Effects of View Layout on Situated Analytics for Multiple-View Representations in Immersive Visualization

Zhen Wen, Wei Zeng, Luoxuan Weng, Yihan Liu, Mingliang Xu, and Wei Chen

Abstract— Multiple-view (MV) representations enabling multi-perspective exploration of large and complex data are often employed on 2D displays. The technique also shows great potential in addressing complex analytic tasks in immersive visualization. However, although useful, the design space of MV representations in immersive visualization lacks in deep exploration. In this paper, we propose a new perspective to this line of research, by examining the effects of view layout for MV representations on situated analytics. Specifically, we disentangle situated analytics in perspectives of *situatedness* regarding spatial relationship between visual representations and physical referents, and *analytics* regarding cross-view data analysis including filtering, refocusing, and connecting tasks. Through an in-depth analysis of existing layout paradigms, we summarize design trade-offs for achieving high situatedness and effective analytics simultaneously. We then distill a list of design requirements for a desired layout that balances situatedness and analytics, and develop a prototype system with an automatic layout adaptation method to fulfill the requirements. The method mainly includes a cylindrical paradigm for egocentric reference frame, and a force-directed method for proper view-view, view-user, and view-referent proximities and high view visibility. We conducted a formal user study that compares layouts by our method with linked and embedded layouts. Quantitative results show that participants finished filtering- and connecting-centered tasks significantly faster with our layouts, and user feedback confirms high usability of the prototype system.

Index Terms—Situated analytics, multiple-view representations, view layout, immersive visualization

1 Introduction

There are many opportunities for data visualization beyond the traditional desktop [44]. Among the future directions, situated analytics makes use of engaging, embodied analysis tools to support data understanding and decision making [19,20]. Recent advancement of interaction and immersive display technologies for augmented reality (AR) has increased the popularity of situated analytics in a variety of applications, such as sports [11,33], digital twins [38,57], and fieldwork [53]. Studies show that augmenting the scene with immersive visualization can bring in many benefits, such as situated analytics, embodied data exploration and increased engagement.

Due to the utilization of three dimensions (3D), immersive visualization by nature faces challenges of 3D visualization such as occlusions and perspective distortions. Multiple-view (MV) paradigm is commonly adopted to manage occlusion in 3D visualization [18]. MV representations are also frequently employed to visualize large and complex abstract data, due to its advantage in supporting multi-perspective exploration [8]. Users can see and interact with information in one view, and observe similar features in another [42]. MV representations have been demonstrated effective for data exploration in immersive visualization [14,43]. Figure 1 presents two usage scenarios in demand of MV representations for abstract data in an AR environment.

- *Scenario 1 – Sport*: In a car racing competition, each car produces a real-time recording of speed changes during the competition. Visualizing the records as time-series graphs and positioning them beside the cars would improve interpretation.
- *Scenario 2 – Board game*: In a board game, each character has multi-variate attributes of the character characteristics. Visualizing the attributes as bar charts and positioning them besides the characters would facilitate comparison.

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Nevertheless, there are challenges for using MV representations in immersive visualization. In 3D space, view occlusion happens, and representations positioned in different depth appear in different view sizes. The challenges hinder cross-view data analysis, such as to compare values in different views. Traditional 2D desktop interfaces leverage visual linkage (*e.g.*, [16]) and coordinated interactions (*e.g.*, [7]) to mitigate the issues. However, directly adapting these techniques to immersive visualization may bring in other issues. For instance, visual linkage rendered in immersive displays with relatively small field-of-view (FOV) can easily cause visual clutter.

This work tackles the challenges from another perspective. We focus on view layout that concerns the positioning of MV representations in 3D immersive space. Existing approaches mainly employ embedded or linked layouts for view positioning in immersive visualization. Both layouts have certain advantages and limitations: embedded layout promotes the linkage between views and referents but hinders analytical tasks like comparison, whilst linked layout is preferable for analytics but difficult to relate views and physical referents (Sect. 3.1). To understand the underlying mechanism, we first summarize design considerations for high levels of spatial situatedness and cross-view data analysis (Sect. 3.2). We then perform an in-depth analysis on design trade-offs between situatedness and analytics, using the ethereal planes framework that specifies design space dimensions for the arrangement of 2D interfaces in 3D space [22]. We distill a list of requirements in aspects of *perspective, movability, proximity*, and *visibility* dimensions for the desired layout that promotes situatedness and analytics simultaneously (Sect. 3.3).

On this basis, we develop a prototype system with an automatic layout adaptation approach to position MV representations in an 3D immersive environment. The method leverages a cylindrical paradigm for *egocentric* reference frame (Sect. 4.2), and a force-directed method to optimize view-view, view-referent, and view-user proximities and maximize view visibility (Sect. 4.3). To validate the effectiveness of our approach, we conducted a formal user study that compare layout by our method with embedded and linked layouts (Sect. 5). Experimental results show that participants accomplished *filtering*- and *connecting*-

Fig. 1. Integrating multiple-view representations into the physical world can benefit applications like sports (left) and board game (right).

centered tasks significantly faster with our layout, and the advantage is more significant in complex scenes (Sect. 5.6). User feedback also validates the prototype system in terms of usability, utility, workload, confidence, and satisfaction (Sect. 5.7).

In summary, the main contributions of this work include:

- We distill a list of design requirements for effective view layout that promotes situatedness and analytics simultaneously.
- We leverage cylindrical reference frame and propose a force-directed approach to automatically position MV representations in immersive visualization.
- We conduct a formal user study that confirms the effectiveness of our proposed method in balancing situatedness and analytics.

2 Related Work

2.1 Multiple-View Representation

MV representations enable users to explore one dataset from different perspectives [41], or different datasets from the same perspective [51]. Design space for MV representations includes visual encoding, layout, and interaction design. An effective MV representation system has a well-designed layout that involves considerations on view coordination, view type, and viewport [46]. Empirical studies also revealed common view layout patterns [8] in MV representations. Visualizations on desktop/tablets can be combined with those on AR headsets in a connected multi-view manner, to help users explore and understand 3D data, *e.g.*, [27, 33, 52]. Designers need to consider the display ecology that engages the entire workflow of a task to better assist analysts in achieving their desired outcomes [15].

There are also opportunities and challenges for using MVs in immersive visualization [43]. FiberClay presents massive airplane trajectories in one primary view, complemented with multiple views on the ground for overview in immersive environments [28]. The trajectories are rendered three dimensional, to better reveal structural insights. As a close work, Liu et al. [36] designed a shelf metaphor to flexibly layout multiple abstract data visualizations (*e.g.*, 3D bar charts) in an immersive space. User study found that semi-circular layout that wraps views around the user in half circle is more preferable. Nevertheless, the study neglects *situatedness* that is an important consideration for situated analytics. We show that the design space for MV representations in AR environments becomes more complicated for situated analytics.

2.2 Situated Analytics

Situated analytics refers to the ability of combining visual analytics and AR techniques for in-situ projection of information onto the physical space, to support the purpose of understanding, sensemaking, and decision making [19, 20]. A main design consideration is to improve situatedness that measures 'the degree the information and person are connected to the task, location, and/or another person' [50], which is a grand challenge for immersive analytics [21]. Many efforts have been devoted to improving *spatial situatedness* that links data visualizations with the real-world entities and spaces to which data corresponds [54]. For example, MARVisT [9] leverages information from reality to assist non-experts to create expressive AR glyph-based visualizations. Other than space, situatedness can also be improved from perspectives of time, place, activity and community [5]. Nevertheless, spatial situatedness that concerns proximity between the visualization and objects or features of the environment is still the primary research focus.

However, existing studies on spatial situatedness are mostly focusing on linking one single representation with the physical world, which may not be enough for complex data and tasks. Many scenarios promote the integration of MV representations for abstract data in the physical world [43]. Nevertheless, presenting abstract data in immersive environments for effective and efficient data understanding is challenging [17, 30]. Specifically, MV representations are often used to support cross-view data analysis like comparison, *e.g.*, to compare speeds of racing cars (Figure 1(left)) or to compare characteristics of game characters (Figure 1(right)). Juxtapositioned layout that keeps MV representations close to each other, is often adopted to facilitate comparison [25, 37]. However, the layout can be in conflict with spatial situatedness that requires the placement of abstract data representations close to the physical referents.

Design trade-offs between situatedness and analytics are to be considered. Specifically, we formulate the design requirements for effective layout of MV representations in immersive visualization, and design an automatic layout approach to generate layouts that are more preferable than conventional embedded and linked ones.

2.3 Interface Design in 3D Space

Due to the nature of the third dimension, situated analytics faces common challenges of 3D visualization. Recommendations for 3D visualization design, like the management of occlusion and perspective distortion [18, 49], can facilitate immersive visualization design. This work regards view layout in immersive visualization as a view management problem in 3D space, which is a primary research topic for interface design in mixed reality. In general, 2D view contents shall be arranged in space to fit the environment [24, 56]. The HCI community also suggests that the arrangement can be adapted according to the semantic context [13, 35] and user behaviors [23, 31]. View management for multiple objects in 3D space further needs to consider spatial and visibility relationships [4]. Layout of MV representations shall accord with these considerations.

To a certain extent, MVs can be simplified as external labels for physical referents, and a large body of literature has been conducted in the direction [3]. Specifically in augmented reality, various external labeling techniques have been proposed, such as identifying important regions in image space for label placement [26], using 3D geometric constraints to keep layout consistency across different viewports [48], and adopting a partially-sorted concentric layout to improve search efficiency [58]. Nevertheless, MV layout design is more comprehensive than external labeling. In addition to linking views to corresponding physical referents (*i.e.*, situatedness), users also need to conduct cross-view data analysis (*i.e.*, analytics). In-depth analyses reveal that common layout options, including embedded and linked methods, fail to support situatedness and analytics simultaneously.

To address the challenge, we leverage the ethereal planes framework [22] and formulate the design considerations as to optimize *view-object*, *view-view*, and *view-user* proximities. We develop an automatic approach with force-directed method to automatically derive the layout that meet the considerations.

3 Design Consideration and Trade-off

In this section, we first list down common terminologies and introduce layout options (Sect. 3.1). Next, we distill design considerations from aspects of *situatedness* and *analytics* (Sect. 3.2), followed by a discussion of design trade-offs in the end (Sect. 3.3).

3.1 Terminology and Layout

As illustrated in Figure 2, this work considers the following properties:

- *View*: Visual structure is the mapping from data to visual representation, and a view is the physical display space where a visual structure is rendered [6]. In this work, we consider multiple views rendered in an AR environment, where each view has a clear boundary that helps isolate views from each other and from the physical world.
- *Referent*: An AR environment comprises of the surrounding entities and physical referents that provide data to be rendered in views.

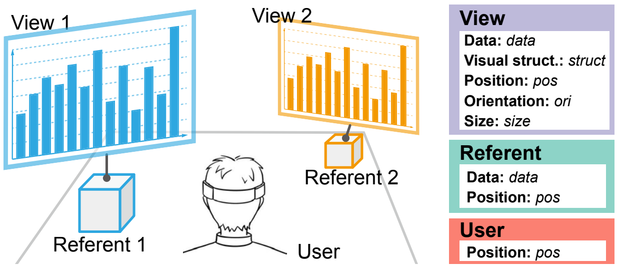


Fig. 2. This work considers properties of *views*, *referents*, and *user* to derive the optimal layout that balances situatedness and analytics.

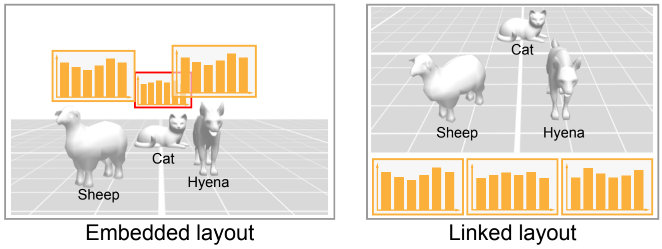


Fig. 3. Embedded and linked layouts are commonly adopted in situated analytics. However, both layouts have certain limitations.

Physical referents are of interest in this work, whilst the surrounding entities provide only the context. Both physical referents and the surrounding entities are fixed and not movable.

- *User*: User is an analyst who would like to complete certain tasks (see Sect. 3.2.2) based on MV representations in an AR environment. The user can freely navigate in the AR environment, and interact with and manipulate views with basic interactions like highlighting, filtering, and view arrangement.

Layout design for MV representations concerns the placement of views in the 3D space, to facilitate situated analytics. Chen et al. [10] summarized three categories of layout design, as follows:

- **Embedded layout**. Embedded data representation deeply integrates visual and physical representations of data with the physical spaces, objects, and entities to which the data refers [54]. Figure 3(left) shows an exemplar embedded layout, where each view is placed on top of its physical referent. Here, proximity between a view and its physical referent is minimized. As such, embedded layout provides high situatedness—users easily get aware of which physical referent a view refers to. On the other hand, since the view positions are fixed, embedded layout can easily cause problems such as occlusion (like the red view on top of Cat) and different sizes, which are not suitable for cross-view data analysis.
- **Linked layout**. Views are separated from physical referents, which can then be organized in parallel or as small multiples as in 2D desktop displays. Figure 3(right) shows an exemplar linked layout. Here, the views are placed side-by-side and assigned the same size. Full visibility for the views is ensured as the views are placed close to the user. However, the user needs to mentally relate a view to its physical referent, which is not straightforward. As in Figure 3(right), the user may feel puzzled whether the second view links to Cat or Hyena: Cat is the second one from left to right, whilst Hyena is the second one from front to back. Visual linkages connecting a view and its referent can mitigate the issue. However, additional visual elements can easily cause visual clutter when there are many views, which is beyond the consideration of this work. As such, linked layout harms the level of situatedness.
- **Mixed layout**. Mixed layout places visual representations and physical referents in a visually continuous manner. With delicate design, mixed layout can achieve proper proximities from a view to its physical referent, to other views, and to the user, to balance situatedness and analytics. Nevertheless, designing proper mixed layout is a non-trivial task, which requires mindful considerations of views and the context in a three dimensional space.

Embedded and linked layouts are simple to implement and have been commonly adopted in situated analytics, yet both layouts have certain limitations. In comparison, mixed layout is lack of exploration.

3.2 Design Considerations

Based on literature reviews and our own experience, we elicit design considerations from aspects of *situatedness* and *analytics*.

3.2.1 Situatedness

Situated visualization provides in-situ projection of information on to the physical space [19]. Bressa et al. [5] expanded the concept of situatedness and characterized five perspectives: space, time, place, activity, and community. This work focuses on layout design of MV representations, which mainly involves the considerations of *space* perspective that concerns spatial arrangement and spatial relationship between physical world and visual representation. More specifically, this work lies spatial situatedness on *spatial proximity* between a visual representation and its physical referent [54], rather than people's activity, context of use, or semantic relationship.

We categorize the level of situatedness as *high* and *low*, based on spatial proximity between a view and its physical referent:

- **High situatedness**: In this case, a view is placed close to its physical referent, such as to put the view aside the referent or overlay on the referent, as in embedded layout (Figure 3(left)). Here, proximity between a view and its physical referent is minimized, whilst proximity among the view and the user can be distant. Since physical referents are fixed, high situatedness may also cause problems such as occlusion and perspective distortion.
- **Low situatedness**: In this case, a view is not aligned with its physical referent. In an extreme case, the views are separated from the physical referents, but organized in parallel or small multiples, as in linked layout (Figure 3(right)). Here, proximity between a view and its physical referent is not guaranteed, requiring the user to mentally relate a view to its physical referent.

3.2.2 Analytics

The quality of processing the data and information is regarded as analytic level. The visualization community has identified several high-level analytics for MV representations. For examples, juxtapositioned views are commonly used for *comparison* [25, 37]. Sun et al. [47] recently identified three types of users operations for cross-view data analysis, *i.e.*, *filtering*-, *refocusing*-, and *connecting*-centered operations. View layout of MV representations also makes a substantial influence on analytics level in immersive visualization. We summarize design considerations for cross-view data analysis [47]:

- **Filtering**. To select and mark data elements of interest is typically a preceding action to subsequent actions. Since the views can be positioned at any location in the 3D space, selection can be challenging for far-away views. Ray-tracing pointer can be ineffective due to small visual marks in the distance. Alternatively, users can select data elements on a near view, and the corresponding data elements in far-away views will also be filtered.
- **Refocusing**. Multiple views enable multi-perspective exploration of a dataset to support complex analytical requirements. Nevertheless, the visualization shall also enable easy focus on some view, allowing users to conduct in-depth examination for the data of a specific physical referent. Two basic requirements here are to enable views of interest presented 1) in full detail and 2) without occlusion.
- **Connecting**. To explore and identify connections between data in multiple views is a fundamental requirement. Connecting can be facilitated by consistent visual encodings [39] or explicit visual linkage [16]. In this work, we focus on designing proper view layout that requires minimum body and head movements to support effective identification of connections between data in multiple views.

Table 1. Linked and embedded layouts have different values in design space dimensions of the ethereal planes framework [22].

Layout	Dimension		Value	Situated	Analytics
Linked	*Perspective*		egocentric	**Low**	**High**
	Movability		movable		
	Proximity	view-user	near		
		view-view	near		
		view-referent	far		
	Visibility		high		
Embed	*Perspective*		exocentric	**High**	**Low**
	Movability		fixed		
	Proximity	view-user	dependent		
		view-view	dependent		
		view-referent	near		
	Visibility		intermediate		

3.3 Design Trade-offs

Situatedness and analytics are two perspectives of consideration when designing MV representations in immersive visualization. Figure 3 illustrates two layouts commonly adopted in existing situated analytics: embedded layout produces high level of spatial situatedness, but low analytics level; in contrast, linked layout is preferable for analytics, but requires substantial efforts for the user to mentally relate views to their physical referents. In the following, we leverage the ethereal planes framework [22] that specifies the ways of arranging 2D information spaces in 3D environments, to discuss the trade-offs between situatedness and analytics.

- *Perspective*: Perspective denotes the conceptual viewpoint of the observer, which can be generally categorized as *egocentric* and *exocentric* reference frames [2]. Egocentric reference frame is set relative to the user reference point, whilst exocentric referent frames are set relative to any object (*e.g.*, the physical referents) reference points. As indicated in Table 1, linked layout is egocentric reference frame, as the layout separates the views from the physical referents. In contrast, embedded layout is exocentric reference frame, as the views are placed close to physical referents.

  This work considers AR scenarios where a single user can freely navigate. Hence, *egocentric* reference frame that moves along with the user on-the-go is more useful [22].

- *Movability*: Movability denotes whether the views are *movable* or *fixed* with respect to the real-world reference frame. Linked layout allows movable placement of the views in the 3D space. Users can arrange the views in parallel or small multiples close to the user, which is preferable for tasks like filtering and connecting. In contrast, embedded layout arranges the views next to their physical referents that are fixed in the real-world reference frame.

  In this work, views shall be *movable* such that far-away views can be moved close to the user to facilitate analytics. Nevertheless, the movability shall be constrained to a certain degree, so the spatial situatedness can also be recalled.

- *Proximity*: Proximity is a spatial property that indicates how close two entities are. Here we consider spatial proximities between view-user, view-view, and view-referent. In linked layout, views are moved to near by each other and to the user, hence view-view and view-user proximities are small. Views close to users are more viewable and manipulable during the analytic process, yet the views are moved away from the referents that increase view-referent proximity. In embedded layout, views are placed adjacent to their referents, hence view-referent proximity is small and spatial situatedness level is high. On the other hand, view-view and view-user proximities are dependent on the proximities among the referents and the user, which can be difficult for analytics.

  In summary, a preferred layout shall provide proper *view-view* proximity to facilitate analytics, proper *view-user* proximity to promote spatial manipulation [22], and proper *view-referent* proximity to improve spatial situatedness [19].

- *Visibility*: Visibility denotes the number of views that clearly shown in the field of view. High visibility is fundamental for analytics, as 'what you see is what you get'. Linked layout organizes views together and close to the view, removing occlusion issue and making high visibility of the views. In contrast, embedded layout may suffer from occlusion issues and the visibility level is low or intermediate, dependent on the user-referent proximities.

  Immersive analytics projects in-situ information onto the physical space [19, 20]. As such, *high* visibility of the information space, *i.e.*, *views*, are necessary for effective analytics.

From the above analysis, the layout shall meet the following requirements: *egocentric* reference frame, *movable* views, proper *view-view*, *view-user*, and *view-referent* proximities, and *high* visibility.

4 Layout Adaptation

In this section, we first present a formal problem definition (Sect. 4.1), followed by a description of cylindrical reference frame that is naturally *egocentric* (Sect. 4.2). Next, we develop a prototype system using a force-directed method to produce the optimal layout (Sect. 4.3), which is complemented with a series of user interactions to facilitate data exploration and layout configuration (Sect. 4.4).

4.1 Problem Formulation

Many efforts have been devoted to optimizing view layout in 3D visualization for the desktop, to mitigate issues like occlusion and perspective distortion [18, 49]. This work further considers the effects of view layout on situatedness (Sect. 3.2.1) and analytics (Sect. 3.2.2). Specifically, this work studies the layout of multiple *views*, denoted as $V := \{v_i\}_{i=1}^{N}$, where $N \geq 2$ is the total number of views. Each view V_i is represented as a tuple $v_i := (data_{v_i}, struct_{v_i}, pos_{v_i}, ori_{v_i}, size_{v_i})$, where $data_{v_i}$ denotes the underlying data associated with a physical referent r_i, $struct_{v_i}$ denotes the visual structure, pos_{v_i} denotes the center position of the view in the 3D space, and ori_{v_i} and $size_{v_i}$ denote the orientation and size of the view respectively. For every physical referent r_i, its position pos_{r_i} is fixed and the associated $data_{v_i}$ is static. The visual structure $struct_{v_i}$ is designed to accord with $data_{v_i}$, with a specific visualization type (*e.g.*, bar chart, line chart, etc.) that is not alterable during the exploration process. Users can manipulate visual elements through interactions like selecting and highlighting a bar. The size $size_{v_i}$ is set up when the immersive visualization is initialized, and orientation ori_{vi} is automatically adjusted in the way that the view plane is perpendicular to user's line of sight when looking at the view. There is one *user* (denoted as u) whose position (pos_u) is known.

As such, this work focuses on the optimization of $\{pos_{v_i}\}_{i=1}^{N}$ for a set of multiple views $\{v_i\}_{i=1}^{N}$ in a 3D space, to balance situatedness and analytics in situated analytics. View positions have direct effects on view-view, view-user, and view-referent proximities and visibility, and consequently on situatedness and analytics levels.

4.2 Cylindrical Reference Frame

As illustrated in Figure 4(a), we adopt a cylindrical paradigm that has been widely adopted in immersive visualization, to represent positions in the 3D space. Specifically, we put the user at the center, and model all other positions in the 3D space as positions on cylindrical surfaces around the center. In this way, position of an object is represented as $pos := (\psi, \theta, z)$, where ψ denotes the radius of the cylindrical surface to the user, θ denotes the angle of the line connecting the object and the user to the North, and z denotes the vertical position. For simplicity, we keep a 2D plane that is tangent to the cylindrical surface, to render visual structures, rather than bend visual structures to fit the cylindrical layout. This is because a view is relatively small, and it would be rather complicated to adapt internal structures when views are repositioned at different distances to the users.

The distance between positions of two objects on the cylindrical surfaces is then computed as the polar coordinates distance, denoted as $dist(pos_i, pos_j)$. For embedded layout that arranges a view on top of the physical referent, the distance between the view and the referent is only the vertical displacement, which is very small. On the other hand,

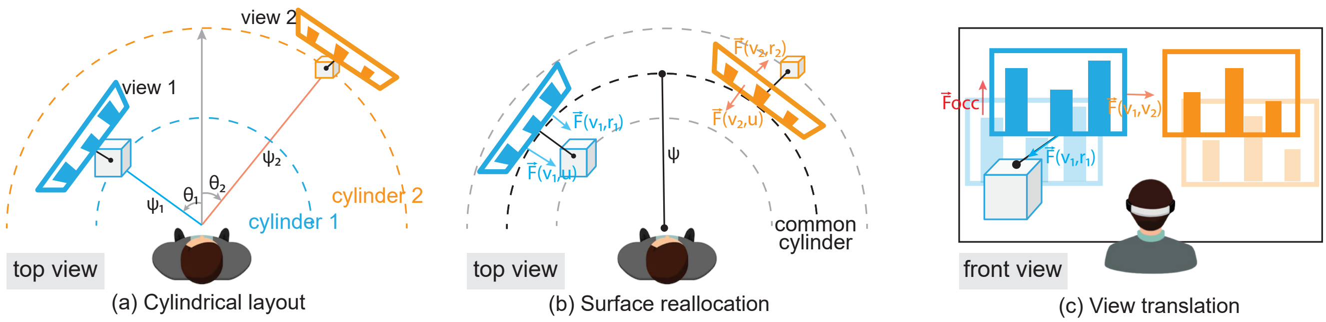


Fig. 4. Illustration of the automatic layout adaptation method: (a) cylindrical layout is adopted as the reference frame to represent positions; (b) surface reallocation is made to balance view-referent and view-user proximities; and (c) view translation is made to remove occlusion and balance view-view and view-referent proximities.

views will be allocated at a distance if their referents are not nearby, such as view 1 and view 2 in Figure 4(a), which will require substantial head movement to connect them. We regard views, referents, and the user as mass points, and proximities among them as springs. For each view V_i, there are multiple attraction forces applied on it:

- *View-referent force* $\vec{F}(v_i,r_i)$ is computed as $|\vec{F}(v_i,r_i)| = K \times dist(pos_{v_i}, pos_{r_i})$ and pointing to the referent pos_{r_i};
- *View-view force* $\vec{F}(v_i,v_j)$: For each $v_{j,j\neq i} \in V$, $F(v_i,v_j)$ is computed as $|\vec{F}(v_i,v_j)| = K \times dist(pos_{v_i}, pos_{v_j})$ and pointing to view pos_{v_j};
- *View-user force* $\vec{F}(v_i,u)$ is computed as $|\vec{F}(v_i,u)| = K \times dist(pos_{v_i}, pos_u)$ and pointing to the user pos_u.

We treat proportional ratios of all forces as the same constant K. With effects of spring forces, the views will reach mechanical equilibrium states that balance the proximities.

4.3 Force Directed Method

On the basis of proximity modeling, we design a twofold process to automatically adapt view layout using a force-directed method. First, we reallocate all views to a common cylindrical surface (Sect. 4.3.1). Second, we adjust view positions leveraging the common cylindrical surface to remove occlusion (Sect. 4.3.2).

4.3.1 Surface reallocation

In the first step, we choose to place all views on a common cylindrical surface, such that 1) views can be arranged in side-by-side or small-multiples as in 2D displays, to promote analytics levels in *refocusing* and *connecting*; and 2) the problem is simplified to identify a cylindrical surface with suitable distance ψ_{all} to the user. All views have the same radius ψ_{all}. We leave the placement of views on the common cylindrical surface in the next step. Since view-view forces for a pair of views are neutralized, we only need to balance view-referent forces $\sum_{i=1}^{N} \vec{F}(v_i,r_i)$ and view-user forces $\sum_{i=1}^{N} \vec{F}(v_i,u)$ when determining the common cylindrical position, as

$$\omega_{vr} \sum_{i=1}^{N} \vec{F}(v_i,r_i) + \omega_{vu} \sum_{i=1}^{N} \vec{F}(v_i,u) = 0. \quad (1)$$

where ω_{vr} and ω_{vu} denote the weights for view-referent forces and view-user forces, respectively. A larger weight ω_{vu} for view-user force will attract the cylindrical surface more towards the user, and vice versa. Here, the resting lengths of $\vec{F}(v_i,r_i)$ and $\vec{F}(v_i,u)$ are all set as zero.

Since view position on the surface is unknown, the measurement of view-referent proximity $dist(pos_{v_i}, pos_{r_i})$ is simplified to $|\psi_{all} - \psi_{r_i}|$, and that of view-user proximity $dist(pos_{v_i}, pos_u)$ is simplified to ψ_{all}. The direction of $\vec{F}(v_i,u)$ is centripetal that is represented as positive. The direction of $\vec{F}(v_i,r_i)$ is dependent on ψ_{all}: if $\psi_{all} < \psi_{r_i}$, the force is centrifugal that is represented as negative, otherwise positive. Hence, Equation 1 is to compute

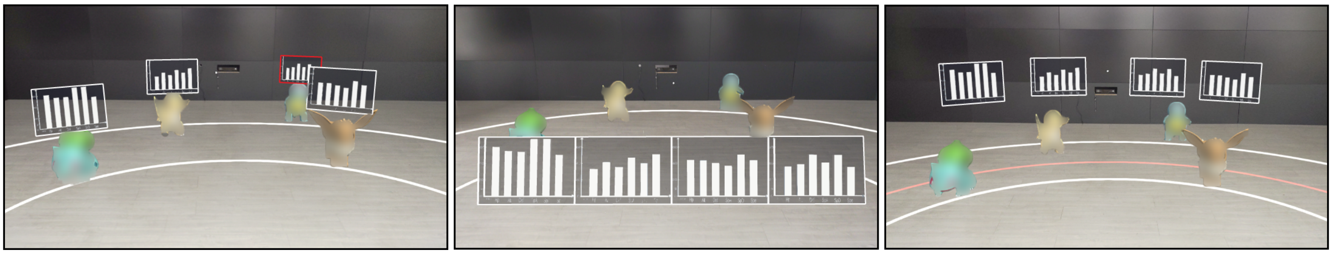
$$\omega_{vr} \sum_{i=1}^{N} K(\psi_{all} - \psi_{r_i}) + \omega_{vu} \sum_{i=1}^{N} K\psi_{all} = 0,$$
$$\sum_{i=1}^{N} ((\omega_{vr} + \omega_{vu})\psi_{all} - \omega_{vr}\psi_{r_i}) = 0. \quad (2)$$

In a special case when $\omega_{vr} = \omega_{vu}$, $\psi_{all} = \sum_{i=1}^{N}(\psi_{r_i}/2N) = \overline{\psi_{r_i}}/2$, *i.e.*, the common cylindrical surface will be placed at half of the mean distance of all referent surfaces. This work adopts an adaptable ratio for $\omega_{vr} : \omega_{vu}$, which can be adjusted by the user via view arrangement interaction described below. However, if there are a large number of views, a low ratio for $\omega_{vr} : \omega_{vu}$ leads to views being placed near to the user, which makes sight crowded. Therefore, the recommended ratio is relative to the number of views. In our experiment (Sect. 5), we set the ratio in complex scene much higher than simple scene.

4.3.2 View translation

Next, we leverage a temporary common cylindrical surface with a constant radius to translate view positions to remove occlusion and balance view-view and view-referent proximities. Here, angle θ and vertical position z of view positions are free to change, whilst radius is fixed. To remove occlusion for views, we introduce occlusion force, denoted as $\vec{F}_{occ}$, that pushes a view away from occluded referents or other views on its positioned cylindrical surface. Specifically, $\vec{F}_{occ}$ is derived from the view-referent force $\vec{F}(v_i,r_i)$ with the resting length set to the sum of view height and referent height, and the view-view force $\vec{F}(v_i,v_j)$ with the resting length set to twice the view length. All occlusion forces are calculated on the common cylindrical surface, but applied on views at their located positions. The direction of $\vec{F}_{occ}$ is either up/down if the occlusion happens in vertical dimension, or left/right if the occlusion happens in horizontal dimension. The value of $\vec{F}_{occ}$ is inversely proportional to the proximity between the occluded objects. Note that the force is applied only to views but not referents, *i.e.*, referents can be occluded. As illustrated in Figure 4(c), the blue view is partially occluded by its referent when the view is translated to the target cylindrical surface. The occlusion force is in up direction, pushing the view upwards. The force becomes weak as the view moves away from its referent and eventually balances with the down-directed view-referent force that attracts the view in down direction. In this way, we identify the vertical position for each view.

Moreover, view-view and view-referent proximities are balanced using view-view and view-referent forces. Here we first align all views side-by-side with the same vertical position, which is set to the maximum vertical position of all views. Next, we consider view-view and view-referent forces in horizontal directions only, which are proportional to the horizontal view-view and view-referent proximities respectively. Ideally all views will reach the equilibrium states after the above steps. However, views can be occluding each other if there are too many of them. In this case, we arrange views in multiple layers vertically, similar to the shelves metaphor, for layout of the views [36].



(a) Embedded layout **(b) Linked layout** **(c) Mixed layout**

Fig. 5. Illustration of layout configurations used in the experiment: (a) Embedded layout places views directly on top of their referents; (b) Linked layout arranges all views side-by-side on a 2D plane that is close to the user; and (c) Mixed layout by our layout adaptation method arranges all views on a common cylindrical surface projecting the pink circle on the ground.

(a) Highlighting (b) Filtering

Fig. 6. Two user interactions provided in the prototype system: (a) highlighting, and (b) filtering.

4.4 User Interaction

Our prototype system is tested on a HoloLens2 AR glass. Users can freely navigate the AR environment. We also incorporate three types of user interactions in the prototype system: *highlighting* (Figure 6(a)), *filtering* (Figure 6(b)), and *view arrangement*. *Highlighting* and *filtering* are designed for data exploration by changing visual elements of a view, whereas *view arrangement* is designed for fine-tuning view layout. All interactions are realized using mid-air gestures provided by HoloLens2.

Users can select a data item in a view, *e.g.*, by clicking on a bar in a bar chart, and the selected item will be highlighted with a different color. Alternatively, users can also filter data items by specifying a data attribute in a certain range. Both operations are coordinated, *i.e.*, data items of the same attribute or within the same range in the other views will also be highlighted/filtered. With *highlighting* operation, users can get cross-view insights more easily, *e.g.*, to identify the extreme value of an attribute. The *filtering* operation helps users search data attributes quickly, *e.g.*, to find the Pokémon with speed attribute over 80.

View arrangement interaction is designed for fine-tuning view layout generated by the automatic approach. Users are allowed to reposition a specific view or multiple views. To rearrange view position, users need to first select one or multiple views, by finger clicking on nearby views or ray casting on far views. The selected view positions will be updated according to the figure/pointer movement. Here, the views are only allowed to move on their positioned cylindrical surfaces, *i.e.*, only angle θ and vertical position z are changing. Alternatively, users can pull the surface closer or push it farther with two-hand gestural interaction. Moreover, the selected views are seen as views of interests, and we adjust the recommended ratio for $\omega_{vr} : \omega_{vu}$ of views according to user interests. In general, the view of interests will be attracted closer to the user. To ease the burden of interactions on users, we provide an automatic view alignment function for view arrangement. All selected views will be restricted on a common cylindrical surface and placed side-by-side. However, we are not sure if the automatic alignment have significant effects on the efficiency of layout. We employ it as an optional function in our prototype system.

5 User Study

We conducted a user study to evaluate the effectiveness of our proposed layout adaptation framework. In particular, we compare the layout by our approach with alternative layouts in terms of analytics and situatedness levels on different analytic tasks involving MV representations.

5.1 Experiment Design

The experiment was set in the background of the popular AR game *Pokémon GO*. We employed virtual entities to simulate AR environment, which is a common way to create a controlled environment for user studies in AR research [29, 34, 40]. From the Pokémon dataset, we selected six Pokémons, and each Pokémon had six quantitative stats in attack, defense, speed, etc. In each experiment trial, we randomly picked several Pokémons and rendered their 3D models on the ground in the AR environment. A stadium was placed at the center of the Pokémon positions as the arena for Pokémon fighting. Participants were asked to compare and identify highest stats among the Pokémons in the training ground. The Pokémon and stadium models were treated as physical *referents* that provided context information, and the Pokémon stats were represented as *views*. Specifically, the view related to the stadium presented the overall stats for all the Pokémons on the ground. Each participant played the role of *user* who was asked to complete tasks comprising of analytics and situatedness components.

For each study, we designed a within-subjects experiment: 3 *layout configurations* × 3 *scene conditions* × 3 *tasks*. As illustrated in Figure 5, we considered 3 layout configurations that produce varied levels of situatedness and analytics:

C1. Embedded layout. All views are placed directly on top of their referents (Figure 5(a)). View positions only depend on those of the physical referents. The layout generates close proximity between each pair of view and referent, yet places views far away from each other and may cause occlusion (red view).

C2. Linked layout. All views are arranged side-by-side on a 2D plane that is close to the user (Figure 5(b)). The order of views follows a predefined rule, including left-to-right or front-to-back order according to the referent position. The rule was random and would be told to the participants before each trial. The layout generates close promixities among views, yet places views far away from their referents.

C3. Mixed layout. All views are arranged on a common cylindrical surface and placed in positions by our layout adaption method (Figure 5(c)). The cylindrical surface balances the distances of all referents to the user, as highlighted by the red circle on the ground. As such, the layout balances view-user, view-referent, and view-view proximities.

We tested the robustness of our proposed method in supporting different levels of scene complexity determined by the number of referents. Since the field of view for AR HMDs is rather limited, we constrain the scene to include maximum six referents. Specifically, view occlusion happens in complex scene, hindering participants from finding answers. We further check if the automatic view alignment can facilitate the completion of tasks in complex scene. As such, we experimented with three scene conditions:

S1. Simple scene. There are three pairs of physical referents and views in the scene. The referents are spread in the scene and no view occlusion happens.

S2. Complex scene. There are six pairs of physical referents and views in the scene. View occlusion happens, and the participant can interact with the scene:

S2.1. without view alignment. Participant can only navigate in the scene to find answers, but not rearrange views.

S2.2. with view alignment. Participants can manually adjust view positions and also navigate in the scene.

Our goal is to achieve a layout that balances situatedness and analytics. As such, we set three sets of user tasks: *filtering + situatedness*, *refocusing + situatedness*, and *connecting + situatedness*. Each task comprises an analytics sub-task that requires the participant to examine multiple views, and a situatedness sub-task that requires the participant to relate views to referents.

T1. Filtering + Situatedness. The tasks are set as:

Analytics: Which view has attribute *A* in the range of *x* to *y*?

Situatedness: Which Pokémon does the view relate to?

Participants need to use filtering interaction to identify answer for the analytics sub-task. After that, participants need to relate the view to a Pokémon on the ground for the situatedness sub-task.

T2. Refocusing + Situatedness. The tasks are set as:

Analytics: Which view has the highest value for attribute *A*?

Situatedness: Which Pokémon does the view relate to?

Highlighting interaction can be utilized to identify answer for the analytics sub-task. Participants only need to highlight attribute *A* in one view, the attributes in other views will also be highlighted. Similar to **T1**, participants are then asked to relate the view to a Pokémon on the ground for the situatedness sub-task.

T3. Connecting + Situatedness. We found it difficult to separate subtasks for connecting-oriented analytics and situatedness. Therefore, we set an overall task here:

Overall: What is the stat for the highest attribute of the Pokémon with the highest overall stats?

To get the answer, participants need to first check the view related to the stadium and identify Pokémon with the highest overall stats in the scene. Next, they need to find the view related to the most powerful Pokémon, and identify the stat for the highest attribute.

5.2 Participants

We recruited 12 participants (8 males and 4 females; age: 22-25, average: 23.7) for our study. Due to the restriction of COVID-19 pandemic, all participants are students in a university. According to the pre-study survey, three participants are familiar with AR techniques, and one of them is experienced in HoloLens 2. None of them has sight or movement disability. For each task, we adjusted the stat of Pokémon and reminded the participants to finish the tasks based on the views rather than prior knowledge. The study was eligible for exempt research as it involves minimal to no risks to the participants, as reviewed by the institutional review board of the university.

5.3 Apparatus

The study was conducted in an indoor space of approximately 5m × 3m size, where the participants could perform body movements and interactions freely. A video wall was around the experimental space, showing the guidance and questions. All AR content was displayed in front of the video wall. During the study, the participants were equipped with Microsoft HoloLens 2−an AR head-mounted display (HMD) with see-through holographic lenses, which was connected to a high-performance workstation through WiFi during the experiment. The view of the HMD was streamed to the workstation in real-time and recorded for analysis. Besides, each participant wore a microphone to answer questions and the voice was recorded during the experiment. In each experiment trial, an experiment regulator was assigned who stood outside of the workspace of the participant and kept watching the AR view of the participant on the screen of the workstation. The regulator would provide in-time guidance to the participant through voice communication. The regulator would stop the experiment if he felt the experiment should not be continued under conditions like the participant feeling dizzy.

5.4 Procedure

For each participant, we first introduced the purpose of the experiment and asked the participant to fill in a pre-study survey regarding their background and experience with AR and sign a consent form. Then, the participant was given an instruction to learn the experiment design and how to use HoloLens to accomplish all tasks. Before the formal experiment, the participant was trained to finish training tasks that have the same settings in terms of layout configurations, scene complexity, and set of tasks. Different Pokémons and varying positions, attributes and questions, are used in the training than those in the formal experiment. We let the participant freely explore in the training scene, and moved to the next stage only when the participant felt confident that she/he was familiar with the system and able to accomplish all tasks.

In the formal experiment, we counterbalanced the order of layout configurations across different participants. All combinations of experiment conditions (3 layout configurations × 3 conditions of scene complexity × 3 tasks) were repeated 2 times so that each participant had to complete 54 experiment trials. The experiment was first conducted in the simple scene (S1), followed by the complex scene without view alignment (S2.1), and finally in the complex scene with view alignment (S2.2). To avoid the effect of user proficiency on completing tasks, we evaluated 3 layout configurations in turn for each task in each scene condition. Before each trial, we gave participants enough time to rest and introduced the next trial to guarantee the analytic efficiency. During the study, participants were encouraged to use *think aloud* technique when answering questions. After completing the trials before S2.2, participants were asked to give feedbacks about the layouts. Then, after finishing S2.2, we collected feedback about the view alignment function and overall feedback regarding the prototype system. Illustration of the study procedure can be found in Supplementary Figure 1.

The whole procedure lasted approximately 1.5 hours, and the participants were compensated with ≈$25 for the time. The first person view videos of all experiment trials were recorded. We evaluated the performance of layouts via the efficiency and accuracy of different conditions of the study from the videos. Efficiency is measured as *completion time* of a task counted from participants entering the scene to making answers to the questions. Completion times of two sequential questions were separated by the time when the first question was answered. *Accuracy* is measured as the percentage of correct answers made to the questions. Qualitative user feedbacks including confidence of answering questions, and usefulness and usability of the prototype system, were collected as well.

5.5 Hypotheses

The design trade-offs analysis (Sect. 3.3) reveals that embedded and linked layouts fail to facilitate situatedness and analytics simultaneously. Our proposed method is supposed to generate mixed layout that meets the design requirements. As such, we hypothesize that

H1. For all scene conditions and tasks, mixed layout (*C3*) by our method would be more efficient and achieve higher accuracy than embedded layout (*C1*) and linked layout (*C2*).

As shown in Table 1, embedded layout produces high spatial situatedness but low analytics level, whilst linked layout is preferable for analytics but not for situatedness. We also hypothesize that

H2. Specifically, mixed layout (*C3*) would outperform embedded layout (*C1*) in analytics-centered sub-tasks, and outperform linked layout (*C2*) in situatedness-centered sub-tasks.

Furthermore, as studies (*e.g.*, [45, 57]) suggest that egocentric interactions facilitate task completion in 3D space, we hypothesize that

H3. For all layout configurations, integrating automatic view alignment would improve efficiency and accuracy than the corresponding layout without view alignment.

5.6 Results

We found that all participants finished the questions with high and approximately the same accuracy across all conditions. Hence, we only compared the efficiency of different layout configurations. Figure 7

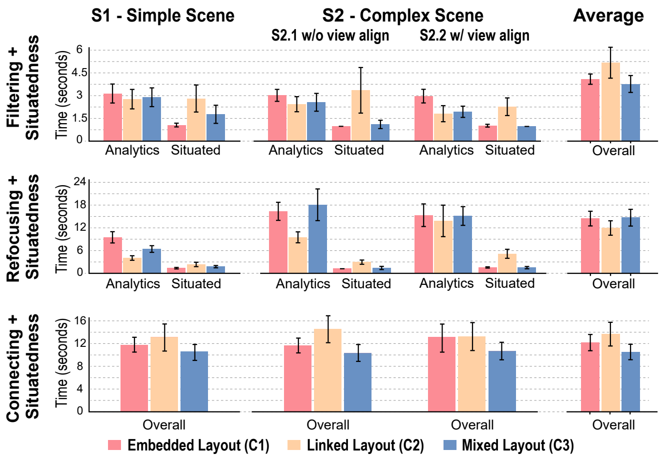


Fig. 7. Average task completion time (seconds) for each condition. Error bars represent 95% confidence intervals.

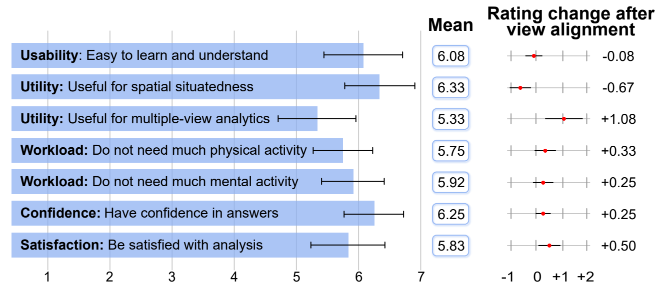


Fig. 8. User feedbacks on *usability*, *utility*, *workload*, *confidence*, and *satisfaction* of mixed layout by our method. Rating changes after providing view alignment is presented on the right.

shows the task completion time for each condition. We used a Friedman test to detect the significant effect of layout configuration on task completion time (at the significance level of $\alpha = .05$). Furthermore, we ran a post-hoc Wilcoxon signed-rank test to perform pairwise comparison of layout conditions. Significant values are reported for $p < .05(*)$, $p < .01(**)$, $p < .001(***)$. Refer to the supplementary material for details on the experimental data and analysis.

Hypothesis 1. H1 is checked using the average overall completion times for both analytics- and situatedness-centered sub-tasks in *Filtering + Situatedness (T1)* and *Refocusing + Situatedness (T2)*, and the average completion times in *Connecting + Situatedness (T3)*. Significant effects of layout configurations on completion time are observed for *T1* $(*)$ and *T2*$(**)$ and *T3* $(***)$, respectively. Specifically, i) for *T1*, *C3* is the best and significantly faster than *C2* $(**)$; ii) for *T2*, *C2* is the best and significantly faster than *C1* $(**)$ and *C3* $(**)$; iii) for *T3*, *C3* is the best and significantly faster than *C1* $(**)$ and *C2* $(**)$. Overall, *C3* achieves the best performance on *T1* and *T3*, partially confirming **H1**.

Hypothesis 2. H2 is checked using the completion time for each analytics- and situatedness-centered sub-tasks. For analytics-centered sub-tasks in *T1*, we find no significant effects of layout conditions on time in the simple scene (*S1*) ($\chi^2(2) = .409$, $p = .815$). When the scene complexity becomes high (*S2*), the significant difference is observed $(*)$, but no significant difference is observed from pairwise comparison. For analytics-centered sub-tasks in *T2*, layout makes significant effects in both *S1*$(***)$ and *S2*$(***)$. Especially, *C3* is significantly faster than *C1* in *S1*$(*)$, but is slightly worse than *C1* in *S2* on average. This is because a participant (P6) accidentally spent much time on *T2*, which increases the average task completion time for *C3*. Nevertheless, Wilcoxon signed-rank test demonstrated that the layouts have no significant difference ($Z = -1.453$, $p = .146$). For situatedness-centered sub-tasks, layout makes significant effects on time with all combinations of tasks and scene complexity. Concretely, *C3* has overall advantages on time consuming over *C2*. In particular, *C3* is significantly faster in *S2* $(**)$. In summary, *C3* only outperforms *C1* in analytics-centered tasks of *T2* with simple scene, whilst *C3* outperforms *C2* in all situatedness-centered sub-tasks, partially confirming **H2**.

Hypothesis 3. H3 is checked by Wilcoxon signed-rank test for the task completion time in *S2* with alignment *vs.* without alignment. In the context of analytics-centered sub-tasks, the results show that the view alignment has significant improvement in *C3* $(*)$ for both *T1* and *T2*. Whereas, it increases the time of *C2* for *T2*. In terms of situatedness-centered sub-tasks, the alignment increases the time for T2 with *C1* $(*)$ and *C2* $(**)$, whilst *C3* has not been significantly influenced ($Z = -.513$, $p = .608$). On the other tasks, the view alignment makes no significant effects. In a word, the automatic view alignment facilitate the performance of *C3* on *T1* and *T2*, partially confirming **H3**.

5.7 User Feedback

We collected user feedbacks regarding the prototype system with layout by our method from the participants, using 7-point Likert-scale questions in the post-study questionnaires. The feedback covers five perspectives: *usability*, *utility*, *workload*, *confidence*, and *satisfaction*. Figure 8 presents the detailed ratings. Overall, the prototype system received all ratings higher than 5 on average, which showed users' satisfaction on our layout method.

- *Usability*: The participants responded positively about the usability of mixed layout by our method ($\mu = 6.08, 95\%\ CI = [5.45, 6.71]$). The usability is high because mixed layout *'manages to mitigate view occlusion'* (P7) compared with embedded layout, and relates views to their referents more intuitively than linked layout that *'confuses me on the mapping rules between views and referents'* (P11).
- *Utility*: The participants appreciated the usefulness of mixed layout on both spatial situatedness ($\mu = 6.33, 95\%\ CI = [5.77, 6.90]$) and level of analytics with MV representations ($\mu = 5.33, 95\%\ CI = [4.71, 5.96]$). Some participants recommended mixed layout as *'balanced layout'* (P3), which benefits both *'context-awareness and multiple-view analysis'* (P10). Interestingly, the participants gave a relatively low rating on level of analytics. Here, a main reason is that mixed layout arranges views out of FOV in the complex scene, which is not ideal for analytics.
- *Workload*: The participants did not feel much physical load ($\mu = 5.75, 95\%\ CI = [5.27, 6.23]$) as well as mental or perceptual load ($\mu = 5.92, 95\%\ CI = [5.41, 6.42]$) during the tasks in the mixed layout condition. This is remarkably encouraging because most participants (9/12) had no experience in AR HMD. Compared with embedded layout, mixed layout placed views closer to the user, which led to *'a clearer sight on views'* (P2) and *'less physical movement'* (P8). Compared with linked layout that *'requires turning head frequently to map views to referents'* (P3), mixed layout received no complaint on the problem. Nevertheless, some participants were unfamiliar or not satisfactory with the mid-air gesture interaction provided by HoloLens. P4 suggested that *'if the interaction could be more friendly, I would feel easier.'*
- *Confidence*: All participants had sufficient confidence in answering the questions with mixed layout ($\mu = 6.25, 95\%\ CI = [5.77, 6.73]$). In contrast, several participants pointed out that they were not sure about their answers when using the embedded layout because of *'comparison inconvenience'* (P2) and *'visual bias'* caused by distance and depth difference between views (P7).
- *Satisfaction*: The participants expressed the satisfaction in situated analytics with mixed layout ($\mu = 5.83, 95\%\ CI = [5.23, 6.43]$). We asked participants about the overall feelings during the analysis process. Some participants praised that the process was *'easy and fun'* (P9), while P6 stated that she had *'sufficient engagement'* in the experiment. A particular reason here is the adoption of cylindrical reference frame that arranges the user in the center of all views.

The participants were asked the same questions after *S2.2* experiment with automatic view alignment. We measured the mean rating differences before and after the experiment. The results are presented in Figure 8(right). The participants gave overall positive feedback on the view alignment function (5/7 questions received higher ratings). Specifically, the improvement on analytics level is the highest ($\mu = 1.08, 95\%\ CI = [0.34, 1.82]$). On the contrary, the awareness of spatial situatedness was relatively weakened ($\mu = -0.67, 95\%\ CI = [-1.08, -0.25]$). This confirms again that situatedness and analytics are contradictory considerations when situated analytics involves MV representations, and mixed layout by our approach strikes a good balance between situatedness and analytics.

6 Discussion, Limitation, and Future Work

The study reveals some interesting findings. First, situated analytics is often regarded as a holistic feature and benefit for immersive visualization. However, our study shows that design recommendations for improving situatedness and those for facilitating analytics with MV representations, can be hard to accomplish simultaneously. The finding opens up research opportunities for better understanding the relationship between situatedness and analytics in immersive visualization. Second, we follow design space dimensions as in the Ethereal planes framework [22] to distill the design requirements, and design the layout adaptation method accordingly. The user study confirms usability and effectiveness of the proposed approach in balancing situatedness and analytics. The result advances our understanding of the design space of immersive visualization. Future studies in this direction may leverage knowledge in interface design and human computer interaction.

Design Implications. The results (Sect. 5.6) and user feedback (Sect. 5.7) confirm that different layout designs have unique advantages on situatedness- and analytics-centered tasks, respectively. Specifically, *movability* and *view-referent proximity* dimensions have significant effects on the efficiency of situatedness-centered tasks, for which both embedded and mixed layouts outperform linked layout. User feedback suggests that view and referent in close proximity promotes the space situatedness, as users can easily connect views to referents. The participants favored fixed views when recalling connections between views and referents, which is consistent with empirical studies [22, 32]. Nevertheless, the participants also acknowledged that fixed views decrease their confidence for analytics-centered tasks, especially when the views are placed at different depths.

In terms of analytics-centered task, *view-view* and *view-user proximities*, together with *perspective* and *visibility* have more explicit effects than other design dimensions. Close view-view proximity significantly promotes analytics−the participants felt more confident on their answers and less workload is needed. View arrangement that allows users to reduce view-user proximity and examine the views at close facilitates analysis. Egocentric reference frame that arranges views on a common cylindrical surface around users can help reduce head & body movement, which are also beneficial for analytic-centered tasks. Last but not least, exploratory data analysis requires clear sight on visualizations. In case of occlusion, participants had to move around to get a clear sight, causing the burden of body movement and a waste of time.

Limitations. There are certain limitations in our current work.

- This work only considers spatial situatedness. Hence we purposely chose an open space for the experiment. As pointed out in [5], situatedness can also be enhanced from other perspectives including time, place, activity, and community. The design space becomes more complex and more researches can be conducted when other perspectives are considered. For example, we can include semantic context as in [13, 35] to improve place situatedness, and user behaviors as in [23, 31] to improve activity situatedness.
- Due to the limited FOV in HoloLens 2, we only evaluated the effectiveness of the proposed method in positioning six views at maximum, yet view occlusion happened and user preference was reduced. We have provided user interactions including view arrangement to mitigate the issue. More interactions can be incorporated to further improve view readability. For example, we plan to allow users select views of interest, and group them as small multiples. Compositing multiple views into one single view [55] that reduces the number of views displayed is promising.
- This work treats each view as a static component with fixed size and visual structure. A more thoughtful solution is to consider responsive design of visual structure and content displayed in a view, which can potentially address the scalability issue caused by limited FOV. The visualization community has proposed methods for adapting MV representations on the desktop to mobile phones [1]. Responsive visualization design for immersive visualization is lack of exploration and worth exploring.

Future Work. There are several promising directions for future works. First, we plan to integrate more advanced interactions in the prototype system. In the experiment, participants complained that the mid-air gestural interactions provided by HoloLens is difficult to use. We plan to improve interactions from the perspectives of modality and accuracy. In terms of modality, the HCI and visualization communities have exploited many other techniques, such as multimodal interactions [27], to facilitate data exploration in immersive visualization. In the context of MV representations, well-designed interactions would require low head and body movements for filtering, refocusing, and connecting views. In terms of accuracy, it is possible to improve interaction accuracy based on user intentions predicted by interaction provenance. For example, we would like to exploit deep learning techniques as in [12] to accurately map from gestural movements to user-intended interactions. Better understanding of user intentions can also improve activity situatedness in situated analytics.

Second, we would like to improve the generalizability of our layout adaptation method. We have discussed potential methods such as responsive design, to fit more complex scene with more views. Besides, the proposed method has the potential to be extended to collaborative analytics scenarios that include more than one users. Nevertheless, multiple-user collaboration also needs to consider sharing and privacy issues other than cross-view data analysis. This brings new challenges and opportunities to improve the algorithm. Moreover, our force-directed layout adaptation method is only tested on static scenes. There are also needs for situated analytics with MV representations in dynamic scenes, such as the car racing competition illustrated in Figure 1. The force-directed method is relatively simple and runs in real-time. However, the method will probably produce inconsistent layouts across different frames, which increases the analysis burden for users. The effects of layout stability on situatedness levels and analytics efficiency in dynamic scenes need to be further studied.

7 Conclusion

We have presented an in-depth study on the effects of view layout on situated analytics for MV representations in immersive visualization. The study is based on a new inspection of the contradictory considerations for situatedness and analytics. A close examination of two common layout paradigms, including embedded and linked layouts, reveals the design trade-offs to be made and implies the considerations for a desired layout that balances situatedness and analytics simultaneously. We leverage design space dimensions for 2D interface arrangement in 3D space, and propose an automatic layout adaptation method that fulfills the considerations. The method includes a cylindrical paradigm for *egocentric* reference frame, and a force-directed method for proper *view-view, view-user,* and *view-referent proximities* and high view *visibility*. Quantitative results and user feedbacks from a formal user study confirm the effectiveness of our proposed method in achieving high level of spatial situatedness and cross-view analysis including filtering, refocusing, and connecting tasks.

With increasing demand and more mature technologies, situated analytics is becoming an emerging field of research. This work illustrates a promising area for future research on situated analytics. More conceptual and empirical research is needed to achieve a better understanding of design space dimensions for situated analytics. The solution shows that knowledge from multiple research communities can be integrated to improve immersive visualization design.

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