Master 2 in Computer Science - Interaction Specialty

Combining External Displays with AR content: a Design Space and Placement Challenges

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Summary

The goal of this thesis is to explore how to combine traditional digital displays with augmented reality (AR) content, when viewing data visualizations. In this thesis, we first explore the design space of combining AR+digital display, focusing on different design dimensions (and choices) about how to present AR content that enhances the digital display. Based on this design space, we demonstrate several new visualization examples that we developed, that illustrate how people can utilize the space in front of a display through the use of AR technology. We also organize and explain how previous work falls in this design space. In the Second part of the thesis we focus on one design dimension *depth*. We build a prototype system to further investigate the benefits and drawbacks of different depth variations when combining AR content with an external display. In this part we focused on specific content common to many visualizations (highlights, annotations, labels). Our study uses a Map-case scenario where participants had to interact and search information on a metro map (i.e., graph visualization) built inside our prototype system. We introduce 3 possible ways that this AR content can be seen when in comes to depth. The ultimate goal of the study was to observe user preferences regarding different depth configurations of visual components in AR (in particularly annotation,label and highlights information in different depth). The result shows that users with different visual searching strategies have various preferences of depth configuration. Finally, we discuss about the challenges we faced running AR user-studies completely virtually (due to the current pandemic constraints) and how we addressed them.

Keywords

Augmented Reality, Graphic navigation, Digital Display, perception, Augmented Display, Information Visualization

CHAPTER 1

Introduction

There are many ways to present digital data. The most common is to view data on physical screens of traditional devices like computer screens, tablets, mobile phones or Wall-size displays. Data can also be shown as virtual content in Augmented Reality(AR) Head-Mounted displays, Virtual Reality Devices(VR) or video projectors. Each of these possible ways of displaying data has their own features and benefits. Combining them together might result in new visualizations and beneficial and interesting results.

Digital screens are great tools in information visualization as they have better resolution (than AR devices) and are commonly used in 2D visualization analysis. However, analysing 3D data in this kind of devices can be difficult, as showing the 3rd dimension may be less effective (e.g., [1]). It is also not trivial to design interactions with 3D data (e.g., [2]).Besides, they also have a natural size limitation as they are physical screens. In these aspects, the potential of combining Augmented Reality (AR) techniques to augment 2D visualization comes to the table. AR can be used to view a 3rd data dimension, to interact with 3D content, to extend the display space without being constraint by a physical display size, etc.

In this thesis, our goal is to identify challenges in placing and understanding information when combining AR with external displays. This falls into the larger domain of information visualization called "immersive visual analytics" [37]. Our unique approach is the focus on combining AR with external displays for information visualization.

We first introduce several visualization examples we build during the design space exploration. The examples intend to show the potential of how placing additional AR content can help on-Screen data analysis. We then focus on one aspect of our design space: the depth placement of content such as highlights and annotations (that are common across visualizations). Here we choose a Metro Map Case to compare different alternatives for placing this content in terms of depth. Finally we discuss the challenges we faced when dealing with running a remote user study that combines AR and physical screens, and how we calibrate and control the physical size of the AR content. We also describe the virtual room we built in order to assist the observation of the remote participants through the network. We close with a discussion and suggestions for future work.

CHAPTER 2

Related Work

In this chapter we will discuss works related to our own, focusing on the use of immersive techniques especially augmented reality for information visualization.

2.1 Immersive analytics

Immersive analytics is defined as " *the use of engaging, embodied analysis tools to support data understanding and decision making* [17]" It's a multi discipline domain built upon the fields of data visualization, virtual reality (VR) and mixed reality (MR) - another name for augmented reality (AR), human computer interaction and computer graphics.

The idea of immersive information exits as early as 1991 [8], where the authors build a 3D room for increasing the capacity of immediate information available to the user. Several previous research papers [13, 15, 38, 24, 46] have already shown there are potential benefits to construct data analysis in an immersive environment, especially in life and health science field. For example,when treating a patient with a complex multi-faceted medical condition, a mix of AR headsets and tiled wall displays potentially support collocated and remote collaboration. [14]

However, the idea that data visualization should adopt new interaction diagrams in immersive environments didn't take off until 2014 [32], and the name "Immersive analytics" was used to describe the possibilities for data visualization in VR and AR at IEEE BDVA [25]. As a recent book on Immersive Analytics [37] argues it has several benefits: using depth to show additional abstract dimensions [39],views on non-flat surfaces [49], visualising abstract data with a spatial embedding [16], arranging multiple views in 3D space [10], and increases engagement [37].

In the past few years, with the arrival of better performance Head Mounted Display(HMD) such as HTC Vive and Microsoft HoloLens, applications for immersive analytic have followed. There are even efforts to build immersive toolkits such as [11] and [12]. Desktop analysis tool such as Pymol [45] and Rasmol [44] are also providing VR extensions.

Most of the toolkits described above are VR based tools. Apart from VR, there are also investigations on using augmented reality. For example on how 3D Node-Link in Augmented reality superimposed on graph visualization will effect the analysis [7]. Immersive analytics will play a increasingly significant role in data analysis. We describe next more examples, focusing on the combination of augmented reality and other external displays in data visualization.

2.2 AR combined with external Displays

Augmented reality is an important dimension in immersive analytics. We are in particularly interested in previous work combining AR with external digital displays for visualization purposes.

Kim et al. [35] proposed an AR solution for combining AR with Static visualizations. They build a prototype that uses a 2D scatter plot on paper as a basis(which can also be implemented on a digital display). In the AR content, they show metadata information (such as highlights and labels) and also link in AR visually that scatterplot with a barchart that exists in AR only. Chen et al. [9] propose four ways to augmented static visualizations using AR: to extend the view of an existing static visualization (for example when new data arrives), to create a composite view (that superimposes additional information on the original visualization), to show small multiples (that shows similar views of the data using the same encoding) and Multiple views (that show additional visualizations). Although these two previous works use as a basis a static visualization on paper, we can envision that the static visualization could be replaced by a different type of display.

Two earlier works propose experimental augmented reality map environments in collaborative tasks [5, 40]. In particular, Benko et al. [5] build a system to show standard 2D information available from an excavation, and a 3D interactive model system which can be placed freely for collaboration purposes. Nilsson et al. [40] present a tool supporting collaboration between rescue services or police in a military crisis management scenario. In their system, they present the 2D map information on a large digital display and 3D models and symbols represent the emergency events as Shareable AR content.

More recent work as [48] and [31] demonstrate the possibility for augmented reality to separate private information from general information and to distinguish information priority level in a wall-size data analysis scenario. Sun et al.[48] build a shared network information shown on the wall, while they show sensitive meta data information with different authorisation levels in the HMD. James et al.[31] use a graph visualization shown in a large external display (such as a metro map in a station), and augment it with private navigation information in the AR headset.

Apart from a wall-size display, there are also works for tablets combined with AR designs. Spindler [47] uses the spatial position and orientation of a tangible tablet to simulate a lens (or a 2D plane) for looking into 3D data. While they do not use AR with with a headset, the tablet plays the role of AR.

Another related work was done by Reipschl age et al. [43] which built a system that combines a high resolution tablet with AR HMD and provided two applications to show the potential of this system. In the first application (DesignAR), they use a 2D display for tangible interaction and extend the function menu for designing AR 3D models from the side of the screen. They also build a second application (ARchitecture) which projects the high resolution technical drawing of a build on the 2D screen and use AR HMD to extend the 3D model of the building as augmented information. In this work the AR content provides 3D information on a model (that is seen in 2D on the external display).

Finally, there is also a commercial tool called Zspace which uses pen interaction to assist immersive analytic on a tablet [51].

These previous works have argued that immersive analytics using AR can have many benefits: e.g, provide immersive engagement [5, 43, 47], enhance collaboration by providing private information input [31, 48, 40],providing interaction with static visualization [35, 9], show new views of the data [9] etc. We will further discuss and classify them in our design space later on in next chapter.

Therefore, several design prototypes exists in the field of AR+Display. Nevertheless, there is still a lack of a systematic discussion about the design space of how to combine AR with external displays, i.e., the what to show in which display, the why, and the how questions of combining AR+digital display.

CHAPTER 3

Design Space Exploration

A Design Space intends to collect existing designs for a certain topic, challenge or context. It is an approach to represent design rationale, using a semiformal notation, called QOC (Questions, Options, and Criteria) [36]. In our exploration of the design space, we have both looked at existing techniques that combine AR and regular displays, and have introduced new visualization designs of our own. By analyzing those techniques, we categorize them into different design axes, determine which possibilities have not yet been explored or combined, and propose new variations.

In this chapter, we focus on visualization works which combine AR and external monitors, focusing particularly on how depth (in front or behind the monitor) can be used to encode information. And our design space includes existing or new immersive visualization techniques. We present the design axes relevant to the relationship between AR information and digital display, and also possible placements of the different types of content in terms of depth.

3.1 Design assumptions

In our work we make the assumption that the main visualization is on the external display, as this has a high resolution and is always accessible (even without an AR headset). The AR in our work (seen through an AR headset) augments this main visualization with additional info (e.g., additional data dimensions not seen in the main visualization, annotations, etc.). We did not take into account fully independent 3D visualizations that exist only in AR, because our main focus is to combine the visualization seen on the digital display with AR as support.

In our work we also make the assumption that users can interact with two ways: either using the AR headset (e.g., using air-taps) or using touch or mouse if they are close to the external display.

3.2 Visualization examples

To better introduce the design space, we firstly introduce several visualization techniques we build during the design space exploration. At the beginning of the master internship we designed wall size visualizations. Nevertheless, due to the pandemic we were forced to work from home. We thus adapted our designs to a monitor-size display. In the examples that follow, all of the 2D visualizations (like scatter plots and bar chart) are supposed to be displayed on the monitor. However, due to time constraints and to make the images of the thesis more legible (as view from the Hololens video is not always clear), in some examples we combine the AR and the monitor view - this is explained in the respective images.

We note, that although the examples mention input using the AR headset (such as air-taps), we have equivalent input implemented also using mouse. So for example air-taps in the AR headset are clicks with the mouse, air-drags are mouse drags, etc.

Bar Chart drawer

The Bar Chart drawer presents a new way to encode different data in the third dimension, by combining two 2D data visualizations perpendicularly.

In this visualization, when focusing on the Bar Chart (seen on the display), a label in AR will appear at a constant offset with a link to connect it to a specific bar. In the Bar Chart drawer, we encoded a line Chart on the third dimension (AR) of each of the Bar Chart. In our prototype the bar chart shows aggregated information of three types of RER incidents over several years. The expanded line chart shows how these incidents are distributed over the 12 months.

There are two types of interaction styles for revealing the line chart. One is the **switch on & off** style. By using air tap when focusing on the Bar Chart, the line chart will slide out as a result. When air tapping again, the line chart will slide back and thus only the 2D visualization will be visible. Another interaction style Fig.3.1,Fig.3.2 is that the user can drag the line chart outside of the 2D visualization, same as dragging a physical drawer in the real world. Meanwhile the line chart will scale up (stretch). In this way, the user can control the depth (3rd) dimension completely.

This novel Bar Chart visualization can be useful when the user wants to explore two dimensions, but more dimensions are available on demand. Here two additional dimensions are added in depth, using a different visual encoding from the original two in the display (here a line chart is shown in depth, on top of a bar of the bar chart on the display). This visualization presented in depth is by default flattened (reducing clutter) and only available on demand.

This concept of attaching a 2D visualization perpendicular to another 2D visualization (or datapoint of the visualization0 can be extended to other examples, with an infinite amount of possible combinations.

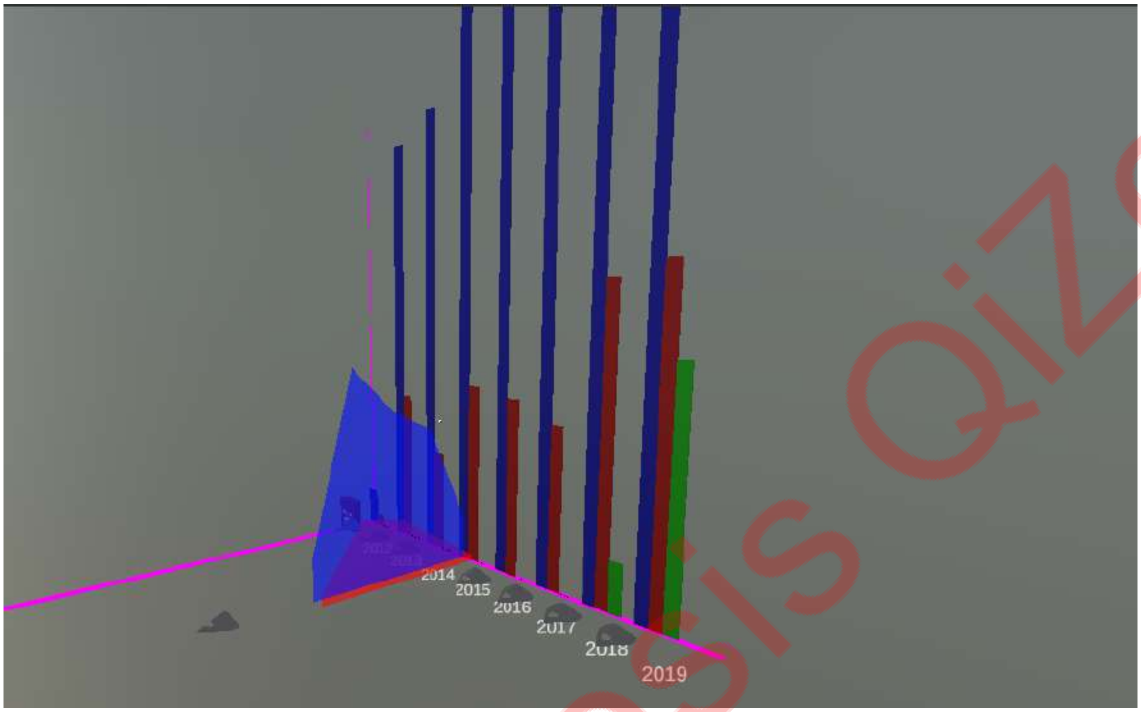
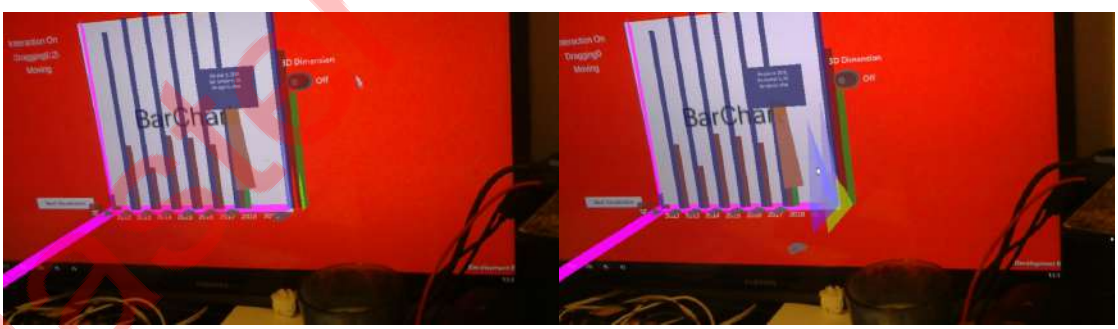


Figure 3.1: The bar chart drawer. The bar chart (with the red,blue and green bars) indicates the part of the visualization that is seen on the monitor. The line and extruded line chart can be "dragged" outside the monitor and exists in AR. In this image we have combined the monitor and the AR view to make it more easily visible).



(a) (b)

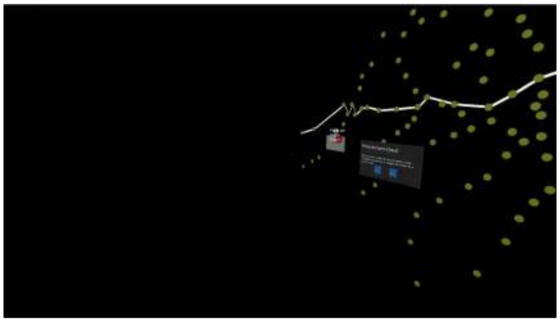
Figure 3.2: The drag style Bar Chart. (a) The bar on the right side is selected; (b) the bar is dragged to the maximum depth, the line chart updates its scale ("stretches") simultaneously.

Metro Map

Another design example in our prototype system is a Map visualization, here of the Paris metro lines Fig. 3.3. The gray points indicate the metro stations (which we adjust to yellow in the following examples of map to better distinguish them from the background). When gazing at a point, a label will appear showing the station name information, and the point will be highlighted red. There is also an annotation panel which displays general information (currently metro station ID). As shown in Fig. 3.4, this visualization also contains an annotation that is applicable to a subpart of the visualization (here an entire metro line) which only responds while user gazes on a preset area (visualization subpart).

This visualization highlights how AR can be used to show meta-data related to the main display visualization (here labels, highlights, additional annotations). It also shows how this information can change with different speeds: for example the labels of specific datapoints and the highlights get immediately updated when the user looks at a specific datapoint. Whereas the subpart annotation is viscus, follows slowly the user gaze. We used this visualization in our user study (chapter 4), so we 'll discuss it in more depth there).

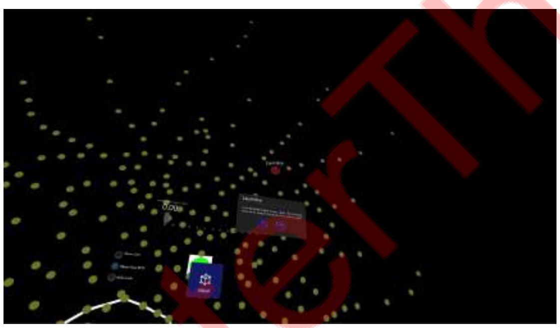
Figure 3.3: Metro map visualization, essentially a graph with nodes and links.


(a)


(b)


(c)


(d)


(e)

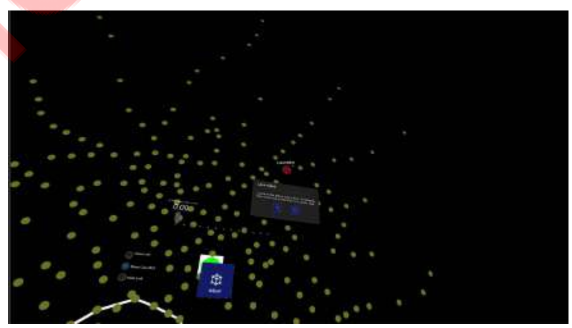
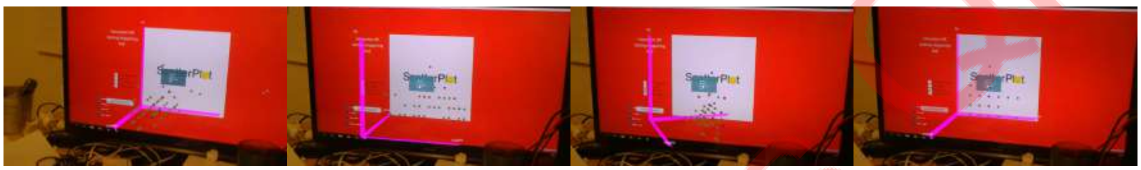

(f)

Figure 3.4: (a)-(d):the subpart visualization annotation of the metro line (the light gray rectangle) follows the user gaze, once the user focus is out of the metro line area, the subpart visualization annotation stop updating.(d)-(f) after the user changes their focus, the annotation displaying general information (the dark gray rectangle) will float slowly from the current location to the newly focus point.

3D Scatter dice

The 3D scatter dice visualization was inspired by scatter dice [19] which uses animated transitions between multiple 2D scatter plots. These 2D scatterplots represent a larger scatterplot matrix. The metaphor used is that the 2D scatterplots are faces on a cube (dice) and the transitions between them are performed as 3D animated rotations of the dice. In the original paper this rotation is psudo-2D. In our case, we use AR to both present a true 3D Scatter plot, but also to perform the scatter dice rotation in true 3D.

This example shows how the depth dimension in AR can be used to provide animated transitions between 2D views on the display, as well as how AR can show a 3rd data dimension.



(a) (b) (c) (d)

Figure 3.5: The Scatter Dice encoded with the data from a dataset on cereal nutrition: (a) A true 3D scatter plot shows combinations of three dimensions (fat, sugar, protein). And an AR scatter dice: (b) a 2D scatter plot with two dimensions (fat, sugar) is seen on the display; when the user wants to switch to another two dimensions a now 3D animation transition-rotation (c) takes place; (d) finishing with another 2D scatter plot (fat, protein).

3D lens

The 3D lens Fig. 3.6 consists of a 2D scatter plot and a view window which will follow the gaze of the user. On the top of the view window, another dimension is shown for each data point in the form of a 3D bars. Thus the AR content creates a 3D barchart on top of a sub-area of the scatterplot. As far as we know this is a novel visualization.

Another 3D lens example uses as a base visualization a 2D map, combining it with 3D Map information. This is similar to previous work regarding 2D and 3D maps [21] which use haptic feedback to raise the 2D environment, or work [47] which uses a tablet to extend the 3D space above the table. While we have the 3D information for the map of Paris, we did not incorporate it in our prototype - but this is possible to do in the future. Using HMD is low-cost (compared to haptic solutions) and more realistic because it can project the 3D maps tightly coupled to the 2D map in the real world compared to the tablet AR solution.

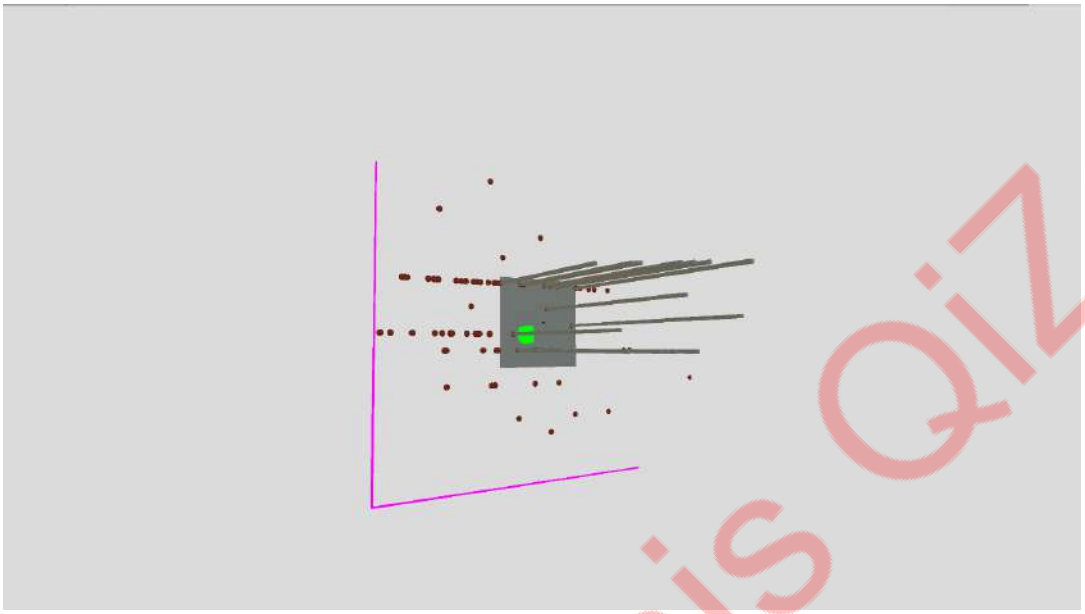


Figure 3.6: 3D Lens. The scatterplot shown here is the main visualization and is supposed to be seen on the monitor. Any points inside the gray square (lens) are extruded in 3D as bars that only exist in AR. In this image we have combined the monitor and the AR view to make it more easily visible).

Magnification lens

The magnification lens Fig. 3.8 is designed to provide a different view of the content the user focuses on. Akin to magnification lenses in the real world, it enlarges the area where the lens is placed.

To explore more the notion of depth, in our case we use depth to determine the level of 'zoom' of this magnification lens. When user do air drag gesture,it will switch between several preset level. This change in zoom is inspired by a discussion of previous work about Multi scale zooming in a 2D environments [22].

Hybrid image

This example is inspired from the work of Hybrid images [41] and hybrid image visualizations [28]. In these original work, the authors can combine two images (using high-pass and low-pass filtering) in a way that one image can be seen when close to it and one when standing further away. In our adaptation, we use AR to take two complementary images and blend them together. One image exists on the external display and the other image exists in AR. As the user moves in front of the display we adjust the transparency of the image in AR to simulate the behavior of hybrid images. The image in AR (inside the HMD) is the same size of the image displayed on the Screen. The transparency of the image in the HMD is adjusted depending on the distance between the user and the monitor display, the nearer the user to the screen, the more transparent the HMD image becomes.

This example shows how we can use implicit interaction / implicit changes in depth, to change the information shown in AR. Apart from hybrid images, this relates to previous work on proxemics in visualization [30].

(a) (b)

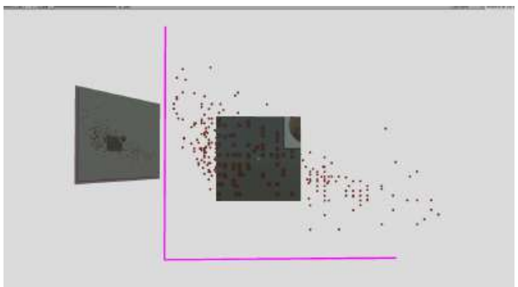
Figure 3.7: Hybrid Image. The transparency of the graph in AR content depends on the distance between the user to the screen (a) When the user is far away from the screen, the Metro image will overlap on the top in AR content. (b) As the user comes closer to the screen, the metro image gradually disappears, showing a more detailed map of Paris that exists on the monitor.

Hierarchy

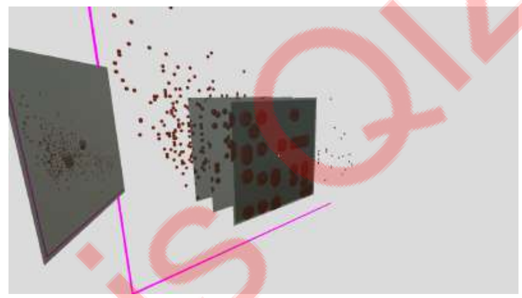
The idea of Hierarchy is inspired by the concept of Multi scale and Multi focus interfaces [33]. In that previous work, the author introduced the "polyzoom" technique which enables users to progressively build hierarchies of focus regions.

In our prototype visualization, the basic 2D visualization is a scatter plot on the display, and we use a 2D viewport to select an area of interest. When the user gives an "extrude window" command, an extended window will spawn at a higher magnification, floating in the 3D space. This new window can further act as a parent for later windows extruded from that viewport. By scaling up the size of the extended window, the user can extend the area of magnification. All extruded windows exist in the AR space and the user can move them around the space. A link connecting two windows shows the parent-child relationship of the two windows (i.e., that one was generated as an extrusion of the other). We modify the transparency of the windows based on its distance from the user. Like the ployzoom application [33], our Hierarchy example can address problems caused by the desert fog phenomenon [34], allowing navigation of the whole visualization (on the monitor) and focus on a detailed points of interest at the same time (in the windows in AR). A major differences is that our extruded windows exist in AR.

This visualization provides an example for how we can use the external space of a digital display by providing additional viewports/views on the data.

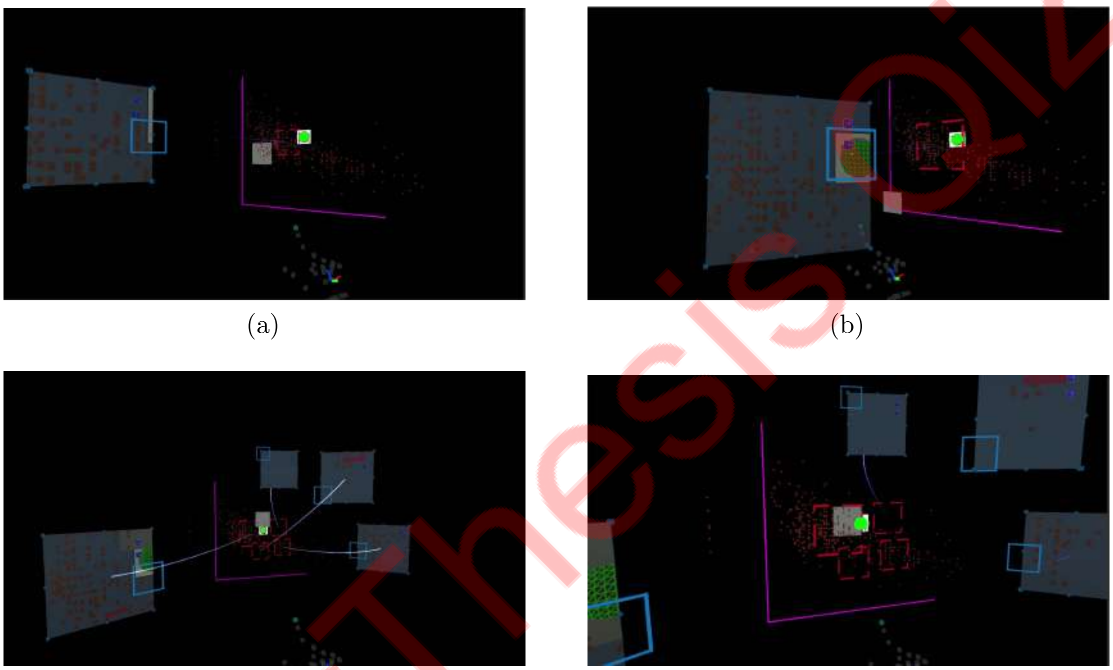


(a)



(b)

Figure 3.8: Magnification Lens, the scatterplot is shown on the monitor, while the lens (gray rectangle) and its content exists in AR. The user can use the left hand air drag gesture in order to switch between different levels of scale. In this image we have combined the monitor and the AR view to make it more easily visible.



(a) (b) (c) (d)

Figure 3.9: Hierarchy. The scatterplot is shown on the monitor, while the extended gray windows and links exist in AR. (a) an extended window (gray on the left) represents a zoomed-in viewport of an area of the scatterplot on the display (on the right). (b) Resizing the extended window enlarges the focus area seen in red on the original scatterplot. (c) When the user is far from the digital display, the parent-child links show the relationship between each extended window. (d) The transparency of these windows depends on the distance between the user and the windows. In this image we have combined the monitor and the AR view to make it more easily visible.

3.3 Dimensions: Goals for adding AR and Display Size

The reasons why we combine AR with a real digital display can be important to be discussed first. AR can be used for different purposes. Imagine three types of possible displays that are very different in size: wall-displays, regular desktop monitors,digital table and a mobile phone or tablet.

For wall-size displays, we can assume that this display can render in high resolution a lot of data, so the AR content can be used as an extended view to provide additional information. This relates to WHAT we can show in AR. Based on our exploration designs, AR can be used to show meta data and annotations (see example on Metro map) or new information (see example on hybrid images). The AR can be used to provide real 3D rendering of 3D data to make interaction and perception of 3D visualization more intuitive (see scatter dice example). It can also be used to show transitions (see scatter dice example) or links (see Hierarchy) on the 2D visualization on the display. The AR can provide a different view of the data completely, like a Magnifier lenses to show more detailed information. Or a different rendering / visualization (e.g., a Bar chart area showing different information with the same mapping of location on the visualization). AR combined with a Wall display can also be used in a collaboration scenario to authorize different degrees of visibility of digital information.

One key factor when discussing Goals for combining AR and a digital display is the size of the digital displays. The examples of how AR can be used in a wall-size display that we discuss previously, can also apply to smaller display sizes (e.g., use AR to see a 3rd dimension in a monitor visualization, or to show annotations in a mobile visualization). But AR can have an additional role in smaller displays, it can also be used to extend the original display of monitor size or even smaller size like mobile devises. For example, they can be used as Focus+Context [4] to increase the display area of the visualization. This depends on whether the original visualization on the monitor is visible 100%, or if part of the visualization is outside the view.

Thus the first two dimensions of our design space are:

Display Size: wall/large display (vis fits comfortably); monitor size (vis may need to be extended beyond display); mobile size (vis likely mostly outside display).

AR goal / WHAT AR shows: show a visualization, show additional data (or parts of data), show meta-data, show transitions and links, extend visualization on the display, add interaction.

3.4 Dimensions related to the Updating of AR content (Coupling/Speed)

Coupling

Let us consider placing meta-data and other visual components like labels and highlights in AR. These components can target different elements of the visualization and for multiple purposes. For example highlights are coupled with one or more specific data points. Same for the data point labels.

Whereas the visualization title refers to the entire visualization, and thus is may make more sense to attach it to the entire visualization all the time (probably at a fixed location).

There is another possibility that the visual components relate to a sub part of the visualization (e.g., a metro line name is connected to several metro stations as we previously discussed in the map visualization example 3.4. Thus the placement/coupling of such a component in AR components can be more "loose" and does not need to be updated/re-positioned every time the focus changes.

So coupling can be tight (on a data point or the entire visualization), or loose (e.g., on sub-part/sub-area of the visualization).

Movement/Updating speed

Another dimension to consider is the dynamic movement of a visual components that need to respond to either the user interaction (e.g., highlight of points that are in focus) or visualization changes (e.g., changing the main axis of a scatter plot). Speeds here can be different. For example highlights and labels need to be updated immediately when a new data point is in focus. Whereas an annotation of sub-part of the visualization may not need to move/update unless that sub part becomes invisible.

We classify the attachment of visual components in AR and the visualization on the display as *tight immediate updating, sticky updating, viscus updating.*

Tight immediate coupling means the visual components will switch to a different position with no delay as soon as the user changes their focus, this shows a strong relationship between the visual component and coupled target. The label in the scatter dice 3.5 and bar chart drawer 3.2, the view port component of the Hierarchy visualization 3.9 and the Magnify Lens 3.8 are examples which constantly update based on user focus change.

We define sticky coupling one where the visual component in AR will stay static until the view of the users moves for a certain distance, this builds a relationship between the visual component and an area rather than a data point. For instance, the metro sub part annotation 3.4 remains static as long as any station of the metro line is in focus.

Viscus coupling has a delay after the user changes their focus. For example it can be a fade-in animation, or a transition annotation that floats slowly from the current location to the newly defined destination. Visual components with this type of coupling can be used for projecting general information and attract user attention with their somewhat slow and asynchronous response time.

3.5 Dimensions related to the 3D rendering of visualizations (representation, information type, visibility)

As mentioned in the "what" we can show in AR, one of the possible content we identified is to show entire visualizations in AR (or sub-parts of them) using the depth in front of the display. This is common in the examples we created (e.g., scatter dice, bar chart, hierarchies, etc.). These added visualizations in AR have two characteristics: the Data Encoding in the third dimension/depth and the AR-Data Persistence.

Representation

For multi-dimensional visualizations we can use augmented reality and depth in front of the display to show a third dimension. This dimension can be encoded using the *same visual encoding as the visualization on the external display, or a different encoding.* The 3D scatter dice 3.5 for example is using the same representation for the third dimension; while the 3D Lens is using a different representation for the third dimension 3.6: the data is represent as dots when they are not focused on, and turn into a 3D bar representation when the viewport focuses on them.

Information type

Beyond rendering, the visualization in AR can show the *same or different type of information.* For example, in the scatter dice 3.5 and 3D lens 3.6 examples above , the AR content presented is another dimension of the same data set. And in the hierarchy example 3.9 it is again a subset of the data, but of the same dimension as the visualization on the display. While in the bar chart drawer that combines a bar chart on the display with a line chart on the third dimension (Fig. 3.1) the AR visualization is now encoding different information on the third dimension (here the details of traffic accidents over months). The same idea exits in the Link view example in Visar [35], they provide ”additional information about the filtered or highlighted data points by visualizing other data attributes of the dataset.”

We feel that when the type of information changes, it makes sense to adopt a different visual representation in the AR visualization.

The AR rendering can also be additional information that helps explain the visualization, such as the example of Hierarchy visualization where the links represent the relationship across visualization windows Fig. 3.9. This kind of node-link diagrams that connect different visualizations in AR are quite common in immersive analytics [6], [42], [20].

Visibility

Most of the AR visualizations are permanently visible (e.g., scatter dice) or user determined (e.g., opening the drawer in the bar chart drawer or re-positioning the different windows in the hierarchy). But there is still possibilities for designing a visualization to use implicit changes related to user position (e.g., hybrid images 3.7).

User defined visibility and positioning ensures the high degree of freedom for customizing AR visualization configuration. People can hide and show different part of the visualization to discard distractions or overlap visualizations together for comparison. However, user defined visualization has its drawbacks. User defined visualization can be cumbersome and difficult to reconstruct again. Implicit transitions on the other hand are predefined and will be trigger by certain condition. In the example of Hybrid Image Fig. 3.7, the transparency of the AR content has a negative relationship with the distance from the user to the screen. The link in the Hierarchy example 3.9 has a similar behavior regarding transparency. This might be useful in switching between immediate points of interest by using simple physical movement. Several works on wall displays indicate that viewers already naturally move at different distances from a display to see information at different scales (e.g., [3, 50]).

3.6 Depth variations

The depth variations relates to the choice of depth placement for any information shown in AR. The choice of depth placement can be: *fixed, unlimited/continuous, transitioning between several preset positions, implicitly change based on user position.*

Some AR information can be shown at a fixed depth. For instance in all our examples that include highlights in AR ,e.g. the map visualization 3.4, the highlights are placed at a fixed depth - on the level of the external display with the original visualization.

Unlimited/continuous placement means that visual components can be placed anywhere in the space, for example wherever the user wants. This is useful for general tools like placing a sticker or some visual components which are not tightly coupled with the monitor display. Examples include the label showing Bar information in the bar chart drawer 3.2, the extrude windows in the Hierarchy 3.9. In parallel to this free placement, transferring between different pre-defined depth can ensure that the visualization designer has more control and makes the end result more predictable. For instance, in the magnification Lens example Fig. 3.8, the user can use air drag to switch between the view window with different depths.

Finally, the depth of the visual component can also be updated implicitly under some condition. For instance, in the application ImAxes [12], the links are updated based on the relative location of the axes.

3.7 Interaction

Interaction is an important part of visual analysis, including immersive analytics. While this thesis (and design space) is mainly concerned with AR *visual* content, we have added *interaction* as a separate dimension in our design space. Depending on the various purposes of the visualization (and AR content), the role of interaction can be also different.

Interaction purpose

In any visual analytics system there are interactions that help data exploration (such as selection, filtering - see [37] for more examples); as well as interactions for determining the visual properties of the visualization (such as colors of points, placement of axis, etc.). Our examples in the design space contain both, for example selection methods for selecting a bar in the bar chart 3.2 or an area in the 3D lens 3.6 and hierarchy 3.9. What is unique in our case, is that interactions related to the visual properties of the visualization may include both 2D and 3D components (e.g., in the Hierarchy 3.9 we would need to both place the 2D scatterplot in the display and position in space the 3D extended windows).

Interaction dimensions (2D vs 3D)

As in our case we are dealing with potentially both 2D and 3D content in AR, there can be 2D and 3D interactions. 2D interaction generally is needed on the 2D visualization in the digital display. This interaction can perform typical navigation and exploration actions such as pan and zoom, focus and selection.

For the 3D visualizations, we can use 3D interaction to interact with the visualization in depth. For example we can use 3D selection gestures, etc. Many examples of 3D selections exist in previous work [5, 47]

We can use 3D interaction to also setup 2D information, as we mentioned in the previous section of Depth variations 3.6. Or to implicitly alter the visualization, as our previous examples of Hybrid image 3.7. These last examples are methods where the 3D dimension is used as an aid for interaction in 2D. We believe there is more space to explore the benefits of 3D interaction as a means to complement 2D visualizations. For example, we could imagine that in cases of overlapping 2D points (e.g., in scatterplots) we could use 3D gestures to "extrude" points in 3D to see their true density.

Interaction input

People have designed different interaction input in order to improve user experience. For the AR content, lots of applications are using Hand gestures. For instance, in the work of Sun et al. [48] they used air tap to show node information and air drag interaction to move the node in the AR content and synchronize with the 2D display via the network. These interactions are integrated in the HoloLens. Another types of interaction tools easily available with MD are controllers which can detect user hand movements like the work in Benko et al. [5], that used a tracked glove and a hand tracker to determine hand movement and position.

When it comes to interacting with the digital display, several techniques are used as well. zSpace [51] provides a way to interact with the tablet surface using digital pens whereas [7] uses the touch screen to manipulate and edit 3D content in AR. The display itself can also be the interaction tool, as is done for instance in the work of Spindler et al. [47]. We also argue that user can interact with the desktop application with mouse and keyboard. This can make sure that the user can interact with small elements on the screen, (e.g. the slider or UI buttons) when such devices are available.

In our visualization examples, we support air drag and air tap interaction which is integrated from the HoloLens. Nevertheless, we additionally use a mouse interaction as in our case users may be sitting in front of their work - and mouse is our main interaction input. Besides normal mouse interaction and GUI interaction, we also build a system to using mouse drag and head gaze to manipulate AR content 3.10. Early stages of user experience with members of our team indicate that in a setup where the user is seated in front of a regular monitor as the external display, this combination of gaze and mouse interaction is the most helpful when it comes to free depth placement of content in AR.

3.8 Design Space Table

To summerize our design space regarding the combination of AR content and digital display in immersive analytics, we collect them to design space table 3.8 - these include examples from designs introduced in our thesis and of previous work.

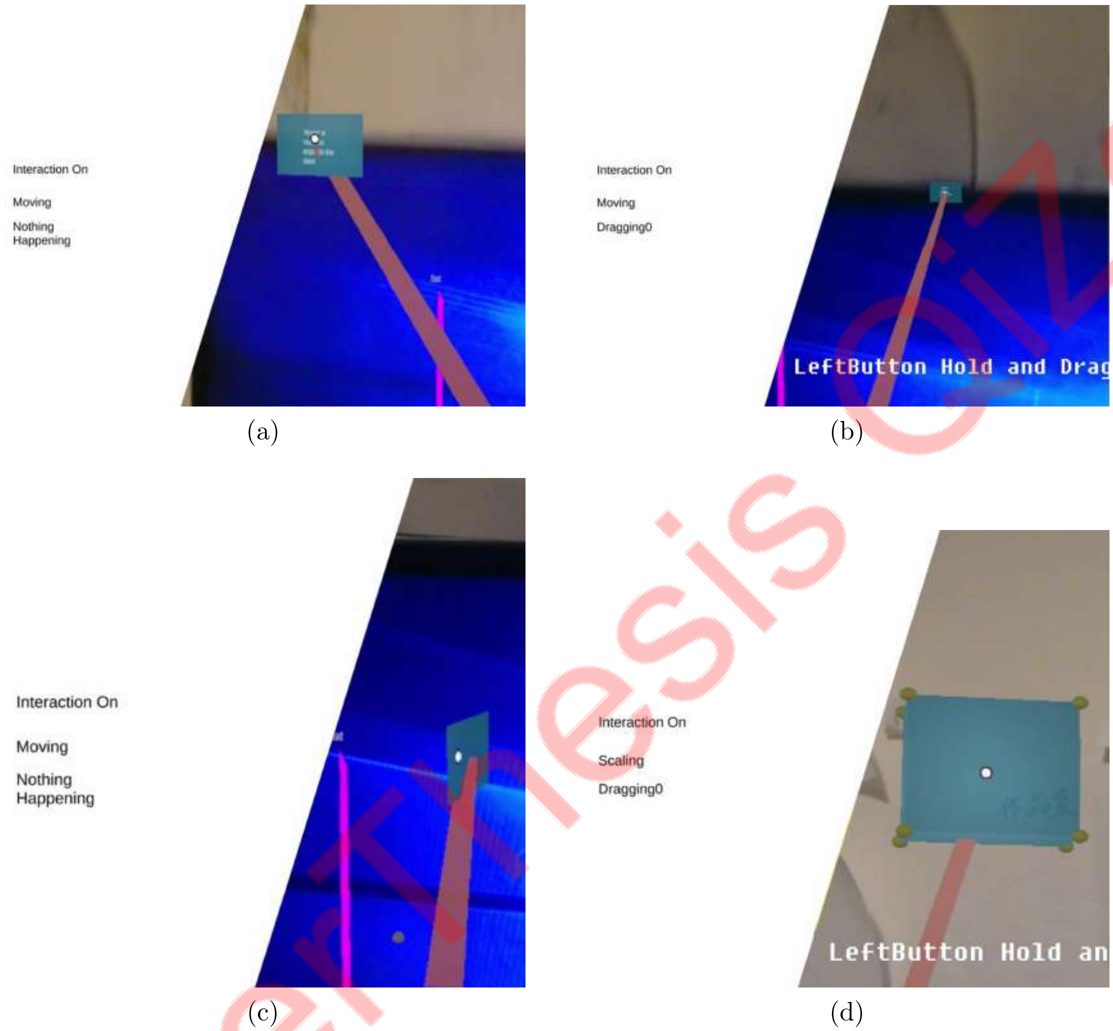


Figure 3.10: Screen shot for mouse interaction. The left part of the images shows the interaction mode (Scaling and Moving). (a) When the user's gaze cursor focuses on an object (label in the figure), a double click sets focus on the visual component. The visual component will follow the user's gaze direction in a constant distance, in other words, the visual component will always move on the surface of a "sphere" around the user. (b) Holding the left button and dragging the mouse enlarges the radius of the "sphere" to make the visual component move further. (c) Scrolling the mouse wheel rotates the object. (d) Clicking the right mouse button switches to the scale mode. The visual component will still follow user's gaze direction. Holding the left mouse button at this time, the visual component will enlarge accordingly. The yellow point on the eight corners indicate the box boundary of the visual component.

	Goals for adding AR and Display size			Update of AR content		3D rendering of visualization			Depth variation	Interaction
Visualization examples	Goals	Display size	Content in AR	Coupling	Movement/ Speed	represent ation	Information type	visibility	Depth variation	Interaction purpose
Map	additional info	Desktop	meta-data	loose/ tight	tight/ viscus/ sticky/	same	same	permanent	fixed	visual
3D Scatter Dice	3D rendering /3D transition	Desktop	visualization, transition	tight	tight	NA	same	permanent	fixed	visual
3D lens	3D rendering	Desktop	additional data	tight	tight	different	same	permanent	fixed	selection/ 2D &3D related
Magnification lens	additional info	Desktop	extend visualization ,links	tight	tight	NA	same	user defined	preset positions	selection
Hierarchy	extend view	Desktop	visualization	loose	NA	NA	same	user defined /implicit	unlimited	selection
Hybrid image	additional info	Desktop	visualization	tight	tight	NA	different	implicit	implicit	visual
Barchart drawer	3D rendering	Desktop	visualization	tight	tight	different	different	user defined	preset positions	2D&3D related
VisAR	additional info	Paper(Any type)	meta-data, visualization	tight	tight	NA	different	user defined	fixed	visual
PapARvis	additional info	Paper(Anytype)	extend visualization, visualization	tight	tight	NA	same	user defined	fixed	visual/ selection
MR archacological excavation	3D rendering	Digital table	visualization	loose	NA	different	different	user defined	unlimited	visual
Cross-organisational collibration in dynamic tasks	additional info	Digital table	additional data	NA	NA	different	different	user defined	unlimited	visual
Spatially aware tangible display	3D rendering	Tablet	NA	tight	tight visual update	NA	NA	implicit	implicit	visual
Augmented displays	extend view	Digital table	visualization	loose	tight	different	different	user defined	fixed/unlimited	2D&3D related
Personal+ context navigation	additional info	Wall	additional data	loose	tight	same	same	implicit	NA	visual
Collaborative visual analysis with multi-level information	additional info	Wall	meta-data, additional data	tight	tight	same	same	user defined	unlimited	filtering

Chapter 4

Metro Map Case User study

Our design space is fairly broad, with many aspects to study. For this thesis, we decided to focus on visual annotation components that are common across visualizations: highlights, labels and larger text annotations/comments. In particular, we wanted to understand where to place them in the AR space when it comes to depth.

We ran a study considering different depth variations and placements for annotation information (annotations, labels, highlights). Our goal was to understand user preference in how to place this information in the depth in front of the external display.

As we will explain later, setting up and running a remote AR study session takes time, and participants cannot wear an AR headset for prolonged periods of time. This constraint the time of the study sessions we can run - thus we could not test each single visualization in our examples. We picked the Metro map one, as such maps are common information which is accessible and familiar to the general public.

4.1 Prototype implementation

Visualization

The metro map for our user study is based on the Map visualization example in the design space. In the study we designed the Map visualization to run as a Focus and Context scenario. Part of the Map is shown on a monitor display and the rest is extended outside as AR content. The highlights, labels and annotations are shown in the AR content with various depth configurations. When user clicks on a Metro line, the line will be highlighted, there will be a label showing the Metro line name and number of incidents they have on a tool tip displayed on the monitor display.

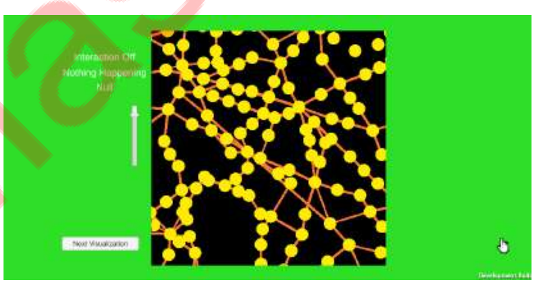


Figure 4.1: View on the monitor display

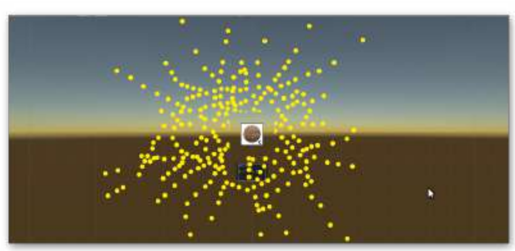


Figure 4.2: View inside the AR HoloLens

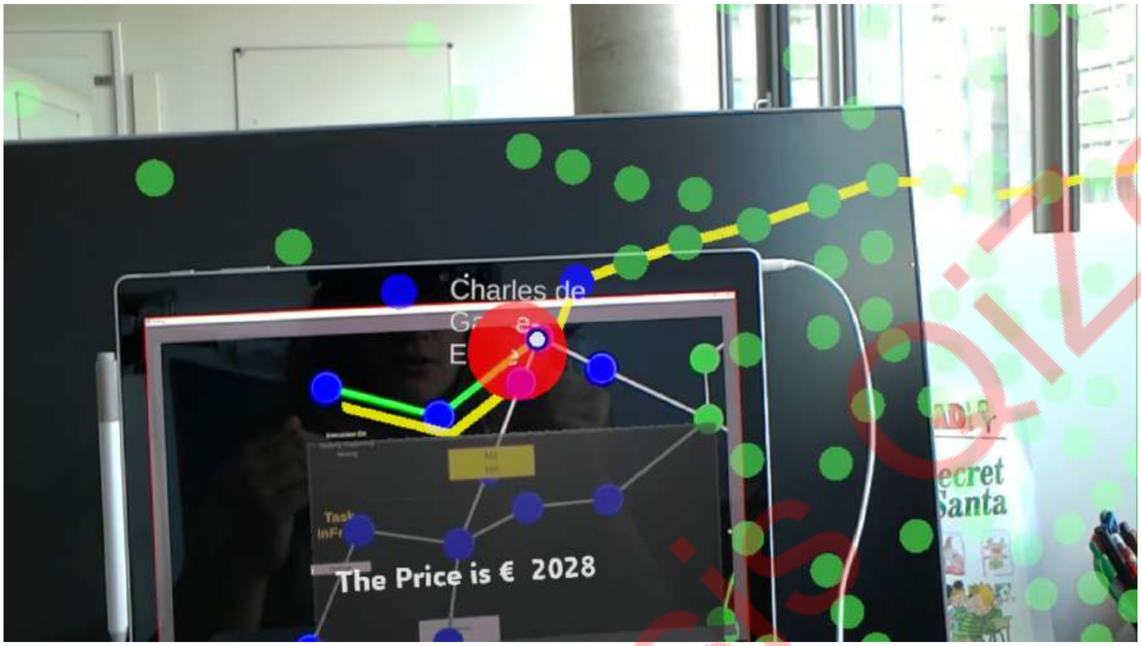


Figure 4.3: Map visualization setup: the blue zone indicates the area that the participants need to explore, the map visualization is shown in-part on the monitor but it also extends to the AR view.

Data sets

The information for the map comes from the Paris metro map. In order to fit into our scenario which we will discuss later on, we fake the metro station information, adding to it information for hotels. In particular, the station includes a fictional hotel name and price. In order to control the conditions of our studies, the number of incidents of the metro lines are changed per task in order to make sure that user can explore multiple metro lines.

Apparatus: Hardware configuration and software implementation

We assume that the participants are wearing a 1st generation Microsoft HoloLens, a wireless OST-HMD. The field of view is approximately 30 degrees horizontally and 17.5 degrees vertically. The participants also need a computer with a monitor display as support for the AR content (i.e., the main visualization). The operational system all the participants use are Windows. The system is nonetheless built in Unity3D, so it is compatible with Mac OS and Linux as well.

Our prototype consists of three separate unity applications: one running on the computer to show the visualization on the monitor, one running on the Hololens to show the AR content, and one running on a virtual room (described next - to help us observe user interactions in real time). The three components are synchronized through a calibration phase. This phase ensures that all participants have the exact same size of the final AR content (extended visualization) and that the AR headset is aware of the exact size of the display (so as too show content outside it for the Focus+Context view). For the alignment between AR content and the display, we use the Vuforia library [27] to detect images. The Vuforia marker is required to be as the same physical size as preset, or otherwise there will be an offset for the calibration. However, due to the variety of resolution and the size of the screens between participants, it's hard to control the marker to be the same size. We propose a method to control the physical size of the AR content in order to match it with the user's monitor size accordingly and ensure a consistent setup across participants. We will discuss with more details in the next chapter section 5.1.

Instead of performing a classic hand interaction available in most HMD, we choose instead Keyboard and GUI for interaction. We made the design choice based on the discussion of the role of the Monitor display. Since the monitor screen in our case is the main focus interface, mouse and keyboard interactions are naturally available and are less fatiguing than mid-air interactions. Also using mouse interaction, that is very precise, makes it easier to interact with the narrow metro line on the screen. In order to communicate between the AR headset and the Monitor display, we build a peer-to-peer computing architecture. The library we use is photon PUN [26]. Once the user interacts with the UI element on the screen (buttons, sliders, clickable metro line, etc.), the event message will be sent to HoloLens through this peer-to-peer connection and trigger the event inside HoloLens.

We also build a virtual room application to assist in running remotely the AR user study. For the purposes of better understanding how people interact with our visualization prototype, we build a remote Usability Lab in the same Network that we utilize to build the connection between Hololens and the monitor screen. The design rational and more details of the virtual will be discussed in the next chapter section 5.2

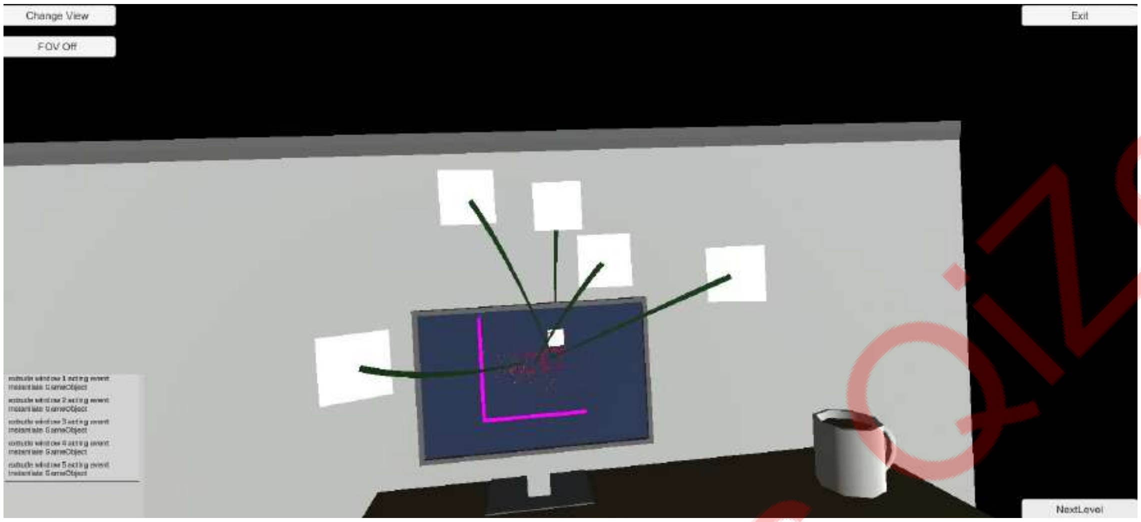


Figure 4.4: A screen shot from the virtual room for the Hierarchy visualization (used by the experimenter). The virtual room is in first person mode. Here the camera is synchronized with HoloLens camera of the remote participant via the Network. The view will update once the participant moves their head in real world. Interactions from the remote participant are also seen in real time (e.g., moving windows in the hierarchy). At the bottom left corner is log list which keeps updating based on user interaction events - and on the right are buttons letting the experimenter control the experiment.

4.2 User study

Participants

Given the current pandemic situation and confinement, we could not ran an in person study. This posed problems when it comes to calibration and setup consistency (discussed in the next chapter), but it also affected our participant pool. We could only recruit participants who already had access to a Hololens in their homes. We were able to recruit three participants for the user study from our local institution (aged 26-44 years old). All of them use HoloLens multiple times per week. Two of them are familiar with the map visualization and the other one has used this kind of visualization once or twice. Two of the participants have combined the HoloLens view with another display before for their own projects.

Scenario and Task

To help participants immerse themselves in the task at hand, we presented them with a fictional scenario. The participant is a student visiting Paris, looking for a place to stay. A friend has indicated that they need to make sure it is easy to reach a specific neighbourhood from their hotel because the neighbourhood is full of recommended restaurants and attractions. The student/participant will use the Metro Map visualization Fig. 4.3 to assist them in finding the best hotel. They first need to pan to find an area of interest to have in their focus/monitor (the area with blue nodes) that the friend has recommended. They then have to look for a hotel that has easy access to this area (on a station on a line that goes through it).

The scenario continues by explaining that they have heard that not all lines are reliable, so participants are asked to choose a hotel on the line that has the less incidents on average (the tool tip indicates the number will jump out when you click on the metro line). Each metro station gives a hotel that is close by and it's price info on an annotation. The participant's goal is to look for the cheapest hotel on the metro line which has the least number of incidents and also goes directly to the recommended area (the blue zone).

Task and Conditions

In summary, the participant's task is to first find a metro line crossing the blue zone with the least number of incidents, and then find the cheapest hotel at that metro line. This task simulates two situations where AR may be needed (based on our design space dimension Goal): as a focus+context display that augments an external monitor (having the blue zone); and as a means to display additional annotation information (highlights, labels, annotations) that the user has to consult in order to conduct their task.

The participants are asked to perform the task three times, once for each condition. In these three conditions, the AR content is placed at different pre-defined depth locations (again inspired by our design space dimension Depth).

The conditions are as following:

1. The labels, annotation and highlights are shown on the screen level (same depth as the external display) B.1.

2. The labels, annotation and highlights are shown with a constant distance from the display (at a depth different from that of the external display) B.2.

3. The labels and annotation are shown as a fixed rectangle on the top left corner (i.e., at a fixed depth from the user - close to them). The highlights are still shown on the screen level B.3.

In the end of the three conditions, in a forth task B.4, the participants are asked to configure on their own a depth combination of the above elements based on their preference and experience in the study.

The main goal of our study is not to measure formal differences between configurations (although we report them here). Rather, our goal is to see what preferences participants have for the placement of AR information, and if their preference of depth may change depending on the nature of the information (e.g., if it is different or not for highlights, labels, annotations).

Procedure

An experimenter administrator is present during each study section to guide the participants through the study and answer questions. There is also at least one experimenter observer, recording the remote scene and keeping notes. The user study session followed the sequence:

- Firstly, the administrator introduces our prototype system and informs participants of risk of the study (device might be overheated causing discomfort, AR headset may cause disorientation). The participants are told that they can take off the HMD at any time and stop the experiment at any time. They then sign an informed consent giving more details about the experiment and risks.
- The administrator sends the participant a package containing all the documents required for installation. Through Skype, the administrator guides the participant on how to install the related applications inside the HoloLens and the computer.
- The administrator guides the participant through the calibration phase and does a quality assessment of the calibration, asking questions regarding offset of information on the monitor and AR view.
- A tutorial session follows, to teach the user how to use the visualization tool. The administrator explains the features of the tool and asks the participant to explore freely. The data set of the tutorial session is different from the real user study in order to prevent users from being familiar with the data set.
- After the tutorial, the administrator explains the purpose of the study which is to decide where to best place meta-data information (such as annotations).
- The participant is then asked to perform the four tasks which have been discussed before. For each condition/task, the participant is able to use the tool a bit before the task starts. In the formal study, the participant is asked to share their screen and use a think aloud protocol through the whole process.
- After the full study session, that includes the task that participants can chose where to place information, the administrator asks the participant to explain

their choice on the customize exercise and talk about their feelings about the whole study process.

* Finally, the participant fills out a final questionnaire.

Measures

The purpose of this user study is to observe people's preference of different AR depth placements. We recorded the user behavior from both the HoloLens Video recording (that includes the real view of the user and their audio), and we also have recording of users' behavior from the virtual room. From the videos, we retrieve their interaction and their opinions during the exercises. In the questionnaire we asked them about their preference of the placement of each AR content(label, annotation, highlights).

4.3 Results and further discussion

Results

We first report the preference of participants for depth placement of each component (highlight, label, annotation) and then discuss how their task strategy may have affected these preferences. These come both from the questionnaire and their verbal comments during the last (open ended placement) task.

Highlights. In our user study, all the participants prefer highlight on the monitor level. One participant says that " *I could not always link the node and the highlight when they were not on the same level. When they were, it was far more comfortable.* " Another participant explained that " *If the highlight of the data point is not on the same level than the other label it makes my eyes refocus often and it could be unpleasant*". This last comment can be justified by previous work that explains how focusing at different depths between a monitor and AR content can be fatiguing [18].

Labels. As for the text labels, participants chose both the depth on the monitor level (2 participants) and using a fixed position (1 participant). The reason for selecting the depth on the monitor level is similar to the one discussed in highlights,"*Having all the data on the same level prevents the need to switch focus*". The participant who choose the fixed position label says that this kind of label "never goes out of the field of view of HoloLens". We discuss this last choice more in the strategy.

Annotations. For the choice of the longer text annotations, two of the participants choose annotations on the monitor level and one choose the fixed position. The reason for selecting a fixed position is because the fixed annotation won't be occluded by any other content (although that participant mentioned that the annotation on the monitor level was the best technique for eyes comfort).

Free Customization. When allowed to freely configure the position of different elements (forth task), two participants preferred to have the label a bit in front of the monitor and one prefer to be on the level of the monitor, whereas all of them prefer the highlights on the level of the monitor. Two participants prefer the annotation to be on screen,and one participant even would prefer to have the annotation as fixed or even "behind" the monitor if it's possible.

Strategy. During the tasks, participants used different strategies when searching for the cheapest Hotel on a selected metro line. One participant focused on one type of information first (price) and then another (name). For them the different depths between these information helped them ignore irrelevant content: " *First I focus on the hotel price, I check with the red points (highlights) and then I am interested on the name of the stations. First I focus on one level of depth, and then another level of depth*". Another strategy adopted during the study is to navigate on each dot (station) and read all of the information afterwards. The participant using this strategy prefer the fixed label. Although the participant mentions that it is not comfortable while switching eye focus, she still prefers this technique because it won't occlude the nodes on the visualization.

Further discussion

In the user study, we found out that switching between different depths between display and AR can cause eye discomfort. This is consistent with the results of [23] and [18] which argue that repeated distance switching causes visual fatigue to steadily increase. Our participants chose to have the AR label and highlights close to the targets on the external display - which might because they are tightly coupled with the node target.

Meanwhile we found out the situation for annotation is more complex. Comments from our participants indicate that different searching strategies may effect the preference of depth combinations. The user who focused on the price information (annotation) first would like to have the annotation on the same level as the Hotels (highlights). Whereas the user who focused on the Hotels and looked through all the information next would like to have the annotation at a fixed position. Also we found out that the fixed annotation might be efficient to provide information which is constantly updated, as one of the participant mentions that " *I didn't have to wait for the labels to be on the field of view of the hololens*"

Overall, there is no one preferred depth placement (at least not for labels and annotations). Different depth placements might actually enhance the searching process and support different search strategies. It might be interesting to produce a new type of focus and context AR rendering, where the user can chose to focus on information at a certain depth level and ignore information on other depth levels.

As our study is largely exploratory and with a small set of participants, we need to further study this phenomenon.

4.4 Untested scenario

In order to verify our finding in the previous sessions, we plan to to a follow up user study. Due to the time limitation, we haven't have time to test it.

Visualization

We choose the Barchart drawer 3.2 as the second visualization. Because it's a common visualization type and it's has a third dimension encoded. We want to observe how the interaction with 3D visualization will effect user behaviors.

Scenario

After Arthur have made a decision about the hotel he wants to stay, he wants to find out when is the best time to visit Paris. He looks at a Barchart that represents the number of incidents over months. He has already selected several months without any exams so that he can come to visit Paris. He focuses on the bars to get more information about incidents on the metro (Annotation showing information about detailed number for each type of incidents and if the data is valid or not.) Now Arthur wants to buy a flight ticket to get back to his city, he needs to avoid the time that the metro is more likely to be delayed. He drags the Barchart handler out and looks closely at the area chart behind it. He looks at the line chart and gives an analysis of what time is more suitable for him (considering time and incident number).

CHAPTER 5

Remote user study challenges

Most of the development for this thesis was performed during the COVID-19 crisis of 2020, where France was under confinement. Due to academic and ethical concerns, we decided to do our user study remotely. This meant that we have to distribute the user study material to the participants and guide them to install everything to their own devices virtually over the internet.

Due to the nature of our study that includes an AR component and an external monitor, we faced several challenges during the phase development. In this chapter we will discuss about our remote user study setup and the solutions we adopted, as some of the challenges are common across any remote AR study. Our hope is that our solutions may be of use to future researchers.

5.1 Calibration Control

We use Vuforia [27], an image tracking package to align our visualization in HMD to the monitor screen. We only use the image detection function instead of image tracking - once the marker image is detected, we project the AR content accordingly and assume that user will not move their monitor. We made this choice because we need to take-over the camera in the HoloLens to record the user's view for further analysis. While this solution works well in a setup where we know a-priori the physical size of the marker and the monitor, the remote context raised the following challenges.

Control of the physical size of the AR content

The method we use to calibrate our visualization with a digital display is using the Vuforia Image Target. To avoid having participants print the marker, we decided to display a digital marker on the screen. Vuforia detects feature points of the target image, so it's important to make sure that the Vuforia marker on each participant's monitor has a size large enough to show these features. Moreover, our AR content is scaled based on the detected size of the marker, as our application knows the physical size of that marker. A marker image that is bigger or smaller size of what our application expects would have moved the AR content forwards or backwards in depth (see Figure 5.1). It is thus important for all the marker image to have the same physical size for all participants, to ensure they see the AR content in the same size.

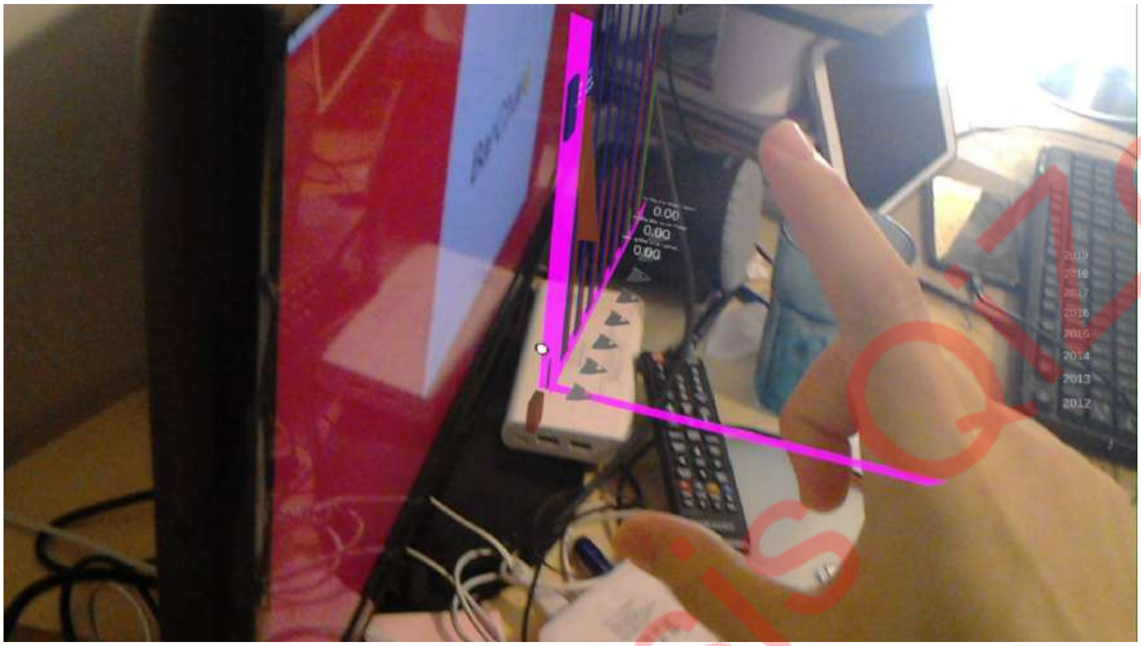


Figure 5.1: The depth offset caused by incorrect calibration marker size

Considering that each user is running the study from home, they may have different resolutions and physical size monitors. It is thus cumbersome to calculate all the parameters to setup the physical size of the Vuforia marker.

Our solution: We come up with an idea of using a international standard size called ISO7810 [29] as a reference. This is a common size in daily life: most of our bank cards, student cards and ID cards in the world are using this standard. Thus to help participants display the correct marker size, we first display a white rectangle with the same aspect ratio as the standard ISO7810 and on the side of this rectangle there is a slider which controls the scale of the rectangle (A.1a). Participants are asked to put a physical card on the screen as reference and adjust the size of the rectangle to match the card as accurate as possible. We then use the size of that rectangle (for which we now know the real physical size) to place the calibration marker. Participants are asked to keep their eye level the same as the marker and then calibrate the AR content.

This issue of not knowing the real resolution and real visual size of virtual items is a common problem in online studies, that are becoming more common using crowdsourcing platforms. We believe our solution is general enough to be of use to future researchers conducting remote studies.

After this calibration step, we also help participants define the size of their work space (monitor display). We use another two sliders to allow participants to adjust the scale of a green rectangle that is the "working area" of their display. This rectangle and its relation to the calibration marker it sent to the HoloLens. This enables the

Hololens to be aware of the physical size and location of the external display, in order to render information appropriately (for example in the Map visualization, the metro nodes/stations are rendered in AR only outside the monitor, as the monitor itself already renders the ones inside its borders/viewport).

Adjust position for shifting after calibration

We also provide interaction for minor adjustments after the calibration, as we found that there is still an offset sometimes. This offset may be caused by the monitor rectangle not being accurate enough or the user not putting their eye level at the center of monitor during calibration. The participants could use three sliders to adjust the location of the AR content, with an AR and a monitor grid indicator showing how good the calibration matching is.

5.2 Observations: Remote Virtual room

For the purpose of better understanding how people interact with our visualization prototype, we build a remote Usability Lab in VR, in the same Network that we used to connect the HoloLens and the monitor screen (described in section 4.1 Apparatus). We build the virtual room using unity, and it supports multi-platform as well. For the remote virtual room, we first designed three functions: Be able to see what users can see. Be able to assist users in a third person view. Be able to communicate via the network.

All the applications the participant are running (HoloLens,desktop application that shows the monitor content) belong to the same network as the remote room. We used a peer-to-peer networking architecture. We have a main virtual room that the administrator is running. The administrator has the authorization to send "approve task" commands to the HoloLens application and other commands to control the process of the experiment. Apart from this, any other experimenter can also connect into a virtual room to observe the user behavior. In our experiments, 1-3 experimenters were connected at any given time from different platforms (Windows, Mac, Android).

From the participant side, we set the HoloLens application and the desktop application as a Client, and the Observation applications are synchronized accordingly. We synchronize objects' and the user camera's location and rotation (Hololens) through the network. Any changes in the Hololens position or orientation is sent to the room. Similarly, complicated hand interactions in the Hololens send events to the room and are encoded in the virtual room scene. Finally, all mouse events from the participant's desktop are sent to the room updating content accordingly. Thus using the Observer application the experimenters can see in VR, in real time, the view and interaction of the remote participant.

We also build a third-person view 5.2 for the observer to better understand how the whole environment looks like and understand the relative position between the user and the monitor screen. By switching between the first-Person VR view and the third-person view, the observer can freely observe how people interact with the visualization.

To complement the VR room, during the actual study, the experimenters also maintained a skype connection with participants to guide them through the installation process, the calibration, and converse with them.

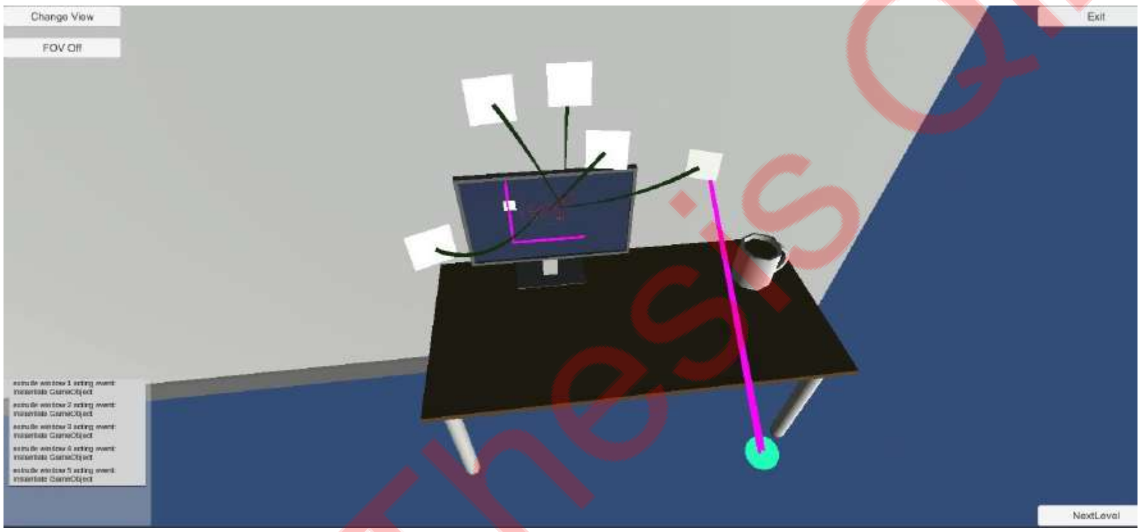


Figure 5.2: The third person view remote room, the greenish sphere represents the position of the HMD camera (the head of the user). A pink ray is extended from the sphere to show the direction of the remote user's gaze. The content of the monitor can also be seen, as well as the AR content floating in space. Buttons allow the observer to switch from 1st to 3rd person view.

5.3 Data recording

Our study was done remotely, so it's hard to understand all the user behaviors and actions just from Skype or the virtual Usability Lab (for example subtle hand movements and body movements). So we developed multiple ways to record the user study process.

We first of course recorded the Skype session and the Usability Lab view as videos. We complemented these, with a recording of what the participant was seeing inside their Hololens. To record this user view, we got access to the HoloLens camera, and when the study began, we started to record the Hololens video until each task was finished. We recorded each task separately, to prevent the potential risk of the HoloLens shutting down caused by overheating.

We additionally recorded a log file of all events arriving to the Usability Lab (including timing and errors, even if these are not reported in this thesis).

Finally, one of the experimenters also took hand-written notes as a backup during the study.

Chapter 6

Conclusion and perspectives

In this thesis, we explore the design space of placing AR content in front of a digital display for information visualization. We introduce several visualization examples we created to illustrate how using AR and depth can be combined with external digital displays. We build a broad design space regarding the goal for combining AR+Digital display, what content we put in AR, and how this AR content will be interacted with and behave. We hope that this design space will help categorize existing work and inspire new immersive analytics designs.

The design space we introduce is broad and can inspire much research on how to best combine different dimensions of the design space. We decided to focus on one aspect of the design space, the placement of meta data. To investigate the benefits and drawbacks of different placements (inspired by our design space), we conduct a user study to provide a practical user case and discuss how the choice of meta data (annotation, label, highlights) will affect the user experience. We found out that different strategies for searching information leads to different preferences in terms of depth placement.

We finally discuss challenges we faced when doing remote AR studies. We propose a process to control the physical size of calibration marker and slightly adjust calibrated AR content. This solution is general enough to help future researchers control the size of AR (or other virtual) content in remote studies. We additionally build a virtual room to assist the participants virtually and observe them that we believe could be of use to other researchers conducting remote AR studies.

However, there are still limitations in our work. First of all, our design space is created based on existing previous work and new designs we introduced. It is possible future research will open the space for new design dimensions. Moreover, our design space focuses mainly on visual aspects and we treat interaction as a separate dimension and don't explore it here in depth. This requires further study.

There are also limitations in our study. Our study only focus on one type of visualization, different visualization techniques might have an impact on the preference of depth placement as well. While in this thesis we had prepared a second scenario + visualization, the duration of the experiment prevent us from running it. Further more, our interactions in our study are inherently 2D and rely on interacting with the 2D visualization on the digital display. Future work could research the integration of 3D interaction in depth as well and how to transition from 2D interaction (with the visualization on the display) to 3D interaction (with the AR content). Additionally, the context of our user study is based on a monitor-size display with a focus and context scenario. We haven't explored how depth preferences could be affected by different size displays such as a Wall-size display, a mobile display and other various sizes. More generally, it might be interesting to see how the size of devices influences the design and interaction of visualizations. This remains future work.

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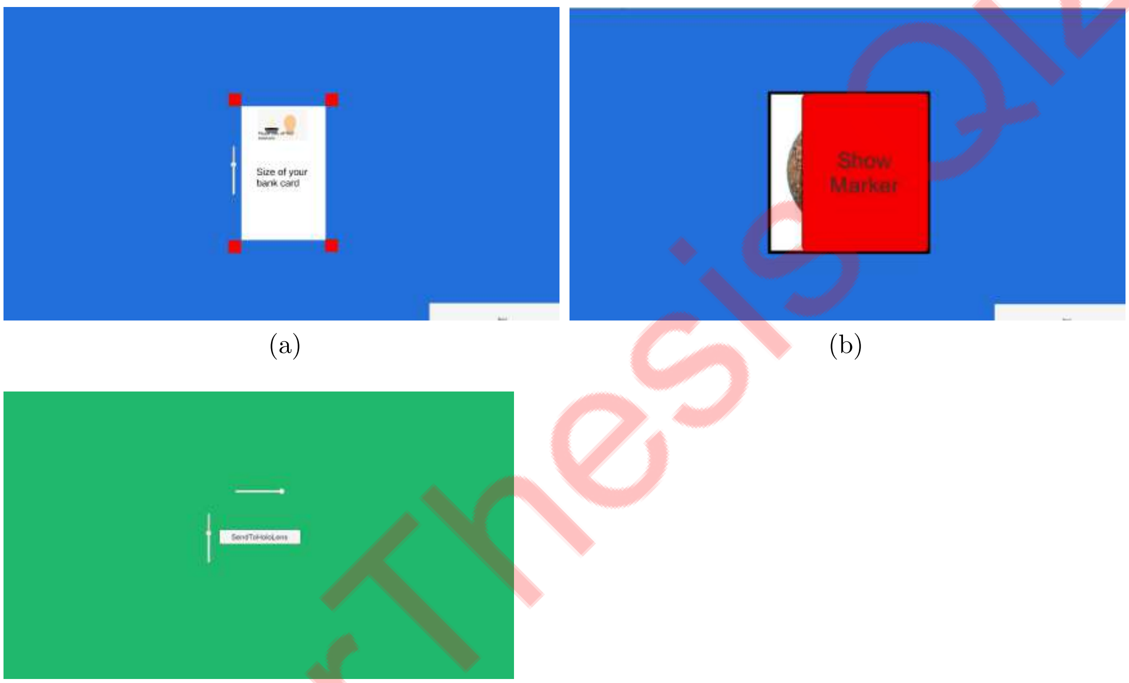
Appendix A

Appendix A - Interfaces for calibration



(a) (b)

(c)

Figure A.1: Calibration Interfaces. (a) The rectangle in the middle has the same aspect ratios with standard size ISO7810, the slider controls the scale of the white rectangle (b) Marker is hidden at first to prevent accidentally calibration. User has to keep the head level the same as the monitor and click the button to show the marker(with HMD on) (c) The green window will define the "workspace"(the black area in the map user case study) of the following study.

Appendix B

Appendix B - User study screen shot

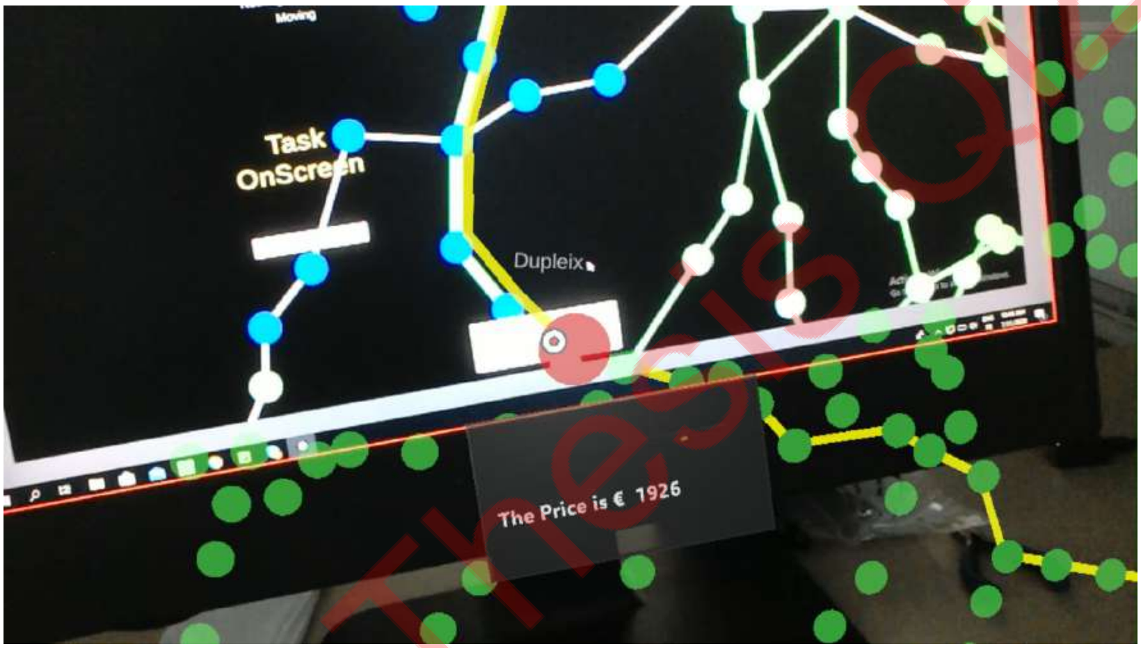


Figure B.1: Screen shot for Onscreen depth

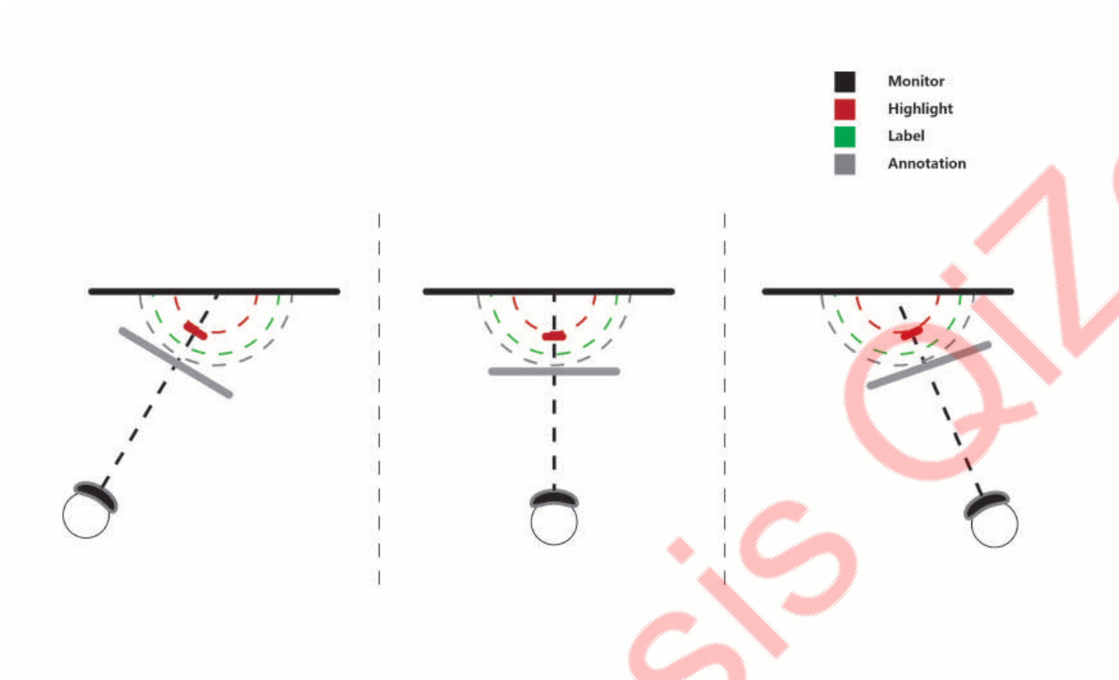


Figure B.2: Screen shot for Infront depth

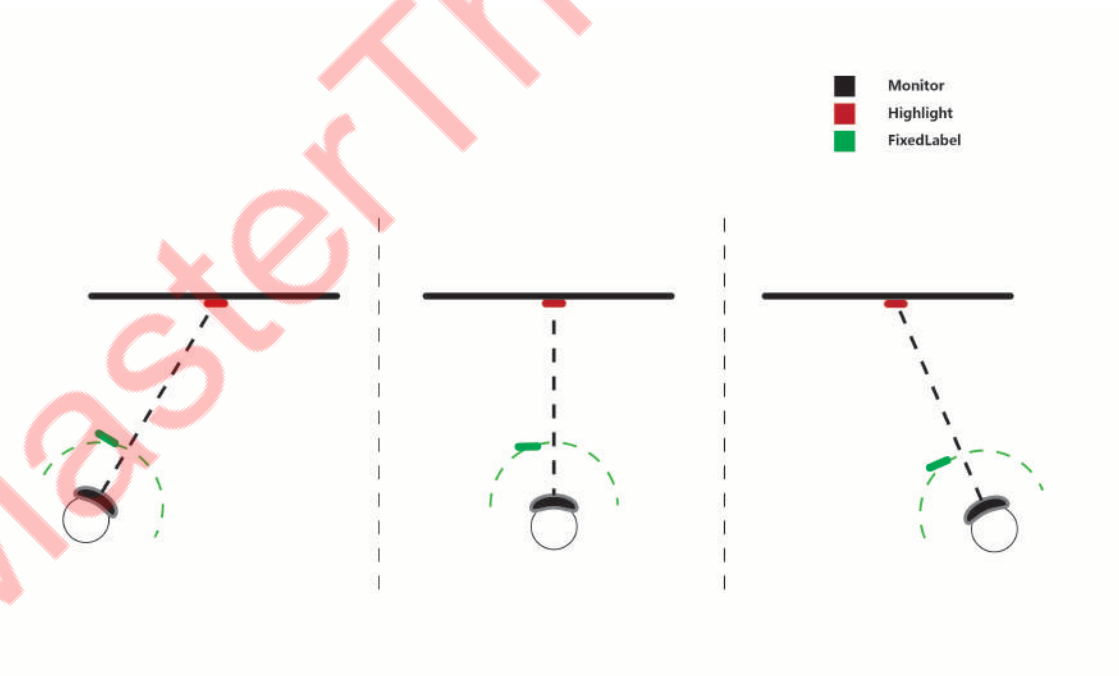


Figure B.3: Screen shot for Fixedlabel depth

Figure B.4: Screen shot for Customize depth