Building Multiple Coordinated Spaces for Effective Immersive Analytics through Distributed Cognition

Tahir Mahmood
UNC Charlotte
tmahmood@uncc.edu

Erik Butler
UNC Charlotte
ecbutler@uncc.edu

Nicholas Davis
UNC Charlotte
ndavis64@uncc.edu

Jian Huang
University of Tennessee
huangj@utk.edu

Aidong Lu
UNC Charlotte
aidong.lu@uncc.edu

***Abstract*—Multiple Coordinated Views (MCV) has been widely used in visualization. This work explores Multiple Coordinated Spaces (MCS), a 3D version of MCV, in order to integrate various 2D displays in a large physical environment as a unified analysis workspace. Built upon the rich background of distributed and embodied cognition, MCS supports interactive analysis in a connected, distributed set of subspaces. For MCS, we have developed visualization and interactive techniques for coordinating augmented reality devices together with classical WIMP GUIs systems. We also demonstrate the usages of MCS using a multivariate, geo-spatial biodiversity application. The major advantage of MCS is a flexible coordination framework for creating new immersive analytics methods by mixing visualizations from different devices, and mixing physical and virtual operations from different environments.**

***Index Terms*—Multiple coordinated space, distributed cognition, immersive analytics, mixed reality.**

I. Introduction

WIMP GUIs (windows, icons, menus, pointer) have dominated visualization designs for the past 30 years [1]. Many visualization approaches and theoretical foundations have relied on WIMP exclusively when designing visual representations and interaction mechanisms to support visual analytics tasks. Unfortunately, WIMP GUIs restrict the design of visualization and interaction to classical desktop settings that are significantly different from the interaction that human beings perform in everyday lives, especially our body, head and eye movements. The effects of natural interaction, reasoning, and cognition and their impacts on the foundation of visual analytics have remained under explored.

We see a great opportunity at the crossing of two disciplines. First, the existing literature in distributed and embodied cognition has shown a promising potential in visual analytics by incorporating physical environments and interactions [2]–[4]. Second, the latest technologies of Augmented Reality (AR) and Mixed Reality (MR) have greatly improved the hardware for mixing virtual information and real objects in a physical environment. Collectively, these two areas should provide a novel foundation for visualization community to explore new types of immersive analytics that go beyond WIMP GUIs [5].

The opportunity of using AR/MR to create new possibilities in visual analytics and sensemaking stems from key differences between conventional desktop visualization and new frontiers of immersive analytics, such as the following.

Physical environments as the workspace: Physical environments are the primary sensemaking medium for human beings [2], as “humans are cognitively well adapted to making use of space to express and perceive relationships between objects” [6]. With AR/MR techniques, we can use the physical environments as a natural workspace through mixing virtual information and real objects, introducing more physical interactions into the sensemaking process. Such workspaces can be applied at any location where a physical space is used.

Distributed and embodied cognition for sensemaking: The distributed and embodied cognition theories describe the importance of environments to support sensemaking. Visualizations, as part of the environment, forms the external representation that communicates with the internal representation of human mind for sensemaking in the cognition process. With the physical environment as the medium of external representations, we can accommodate new types of visualizations for physical spaces that can better connect the internal and external representations and promote more efficient sensemaking processes.

Large rendering space with unlimited pixels and cognitive offloading: The large physical space provides a large rendering canvas, potentially unlimited number of pixel without the restriction of display resolutions, which is suitable for complex tasks such as big data analysis [7], multivariate, geo-spatial analysis. In addition, it lowers the barrier of externalization, both cognitively and pragmatically [2]. Similarly, large, high-resolution displays create a spatial environment for replacing virtual navigation with physical, which has demonstrated promising cognitive advantages, such as increasing performance and decreasing user frustration [8], [9].

New interaction methods mixing physical and virtual operations: Physical space and physical navigation have been studied for interaction with the system [10], [11] and sensemaking, such as spatial organization [6] and spatial hypermedia [12]. The theory of embodied cognition also suggests that “physical navigation engages more embodied resources, providing a greater opportunity for users to couple with the space, providing more meaning to locations and encouraging a more cohesive view of the entire workspace” [13]. Since physical workspaces combine different types of visualization mediums, the physical and virtual interaction methods can be performed in a mixed fashion, creating new capabilities of interaction functions.

The challenges of creating new types of immersive analytics are not only from the technical aspects of AR, 3D visualiza-

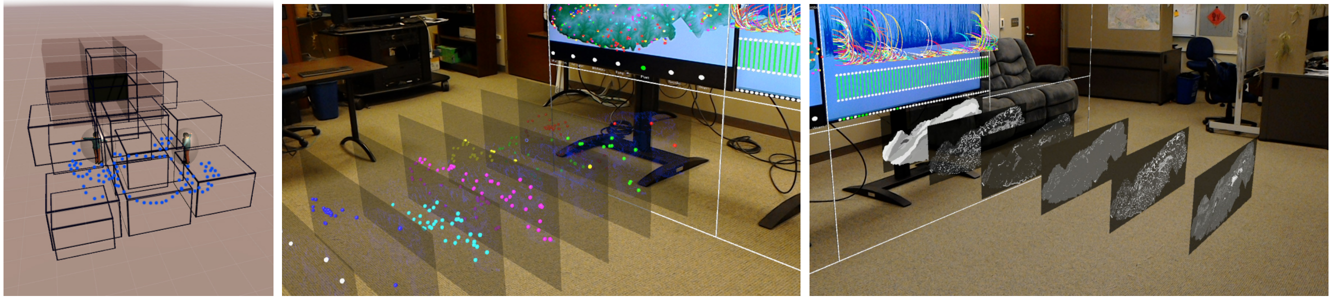


Fig. 1. Example multiple coordinated spaces created for immersive analytics utilizing the physical environment. The left figure illustrates the user trace in MCS during investigation and marks the two positions where snapshots shown on the right are taken from HoloLens. The right two figures demonstrate visualizations from different devices are combined in the physical environment for analysis.

tion and interaction, but also from the cognitive aspects, i.e. designing effective visual analytics workspaces. Specifically, this work aims to study the following problem: given a large physical space, how can we design it as an encouraging environment for immersive analytics? Our approach integrates the physical environment with existing 2D displays, such as large screens and white boards, to create a flexible framework that can be applied to different scenarios and leverage the advantages of both WIMP and post-WIMP interactions.

This paper presents an approach of MCS (multiple coordinated spaces), which organizes a large physical environment with 2D displays as multiple subspaces and provides coordinated visualization and interaction for promoting immersive analytics. Shown in Figure 1, we have developed a prototype system with multiple visualization and interactive techniques supporting the coordinated analysis between different spaces and devices. A complex biodiversity application is used to demonstrate that MCS can be used to promote the interactive exploration process by making efficient comparisons of hundreds of species and how the species depend on the many different environmental variables.

The rest of the paper is organized as following. We first review the previous work in Section II. We then describe how to construct and use MCS in Section III. Section IV presents the prototype system and section V provides case studies. Section VI concludes the paper and presents the future work.

II. Related Work

A. Distributed and Embodied Cognition

The theory of distributed cognition (DCog) expands the unit of analysis for cognition beyond one individual human to a *distributed cognitive system* that can include "a collection of individuals and artifacts and their relations to each other in a particular work practice" [14]. DCog emphasizes the idea that cognition is off-loaded onto the environment through social and technological means; which supports considering visualizations as part of the external environment during the reasoning and cognition process [15]. Since DCog provides a radical reorientation of system and human-computer interaction design, it has been proposed as a theoretical foundation to study human-computer interaction [16] and information visualization [4]. Due to the generalities of DCog theory, it can be widely applied to various technologies, including both classical desktop systems and beyond WIMP GUIs (graphical user interfaces based on windows, icons, menus, and a pointer) [1]. This work explores DCog on understanding interactions among users and augmented reality technologies and the design of immersive analytics.

Two principles of DCog are essential to the design of immersive analytics beyond WIMP GUIs. First, cognitive processes often involve coordination between internal and external (material or environmental) structures. While much cognitive science research has investigated how internal information is stored and processed inside the brain, the environment provides indispensable content for thinking. The theory of mental models [3] proposes that a coupled system combining the internal and external realms should enable seamless information flow between the human and visualizations while minimizing the cognitive work that has to be performed internally or interactively. The conventional view is that tools amplify cognition, especially in visualization, artifacts are scaffolds for cognition. In some instances, the external representation, such as visualization, provide a means of accomplishing tasks that could not be performed without the tools. Since the external representations of immersive analytics allow designers to layout visualizations spatially in the physical environment, there are significant opportunities to create new tools.

Second, accomplishing each individual step or task, in and of itself, does not amplify our cognitive abilities. It is the combination of steps that has the potential to amplify our cognitive abilities. According to Hutchins [17], difficult mental tasks can be transformed into simple ones by offloading some features of the task onto the environment. Once transformed to the physical domain, these tasks can be handled with basic cognitive operations, such as pattern matching, manipulation of simple physical systems, or mental simulations of manipulations of simple physical systems. Cognitive processes may be distributed through time as well, so that previous experiences and knowledge can assist later tasks. According to the mental model literature [3], activated past experience and knowledge that are relevant in the current context are an important component of mental modeling, represented internally and arguably in the form of frames, schemata or propositions. In addition, three primary functionalities of interaction are proposed: to enable external anchoring, information foraging and cognitive offloading [3]. Each interaction function enables a task involved in the cognition processes between internal and external representations.

DCog has been applied to the design of sense-making systems. For example, Andrews and North created the Analyst's Workspace (AW) on a large, high-resolution display by combining the spatial layout of documents and other artifacts with an entity-centric, explorative and investigative approach [2]. Badam et al. [18] presented a software framework, Munin, for building ubiquitous analytics environments consisting of multiple input and output surfaces. Wheat et al. examined the role of representational artefacts in sensemaking, using maps, charts and lists to furnish sensemakers with the ability to perform tasks that may be difficult to do solely in their mind [19]. The locus of control, which represents a person's tendency to see themselves as controlled by or in control of external events, is used to study the importance of internal and external representations [20]. Large tiled displays have also been used for distributed cognition and collaboration [21].

Embodiment or embodied cognition is a cognitive science theory that recognizes the primary and fundamental role the body plays in constituting cognition [22]. It grew out of a reaction to cognitivism [23], which posited that cognition is an abstract manipulation of symbols in the brain, meaning cognition can be readily implemented in a computer just as easily as a brain. We later learned that the human body is inextricably bound to the function of cognition, including concept formation [24], language formation [25], reasoning [26], and perception [27]. Since the human body has such an important function in cognition, it follows that our technological designs should take special consideration in designing interactions that allow the user to experience a sense of agency and bodily presence during the interaction. Therefore, technologies that strive to augment cognition should consider embodiment and the unique role of the body in their target application to fully leverage how cognition currently functions.

B. Multiple Coordinated Visualization

Multiple coordinated views (MCVs), using two or more coordinated distinct views to support investigation of a single conceptual entity [28], is a concept emerged in late 1990s [29]. One of the earlier works includes a high level taxonomy on MCVs based on focus zones and data representations [30]. Further, several papers presented guidelines regarding design choices for when and how to use MCVs and presented comprehensive reviews of MCV systems [28], [31]–[34].

Previously work has studied the effectiveness of MCVs and demonstrated improvement of user performance in different visualization and visual analytics scenarios. For instance, selecting a group of data items in one view in coordination with the selection of the same items in another can reveal new relationships and dependencies which might otherwise remain hidden [33]. North and Shneiderman also observed that multiple window coordination offered improved user performance, discovery of unforeseen relationships; and minimized cognitive overhead of a single complex view of data [30]. However, if used in the wrong way, multiple views can have quite the opposite effect [28]. Several guideline rules have been presented for when and how MCVs should be used [28]. While these guidelines are primarily for desktop system design, we found them equally helpful for immersive analytics.

MCVs have been explored extensively in visualization to support exploratory data analysis and sense-making [32], ranging from network traffic analysis [35] to exploring spatio-temportal data [36]. For example, the WebPrisma [37] is an information visualization web tool that uses MCV. Similarly, VisLink [38] used 2D visualizations and layouts to explore relationships between visualizations. The challenges of designing MCV visualizations include development of easy interaction mechanisms for coordination, configuration and organization of layouts among views [32], [39].

One of the objectives of AR as a research area is to provide more natural and intuitive interfaces for interaction with computational systems [39]. Meiguins et al. [39], [40] used AR with MCV visualization and concluded that this combination allowed better and faster data comparison and analysis than desktop environment.

C. Immersive Analytics

A number of recent studies on immersive analytics provide favorable results for stereoscopic techniques. For example, Alper et al. [41] presented stereoscopic highlighting to help answer accessibility and adjacency queries when interacting with a node-link diagram, and the evaluation results showed that they could significantly enhance graph visualizations for certain use cases. Ware and Mitchell [42] studied the perception of variations of 3D node-link diagrams and showed that stereoscopy reduced errors and response time in a very high resolution stereoscopic display. Similarly, Greffard et al. compared 3D stereoscopy with 2D visualization and 3D monoscopy, and found that stereoscopy outperforms both 2D and 3D monoscopy [43]. The effectiveness of immersive analytics still needs to be explored. The differences depend on the approaches as well as the applications [44], [45]. Systems that combine different devices have also been developed for visualization and visual analytics [46]–[48]. Our MCS approach is different from the previous work by focusing on making the physical environment as an effective workspace.

III. Multiple Coordinated Spaces (MCS)

We start by introducing the main purpose of MCS; then describe our approach to construct MCS given a physical environment.

A. Creating Distributed Workspace with AR/MR

MCS is designed to enable users to take advantage of many physical environments, like an office or work sites, as a distributed analysis space. We choose to combine AR/MR technologies, as they are uniquely positioned to be an embodied technology – giving the user full range of motion to explore an environment that is rich with data. In particular, AR/MR align with the embodied concept of active perception [27], which reconceptualized perception from a passive reception of sensory data to an active process of reaching out into the world to understand its interactive potential.

Our design of MCS is a distributed workspace which flexibly combines a number of 2D surfaces and 3D spaces, such as real 2D displays and virtual 3D visualization from AR. The 2D surfaces are important mediums for visualization and collaboration. They can be 2D displays, such as monitor or large screens, for integrating any existed visualization methods and devices; as well as 2D surfaces, such as white boards and tables, for applying traditional pen and paper methods. The 3D spaces are the physical environments which support physical navigation and interaction, such as moving around and observing data from different directions. Any spaces in MCS can also be divided to 2D or 3D subspaces and organized according to their spatial relationships.

The MCS framework allows a flexible combination of 2D/2D, 2D/3D, and 3D/3D spaces from choices above; and the user can focus on any subspace or region during the analysis process. This design allows us to utilize any 2D displays and surfaces in the physical environments and combine visualization systems from different devices to generate a powerful data analysis workspace.

B. Construction of MCS

The construction of MCS requires two components to start: (i) the registration of physical environment and virtual world, so that physical interactions such as moving around can make sense to both worlds; (ii) the identifying of important 2D surfaces that exist in the physical environment, specifically locations and sizes of 2D surfaces. We have explored both semi-automatic and interactive construction methods to achieve these two components.

- The semi-automatic approach is designed to use fixed large displays in the physical environments. We use Vuforia markers [49] to represent 2D surfaces with different sizes. The positions of the Vuforia markers are used to obtain the physical locations of displays automatically.
- The interactive approach can accommodate unfixed settings, such as a white board being moved around in the room. We use the Air tap gesture of HoloLens to specify the board location and apply scaling to adjust size. With the interactive approach, users can create 2D spaces of any size based on their needs.

After obtaining the positions of 2D surfaces in the physical environment, the next step is to construct multiple 3D spaces around them. This construction process can be described as follows: given t 2D surfaces $p_1, ..., p_t$, divide a 3D space into a set S with n sub-spaces: $s_1, s_2, ..., s_n$. The following describes the construction algorithm and the procedure is illustrated in Figure 2.

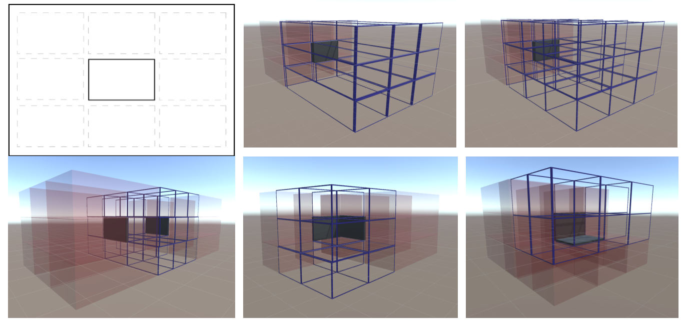


Fig. 2. Illustration of MCS construction: multiple 2D surfaces are used to divide the space into a connected, distributed set of subspaces. The first row shows that each 2D surface generates a 3x3 grid and cuts the space, and the subspaces are further adjusted and divided to similar sizes. The second row shows the subspaces constructed from different settings.

1) It starts from one space $S = s_1$, representing the physical environment.
2) Sort all 2D displays according to their sizes in non-increasing order and divide the S by applying steps 3 - 5 to each 2D display.
3) For the 2D plane embedding the 2D display p_i, we first divide it to a 3×3 grid with p_i fitted in the middle.
4) Search the processed $p_1, ..., p_{i-1}$ for parallel/vertical displays. If found, use the largest sizes to adjust the 3×3 grids so that subspaces can be merged. This may increase the size of the center grid, but it avoids overcutting the subspaces that are too small to use.
5) The grid is used to divide the set S by extending each grid on the third dimension. For example, a grid which aligns on a x, y plane cuts on the z direction, generating 3×3 3D subspaces on each side of the plane.
6) In the end, large subspaces are divided based on their largest dimension of 2D surfaces.

Figure 2 demonstrates several MCS examples constructed from physical environments. While we mainly focus on scenarios with parallel or orthogonal surfaces, our construction approach can handle a variety of display settings with different numbers of 2D surfaces.

C. Working with MCS

Working with MCS is similar to working in a real environment, in the sense that users can physically move around, organize data as files at different locations, and visualize data from different directions. This section describes our design for equipping MCS as an analytics workspace.

Organizing MCS as a connected, distributed workspace: With the flexible organization MCS offers, a user can create a workspace by separating a large space into connected regions represented by subspaces and subsequently organizing data/visualization in the workspace. Every subspace can locate its direct neighbors and find a path of subspaces to reach any location where the user or a specific data component is located. The organization of MCS is important to supporting efficient interaction functions with a set of concepts that are part of human's everyday work but rare in visualization, including "neighborhood", "physical location", "distance", and "path", into the visual analytics process.

Embodiment for interaction: Embodied cognition describes the physical constraints of the body and how those influence cognition. Among embodiment theorists, the concept of an image schema emerged as a way to explain how the body shaped early concept formation [24]. Image schemas are "directly meaningful ('experiential'/'embodied')", preconceptual structures, which arise from, or are grounded in, human recurrent bodily movements through space, perceptual interactions, and ways of manipulating objects [24]. Two image schemas relevant to the design of AR systems are center-periphery and front-back [24]. The center-periphery schema describes how humans orient the center of their focus to the primary and most interesting information while other details surround the periphery. The front-back image schema describes how elements in front of the body are perceptible and therefore valuable, while those information behind the body cannot be immediately seen and is therefore secondary.

We use these two image schemas to help organize the AR space in a way that is intuitive to users. We automatically measure the importance weights of subspaces as $w_1, w_2, ..., w_n$, so that new pieces of information are shown at the right locations. Specifically, we set up a user coordination system and use it to control the MCS during user navigation in the space. As shown in Figure 3, the space is divided to front, side, and back according to the user location and direction. This coordination system moves with the user and suggests the physical locations and the data/visualization that are the main focus of the user. Generally, the subspaces that are in front of user and closer to the user receive higher weights and are used to visualize important data pieces.

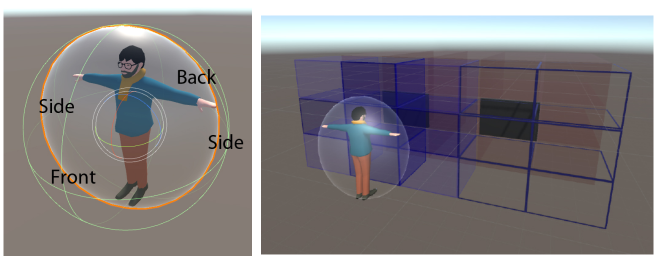


Fig. 3. Embodiment for interaction. The weights of subspaces are updated automatically with user space along the movement.

Externalizing insights: During the course of exploratory sensemaking, it is necessary to preserve interesting entities, discoveries and insights. These internal structures or representations can be given stable external forms in the working environment and by doing so we can reduce the amount information kept in working memory and thus achieve cognitive offloading. We accomplish this by allowing user to explicitly save a state of visualizations or the subspaces in the form of an external representation. The state of all subspaces in the form of external representation can be later retrieved. This way the user can revisit and piece together the insights from previous visualizations into an understandable and compelling whole.

Exploration and sensemaking: Some of the most fundamental aspects of human cognition are the ability to reason, recognize patterns, compare results, differentiate between what makes sense and what does not, and make decisions [50]. These tasks can be applied effectively to exploratory analysis and sensemaking. The MCS in the environment of AR creates an exploration workspace where users can perform classic visual analytics on high-resolution 2D displays, immersive analytics in the physical space, and combine traditional pen and paper operations into one integrated workspace. The flexibility to transfer data and visualizations among these three different platforms allows users to take advantage of each platform without the burden of copying data and interaction operations. This new approach also supports new mixed sensemaking actions that may offer unique cognitive benefits.

Tracing interaction history: Apart from addressing common visualization tasks and interactions and to further ease the process of sensemaking, we expanded our design to facilitate distributed cognition by allowing users to revisit any interactions leading them to the current analysis of the data. Cognitive constructs evolve during sensemaking when we encounter a new situation to reason about or when we find a dead end. One method to facilitate this aspect of sensemaking is to record important intermediate results which can be revisited.

The idea is to augment sensemaking by allowing user to go back and revisit the interactions made earlier. This way the user externalizes sensemaking as part of the exploration, which is itself integrated into the visual representations of the data. We provide an option to save and record important intermediate results obtained along the exploration process so that user can later revisit and piece them back together into an understandable and compelling whole. This process of breaking down the results into vital components and then putting them back together into a comprehensive whole is the cognitively demanding task that lies at the heart of sensemaking and exploratory analysis [51].

IV. MCS System for Biodiversity Analysis

We have developed a prototype MCS system for visualizing a complex biodiversity study from the Great Smokey Mountain National Park (GSMNP), which is one of the most important national parks in The United States. As a World Heritage Site and International Biosphere Reserve, the GSMNP contains one of the largest remnant never-cut forests in the eastern US, and it is the most biologically diverse park in the United States National Park system.

A. Prototype System for Biodiversity Analysis

For the biodiversity application, we have included the following data components in the system:

- Observed habitat locations of 869 species
- Geo-distribution simulations of 869 species
- Geo-distribution of effects of 59 environmental variables

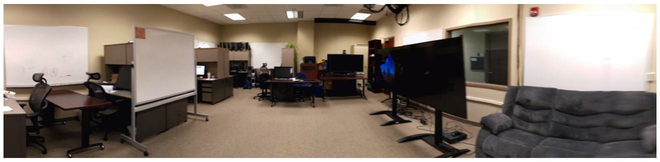


Fig. 4. The physical environment used in the study.

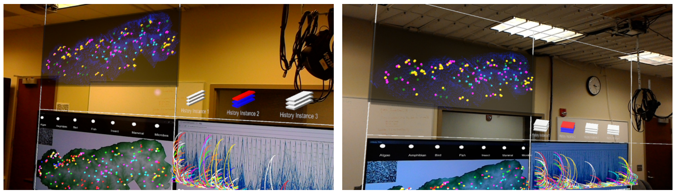


Fig. 5. The history subspace is used to review previous recorded exploration stages through interacting with miniatures from HoloLens.

- Species are further divided into 14 types, i.e: birds, plants, insects, reptiles, fish, worm, mammal, and amphibian.

The derived information includes the following:

- Inter-dependencies of species based on habitat locations
- Inter-dependencies of environmental variables
- Correlations between species and environmental variables

Our MCS system is developed using Unity3D [52], Vuforia library [49], and D3.js [53]. Unity3D is a common platform for development on Microsoft HoloLens. We also use D3.js to visualize parallel coordinate graph on one 2D display.

The MCS system starts with registering the physical environment with the virtual world of HoloLens. The system starts and waits for detection of 2D surfaces by Vuforia markers [49] using the HoloLens camera. Once the markers are detected by Vuforia, our system registers both the locations and sizes of the corresponding 2D surfaces into the virtual world.

The system then loads all the data and directs the user to an overview subspace, which provides a spatial organization of the overview visualization and connects users to all the data and visualization methods. As shown in Figure 7, the overview subspace simulates an operating panel and organizes the miniatures or labels for all data and visualization methods. We use it as the starting point, following Shneiderman's mantra for visual data analysis "overview first, zoom and filter, then details-on-demand" [54]. The overview also serves as an external anchor point, a fixed subspace, where users can keep coming back to connect information in mind and in space.

From a distributed cognition point of view, revisiting the exploratory interactions externalizes sensemaking as part of the investigation, which is itself integrated into the visual representation of the data. It also reduces the cognitive load of remembering previous observations and preliminary results. Thus, there is a subspace reserved for keeping exploration history. This subspace is generally placed adjacent to important 2D surfaces for convenience, as shown in Figure 5.

B. Visualization Methods

Several visualization methods are provided in our system to support the analysis of multiple data components and derived information. Figures 1, 5, 6, provide several example results, which are all taken from HoloLens directly. We classify the visualization methods based on the deployed devices to the following three categories.

Visualizations for 2D displays. As web-based visualizations are deployed on a server to support the 2D displays, any visualization methods developed based on WIMP GUIs can be adopted. We provide two methods for the displays as examples: parallel coordinate for illustrating the correlation of species and environmental variables; and a topographic map of GSMNP for observing terrain features.

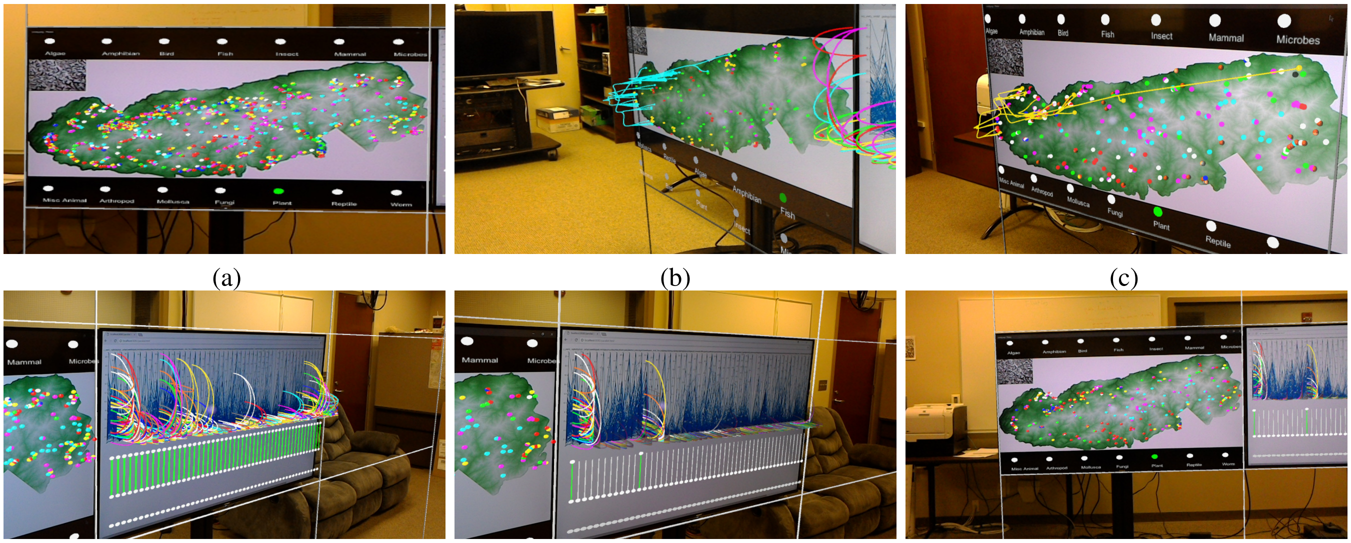
Visualizations for 3D subspaces on HoloLens. *Holographic maps* shown as semi-transparent layers with 3D points are used to visualize the observed habitat locations of one species. The holographic maps are often shown as a stack of vertical or horizontal parallel layers in subspaces and can be moved around for comparison. *Heat maps* depicts the simulated distribution of species or of environmental variables as images. They are constructed based on the map of GSMNP. *Edge bundle graph* groups the data points of a single species and visualizes the connection as 3D edges arching out of the screen. It is a tool to distinguish species habitats from each other and analyze clusters of habitat locations of a species. *3D Scatter plot* are used to visualize clusters of species and also clusters of environmental variables in the dataset. These clusters are computed based on similarities in distribution of species and environmental variables.

Visualizations for connecting 2D displays and 3D subspaces on HoloLens. For parallel coordinates, we highlight the data related to user selected species and environmental variables with 3D curved lines arching out the screen. For the topographic map, habitat locations can be flexibly overlaid on the top of the topographic map. Each habitat location is visualized as a data point and habitat locations of a particular species are given a different color to distinguish between them.

C. Interactive Techniques

We integrate several interactive techniques from HoloLens, including voice commands, gaze, and hand gestures (air tap for selection, pinch for scaling and moving). Each interaction is achieved by a combination of the HoloLens operations and physical interactions. For example, selection starts with the user gazing at an object such as a button or a subspace, and then use the air tap gesture to confirm. Voice commands are achieved by speech recognition of a phrase or sentence to activate an interaction state; followed by the above selection procedure to complete the interaction. We refer to these techniques directly by the names such as HoloLens selection and voice commands in the following.

Coordination between displays. While the MCS system contains visualizations running on both web server and HoloLens, we achieve the coordination between them through the registered physical environment and virtual world on HoloLens. Our approach is to overlay the HoloLens visualization and interaction methods such as buttons and sliders on the 2D displays, and ensure that the combined representations



(a) (b) (c)

(d) (e) (f)

Fig. 6. Mixing visualization and interactions from different devices (high-resolution displays and HoloLens): (a) mixing the topographic map from 2D display and holographs from HoloLens, where virtual buttons are provided to interact with the combined visualization; (b, c) edge bundles for highlighting selected species types; (d, e) parallel coordinates interacted through HoloLens with virtual sliders on the bottom; (f) updated habitat locations after filtering. Our approaches of virtual buttons and sliders can be applied to general WIMP-based visualization methods.

are consistent with the original visualization methods in both 2D and 3D subspaces. We demonstrate this technique on both the topographic map and parallel coordinates.

For the topographic map, we add a menu of multiple choices with spherical buttons on the bottom. As shown in Figure 6, the buttons of selected species are colored and their observed habitat locations are visualized on the map.

For the parallel coordinates, we use the spherical buttons to indicate the selection of environmental variables. To represent the filtering operation, we use a 3D slider which is restricted to move along the axes of parallel coordinates. The 3D slider can be moved through selection and drag, indicating the low threshold to filter the data.

Interacting and manipulating MCS subspaces. We provide several interactive techniques for working with the 3D subspaces. *Drag-and-drop*: This interaction allows placement of visualizations in different subspaces based on user needs. It is achieved by a HoloLens selection, choosing a source subspace, physical movements, and another HoloLens selection choosing the destination subspace. *3D Manipulation*: Similar to drag-and-drop, users can scale and rotate the visualization in a subspace. Voice commands “scale” and “rotate” activate the interaction states and hand gestures are used to complete the manipulation. *Show/Hide visualizations*: The user can interactively choose to show or hide visualizations in selected subspaces using voice commands “show” or “hide” and HoloLens selection. *Details on demand*: Similar to mouse hover, we use the head movement of user to indicate the focus-of-interest. The text label of focused data element is automatically shown to reveal details.

Data selection: Several methods are provided to support flexible selection of different data components or a combination of them. Different species types or derived information can be selected using HoloLens selection on the overview subspace. From parallel coordinates, a set of species can be filtered with our coordination method of using HoloLens sliders. The species or environmental variables can also be selected from a subspace with HoloLens selection, or using the 3D MDS scatter plot to select a data range.

Visualization selection: Users can choose a specific visualization from the overview and drag-and-drop it to a desired subspace.

Exploration history: The voice command “create history” records the current configuration of MCS and creates an icon representing this history instance on the history subspace. HoloLens selection from the history subspace is used to bring a previous record back.

D. Implementation and Performance

The prototype system is deployed in our lab with an open space of 4 by 6 meters. As shown as in Figure 4, two 75inch 4K displays and multiple white boards are provided. The displays in the open space can be moved around and placed vertically or horizontally, creating different environments.

The observation data are kept and simulated density data are reduced to fit in the HoloLens storage. The performance of the system is interactive. Among the provided visualization methods, the total number of species and the number of transparent images layers are the main factors affecting the performance. We accelerate the system by hiding visualizations that are on the back of the user. There are no obvious delay for all the interactive operations, except the detection of Vuforia marker generally takes around two seconds at the beginning.

(a) (b) (c)

Fig. 7. (a) Overview visualization overlaid on the 2D subspace of a white board providing all available data components and visualization methods, which can be activated with HoloLens selection. (b) Mixing scatter plot from HoloLens and physical interaction provides a new way to interact with data, where users can combine virtual interaction for adjusting scatter plot and physical interaction for drawing clusters on the white board seamlessly. This figure adds the scatter plot taken from HoloLens to the picture to illustrate the interaction. (c) Analyzing different clusters of species habitats.

V. Results and Case Studies

This section presents three examples of using our MCS system for exploratory analysis tasks.

Comparing spatial features of habitat distributions: One of the common tasks in biodiversity analysis is to compare habitat distributions of multiple species. The spatial features of habitat distributions help in perceiving dependencies of species on one another. MCS provides a large 3D space to place multiple species around and also visualizes selected species in parallel holographic layers for comparison.

For example, while exploring amphibian species, users can make use of 3D space around them to spread-out individual holographic layers, as shown in Figure 8(a). The layout allows users to move around and inspect habitat distribution of each species for identifying different species with completely identical habitat distribution, including *Hyla chrysoscelis* (Cope's Gray Tree frog), *Eurycea longicauda longicauda* (Eastern Long-tailed Salamander), *Lithobates clamitans melanota* (Green Frog) and *Pseudacris crucifer* (Spring Peeper). Users can also observe species with very different habitat distributions, such as *Gyrinophilus porphyriticus danielsi* (Blue Ridge Spring Salamander), *Pseudacris crucifer* (Spring Peeper) and *Anaxyrus americanus* (Eastern American Toad).

This comparison helps us to identify spatial regions associated to species clusters. We can further classify sets of similar species into groups and visualize them on top of each other in separate subspaces. The regions with no observed occurrences of any amphibian species are discovered, shown in the Figure 8(b). This intrigues us to explore the reasons by using parallel coordinates and heat maps of environmental variables. We further learn that areas with high elevation and increased frequency of precipitation are not favorable for habitats of Amphibian species, explaining these regions according to terrain features. This is confirmed by re-positioning heat maps of relevant environmental variables onto topographic map of GSMNP and holographic layers in separate subspaces.

Further analysis with the environmental variables reveals that all these species have positive relationships with average yearly rainfall, available water supply above 25cm, wetlands and soil moisture; and negative relationships with frequency of climatic change, low temperature, and precipitation frequency. We can group and visualize the heat maps of environmental variables orthogonally or side-by-side in 3D subspaces(Figure 8(c, d)) to confirm these results.

Identifying species clusters: Identifying species clusters is useful to explore the combined features of species at GSMNP while apprehending the effects of environmental variables. For example, few plant species may depend on a number of insect species for pollination and thus those plant species always have habitats closer to those of insects.

While exploring clusters of bird species habitats, users can identify major cluster consisting of *Agelaius phoeniceus* (Red-winged Blackbird), *Spizella passerina* (chipping sparrow), *Strix varia* (Barred owl), *Melospiza melodia* (Song Sparrow), *Meleagris gallopavo* (Wild Turkey) and *Catharus ustulatus* (Swainson's Thrush), shown on the left of Figure 7(c). Parallel coordinates provide additional clues for such habitat clusters. They are all dependent on the variables of geology, average yearly rainfall, seedling and soil hydric rating. These species also show negative relationship with precipitation frequency and elevation.

Similarly, users can identify another species cluster with *Spinus pinus* (Pine Siskin), *Loxia curvirostra* (Red Crossbill), *Bonasa umbellus* (Ruffed Grouse), *Coccyzus americanus* (Yellow-billed Cuckoo) and *Setophaga pensylvanica* (Chestnut-sided Warbler), shown on the right of Figure 7(c). We find that this cluster is located around lakes and areas with high available water supply. These species also depend on variables of vegetation, low elevation zones and surficial geology. Users can drag-and-drop the two species clusters on the top, so that their detailed information can be spread out for further analysis in the open 3D space.

Exploring dependency on environmental variables: An important job of biodiversity analysis is to interpret dependencies and relationships between species and environmental variables. The purpose is to understand which set of environmental variables are indispensable for certain species and which ones are not. It is also important to investigate the consequences that small perturbations in these variables have on the species. Such questions are imperative for informed biodiversity sensemaking and by extension, decision making. Moreover, correlation with environmental variables can be used to classify a set of species into different groups. For

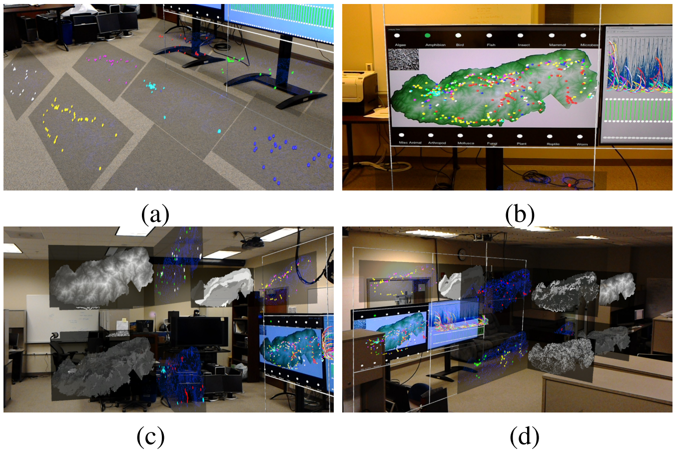


Fig. 8. Comparing spatial features of habitat distributions (a) spread-out view of holographic maps in 3D space to analyze distribution of each species, (b) identifying spatial regions with no occurrence of species habitats, (c,d) using heat maps of environmental variables to confirm their relationships with groups of similar species.

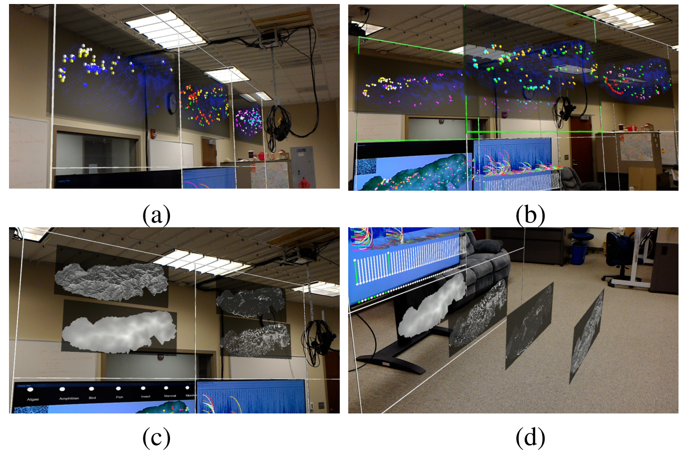


Fig. 9. Exploring relationships of species and environmental variables: (a) grouping species based on elevation zones, (b) grouping by distribution similarities, (c, d) comparing heat maps of environmental variables.

example, a set of plant species can be classified into groups based on their presence in high, middle and low elevation zones of smokey mountains. This grouping can further help in finding crucial climatic conditions for species in each group.

For this task, users can start from the map shown in Figure 6(a). Focusing on environmental variables of sunlight condition and soil surface texture, we can filter species that depends on these variables Figure 6(e), which updates the map visualization (Figure 6(f)). Users can save these results as interaction history. To classify different plant species based on their existence in high, middle and low elevation zones, we further adjust the range of environmental variable of elevation. Species belonging to each elevation zone can be visualized in separate subspaces, shown in Figure 9(a), and the process can be saved as an interaction history. Results show that each group has varying number of species and low elevation zone has most number of species compared to other zones. For instance, a few species in low elevation zones are *Vitis vulpina* (frost grape), *Eurybia surculosa* (creeping aster), *Juncus effusus solutus* (Lamp Rush), *Quercus stellata* (Post Oak), *Carex laxiflora variety* (Broad Looseflower Sedge), *Verbesina occidentalis* (Yellow Crownbeard) and *Salix sericea* (Silky Willow).

We can further use parallel coordinates and identify that species within each group have similar relationship with variables including direct solar radiation, average yearly rainfall, soil parent material and soil drainage class shown in Figure 9(c, d). This allows us to observe which species or group of species are most affected by conditions like higher or lower than usual rainfall, lack of enough direct sunlight and aggravating soil conditions.

Finally, user can revisit each preliminary result to gain further insights by comparing them and making final analysis easy to verify and contemplate.

VI. Conclusions and Future Work

We have presented a way to create multiple coordinated spaces for performing immersive analytics in a physical environment. Our design of MCS builds upon the knowledge base from two disciplines: distributed and embodied cognition, and multiple coordinated visualization. Using MCS, we have found a great flexibility of combining visualizations on 2D displays and 3D visualizations through augmented reality devices. The same approach can be applied to a variety of scenarios, ranging from offices where displays are common to factories where displays are rare. We have also included three case studies to demonstrate the advantages of integrating physical environments as an important component of distributed cognition and immersive analytics.

We believe further research of the MCS framework will be a very fruitful area of research to study the distributed and embodied cognition theories for immersive analytics, especially because there are still many unanswered questions related to human's cognition and reasoning processes. For example, what happens to the communication between internal and external representations during the reasoning process inside our mind? While much research has been devoted to this topic, human cognition is still a black box to us. The answers to these questions are crucial to designing effective visualizations and efficient visual analytics methods to assist the reasoning process.

Lastly, the visualization/interaction mechanisms of immersive analytics are by nature novel, in comparison to conventional WIMP operations. We plan to further expand our design space to explore and create additional MCS methods and evaluate them in a much larger variety of environments and application settings.

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