these two assumed approaches might be the case.

Similarly, tasks and activities that require, e.g., text input via a keyboard will presumably be performed in the non-immersive view whereas activities that require the 3D environment of the actual user study will rather be performed in the immersive view. However, the analysis workflow of mixed reality user study data can differ heavily across different user studies [2]. Therefore, future research should study analysis and exploration workflows regarding device-specific and view-specific efficiency, effectiveness, and preferences.

3.2 CO2 – Interplay between Immersive and Non-Immersive Analysis

Depending on the workflow, analysts might transition or switch between the immersive and non-immersive environments. Here, a discrete switch between the environments might be an efficient way to move from one view to the other [26]. However, this switch might come at the cost of losing context. Alternatively, a continuous transition could prevent analysts from re-orienting in the data representations. Yet, as the input modalities of the immersive and non-immersive views might differ (e.g., mouse vs. controller), analysts might run into trouble when the handling of input devices requires more cognitive capacities than the current task at hand.

The loss of context due to discrete switches and the increased cognitive load of handling view-specific input modalities can be addressed via (1) the adaptation of established techniques for analyzing multiple coordinated views and (2) input devices that can be used across environments.

Multiple coordinated views can traditionally be analyzed with linking and brushing techniques: Here, the selection of a data point in one visualization results in a visual highlight of the same data point in a coordinated visualization. Similarly, having synchronized immersive and non-immersive views, the potential for a cross-reality linking and brushing technique becomes promising. This might support analysts in their exploration of the visualized data and reduce the loss of context, as they might directly start where they left in the previous step. Future research should study the effects and influences of cross-reality linking and brushing for analyzing mixed reality user study data. Additionally, to reduce the cognitive load of handling multiple modalities, a hybrid input device could be used across environments. In the non-immersive view, it can be used like a mouse and be placed on a desk environment. When transitioning to the immersive view, it can be used like a controller.

3.3 CO3 – Transitional User Representations

User representations (e.g., virtual avatars) can be used to create awareness of a collaborator's activities [8]. In immersive environments, remote collaboration can be enriched with highly-realistic avatars that provide qualities usually attributed to co-located collaboration, such as facial expressions, deictic referencing, or the sensation of presence. In common non-immersive interfaces (e.g., Overleaf, Google Docs, or Microsoft Office), collaborators are often represented as a colored cursor or representative icon to communicate e.g., the current position in a document. Having a mixed-immersion environment with immersive and non-immersive views, a user representation is not only beneficial to support remote collaboration, but also to create awareness in co-located activities, especially when each collaborator is working within a different level of immersion. The two named options define the extremes of a user representation continuum: On the immersive end, there are highly-realistic avatars resembling all qualities of a co-located collaborator and on the non-immersive end, there is a cursor that shows the location within a document.

For remote collaboration, this leads at least to two research opportunities: (1) the user representation across different levels of immersion and (2) the transition of the user representation between different levels of immersion.

There is extensive research on user representations in mixed reality – from viewing frustums [20] to avatars [8]. However, combining different levels of immersions leads to new challenges: While we can use established techniques to represent others when being within the same level of immersion (e.g., avatars in virtual reality), it is unclear how to visualize the other person across different levels of immersion. Here, the user representation can also be further differentiated between being true to the physical environment (e.g., an avatar sitting at an office table working in the non-immersive view) and being true to the visualized data that is currently analyzed (e.g., positioning a user representation in close proximity to a 3D visualization in the immersive view).

Here, each view comes with unique opportunities: When being in the immersive view and the other person analyzes data within the non-immersive environment, this allows to represent this user, e.g., as an avatar sitting at an office table, re-arranged to match the local environment (cf. [8]); as a see-through option of the actual person and their environment (i.e., augmented virtuality); or as a representative icon that is bound to a data visualization (e.g., being true to the data that is currently analyzed). Additionally, the user representation could not only be used, e.g., to create awareness but also to communicate the current capabilities of the person within their own local environment (e.g., interacting with a mouse). Also, this could further lead to multiple user representations of the same user, such as an avatar being true to the physical environment, sitting at an office table and additionally, a representative icon being bound to a data visualization to further indicate the current activity (cf. cross-reality linking and brushing).

When working in the non-immersive view and the other person currently analyzes data in the immersive environment, this allows to represent the other user true to the data, e.g., as a representative icon bound to a data visualization. However, imagining a scenario where the user in the non-immersive view still wears a mixed-reality headset with see-through option, this further allows to represent the other user as an avatar in augmented reality, allowing the analyst to proceed working within their local physical environment.

As the non-immersive and immersive views are synchronized and allow analysts to fluidly switch or transition between the environments, their user representation should also match these transitions. Here, complementing the visual representation of users with additional auditory output can create awareness: On the one hand, symbolic sounds could indicate entering or exiting an environment. On the other hand, spatial sound can increase awareness of the other person's location and influence the sensation of presence [8].

Further, it is necessary to understand user representations for co-located activities. Being in the same physical space already brings some benefits compared to the remote counterpart (e.g., verbal communication). However, the opportunity to work within different levels of immersion leads to the need of some form of user representation. Similarly to remote collaboration, a user representation can support the collaboration by increasing the awareness of each others' activities by representing the other person true to the physical environment or visualized data.

3.4 CO4 – Collaborative Coupling Styles and Symmetry of Collaboration

The combination of synchronized immersive and non-immersive views allows multiple analysts to gain a broader perspective on the visualized data. Here, the immersive view might invite analysts to explore 3D simulations of the actual study environment, while as the non-immersive view can support analysts in detailed analyses, and vice versa. This can also lead to a mixed-focus collaboration [10,27], where peers transition between loosely-coupled parallel work (e.g., individually analyzing data visualizations) and closely-coupled activities (e.g., active discussions on the data). Previous work identified coupling styles for a variety of collaborative scenarios (e.g., multi-device collaboration [3] or hybrid scenarios [22]) and we were successfully able to classify collaborative activities during remote collaboration using these well-established coupling styles [8]. Although coupling styles have been proven useful to classify and characterize collaboration in co-located and remote settings, it remains unclear to what extent they can be re-used to classify mixed-immersion collaboration. The characterization of collaborative activities (co-located and remote) in these mixed-immersion environments is crucial to describe the quality of interaction.

An additional way to characterize collaborative behavior is to describe its symmetry: We studied symmetrical collaborative activities (i.e., equal opportunities and features) for remote settings [8]. However, for remote settings, there is often the need for asymmetrical settings [25], such as remote assistance scenarios, where an expert can guide a novice in solving a task (i.e., representing roles). Having the combination of immersive and non-immersive views can likewise lead to an asymmetry of collaboration. Here, one analyst might guide the other person in their exploration of the visualized data to identify, e.g., outliers in the data. This might be done within the same level of immersion or across different levels of immersion. Additionally, this might also be highly dynamic – leading to frequent switches of roles.

4 Conclusion

In this position paper, we motivate the use case for a collaborative mixed-immersion evaluation framework for the analysis and exploration of mixed reality user study data. Our gained knowledge of designing, developing, and evaluating ReLive [11] as an asynchronous hybrid user interface for a single user provides us a suitable starting point to identify challenges and opportunities that may serve as pointers for future research and design of complementary interfaces with a focus on collaborative immersive analytics.

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