ImWeb: Cross-Platform Immersive Web Browsing for Online 3D Neuron Database Exploration

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ABSTRACT

Web services have become one major way for people to obtain and explore information nowadays. However, web browsers currently only offer limited data analysis capabilities, especially for large-scale 3D datasets. This project presents a method of immersive web browsing (ImWeb) to enable effective exploration of multiple datasets over the web with augmented reality (AR) techniques. The ImWeb system allows inputs from both the web browser and AR and provides a set of immersive analytics methods for enhanced web browsing, exploration, comparison, and summary tasks. We have also integrated 3D neuron mining and abstraction approaches to support efficient analysis functions. The architecture of ImWeb system flexibly separates the tasks on web browser and AR and supports smooth networking among the system, so that ImWeb can be adopted by different platforms, such as desktops, large displays, and tablets. We use an online 3D neuron database to demonstrate that ImWeb enables new experiences of exploring 3D datasets over the web. We expect that our approach can be applied to various other online databases and become one useful addition to future web services.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *Visualization techniques*; Web-based interaction.

KEYWORDS

Immersive web browsing, augmented reality, visual analytics, online database, 3D neuron exploration

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1 INTRODUCTION

In the era of big data, the web is one of the dominant platforms for obtaining information, as many resources are publicly available online. Among which, online database exploration has become a common task performed by various users in many disciplines. These databases are often domain specific and require significant efforts to study. Therefore, there is potentially a great benefit when suitable data exploration tools are provided. For example, dozens of 3D neuron databases [2] generated from ultra-scale brain images are the common interests of researchers in the fields of neurology, computer vision, deep learning, geometry modeling, visualization, and cognition. Being able to dig into different sets of information promotes advantages on the domain fields and interdisciplinary collaborations.

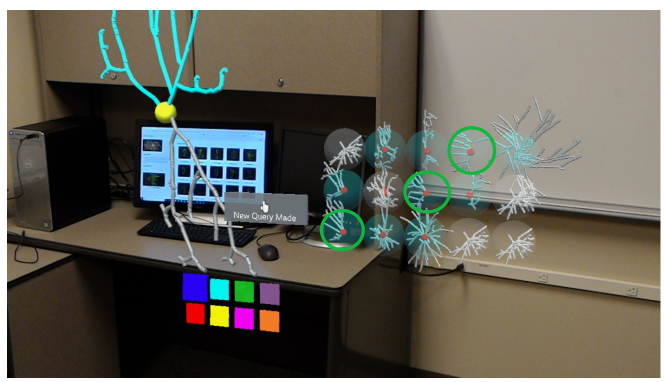


Figure 1: Immersive web browsing enables effective exploration of multiple 3D neuron datasets over the web with a set of intelligent and interactive immersive analytics techniques. This hybrid visualization generates floating panels around the space to provide useful information for the dataset that the user is gazing at on the web.

Currently, the websites of online databases only provide very limited exploration functions, such as index by species and name-based search. The limitations mainly come from the two following aspects. First, the design of a database website is often achieved by having a group of people as the potential users, such as neurologist, vision researcher, students, or the general public. It is also hard for one website design to fit all users. Over-complicated websites that try to meet diverse needs may overwhelm users with too many choices and generate negative impacts. Secondly, so far, web browsers do not have powerful capabilities of 3D visualization and interaction, compared to standalone 3D systems that optimize various resources; not to mention complex 3D visual analysis functions that requires specialized rendering techniques. Therefore, it is not practical to expect websites alone to provide various complex and adaptive exploration functions.

In this work, we present a new method for online database exploration, immersive web browsing (ImWeb), to overcome the two limitations described above. ImWeb aims at a flexible architecture that combines the features of both AR and the web, so that it can adapt to different needs of users without changing the hardware infrastructure. Specifically, web browsers are good for reading information. They can easily access large databases hosted on web servers and integrate extensive computing components such as deep learning algorithms. While AR is better suited for 3D visualization, enhanced depth perception, multi-model interactions, and using large physical environments, which greatly expand the limited rendering space on fixed displays such as monitors or touch screens.

Through a design study, we have identified application requirements and our main design goals. A set of mixed immersive visualization and interaction techniques are developed based on the focus of users in the physical space, including hybrid visualization for enhanced web browsing, immersive visualization to support 3D visualization and comparison in AR, and mixed data exploration techniques that allow users to switch between AR and the web freely for performing advanced analysis tasks.

The architecture of ImWeb supports flexible networking and registration mechanisms among web browsers, servers, and AR devices. ImWeb supports multi-model interactions that are achieved by mixed inputs from voice, gaze, gesture, body movement, keyboard and mouse. One important feature of ImWeb is to achieve smart analysis functions by integrating 3D neuron query and abstraction methods run on the server, and retrieving results directly for immersive analysis on both AR and the web.

We use an online 3D neuron database to demonstrate ImWeb on platforms with different display sizes, including tablets, desktop monitors, and large displays. We demonstrate ImWeb on a set of advanced data exploration, comparison, and summary tasks that cannot be achieved with only web browsers or AR. We also show that ImWeb provides personalized browsing based on user interaction from three different usage scenarios.

Our evaluation provides an informal study of the system usability from general users and domain experts. The results show that compared to the original database websites, ImWeb enables users to perform exploration and analysis tasks, significantly improve the understanding of 3D structures, and inspire more questions to ask about the datasets.

The remainder of the paper is organized as follows. We first present related work in Section 2. Section 3 overviews our design and architecture of the ImWeb system. We then describe the 3D neuron mining and abstraction algorithms in Section 4 and 3D immersive visualization and interaction methods in Section 5. Section 6 presents the case studies of ImWeb applied to different platforms and interaction tasks. Section 7 describes our evaluation and discusses the results. Finally, Section 8 concludes this paper and lists our future work.

2 RELATED WORK

2.1 Immersive Analytics

Immersive analytics [10] extend the classical desktop visualization into a variety of new environments, including AR and VR. While still in its early stages, immersive analytics has attracted the interests of many researchers. Both prototype systems of immersive analytics systems have been developed, utilizing the 3D virtual or physical space to explore different data tasks and interactions, and evaluation studies have been performed on the effectiveness of these approaches [22].

AR superimposes holograms with the environment around users and allows interaction with holograms and everyday objects together. The Microsoft HoloLens is a common example [11]. AR is more suitable for real action with the integration of virtual information in real physical environments. For example, AR was used as a tool to support the collaboration between rescue services for the police and military personnel in a crisis management scenario [29]. AR techniques were used to support quick context-related information exchange for operational units in the security domain that work together in teams [16]. AR-based mobile assistance systems in context-based provision of facility-related information [25] were shown to minimize the intensive recall required in this domain. Mahfoud et al. [26] presented an immersive visualization approach for investigating abnormal events in heterogeneous, multi-source, and time-series sensor data. Tahir et al. [27] explored AR for visualizing bio-diversity data in a large physical environment. Recently, a toolkit for building immersive data visualizations based on the Unity development platform has been published [33].

VR artificially creates sensory experiences, which may include sight, hearing, touch, and smell. Generally, VR is used for training purposes and it allows users to experiment in real time under various situations such as evacuation scenarios [34], Immersive analytics techniques in VR often take advantage of the advanced rendering and storage capabilities Kwon et al. [20] investigated the effectiveness of graph visualization and the impact of different layout techniques on readability in an HMD, and they concluded that the 3D stereoscopic graph visualization using Oculus Rift outperformed traditional 2D graph visualizations. Usher et al. [36] developed a VR system for users to trace 3D neuron structures from high-resolution images. Cordeil et al. [13] presented ImAxes system which allowed users to manipulate 3D axes like physical objects and combine them into sophisticated visualization for exploring multivariate data. Yang et al. [40, 41] explored different ways to render world-wide geographic maps and and studied the origin-destination flow data in a global geographic context.

Specifically related to immersive analytics, a number of recent studies have been performed and the results are still mixed. For example, studies of performance on collaborative immersive visualization using the recent HMDs, such as Oculus Rift and HTC

Vive, have shown no difference with expensive equipment such as cave-style environments [14]; while Kwon et al. [20] concluded that the 3D stereoscopic graph visualization with an Oculus Rift out-performed traditional 2D graph visualizations. also, Bach et al. [8] showed that both desktop and immersive environments are more effective for certain tasks, but that generally the desktop environment was still fastest and most precise in almost all cases. Recently, immersive navigation [39] showed significant performance improvement in VR and AR environments, on tasks that include tracking, matching, searching, and ambushing objects of interest. Overall, Some advantages of immersive analytics have been demonstrated, especially favorable results for stereoscopic techniques [14, 20, 38].

This work presents an AR system, requiring us to handle issues of networking between online servers and AR devices and registration of AR devices with the real world. We take advantage of the stereoscopic visualization of 3D neuron structures and develop interactive immersive comparison approach for exploring multiple 3D datasets.

2.2 Cross-Device Techniques

AR developers face a proliferation of new platforms, devices, and frameworks, leading to new applications and techniques created with cross-device approaches. Similarly, ubiquitous analysis integrating different devices and frameworks were also proposed [17]. For example, the GraSp approach [19] demonstrated that spatially-aware mobile displays and a large display wall can be coupled to support graph visualization and interaction. Horak et al [18] presented the combination of smartwatches and a large interactive display to support visual data analysis. Butscher et al. [9] combined a touch-sensitive tabletop and AR headsets to visualize clusters, trends, and outliers in multidimensional data. Recently, Speicher et al [35] developed a taxonomy of AR system components and identified key challenges and opportunities in making them work together through a review of existing AR platforms and a survey of 30 AR designers, developers, and users.

Cross-device techniques often need to handle the networking and communication among multiple devices. For example, VisHive [15] constructed web-based visualization applications that can transparently connect multiple devices. Similarly, our approach contains a server-device networking component to stream data from online servers to devices upon request.

2.3 Augmented Reality Browsers

The web has also started to intertwine with AR and VR. It is worth to mention low-cost AR browsers, such as [21], [28], and [12]. These projects use mobile phones as the device users look at, to see the virtual content augmented onto the real environment. Mobile Phones are the most accessible and popular AR devices for the general public to experience AR applications and therefore are a natural avenue for development. Web browsers, such as Firefox Reality [3], is released recently and is also under-development for more AR/VR functionalities. When viewing in AR/VR devices, AR web browsers allow users to view objects/models in 3D and also interact with them.

It is also worth mentioning that the latest in-development AR web browsers are less likely to overcome the limitations described in the introduction. In addition, AR browsers transform the web browsers into 3D and may lose the advantages of web browsing on regular displays, which we have already been very familiar with. Distinct from the above AR browsers, our approach provides a flexible architecture to connect web host and AR devices, allowing the same AR devices to be applied on different web host and supporting advanced 3D visualization, visual analytics and comparison techniques.

3 CREATING IMWEB SYSTEM FOR ONLINE DATABASE EXPLORATION

3.1 Application Requirements

In this work, we focus on an important and challenging application of web browsing, online 3D neuron database, as it often requires expert knowledge in neurology and 3D interaction techniques to explore neuron structures. Neuroscientists have been striving to understand the neural structure of the brain by seeking more information about individual neurons and analyzing the connections between neurons.

The analysis of neuron structures, otherwise known as neuron morphology, is an important part of determining a neuron’s function. A typical neuron consists of a cell body (soma), dendrites and axon. The structure of neuron is essentially a collection of polylines that represent dendrites and axons leading from the nucleus. The length of dendrites and the amount of branches in the dendritic morphology can be indicative of the type of neuron.

We use the NeuroMorpho database [1, 7], which has the largest collection of publicly accessible 3D reconstructed neuron data. These datasets are from several species including baboon, celegans, chimpanzee, drosophila melanogaster, giraffe, human, monkey, mouse, and rat. Each dataset contains the spatial coordinates of the sample points of a neuron and their connections in addition to the width of the dendrite or axon at that point. We can model a dataset with N nodes as a collection of links from a parent node n_p to the child node n_c, where the node coordinates are also included:

$$T = \{n_p \rightarrow n_c, p, c \in [1, N]\} \quad (1)$$

Currently, the existing software available to view these structures are only designed for 2D screens. It will be ideal to provide 3D visualization and analysis functions for users to further explore neuron morphology and the related functional properties. For example, given a query neuron, the system can provide its top similar neurons by measuring morphological features with every other neuron in the database. Subsequently, comparison of similar neurons can be carried out from holistic to fine-grained level, such as comparing two neurons segment-to-segment or point-to-point.

3.2 Design Goals

We use online neuron exploration as the model-driven application to design our ImWeb system. The following describes our primary high-level goals that drove the design of the system.

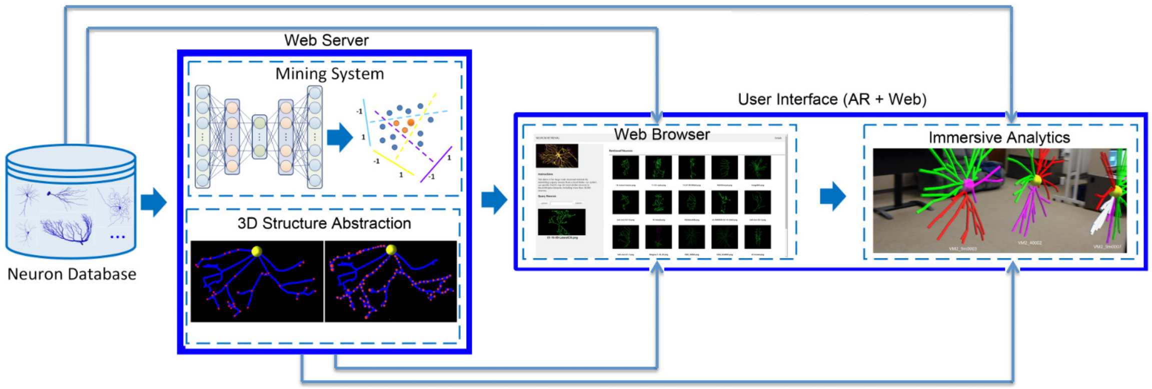


Figure 2: The architecture of ImWeb. The data flow is from the database, to servers where complex 3D neuron mining and abstraction algorithms are performed, to the mixed user interface of AR and the web. Among the user interface, AR registers the location of web browser in the physical space and retrieves 3D models of the snapshots shown on the browser from the database automatically. The wide blue arrows mark the order of several system components, and the thin connectors label the actual data flow from database and server to the web browser and AR devices separately.

DG1. Facilitate a variety of input integration for mixed multi-modal interaction. Integrating web browsing and AR offers challenges for interaction between the two paradigms. Our goal is to support not just a unique way for interaction between the paradigms but to offer a variety of interaction patterns. This goal requires us to consider synergies between the two paradigms while designing the interface and offer not just explicit and follow-up but also contextual interactions.

DG2. Facilitate a variety of information integration methods for providing intelligent personalized visual interface. With the mixed multi-modal interaction, there are many opportunities to integrate information extracted from user behaviors and data analysis algorithms. We could extract information regarding user's focus and objects of interest and intelligently integrate them into the system to provide personalized interactions and visualizations.

DG3. Facilitate a variety of exploratory analysis tasks that are cross-platforms for different users. A core goal for our system is to enable exploratory tasks for neuron structures in an immersive, multi-modal setting for the user. More specifically, we focused on supporting tasks including immersive exploration, interactive comparison and classification of neuron structures, and finally the ability to summarize results of exploration and comparison for overall sensemaking.

3.3 Overview of System Architecture

As shown in Figure 2, the ImWeb system contains three main components: a website for browsing online neuron database, an AR device for immersive analytics, and a web server for supporting the web browser and AR devices.

- The Apache server is set up using the web development platform known as WampServer in order to query the web interface and send the query results to AR devices. The server also handles the abstraction of 3D neuron structures when the user requests various levels of simplified neurons to be displayed in AR.
- The Web interface is developed with Django. The main function of the website is to query neurons with similar 3D morphologies and provide the snapshots and names of the top query results. The website can run on any modern web browsers on different platforms.
- For AR, we use Microsoft HoloLens to demonstrate immersive analytics functions. Interactions achieved through the Hololens automatically send HTTP requests to the server for the retrieval of relevant data.

In our ImWeb system, the web browser and AR devices are built from completely separate libraries. They are not connected through networking directly. Instead, AR devices register the 3D location of the website in the physical environment, so that web browsers can be combined with other virtual renderings in AR for immersive analytics. The following provides the details of two types of connections in our system.

3.3.1 Networking and Data Transfer. The three system components are loosely connected through the shared files stored on the web server. As shown in Figure 2, both the web browser and AR devices can send requests to the web server and retrieve the datasets or results from the mining system and data abstraction algorithms. The connections between the web browser to server and between AR devices to server can be built differently, so that they do not rely on specific devices or platforms. The inputs (such as the input of the query) are stored and results are shared on the server.

To reduce the memory required for the application to run on the HoloLens and to reduce its computational load, we have chosen a client-server approach to send and store data collected from the NeuroMorpho database. HoloLens can automatically request any recorded information or data from the database via HTTP requests to the server. The datasets are stored in a WAMP server that queries the website to determine which neurons the user is interested in and then proceeds to send the data via GET requests upon user request.

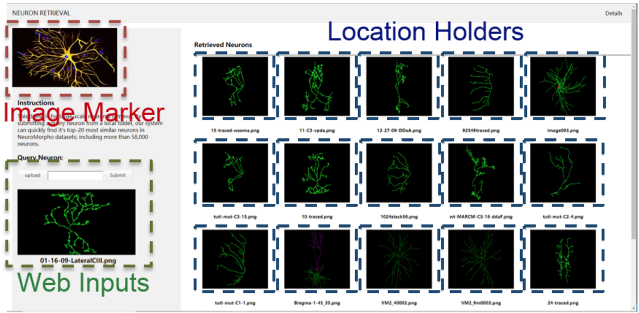


Figure 3: An example interface of the neuron database website. The main function of this website is to search a neuron by name from the NeuroMorpho Database and return snapshots of the top 15 query results shown on the right panel. The only change we made to the website is the image marker circled in red, representing the neuron database and being used to register the 3D location of the website in AR. The location holders marked in blue are used to detect if the user is gazing at a specific dataset. The green zone marks where the user can provide input to query the database.

3.3.2 System Registration. The ImWeb system achieves the coordination between AR devices and the web by registering the physical environment containing displays for hosting the web interface, to the virtual world where 3D renderings are provided by AR devices. The same approach can be applied to platforms with different operating systems or display sizes, such as tablets, desktop monitors, or large displays.

As the example interface shown in Figure 3, we separate the web interface into three zones. The red image marker is the only change we add to the website and is used as the anchor point between the virtual and real worlds. The registration is achieved by incorporating the Vuforia Engine [5] and its image target recognition functionality. Once the user gazes at the image target on the website, the AR world snaps to that position in order to have a reference to where the user is looking in the real world.

The blue and green zones are computed by their relative locations and sizes to the red image marker. Once the system is registered, the AR device can track the gaze locations on the website by matching the gaze to one of the location holders colored in blue. The index of the location holder is further used to find the dataset name from the query results shared on the server. Next, AR devices can retrieve the corresponding 3D datasets from databases directly and visualize their information or 3D structures in space. The green zone of the web inputs can also be modeled in the similar fashion, so that gaze patterns of users during the exploration can be recorded and utilized to provide adaptive interaction functions.

3.3.3 Multi-Model Interaction. The inputs from both AR devices and the web can be combined to support multi-model interaction. Users can focus on the website using keyboard and mouse while looking at enhanced information provided by the AR device. Users can also use a combination of hand gestures, voice, gaze, and physical movements to interact with virtual objects. Our case studies provide three usage scenarios to demonstrate that our ImWeb system can provide enhanced web browsing interactions through the mixed inputs from all devices (DG1).

As the system architecture shown in Figure 2, the root of the user interface is set on the web browser. The expected workflow when using our ImWeb system consists of exploring the data through the web interface first and then bringing a few specific neurons into the physical space with AR devices and performing more in-depth analysis there.

4 MINING AND ABSTRACTING 3D NEURON DATA

We provide the following two methods as examples of intelligent algorithms that can be integrated to support smart interactions in our system. They are both performed on the web server, which supports various heavy-load computations efficiently.

4.1 Interactive Mining using Machine Learning

The main objective of our mining approach is to provide a robust and efficient comparison system that automatically searches for neurons with similar morphologies. According to related works of neuron mining [23, 24], the first step in the mining system is the quantitative description – using feature vectors to represent all neurons in the database. Particularly, both the deep learning based features [23] and the measurement based features [32] are used for the quantitative description of neurons.

Subsequently, considering the current database already includes huge amounts of neurons, it would be very time-consuming to perform an exhaustive search of similar samples using the long neuron features. Here, we employ the large-scale mining method (i.e. binary coding [37]) which can compress neuron features into short binary coding, while preserving their original similarities.

This neuron mining system enables a user to narrow down their search when users specify a query neuron. The system can accurately provide its top similar neurons in real-time.

4.2 Shape-Preserving Abstraction of 3D Structures

Due to the limited performance on AR devices, we need to control the sizes of all datasets that are required to be transferred to and stored on the HoloLens. Neurons consisting of only one thousand sample points would still cause the frame rate of application in the Hololens to fall below 20 frames per second. We have explored abstraction methods to simplify the details of 3D neuron datasets and preserve important shape features for analysis.

As the example shown in Figure 4, the nodes on the original datasets are often densely distributed, especially when the variations of dendrites are small and they are closer to the soma colored in yellow. We have considered several aspects for abstraction, including preserving the branches for structures, curvatures for shapes, and weights of branches. For efficiency, we simplify the curvatures $c(n_i)$ at each node n_i with the distance $d(n_i)$ of the node n_i projected on the line formed by adjacent nodes n_{i-1} and n_{i+1} [4]:

$$d(n_i) = \frac{(|\overrightarrow{n_i} - \overrightarrow{n_{i-1}}|) \times (|\overrightarrow{n_i} - \overrightarrow{n_{i+1}}|)}{|\overrightarrow{n_{i-1}} - \overrightarrow{n_{i+1}}|} \quad (2)$$

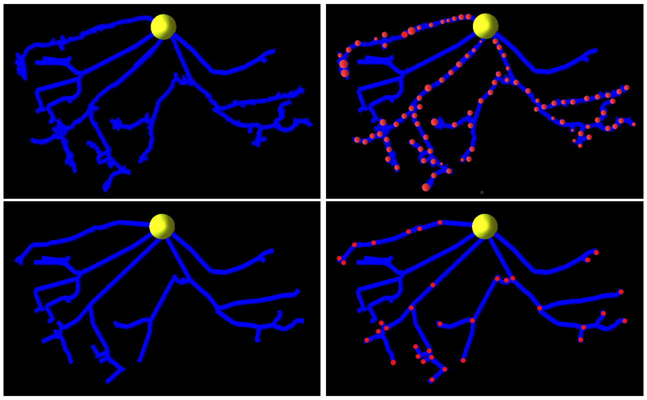


Figure 4: Abstraction of neuron structure. The first row shows the original dataset (left) with nodes on several complex branches highlighted in red (right); and the second row shows an example of the results of simplification. While we reduce the data sizes significantly, the important shapes of the branches are preserved.

$$c(n_i) = d(n_i)/|\overrightarrow{n_{i-1}} - \overrightarrow{n_{i+1}}| \quad (3)$$

where $\overrightarrow{n_i}$ is the 3D location vector of node n_i. The $c(n_i)$ removes the factor of absolute distance from the shape variation.

We traverse the neuron structures from soma at the root to the leaves to generate a simplified version. For every node except the root and leaves, we compute $c(n_i)$ and only keep the node when $c(n_i) > T_d$, where T_d is an adapted threshold. We initialize T_d with a pre-defined value based on experience. When no nodes are removed, we reduce T_d to a proportion and repeat the process. Several iterations are often performed until the ideal data size is reached. As the example shown in Figure 4, our approach reduces the amount of nodes needed to be rendered without losing important shape features.

To provide high-quality visualization, we request abstracted datasets only for very large datasets or when multiple datasets are transferred at the same time. Based on the situation, we can request datasets abstracted at different levels by identifying the ideal data sizes. In addition, we can switch the details of individual branches by using the original detailed structure for that branch when the user selects and interacts with it.

5 IMMERSIVE VISUALIZATION AND INTERACTION

Our ImWeb system supports interactions through different types of immersive visualization and visual analytics functions. The HoloLens API is used to implement the inputs from voice, gaze, and hand gestures for immersive analysis.

We cover all three options based on the user's focus where interactions are mainly performed: the web, AR, or the combination. The following describes each option in details.

5.1 Hybrid Visualization for the Web

Based on our system infrastructure, we have designed a hybrid visualization that generates immersive displays and visual cues based on the user interaction on the web *(DG2)*. The hybrid visualization assumes that the web browser is the main interaction domain. We can use AR as a second display for showing additional useful information, which overcomes the limits of web interfaces with a fixed layout. The following describes two types of hybrid visualization, floating visualization on the side of user's gaze and virtual labels overlapping with the contents on the web.

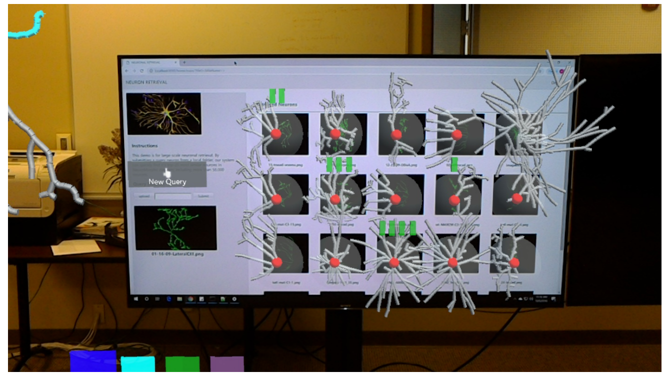


Figure 5: Hybrid visualization enhances the web interface with the overlaid virtual labels (green tally marks on the top of snapshots) and miniature 3D renderings (overlaid on the snapshots shown on the web browser).

The first design - an immersive floating window - generates an additional visualization panel through AR that serves the role of an assistant. The assistant tracks the gaze of the user, collects relevant information, and selectively displays additional information *(DG2)*. For example, Figure 1 shows the floating window providing additional information describing the neuron structure being observed by the user.

The second design - virtual labels - overlays helpful information on the web interface. Our ImWeb infrastructure supports the registration of AR and web interface, so that visual labels can be added through AR, enhancing the website with additional information, such as certain data statistics. As shown in Figure 5, we show tally marks to keep count of user interaction with a specific dataset. Figure 1 demonstrates that the user can also add highlighted bounding circles around query results to show their similarities.

One advantage of such hybrid approach is to enhance the original website without re-designing it. Additionally, this allows convenient integration of voice commands provided by AR devices with different web interfaces. In our design, users can use voice commands to switch among different interaction functions, for instance, switching focus between web and AR *(DG1)*.

5.2 Immersive Visualization and Interaction with AR

Our immersive visualization component for HoloLens is built with Unity3D, a game engine that supports development for AR/VR devices. We used Unity's primitive objects to create the neuron structure out of cylinders and spheres. The figures in case studies provide several examples of our 3D neuron visualization.

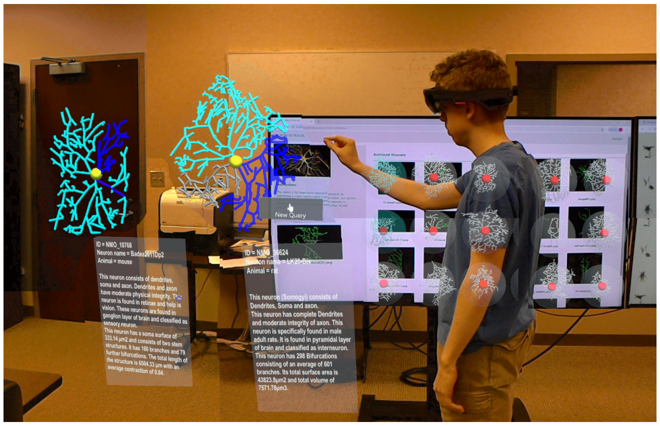


Figure 6: User interactively exploring and comparing 3D neuron structures in front of the large display. (Only this image in this paper merges several snapshots from HoloLens using PhotoShop. All the other images are snapshots taken from HoloLens directly.)

In AR viewed through the HoloLens, different combinations of user’s gaze, hand gestures and voice commands are incorporated to make AR interactions intuitive and immersive. For instance, a combination of gaze and hand gestures allows *drag-and-drop* interaction, combination of voice command and hand gesture allows *3D manipulations* such as scaling and rotation. Users can also choose to hide, show or convert structures to miniature versions using gaze and voice commands.

The user can move, rotate, and scale neurons by switching to the corresponding mode via speech commands and then performing a dragging motion with their hand *(DG3)*. Users can also airtap the pictures on the website while looking at them to visualize their 3D structures in the virtual space. The only interaction currently allowed on the website is the querying function which displays the most similar neurons under the “Retrieved Neurons" heading.

5.3 Mixed Data Exploration and Analysis

For complex tasks, such as comparing multiple 3D structures or exploring relationships between two groups of datasets, the focus of user is expected to switch between the web and AR. Our interaction and exploratory analysis functions are achieved by integrating intelligent algorithms for 3D neuron queries and structure simplification on the web with interactive 3D visualization of heterogeneous information from the web and database *(DG3)*. We describe the details of mixed data exploration, comparison, and summary as example tasks in the following.

5.3.1 Data exploration. While a user is browsing the datasets on the web, HoloLens allows tracking of user’s gaze and shows individual 3D structures alongside their detailed description. The user can continue to explore different datasets or switch to observe the detailed 3D structures in the AR visualization and immersively interact with it in the physical space around them. The HoloLens also records all user behaviours, including details about the dataset(s) explored from the web and branches and structures which the user interacted with using AR. This feature can help us to understand the work-flow of users and provides data to create intelligent suggestions in the interface.

To augment sensemaking during data exploration, we use AR to visualize the history of user interaction. Our system keeps track of datasets the user has explored so far and user can observe them again using simple voice command “show history". This allows users to revisit any interactions that lead to the current visualization, enabling users to connect results from different datasets or groups. Our mixed interaction allows users to explore 3D structures immersively and it provides important 3D visual cues that are hard to achieve with only web based visualization.

5.3.2 Structural comparison. To explore the relations of multiple similar datasets, visualizing only one dataset at a time is not enough. We needed to provide effective visual comparison methods to help users explore similarities between multiple datasets, so that we can better understand their purpose, either individually or as a group, based on functional classification.

For comparison, users can interact with multiple 3D structures on the web interface and visualize them in AR. Our system intelligently positions them in the physical environment such that the structures are not overlapping with each other and are scaled properly to make sense of comparison. For example, when comparing multiple misproportioned neurons, our system intelligently and proportionally scales them to allow effective comparison. This process is vital according to the theory of distributed cognition[31] as it allows seamless information flow between internal and external representation of visualization. By externalizing the process of reasoning and cognition, we achieve cognitive off-loading.

During comparison mode, all the structures are colored gray so that user can compare individual and collective structural components and color them interactively using hand gestures based on their similarities. To visualize similar sub-structures, user chooses a color from the color palette and uses hand gestures to select the start and end point of a branch. The system then automatically colors every link between the endpoints with the selected color. This process also allows users to re-confirm results from web interface based comparison.

5.3.3 Summary visualization. To assist users to comprehend information from large datasets and similarities between their complex structures, we integrate information analyzed from the whole database and the interests of users during their use of ImWeb. The summary visualization provides a high-level visual report of a user’s selected group of datasets. It generates a high level overview of what the user has explored. This process is important to piece together all the insights into an understandable and compelling whole.

As context, we provide a 3D scatter plot visualization computed using MDS algorithm on similarity matrix of the whole database. As focus, we highlight data-point of the structures user has explored using AR or the web interface. We also suggest similar structures for the user to explore as shown in Figure 8(a) by creating arrows pointing to them. First, by viewing structures explored so far, users can understand their cluster classification based on species and then interact with the scatter plot to visualize highlighted suggestions in the AR environment. This provides an interactive 3D interface to summarize multiple datasets with their similarity relationships and detailed structures; at the same time allowing users to explore additional information interactively.

6 CASE STUDIES AND USAGE SCENARIOS

To demonstrate our cross-platform approach, we provide three case studies of immersive web experiences with the database website hosted at different devices, including iPad, desktop, and large screen. They demonstrate the flexibility of our approach on the most frequently used displays from small to large and a variety of intelligent interactions that can be provided to assist users on different tasks.

6.1 Exploration of Neuron Morphology on Desktop

Consider students at a school interested in exploring and learning different neuron structures for a class project. Instead of observing their complex anatomy using a 2D microscope, students use our system in combination with a desktop computer to study a large number of 3D neuron structures on their desk. Students can start with simple neuron structures to understand the common structural theme of soma, axon and multiple dendrites within neurons. They browse through different datasets on the websites and choose among structures to view in AR using exploration mode. Our system visualizes the structures in 3D details when using exploration mode, as shown in Figure 7(b). They comprehend detailed description of each neuron provided by the system (Figure 7(a)) to understand function and classification of the neuron.

Next, they can either use web interface or floating windows in AR to choose and then visualize more complex structures and explore how each neuron connects and communicates to other neurons through synapses, tiny junctions between dendrites of two different neurons. These connections stimulate or inhibit neural activity, forming circuits that can process incoming information and carry out a response. Students make use of the physical space to move around and observe neurons and how they connect to each other from different standpoints. They scale and re-position neurons using hand gestures and interact with branches (dendrites) in the structures to comprehend them in detail (Figure 7(c)).

Finally, students make use of history visualization (Figure 7(d)) to revisit their interactions from the start and note down their observations of anatomy of neurons and how they communicate with each other to understand their collective dynamics and astonishing collective functions.

6.2 Interactive Visual Comparison on Large Display

Consider domain experts in deep learning at a university who have implemented algorithms for measuring similarities among large-scale 3D neuron structures. They use the algorithms to find datasets with the most similar structures and wish to validate their results. Validation is often achieved by interactive comparison of the query inputs and results by domain experts. Our system allows users to compare multiple structures side-by-side and color sub-structures that are wrongly classified for providing feedback of improvement.

First, using the web interface on a large display, the user queries a neuron structure of interest. ImWeb then generates results in order of non-increasing structural similarities using a data mining and machine learning algorithm. Now to explore the structures in 3D, user registers HoloLens with large display using Vuforia marker. This introduces immersive floating window in AR showing detailed description of query neuron and also 3D miniature of query results for the user to interact with. User brings 3D structures of query results into physical space by interacting with miniature structures (Figure 6). Now to effectively arrange them into the space, the user makes use of 3D scatter plot as shown in Figure 8(a) to understand the cluster classification of selected neurons. Classification of neurons is based on the species they belong to and also similar neurons are positioned closer to each other, signifying comparable equivalence. Neurons selected by the user on web interface are also highlighted in the scatter plot and their names are shown when gazed upon.

After positioning multiple neuron structures based on their classification in the scatter plot, the user moves around in physical space to observe and explore each structure separately. After comprehending structural details, the user switches to comparison mode in HoloLens using voice command, where all neuron structures are colored gray to allow interactive coloring of similar sub-structures using hand gesture airtap. The user selects a color from the color palette and taps on the start and end point of branch or sub-branch structure to interactively color them in multiple neural structures. This process of interactive coloring allows user to visualize similar sub-structures in multiple neurons, classify them into sub-groups based on similarities and also confirm results from the algorithms as shown in Figure 8(b). The user also makes use of functionalities like re-positioning, re-orientation and scaling of neurons to make process of comparative analysis easier and simpler. For instance, the user observes that structures named *DEV174T4*, *DEV98T1* and *LK20-Bis* have a lot of similarities and classifies them into one group. These neural structures are found in *Hippocampus* of *Rattus*(brown rat). Similarly, user classifies neuron structures named *Basin-4-a4r*, *gorogoro-t2r*, *Ipsiphone-L* and *ddaC-a1L* into one group. These structures are part of peripheral nervous system of *drosophila melanogaster* (common fruit fly).

After successful interactive comparison of multiple structures, user can use the voice command "shrink neuron" to convert the structures into miniature versions and place them into groups to revisit the earlier interactive analysis as a sensemaking task as shown in Figure 8(c). This allows the user to then take snapshots of the history view for future reference outside of the Mixed Reality environment.

6.3 Summarizing Exploratory Analysis on Tablet

Consider users visiting a science museum, who are interested in exploring and understanding neuron structures in 3D. Due to the public place setting of the museum, users can use iPad tablets to explore the web interface of our system. User explores different neuron structures using a combination of iPad and HoloLens headset (Figure 9). Users peruse description of each neuron to understand their classification and the high level purpose while observing their

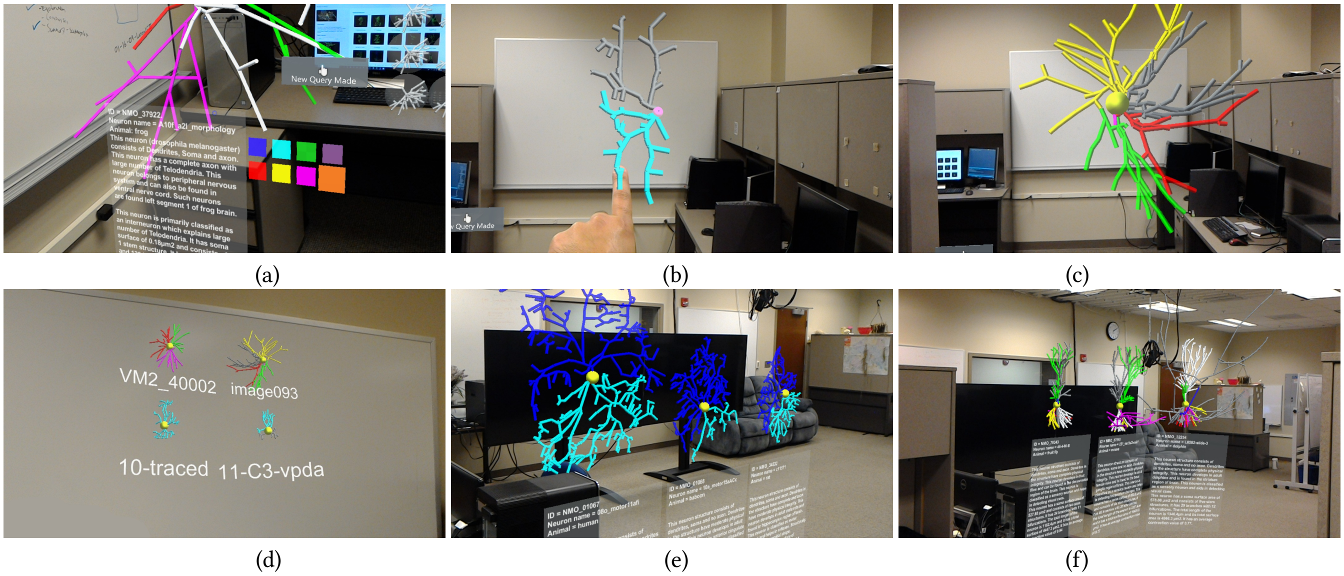


Figure 7: Exploring the morphology of different neuron structures: (a) Structural description of each neuron to understand its function and classification, (b, c) immersive exploration of different neuron datasets to understand common structural theme of neurons and various substructures, (d) history visualization to revisit user interaction which enables better sensemaking, (e) exploring different motor neurons and understanding their description, (f) grouping and exploring multiple sensory neurons to understand their function.

structures. Detailed description provides information regarding to common and scientific names of species the neuron belongs to and which part in central nervous system the neuron is commonly found. This also informs user regarding possible action(s) the neuron might be responsible for. For example, user discovers that neurons classified as motor neurons are responsible for reflex actions and are mostly found in spinal cord. Based on this description, user verifies that motor neurons are *multi-polar*, meaning that each structure contains a single axon and multiple dendrites as these dendrites have endings in multiple control muscles, making reflex action possible.

After exploring different types of motor neurons in the database using the query feature (Figure 7(e)), user is intrigued to explore further types of neurons. User starts to investigate sensory neurons which are responsible for stimulating motor neurons in the first place (Figure 7(f)). Sensory neurons consists of a large number of receptors that transfer information about external stimuli to central nervous system. User reads and observes that these receptors can be of different types that respond to different kinds of stimuli, for instance taste, smell, vision, sound, touch and temperature. User further explores 3D structural differences between different kinds of sensory neurons using HoloLens and further analyzes their detailed structure by interacting with branch structures.

Finally, user converts each neural structure explored into the miniature version and positions them separately based on their functional classification as inter-neuron, sensory or motor neuron. This process allows user to revisit his earlier explorations and understand their prominent structural differences, if any.

6.4 System Performance

As shown in Figure 2, our system contains several components that their performances can be measured separately. The data storage, rendering, and file transfer speeds are affected by the sizes of involved neuron datasets directly.

Overall, our system has achieved interactive performance for all the examples and case studies. We did use simplified neurons when multiple complex neuron datasets are involved. To maintain interactive rendering speed on HoloLens, we generally keep the numbers of nodes at the level of hundreds. The final node numbers depend on the complexity of the neuron structures.

The frame rate per second of our HoloLens program remains above 25 while displaying neurons in the controlled size ranges, but can start to deteriorate for very large datasets. When retrieving data from the database the transfer time for files up to 2MB takes less than four seconds generally. We have found that this performance is suitable for most use cases, but improving performance will be an avenue for future work.

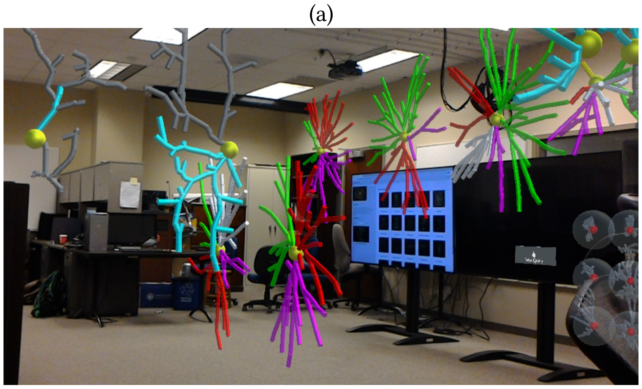
7 EVALUATION

We received informal assessment from general users and domain experts in neurology. Here we describe their comments, advantages and limitations of the system. We also provide a discussion to summarize our findings from the informal assessment.

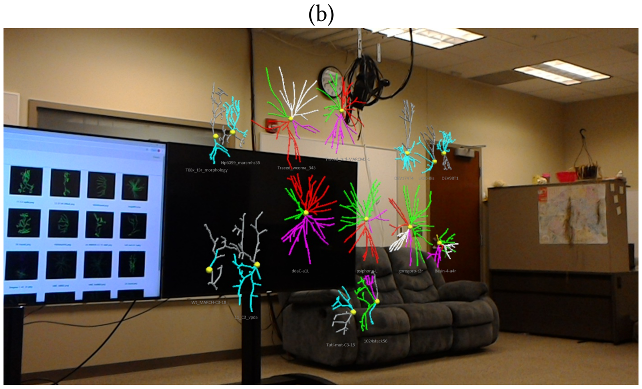
7.1 Informal Study with General Users

To get a hands-on feedback with our system, we performed an informal study with 8 graduate and undergraduate students to understand their work flow and evaluate usability of our system. All

(a)



(b)



(c)

Figure 8: Interactive comparison and classification of neurons. (a) 3D scatter plot showing clusters of neurons in the database, (b) interactive comparing and classifying of results from the web interface using HoloLens, (c) history visualization using miniature version of all neuron datasets compared by the user.

users were computer science major and had moderate knowledge about visualization systems. Most of the participants had previously used HoloLens but only for a very brief time interval, thus they had very little experience with visualization on HoloLens and interaction on HoloLens using voice commands and hand gestures.

Our evaluation goal is to assess the combined immersive approach of AR and web browsers using our prototype system. Since it is hard to compare our system with websites or AR programs

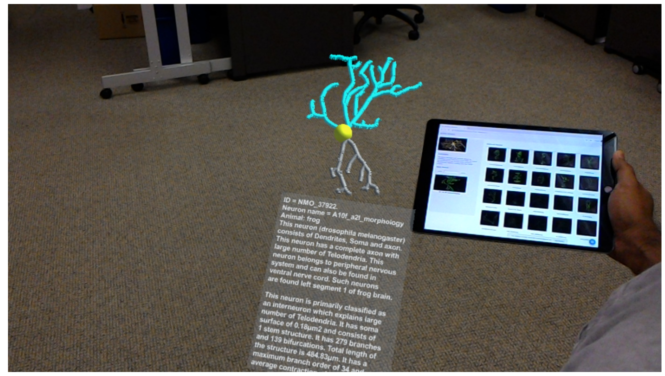


Figure 9: Using iPad device to explore neural morphology.

due to the obvious drawbacks of standalone systems, we did not perform a usability study. Instead, we performed an informal study to observe how users interacted with our ImWeb system. During the study, users were asked to explore different neural structures using combination of web interface and AR and also interactively compare them in the physical space using the provided set of interactions and visualizations.

We summarized our findings through observation as follows. In general, most users appreciated the system and our approach to integrate web interface and AR. They considered it a novel concept and found it useful to promote exploration, knowledge discovery and immersive comparison.

During interactive exploration process, users often moved around in the physical space and made use of hand gestures as well as voice commands. While some users preferred exploration and interaction with virtual objects from a distance (2-3 meters), most users favored observing them closely with scaling, re-positioning and rotating interactions. This demonstrated that intuitive multi-model interaction could be easily integrated into web browsing experiences through AR.

In particular, all users liked the ability to actually visualize 3D neural structures as it reveals all structural details. Users appreciated different set of visualizations in our system, especially 3D scatter plot as it provided them high level overview of the dataset. Users also admired history visualization that allowed them to revisit earlier interactions with the system, enabling cognitive offloading.

7.2 Expert Feedback

We have provided ImWeb system to 2 experts of neurology and obtained their feedback on both advantages and limitations. Both experts have extensive knowledge on the neuron datasets, but very limited experience with AR and HoloLens.

Advantages: The experts have commented that the ImWeb system provided a new avenue for the neuromorphological analysis with the 3D AR feature. In comparison with currently most widely used neuron visualization systems [6, 30], experts mentioned three main advantages of the ImWeb system for neuroscience research. Firstly, the web system is easy to access, which does not require any installation and configuration. Researches can explore neurons conveniently using various platforms such as desktop, tablet and large display. Secondly, the embedded interactive mining algorithms using machine learning can automatically compute analytical results of neuron for users, e.g., searching neurons with similar morphologies, presenting functional properties for each neuron. These results are helpful for neuronal exploration and mining. Most importantly, the AR application brings new perspective for neuron analysis, i.e., in an interactive and immersive manner. Particularly, multiple neuron analytical tasks can be improved by employing the AR based system, e.g., comparing two neurons in different scales (from holistic to fine-grained level) and view points. Simultaneously analyzing neurons with similar morphologies and correlating neuron morphologies with functions, all of which require a comprehensive and exhaustive visualization of 3D neuron morphology.

Limitations and suggestions: The experts suggested more immersive analytics functions and more mining algorithms for various neuronal exploration tasks. We believe that each component of our ImWeb system can be expanded with additional capabilities. Experts also suggested higher requirements of AR devices, including better view-of-angle for visualizing more datasets in sight at the same time; better performance for visualizing massive neurons with gigabyte to terabyte of data size; and more interaction methods, especially more hand gestures for immersive analytics. These suggestions are hardware specific, requiring better AR devices that are expected to be available in the future.

7.3 Discussions

The neuron morphology exploration can be mainly performed using either the website or AR, such as querying similar datasets on the web interface or visualizing 3D structures in AR. Exploration through the web interface is a faster and less detailed approach because the user can only see images of neurons from one point of view and in 2D. Exploration in AR allows the user to visualize and interact with 3D structure of the neurons in detail.

The combination of the useful interaction options that both AR and the Web provide opens new methods of exploring data. Some of the AR inputs, such as voice and gaze tracker, may be integrated with web browsers in the future. Other inputs, such as the body movements of users, can not be integrated into the web browser without special devices. With the advances of AR technology, commercial AR devices can nicely provide inputs from many of these channels.

The architecture of ImWeb system is necessary, as AR devices only have limited storage and processing capabilities. The web server simplifies data storage and management greatly than storing all the data on HoloLens itself. This is important because of the sheer volume of data in the NeuroMorpho database. Additionally, the webserver can handle the complex calculations involved with data simplification and comparison in order for the HoloLens to focus on rendering efficiently.

The perception difference from our abstraction method is neglectable, as we preserve the shapes of neuron branches. Compared to the 2D snapshots and 3D renderings on a website, AR significantly enhances the understanding of 3D structures because of the enhanced depth perception.

8 CONCLUSION AND FUTURE WORK

This paper presents ImWeb, an immersive web browsing method, for exploring online 3D neuron database. Our method combines the web server for hosting and browsing a large database, and AR for coordinating and visualizing 3D structures. The mixed exploration method overcomes the limits of standard web browsing with perceptually effective 3D renderings, multi-model interactions, and advanced analysis functions. It also provides new example exploration fashions that are beyond the 2D and 3D visualization techniques. Our approach is demonstrated with a large 3D neuron database and can be extended to visualize and compare data from other online databases as well.

With ever increasing use of AR devices, we expect that such mixed visualization mechanisms will become more popular in the near future. We plan to continue to explore additional ways to integrate VR and AR devices into the data visualization pipeline for providing potential perception and cognition benefits. Our future work also include exploring multiple user interactive collaboration systems with AR devices, which require additional components to improve collaborative analysis functions. At the end, we plan to perform systematic evaluation to study any significant differences between the mixed and classical visualization methods for obtaining useful design guidelines.

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