Thesis Defense in Computer and Information Science

Supporting Data Interaction and Hybrid Asymmetric Collaboration Using Virtual Reality Within the Context of Immersive Analytics

Nico Reski (doctoral candidate)

30th September 2022

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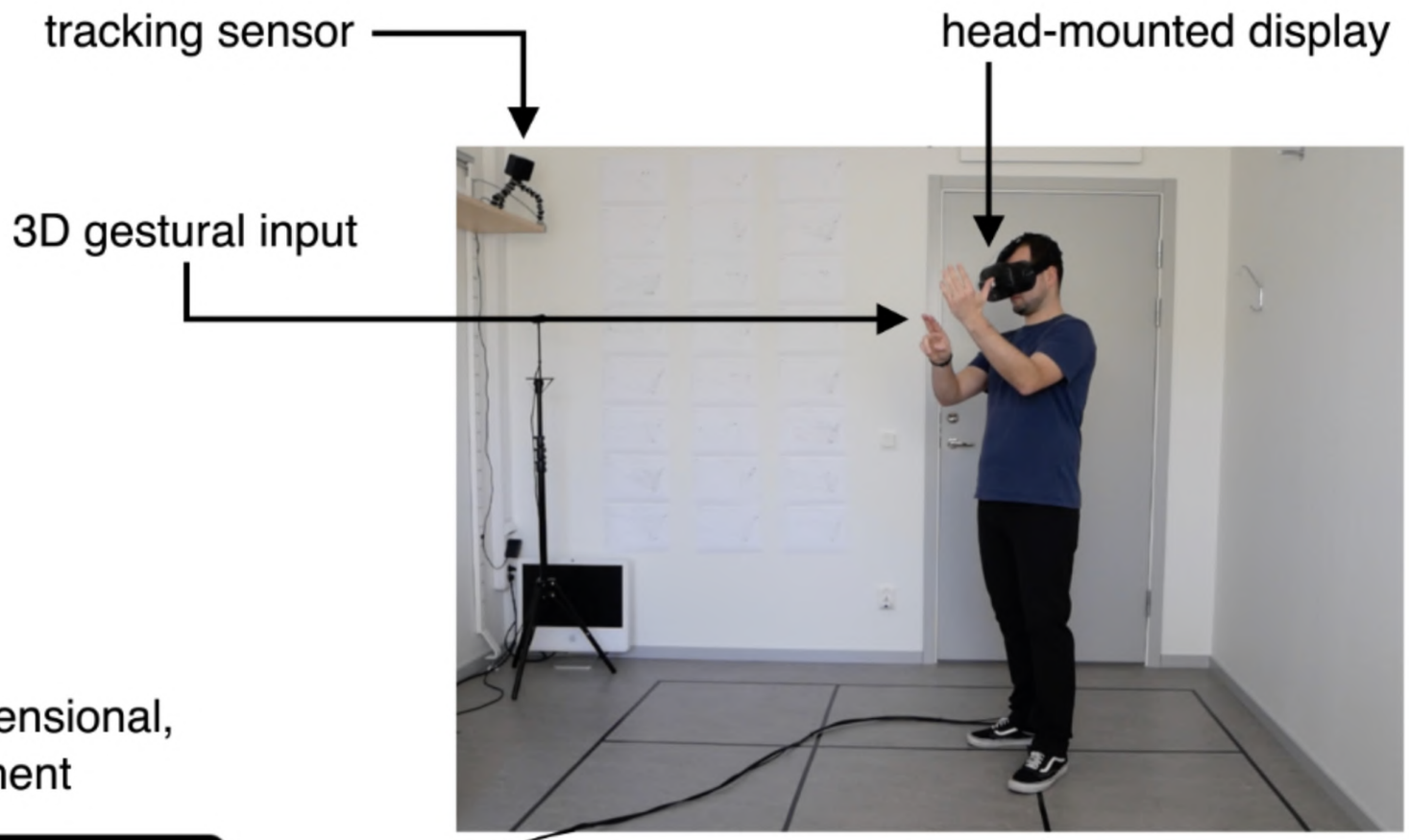
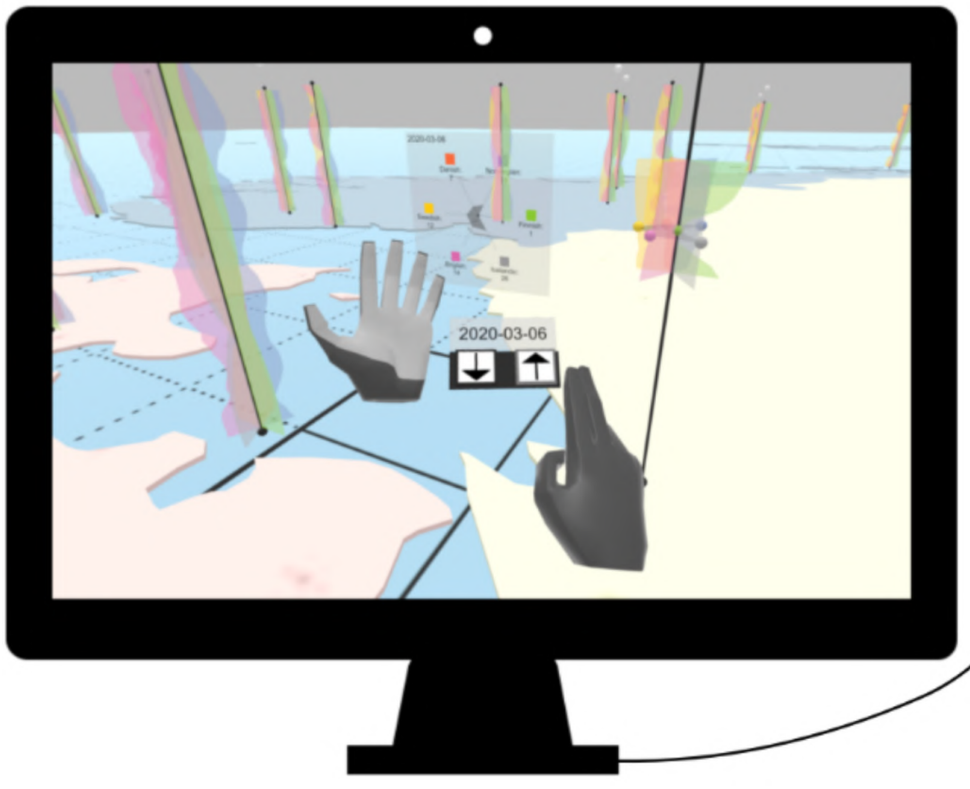
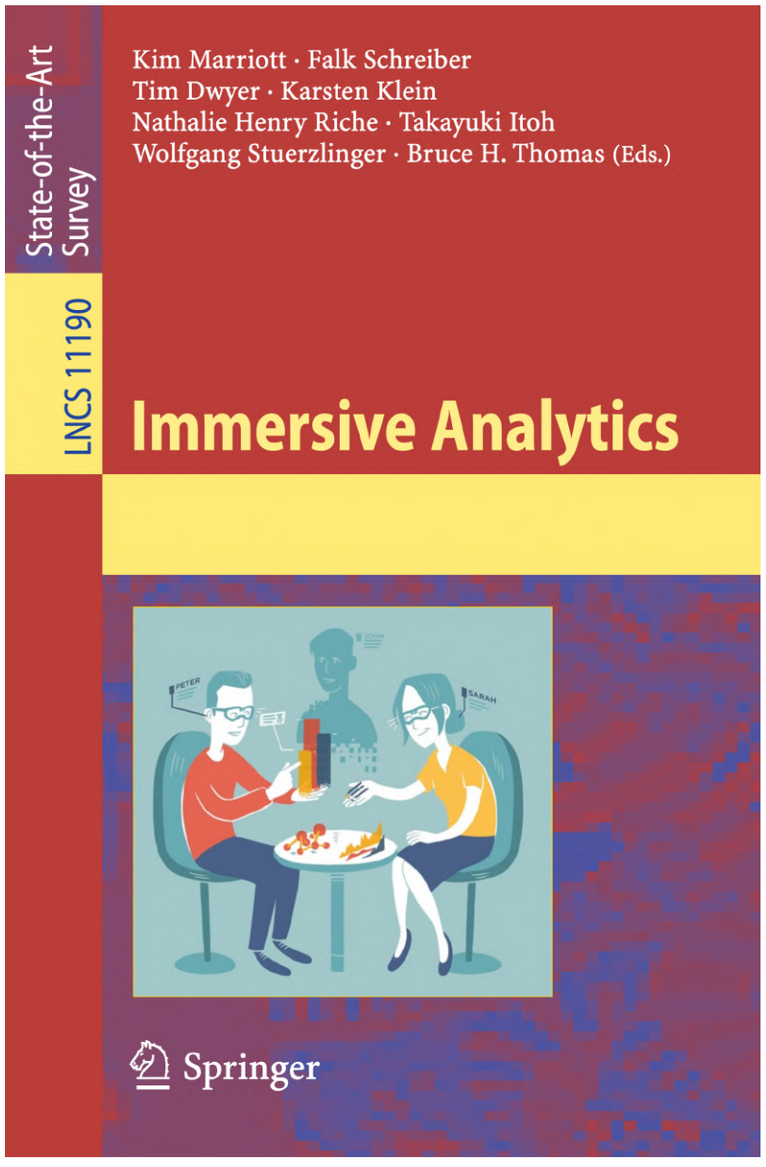


physical real-world space

computer-generated, three-dimensional,
interactive virtual environment





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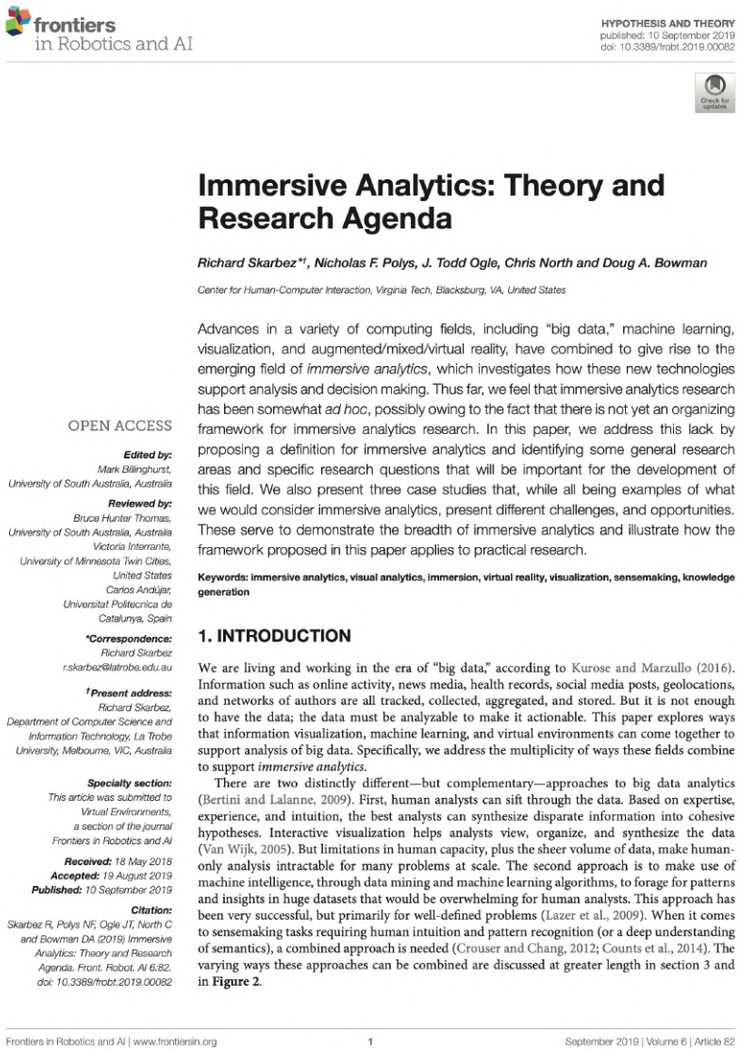
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HYPOTHESIS AND THEORY
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Immersive Analytics: Theory and Research Agenda

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Advances in a variety of computing fields, including "big data," machine learning, visualization, and augmented/mixed/virtual reality, have combined to give rise to the emerging field of *immersive analytics*, which investigates how these new technologies support analysis and decision making. Thus far, we feel that immersive analytics research has been somewhat *ad hoc*, possibly owing to the fact that there is not yet an organizing framework for immersive analytics research. In this paper, we address this lack by proposing a definition for immersive analytics and identifying some general research areas and specific research questions that will be important for the development of this field. We also present three case studies that, while all being examples of what we would consider immersive analytics, present different challenges, and opportunities. These serve to demonstrate the breadth of immersive analytics and illustrate how the framework proposed in this paper applies to practical research.

Keywords: immersive analytics, visual analytics, immersion, virtual reality, visualization, sensemaking, knowledge generation

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1. INTRODUCTION

We are living and working in the era of "big data," according to Kurose and Marzullo (2016). Information such as online activity, news media, health records, social media posts, geolocations, and networks of authors are all tracked, collected, aggregated, and stored. But it is not enough to have the data; the data must be analyzable to make it actionable. This paper explores ways that information visualization, machine learning, and virtual environments can come together to support analysis of big data. Specifically, we address the multiplicity of ways these fields combine to support *immersive analytics*.

There are two distinctly different—but complementary—approaches to big data analytics (Bertini and Lalanne, 2009). First, human analysts can sift through the data. Based on expertise, experience, and intuition, the best analysts can synthesize disparate information into cohesive hypotheses. Interactive visualization helps analysts view, organize, and synthesize the data (Van Wijk, 2005). But limitations in human capacity, plus the sheer volume of data, make human-only analysis intractable for many problems at scale. The second approach is to make use of machine intelligence, through data mining and machine learning algorithms, to forage for patterns and insights in huge datasets that would be overwhelming for human analysts. This approach has been very successful, but primarily for well-defined problems (Lazer et al., 2009). When it comes to sensemaking tasks requiring human intuition and pattern recognition (or a deep understanding of semantics), a combined approach is needed (Crouser and Chang, 2012; Counts et al., 2014). The varying ways these approaches can be combined are discussed at greater length in section 3 and in **Figure 2**.

2019 | Frontiers

Grand Challenges in Immersive Analytics

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ABSTRACT

Immersive Analytics is a quickly evolving field that unites several areas such as visualisation, immersive environments, and human-computer interaction to support human data analysis with emerging technologies. This research has thrived over the past years with multiple workshops, seminars, and a growing body of publications, spanning several conferences. Given the rapid advancement of interaction technologies and novel application domains, this paper aims toward a broader research agenda to enable widespread adoption. We present 17 key research challenges developed over multiple sessions by a diverse group of 24 international experts, initiated from a virtual scientific workshop at ACM CHI 2020. These challenges aim to coordinate future work by providing a systematic roadmap of current directions and impending hurdles to facilitate productive and effective applications for Immersive Analytics.

CHI '21, May 8–13, 2021, Yokohama, Japan

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2021 | ACM CHI

Spatio-Temporal Data

Multivariate Data that feature

- data variables that describe a **spatial** context, and
- data variables that describe a **temporal** context.

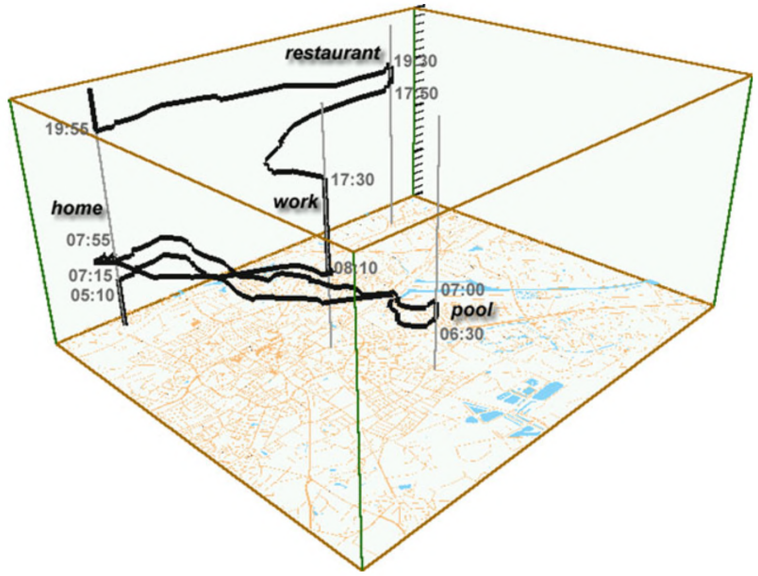


Fig. 7.96: A space-time path is embedded into a space-time cube and shows a person's movement For better orientation, important places are marked by vertical lines and annotations.
Source: Kraak (2003), © 2003 International Cartographic Association (ICA). Used with permission.

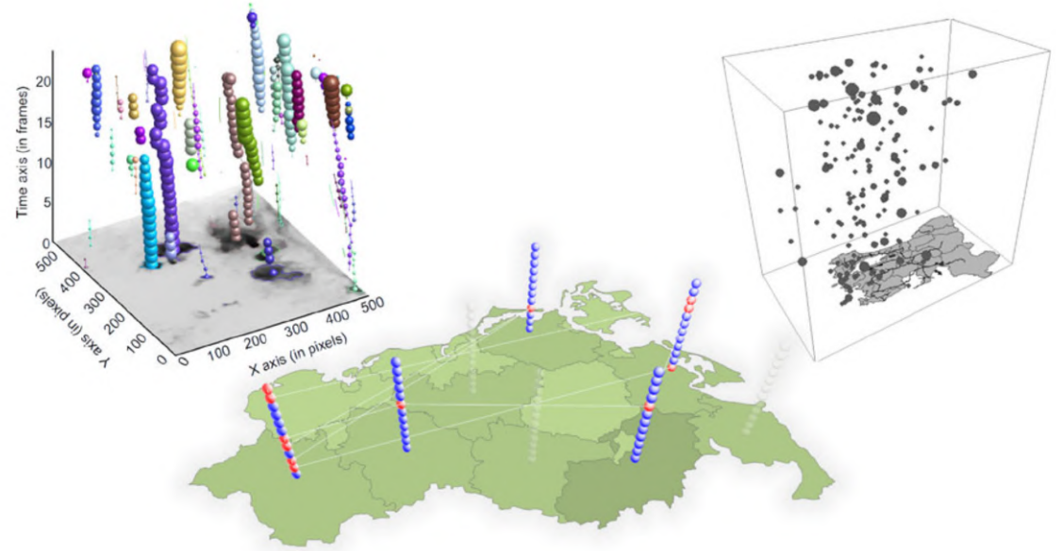


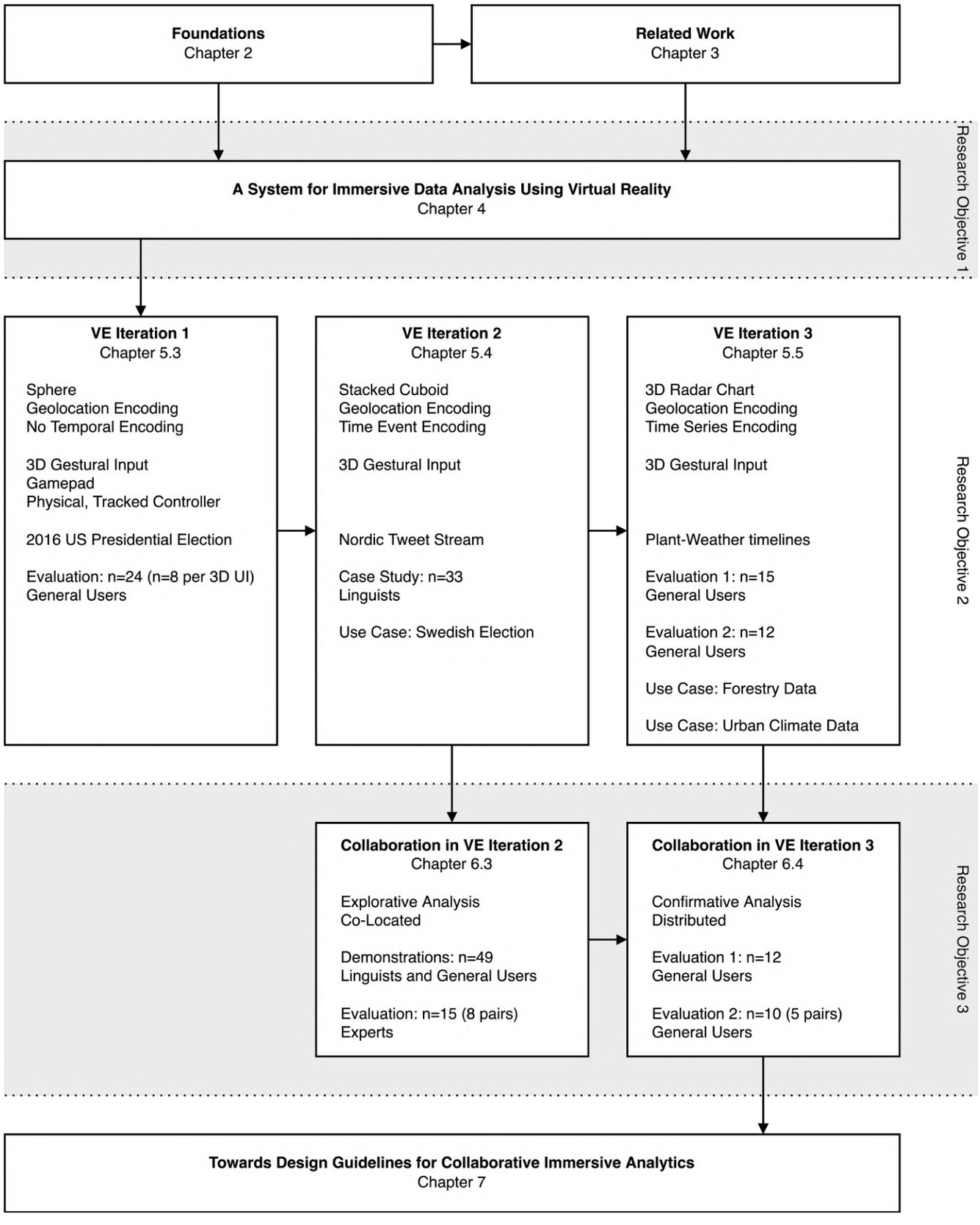
Fig. 7.95: Events in space and time are visualized by embedding graphical objects of varying size and color into space-time cubes. From left to right, the cubes show events related to convective clouds, human health data, and earthquakes.
Source: Left: Turdukulov et al. (2007), © 2007 Elsevier. Used with permission. Center: Generated with the LandVis system. Right: Gatalsky et al. (2004), © 2004 IEEE. Used with permission.

Research Objective 1
Design and implementation of a **system** that allows for multivariate data analysis using immersive display and interaction technologies.

Research Objective 2
Investigation of 3D UI design approaches to support immersive **interaction** with spatio-temporal data.

Research Objective 3
Extension of the immersive data analysis system to support **collaboration** using heterogeneous interfaces and user roles.

Thesis Outline



Thesis Outline

Foundations
Chapter 2

Related Work
Chapter 3

A System for Immersive Data Analysis Using Virtual Reality
Chapter 4

Research Objective 1

VE Iteration 1
Chapter 5.3

Sphere
Geolocation Encoding
No Temporal Encoding

3D Gestural Input
Gamepad
Physical, Tracked Controller

2016 US Presidential Election

Evaluation: n=24 (n=8 per 3D UI)
General Users

VE Iteration 2
Chapter 5.4

Stacked Cuboid
Geolocation Encoding
Time Event Encoding

3D Gestural Input

Nordic Tweet Stream

Case Study: n=33
Linguists

Use Case: Swedish Election

VE Iteration 3
Chapter 5.5

3D Radar Chart
Geolocation Encoding
Time Series Encoding

3D Gestural Input

Plant-Weather timelines

Evaluation 1: n=15
General Users

Evaluation 2: n=12
General Users

Use Case: Forestry Data

Use Case: Urban Climate Data

Research Objective 2

Collaboration in VE Iteration 2
Chapter 6.3

Explorative Analysis
Co-Located

Demonstrations: n=49
Linguists and General Users

Evaluation: n=15 (8 pairs)
Experts

Collaboration in VE Iteration 3
Chapter 6.4

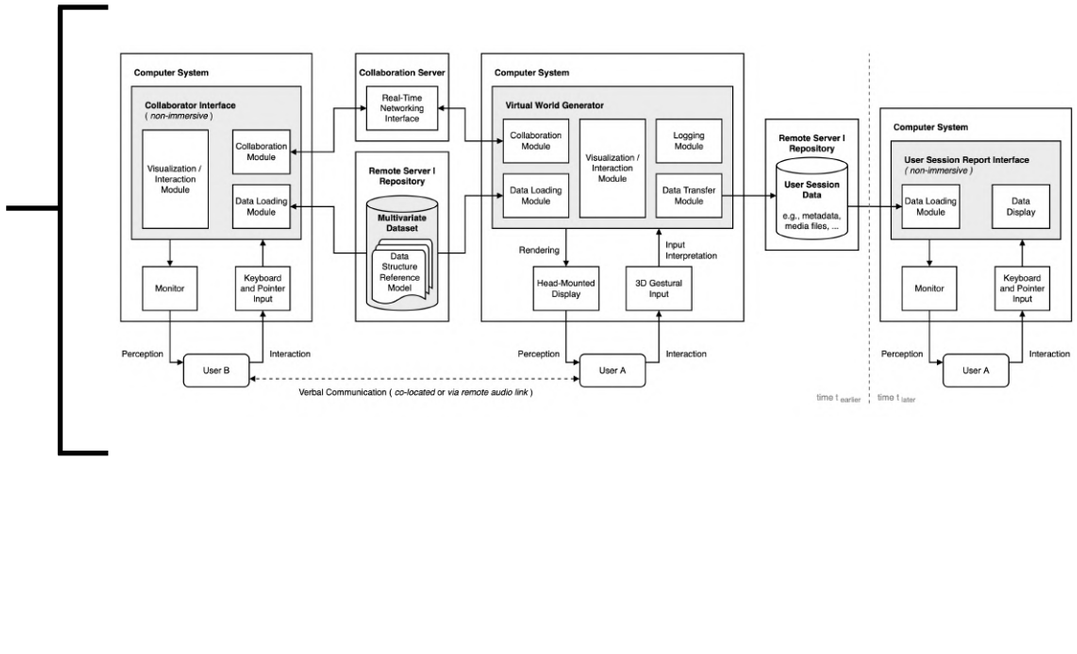
Confirmative Analysis
Distributed

Evaluation 1: n=12
General Users

Evaluation 2: n=10 (5 pairs)
General Users

Research Objective 3

Towards Design Guidelines for Collaborative Immersive Analytics
Chapter 7



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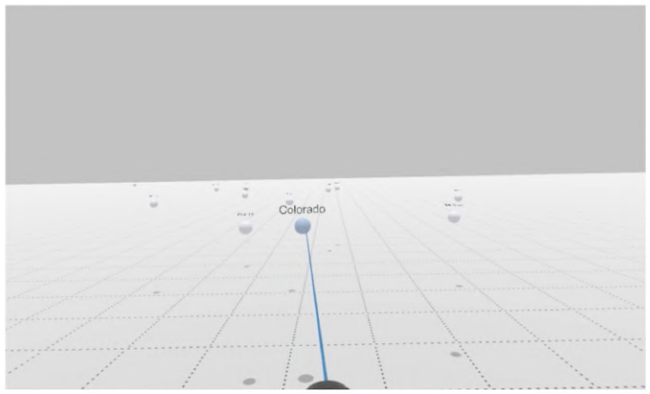
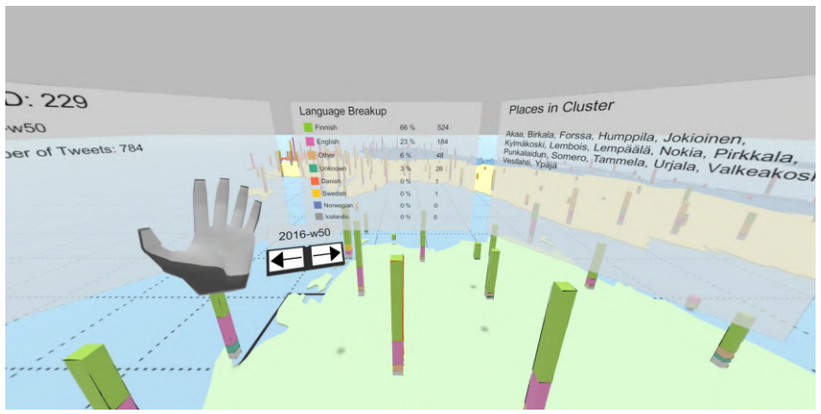
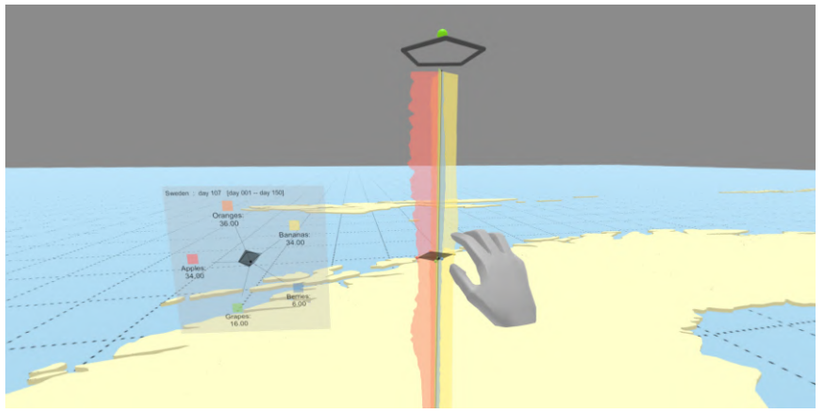


Sphere - VE Iteration 1



Stacked Cuboid - VE Iteration 2



3D Radar Chart - VE Iteration 3

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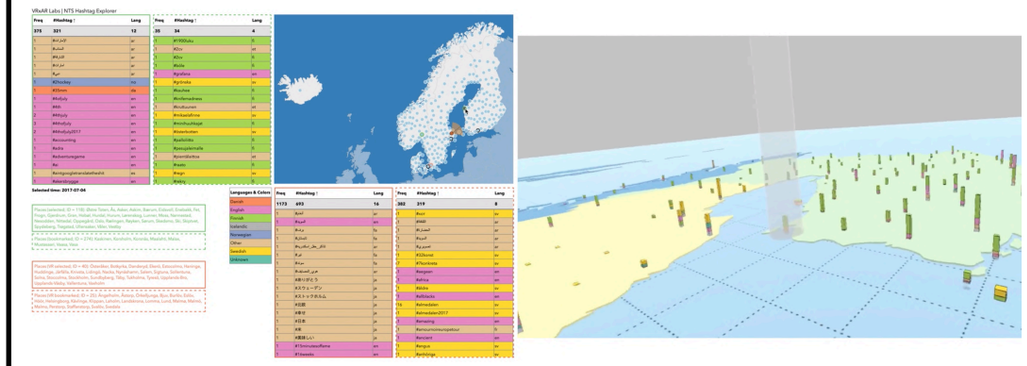
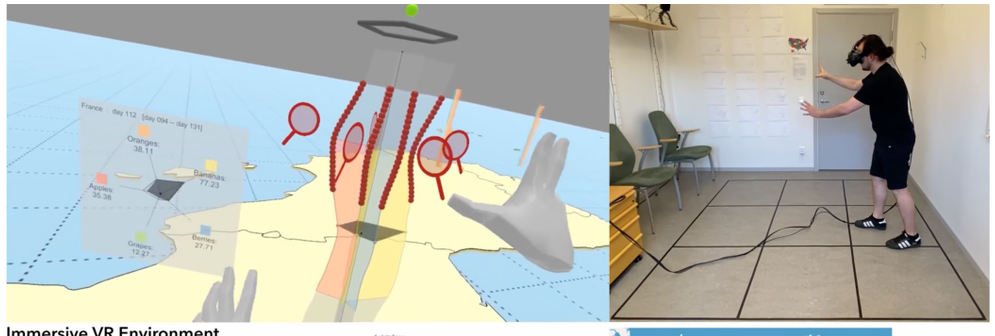


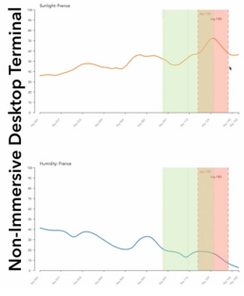
Collaboration in VE Iteration 2



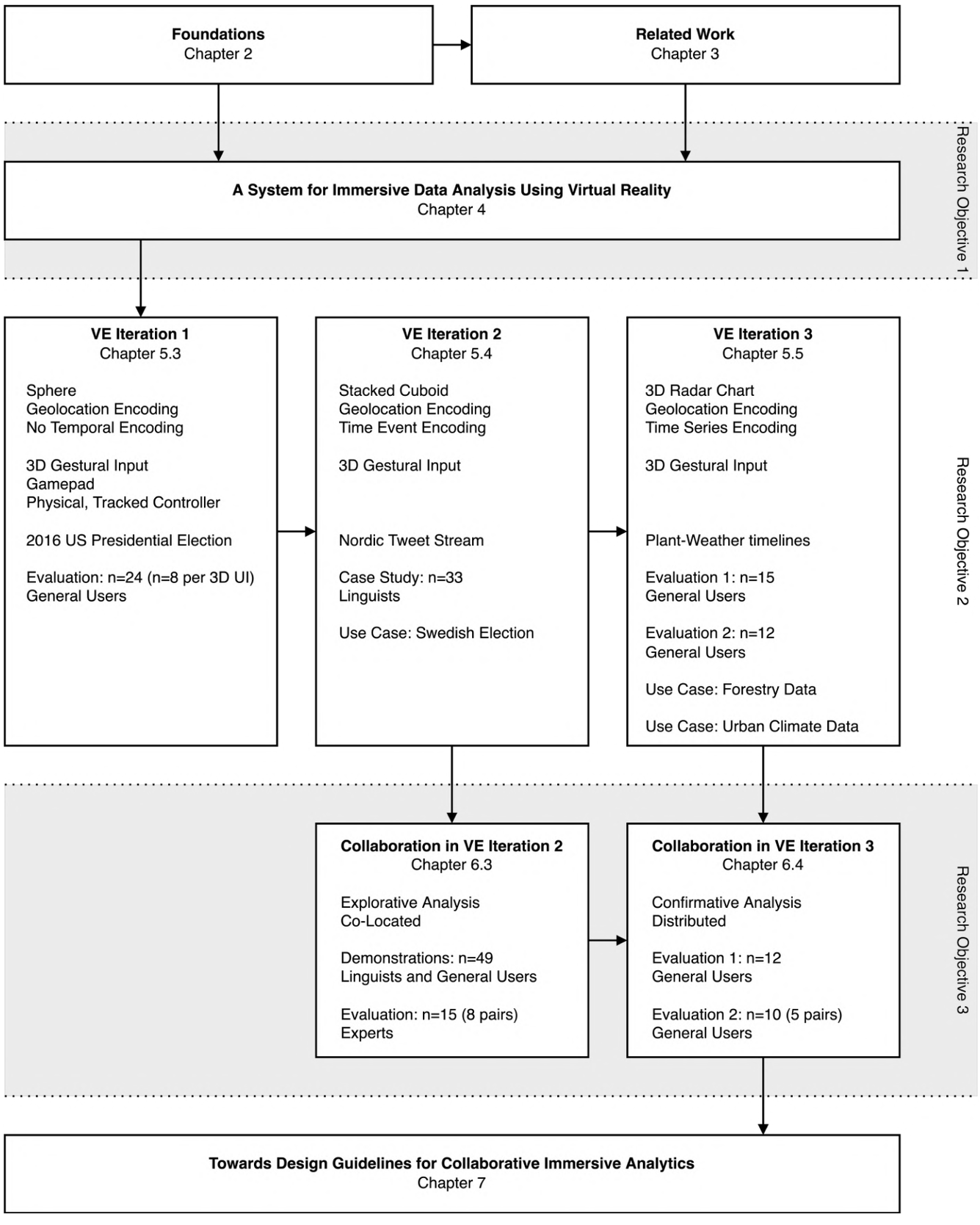
Immersive VR Environment

[Synchronous Collaborative Features]

- Spatial References
- Temporal References
  - Time Event
  - Time Range



Collaboration in VE Iteration 3



Design Guideline 1

Consider providing supporting artifacts that facilitate orientation and interpretation of the spatial data context.

Design Guideline 2

Consider the visual mapping for the integration of the temporal data variables into each data entity.

Design Guideline 3

Design for hand interaction.

Design Guideline 4

Design with hand posture complexity in mind; utilize simple uni-manual techniques for frequent tasks, and more complex bimanual techniques for less frequent ones.

Design Guideline 5

Limit available interactions based on the user's in-situ context.

Design Guideline 6

Consider workflow integration with non-immersive tools.

Design Guideline 7

Facilitate collaboration by enabling multimodal communication using a mixture of verbal and nonverbal tools.

Design Guideline 8

Consider the design of the nonverbal collaborative information cues; modify or add artifacts to a data entity, or modify its environment.

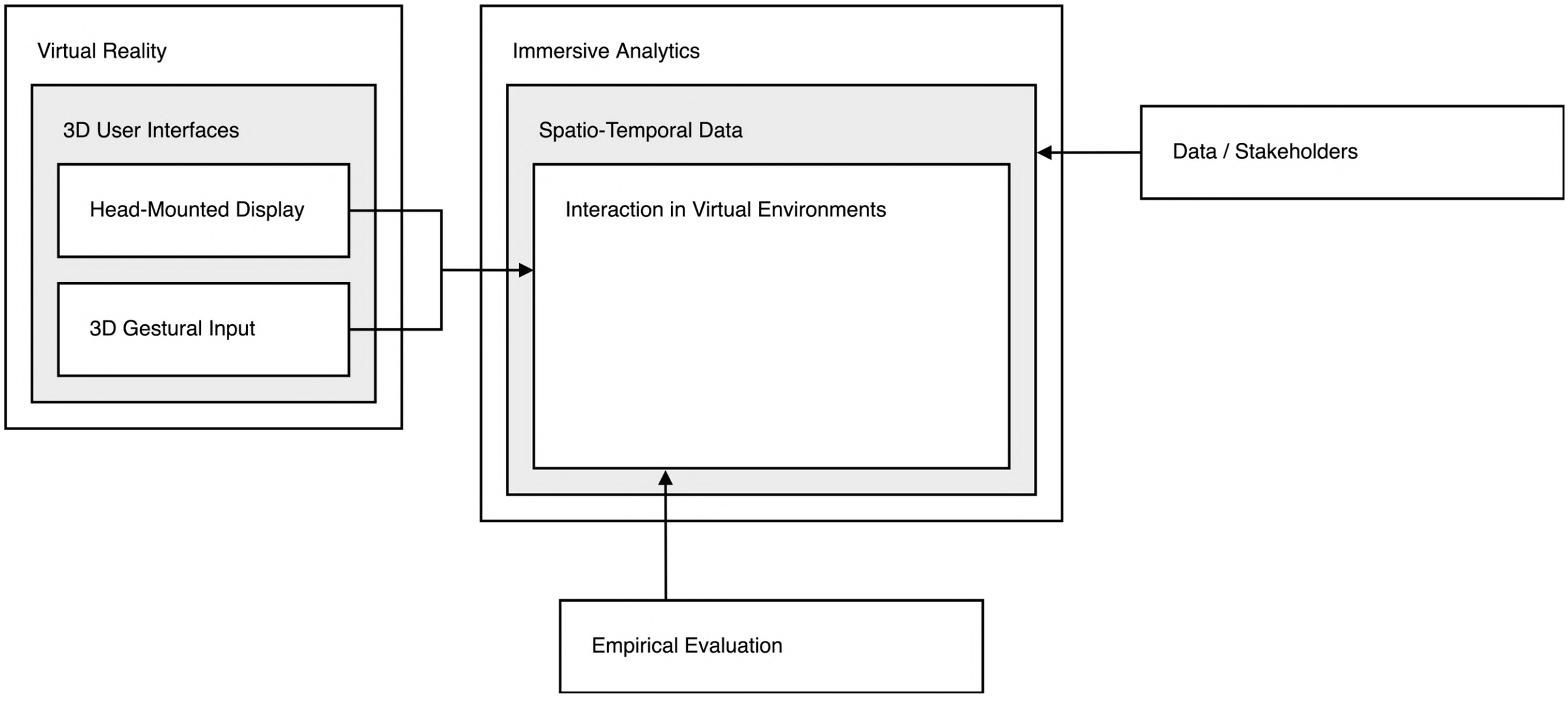
Design Guideline 9

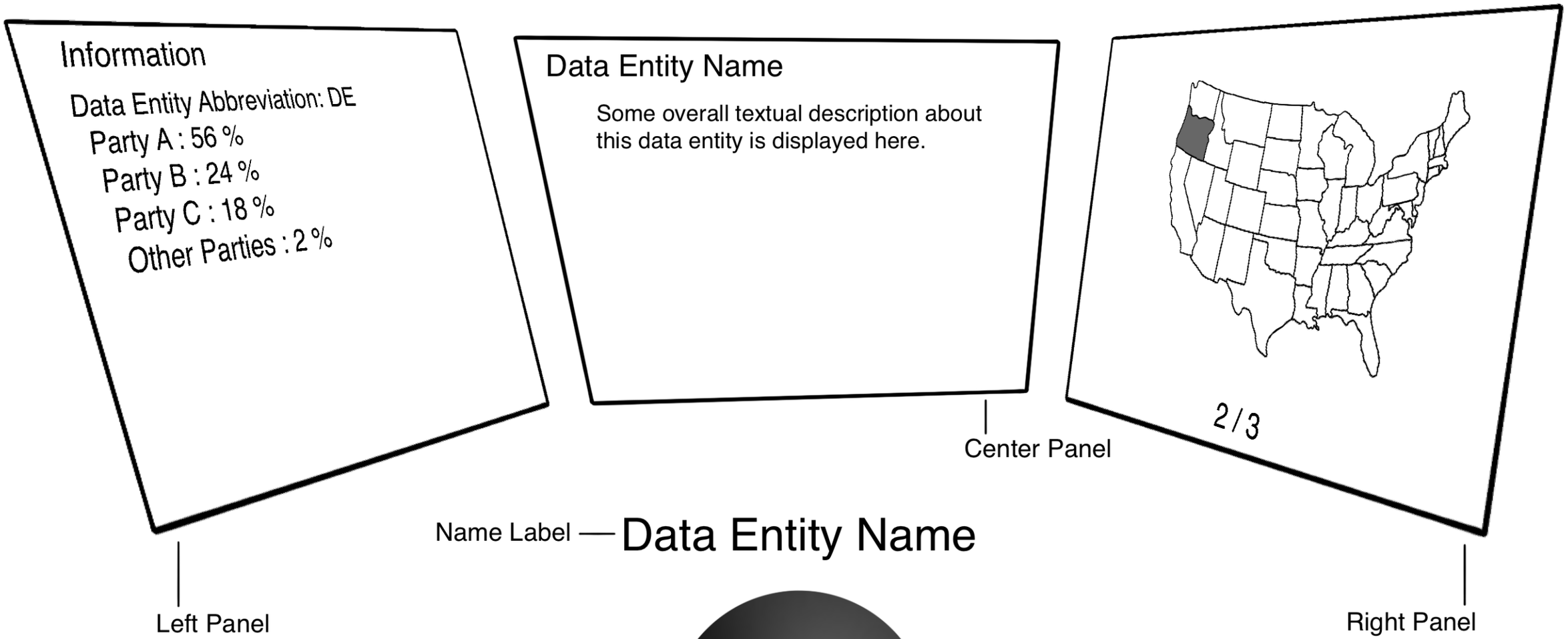
Consider the update frequency of the nonverbal collaborative information cues; utilize continuous updates to allow for fluent collaboration, and on demand updates for focused ad hoc group efforts.

Design Guideline 10

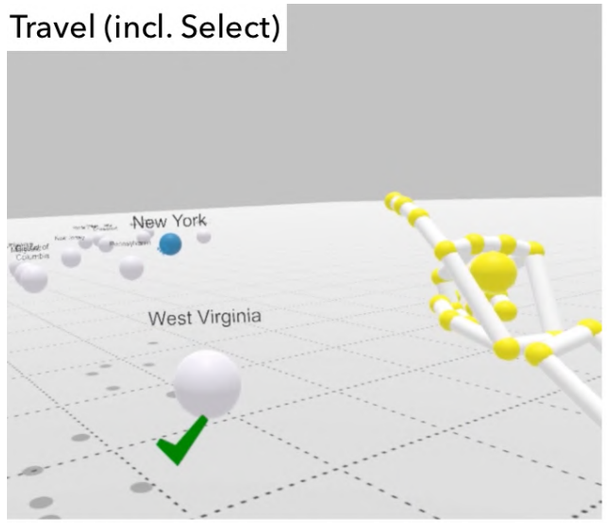
Consider the classification of the collaborative data analysis experience; take into account data context, scenario, tasks, technologies, and user roles.

Thesis Design Space
(partial; interaction only; research objective 2)




Information
Data Entity Abbreviation: DE
Party A : 56 %
Party B : 24 %
Party C : 18 %
Other Parties : 2 %
Data Entity Name
Some overall textual description about this data entity is displayed here.
2/3
Center Panel
Name Label — Data Entity Name
Left Panel
Right Panel
Sphere

Travel (incl. Select)



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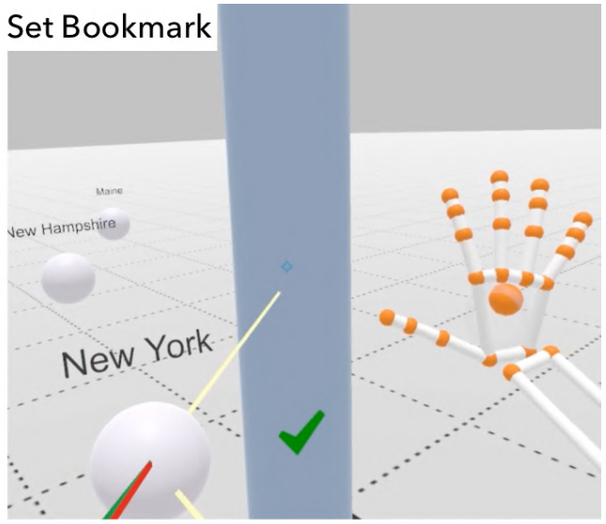

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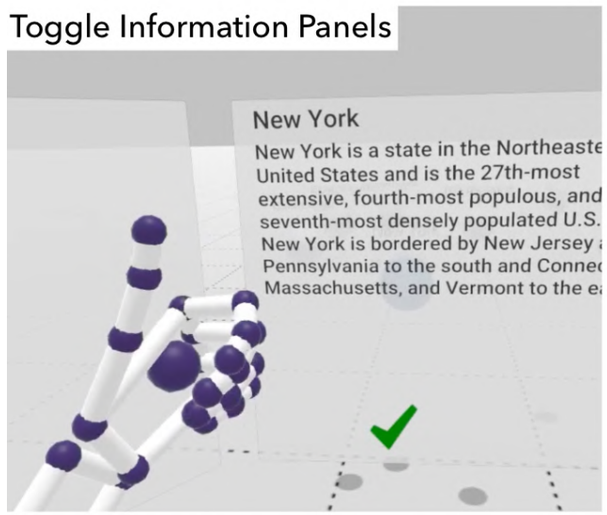

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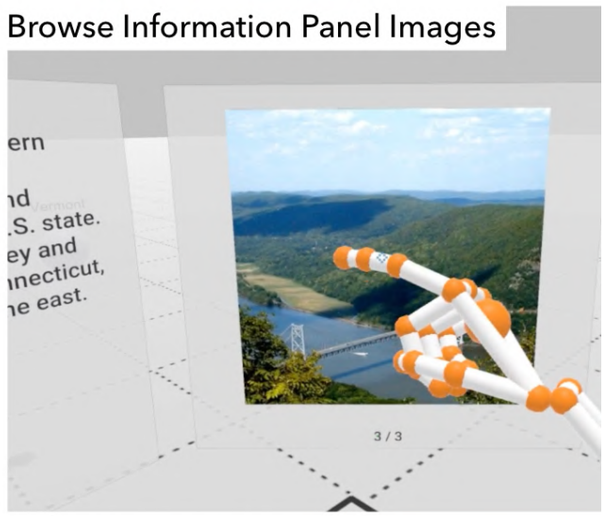
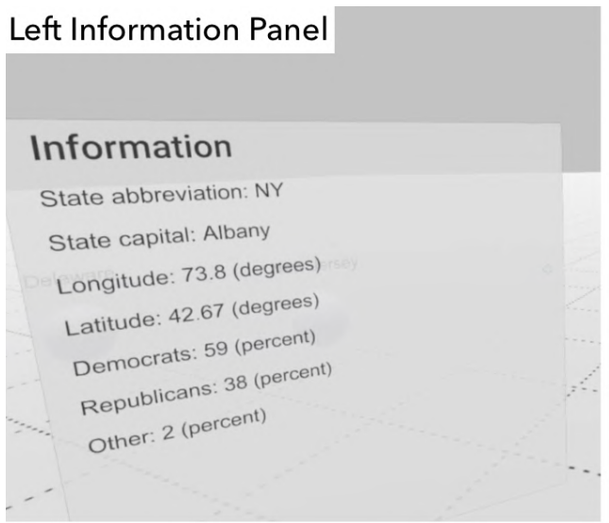
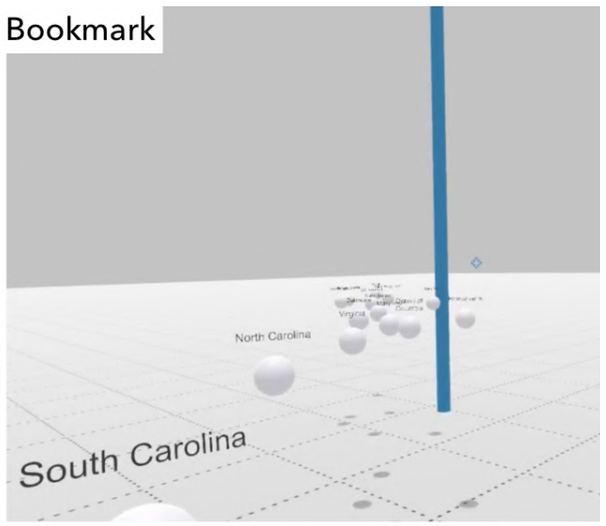


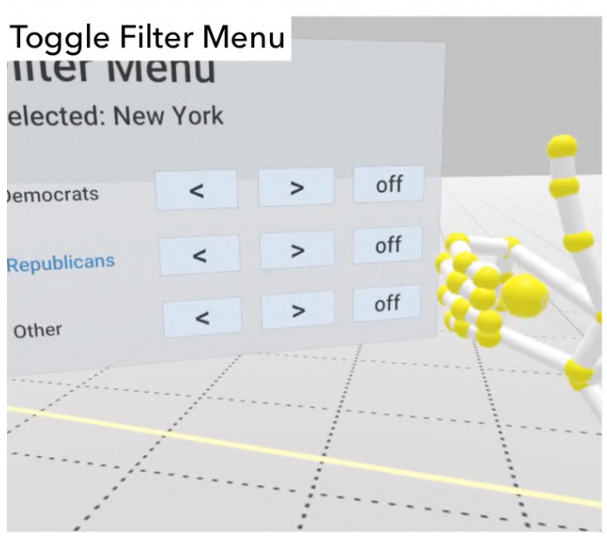
Left Information Panel



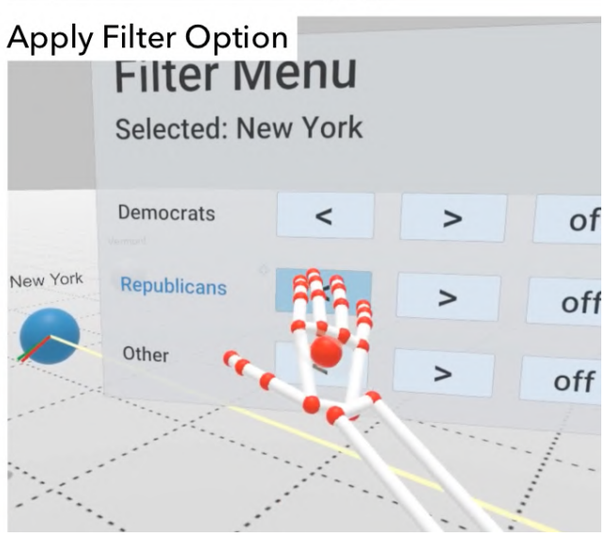
Bookmark



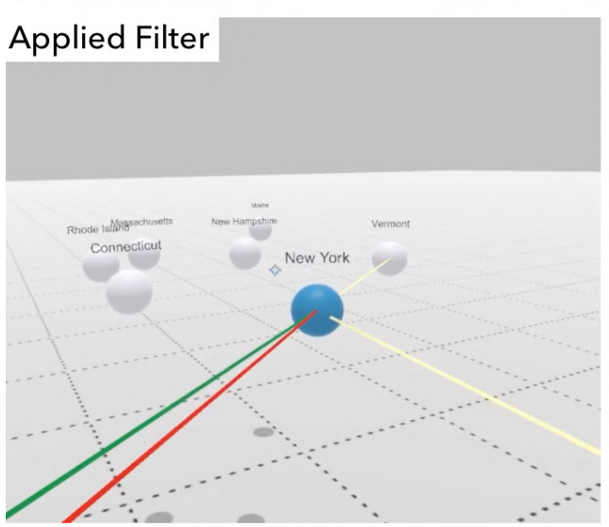
Toggle Filter Menu



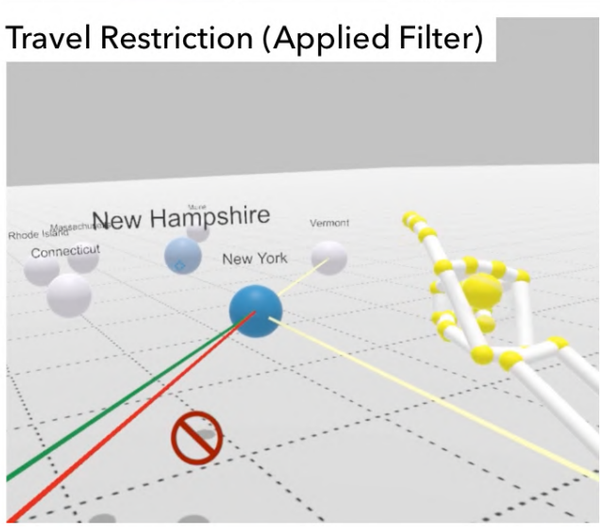
Apply Filter Option



Applied Filter



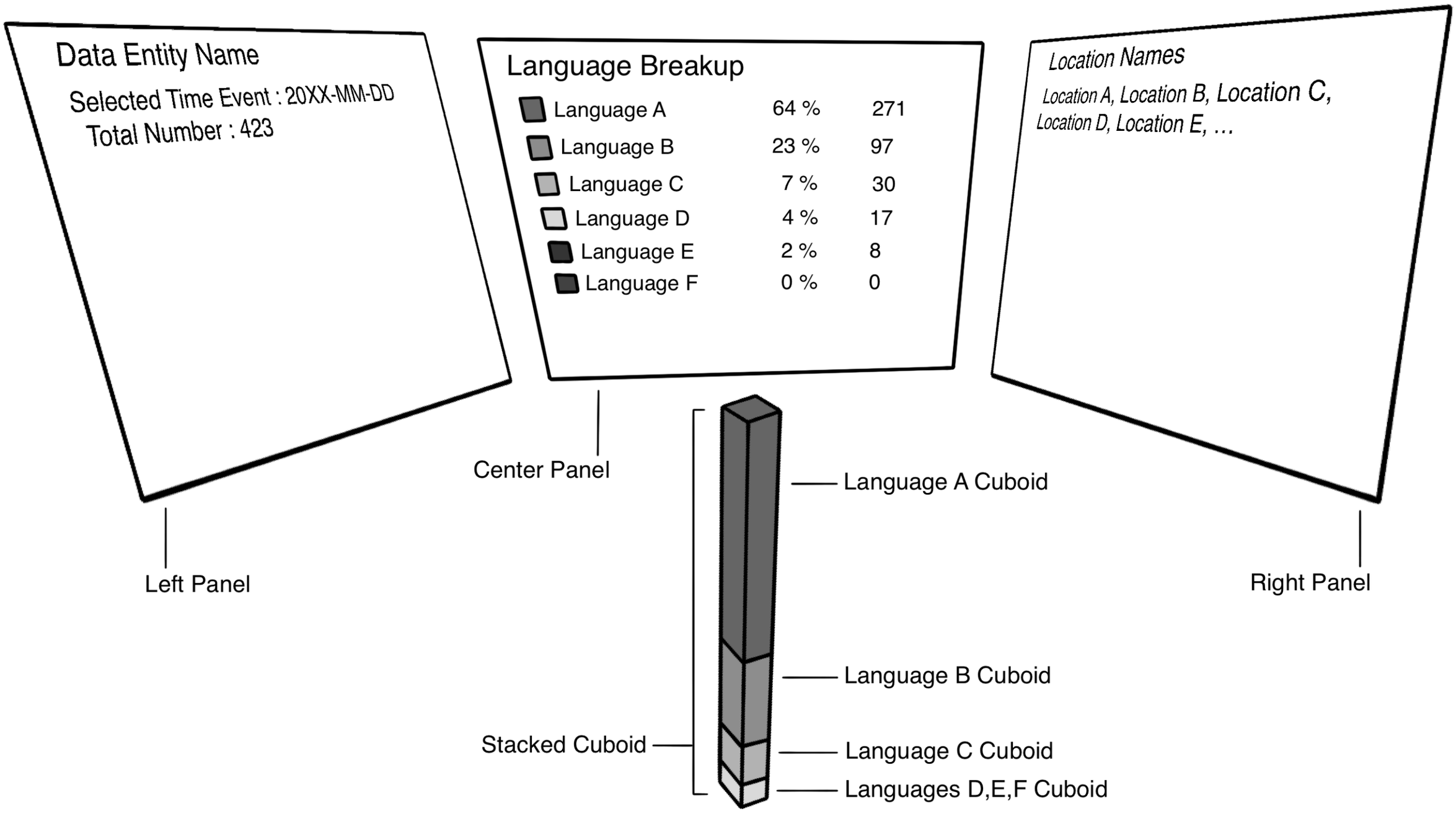
Travel Restriction (Applied Filter)



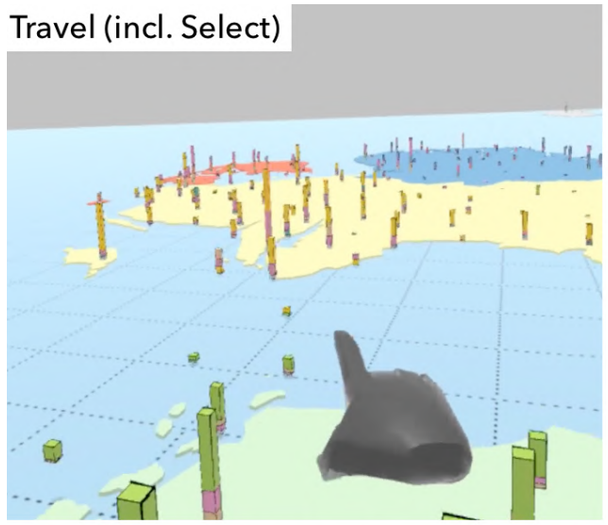
Gamepad

3D Gestural Input

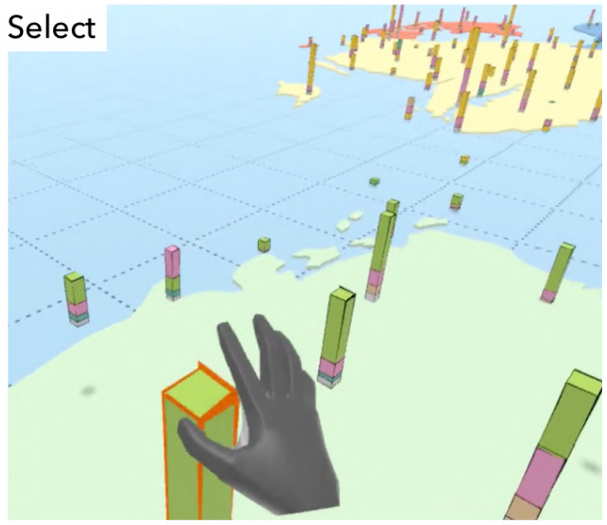
Physical, Tracked Controller


Data Entity Name
Selected Time Event : 20XX-MM-DD
Total Number : 423
Language Breakup
Language A 64 % 271
Language B 23 % 97
Language C 7 % 30
Language D 4 % 17
Language E 2 % 8
Language F 0 % 0
Location Names
Location A, Location B, Location C,
Location D, Location E, …
Left Panel
Center Panel
Right Panel
Language A Cuboid
Language B Cuboid
Language C Cuboid
Languages D,E,F Cuboid
Stacked Cuboid

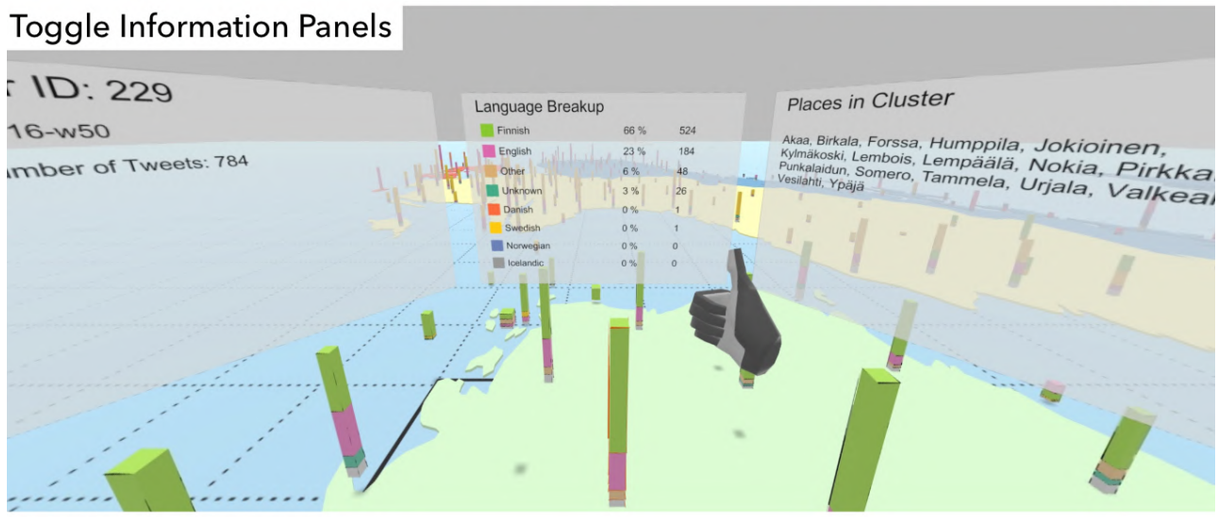
Travel (incl. Select)



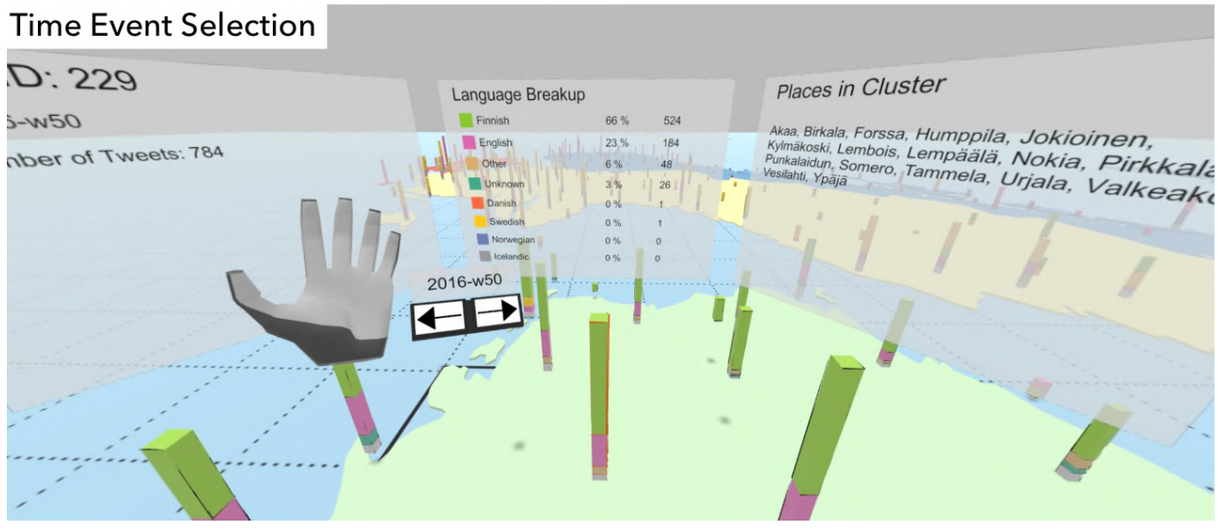
Select



Toggle Information Panels



Time Event Selection

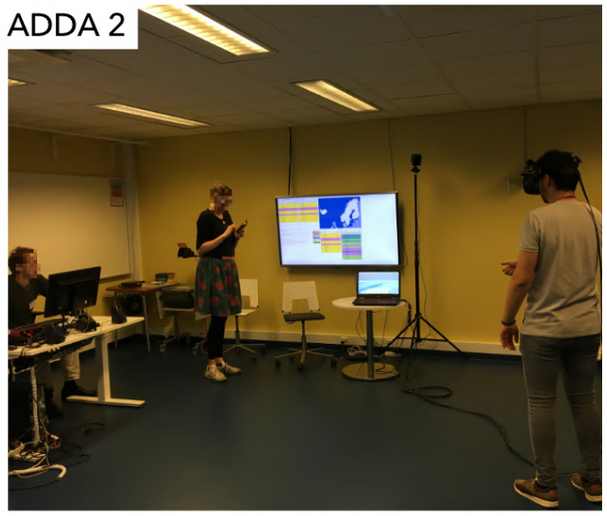


ICAME 39

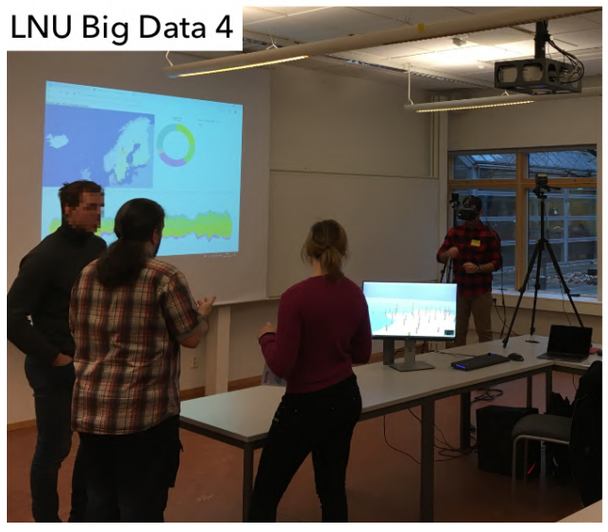
ICAME 39

ADDA 2

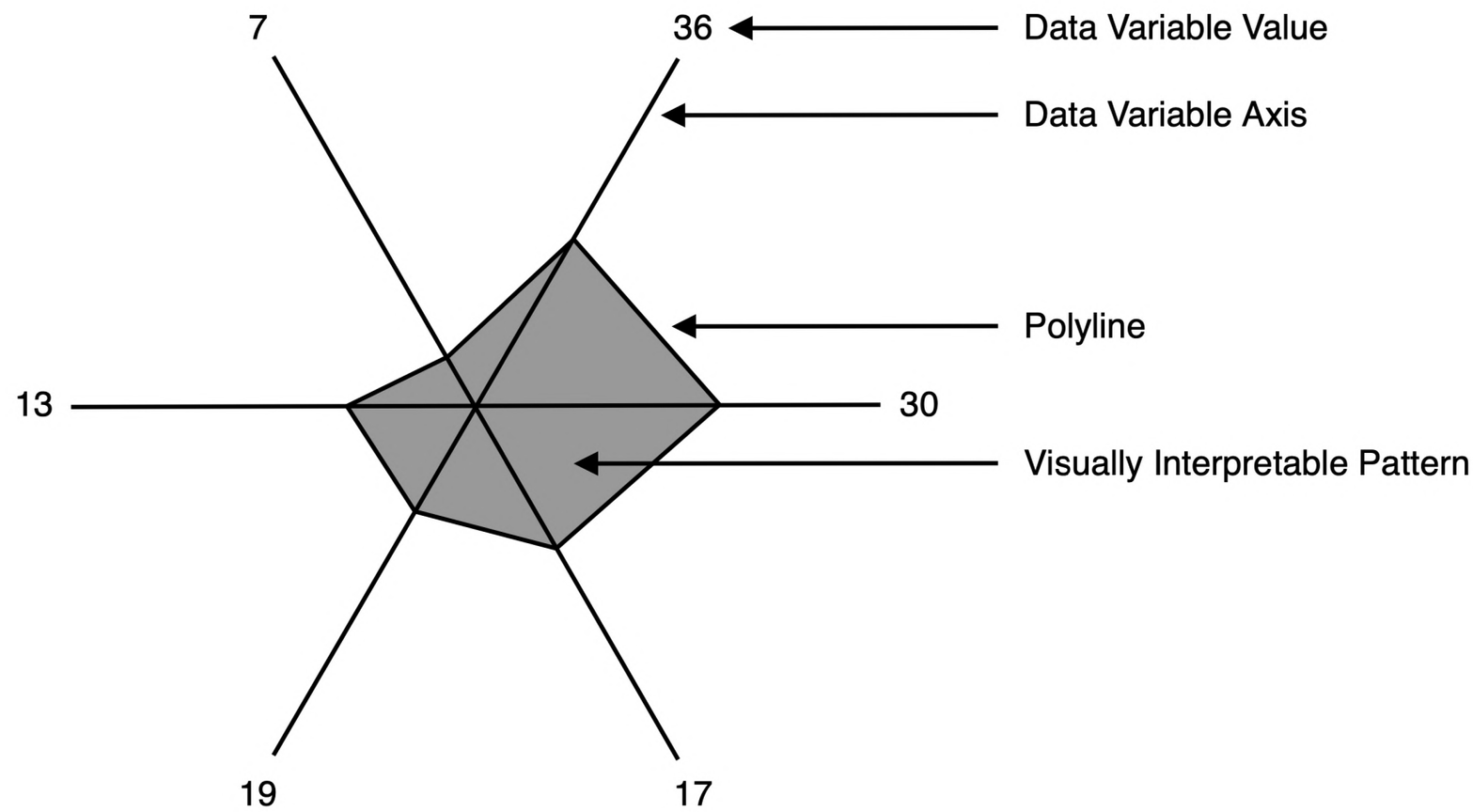
ADDA 2

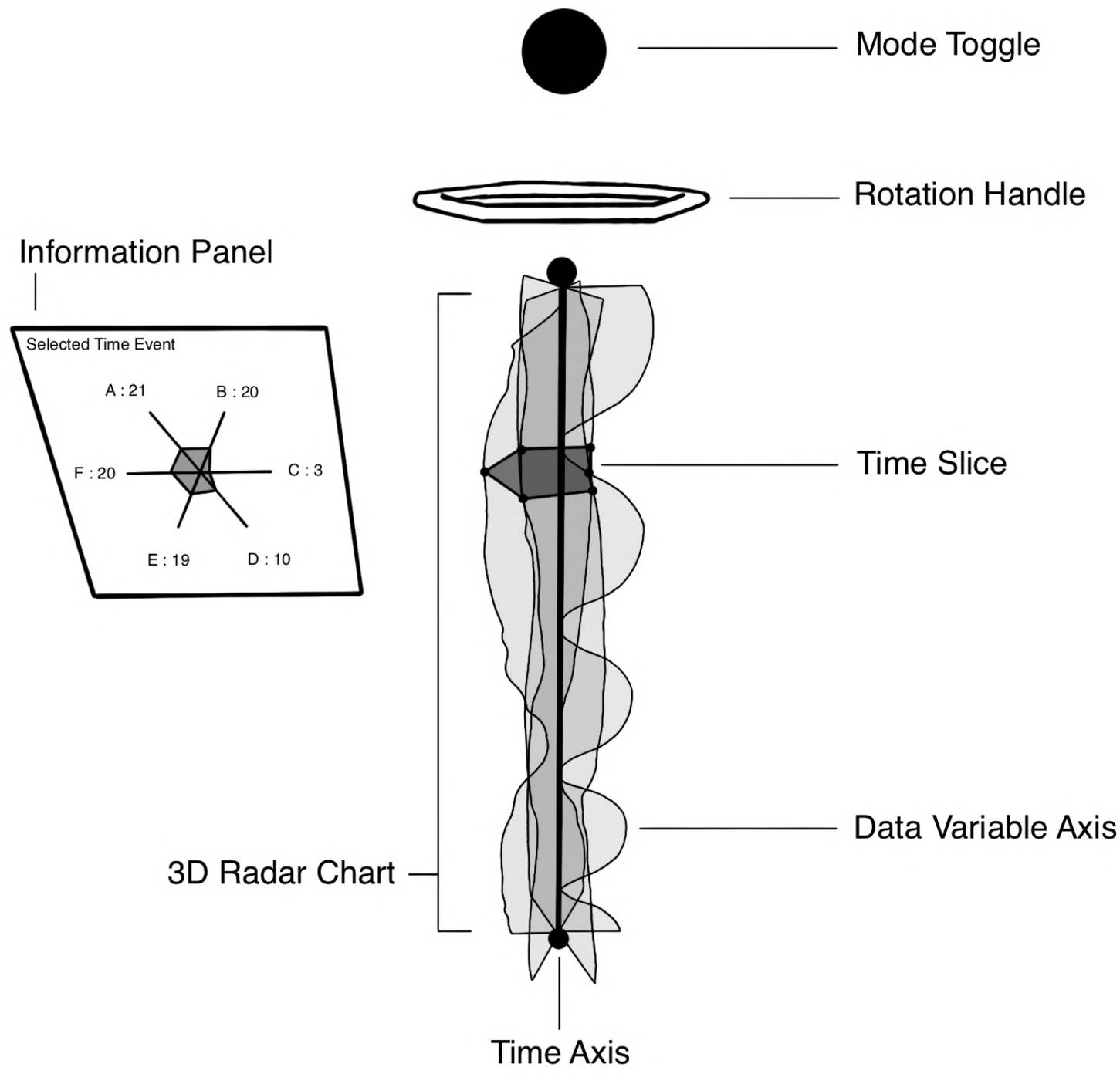


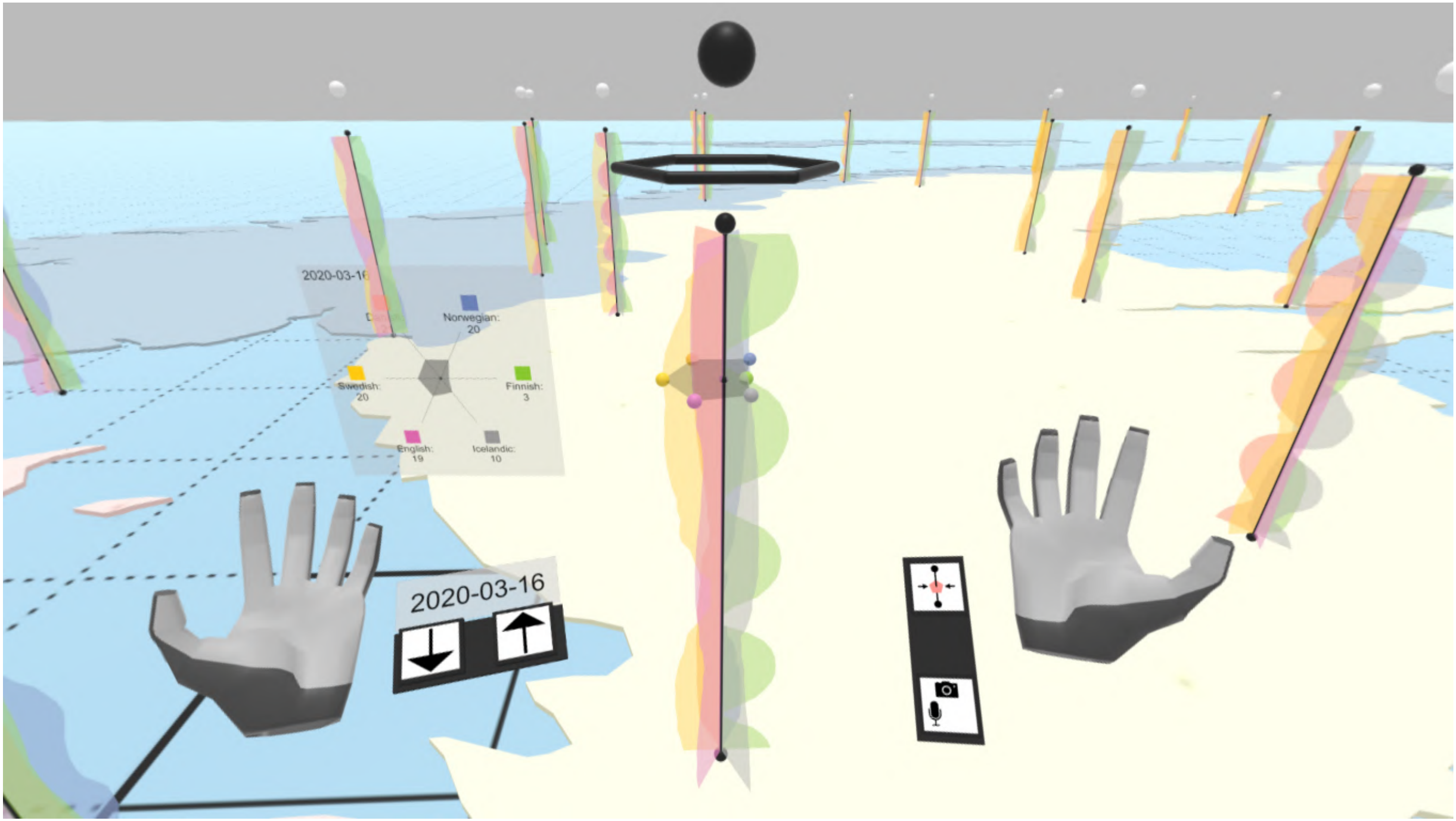
LNU Big Data 4

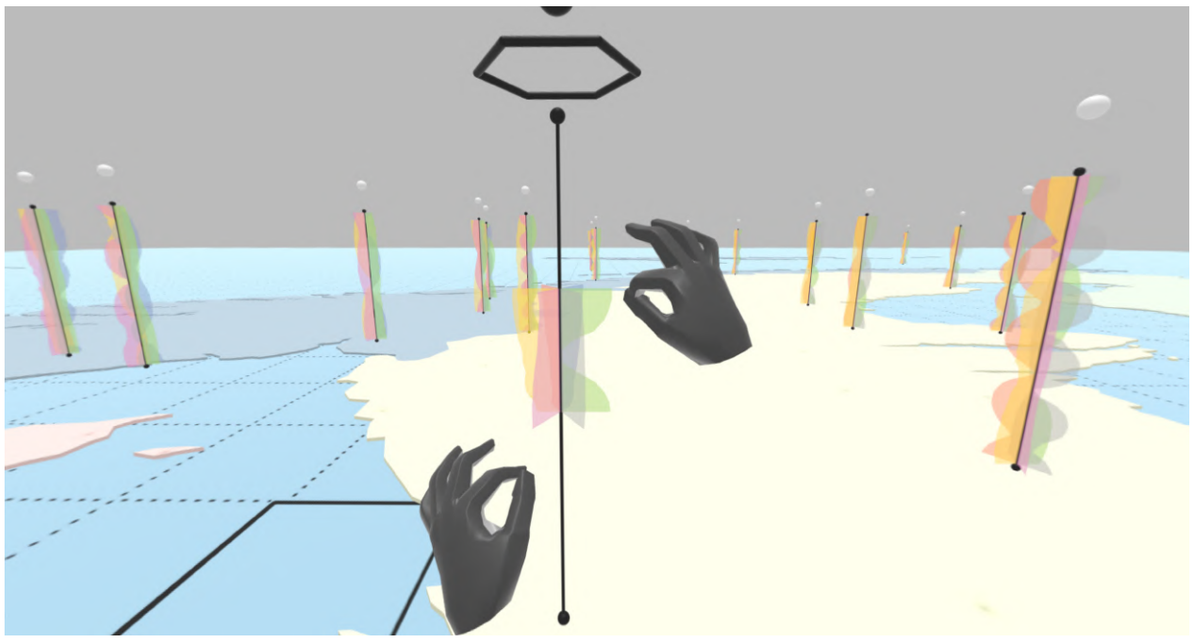


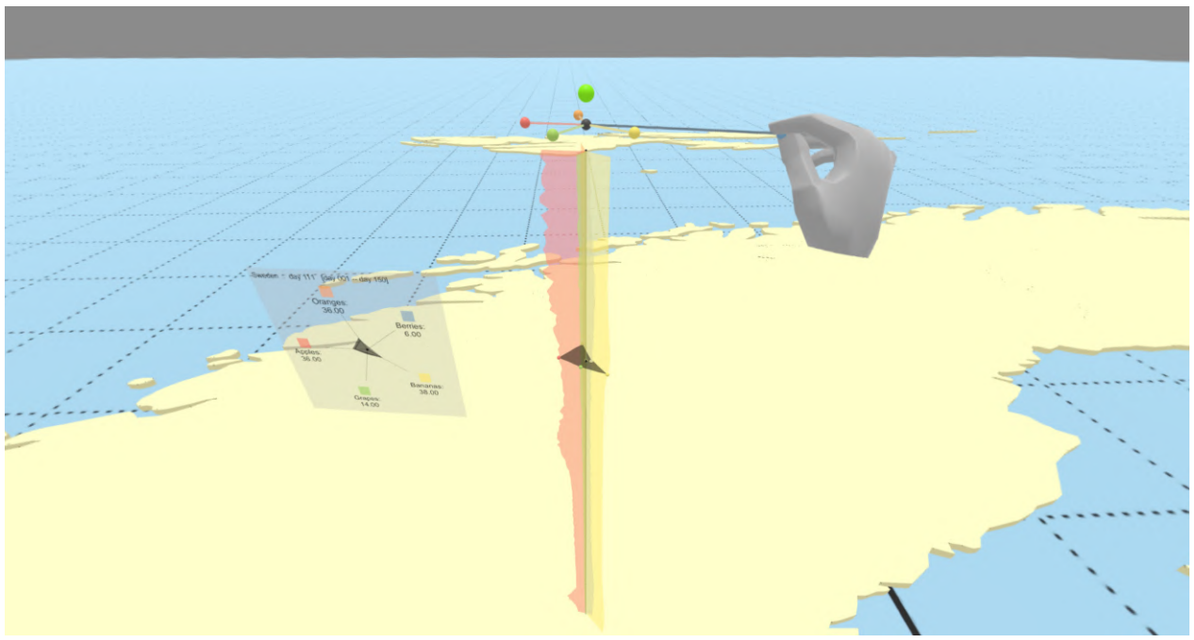
LNU Big Data 5


7
36
Data Variable Value
Data Variable Axis
Polyline
13
30
Visually Interpretable Pattern
19
17


Mode Toggle
Rotation Handle
Information Panel
Selected Time Event
A : 21
B : 20
F : 20
C : 3
E : 19
D : 10
Time Slice
Data Variable Axis
3D Radar Chart
Time Axis


2020-03-16
Norwegian:
20
Swedish:
20
Finnish:
3
English:
19
Icelandic:
10
2020-03-16

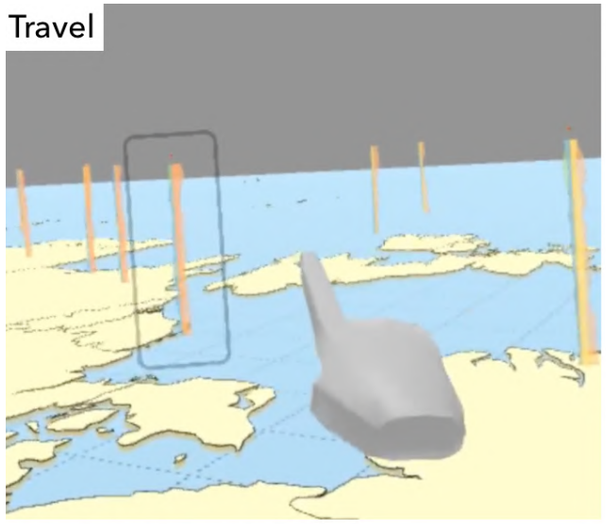




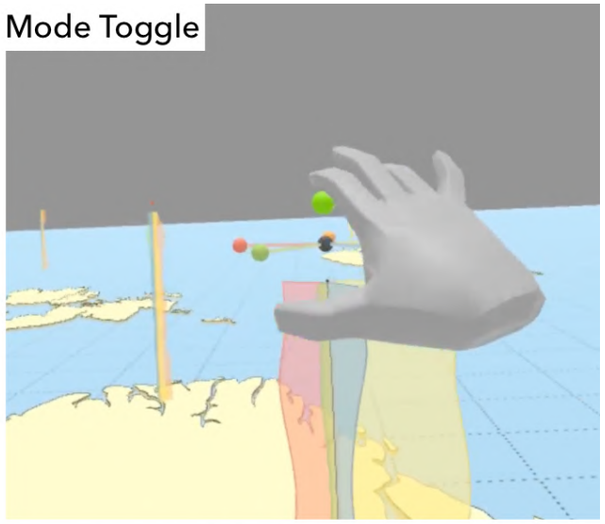
Visualization Approach Validation

Uniform 3D Gestural Interface Design

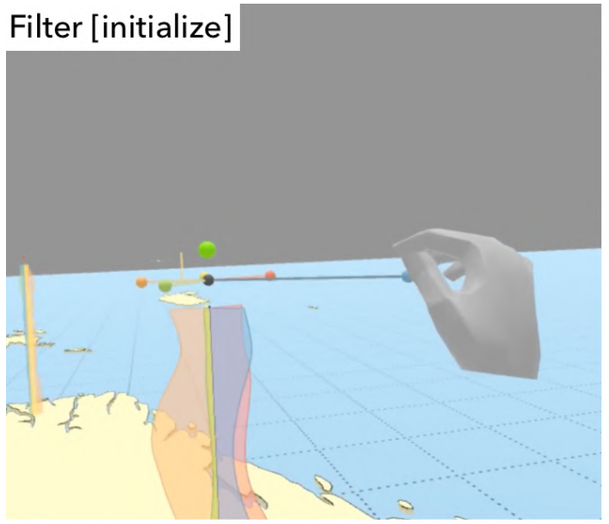
Travel



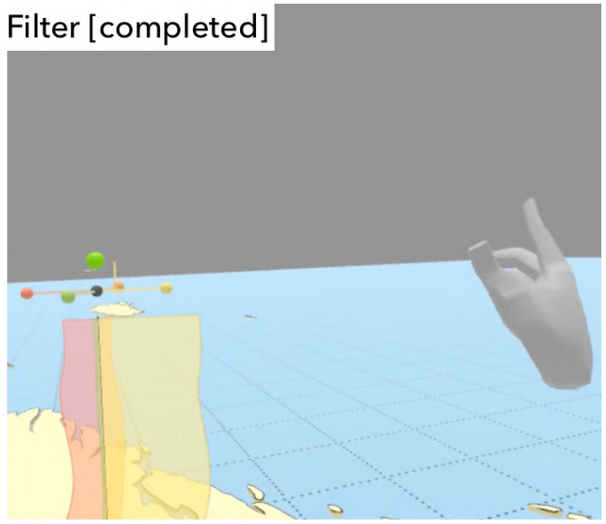
Mode Toggle



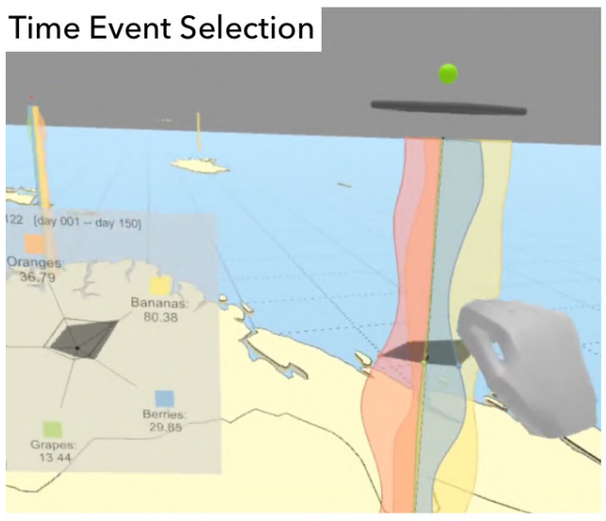
Filter [initialize]



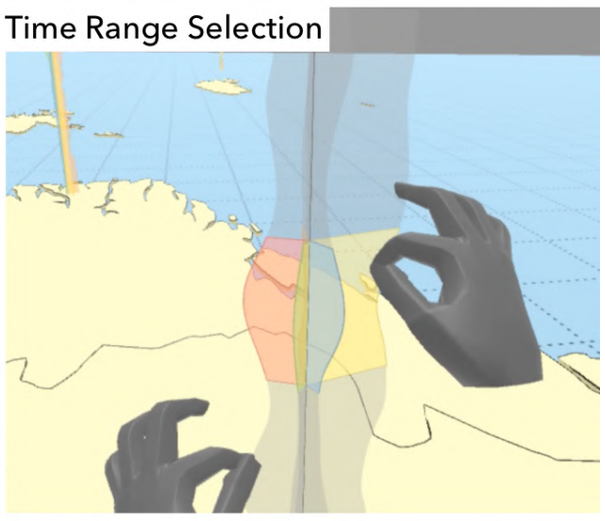
Filter [completed]



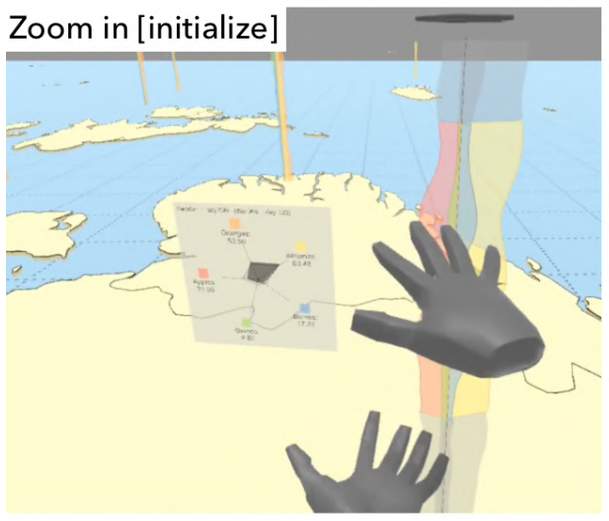
Time Event Selection



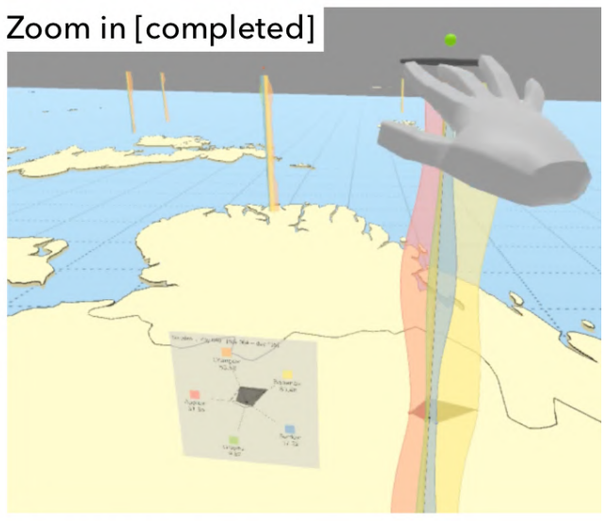
Time Range Selection



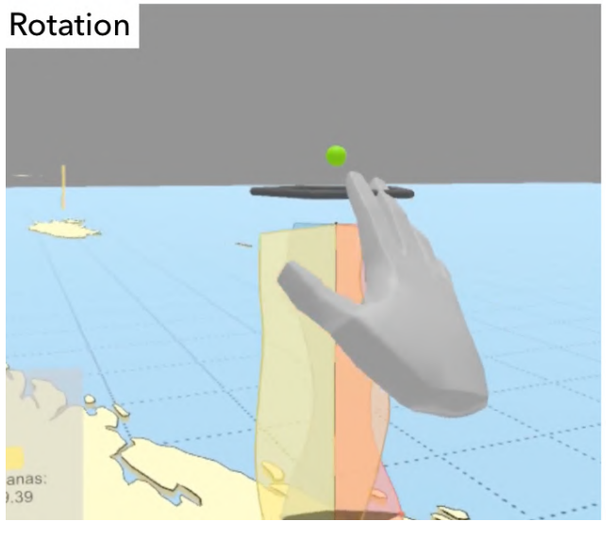
Zoom in [initialize]



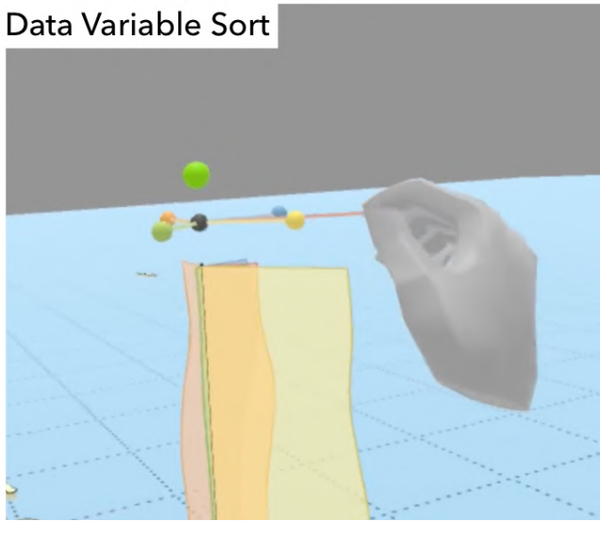
Zoom in [completed]



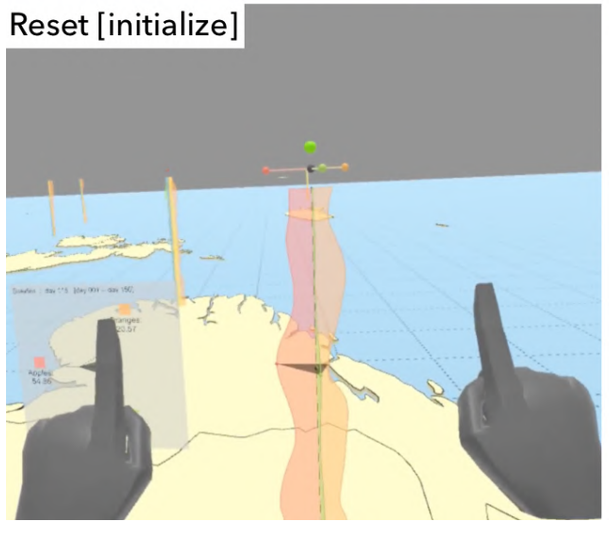
Rotation



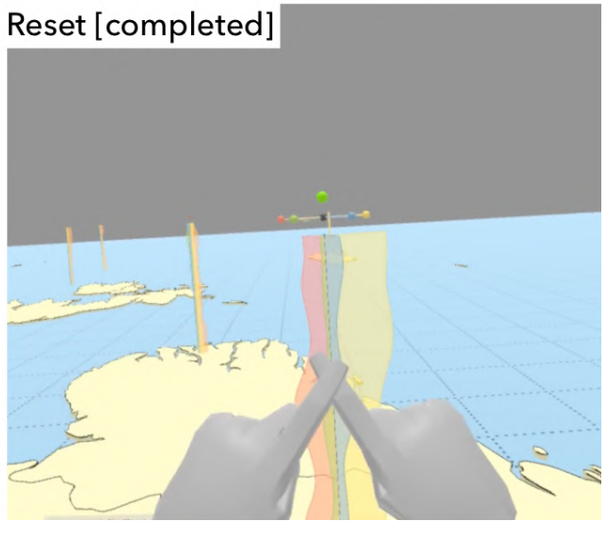
Data Variable Sort

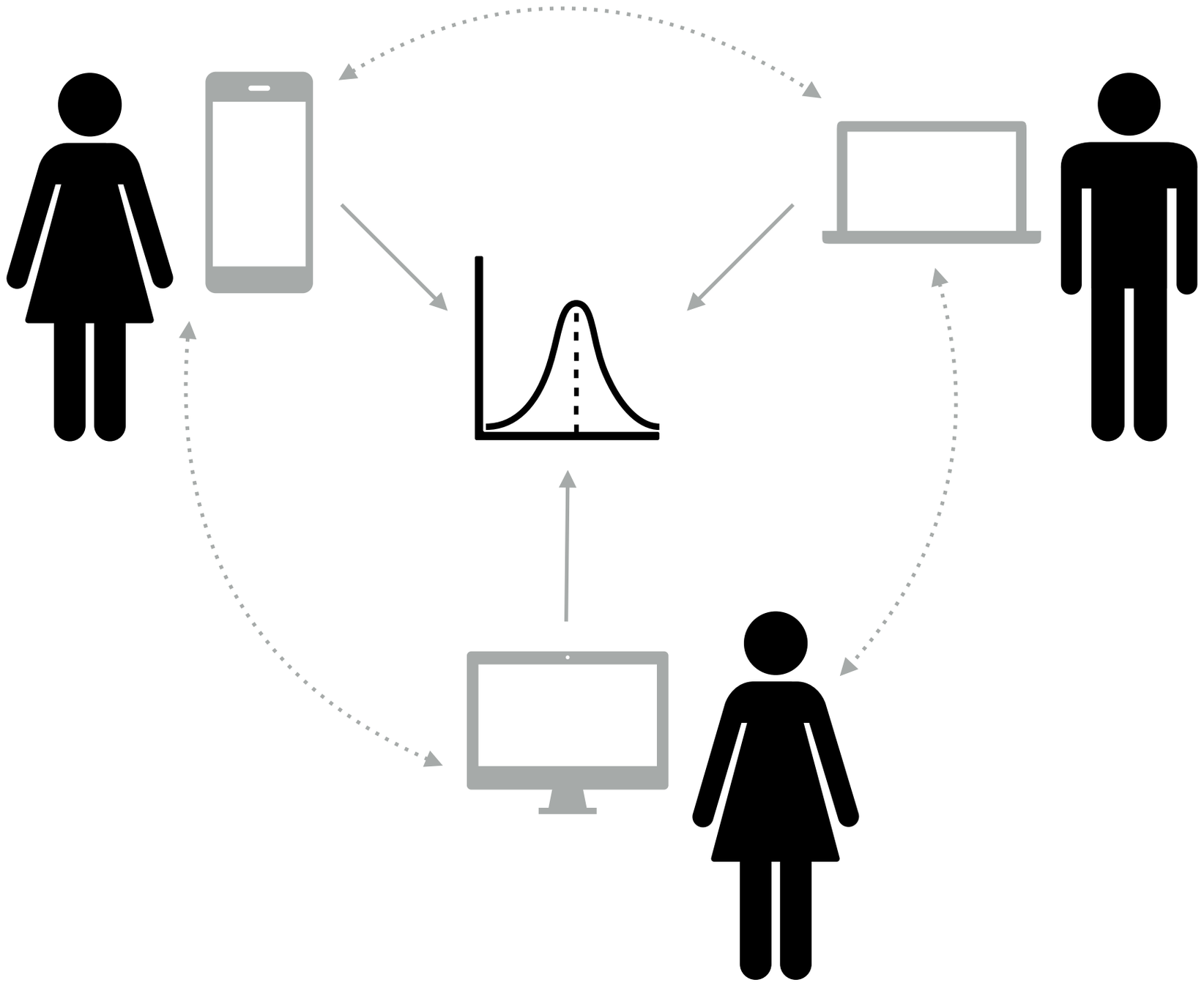


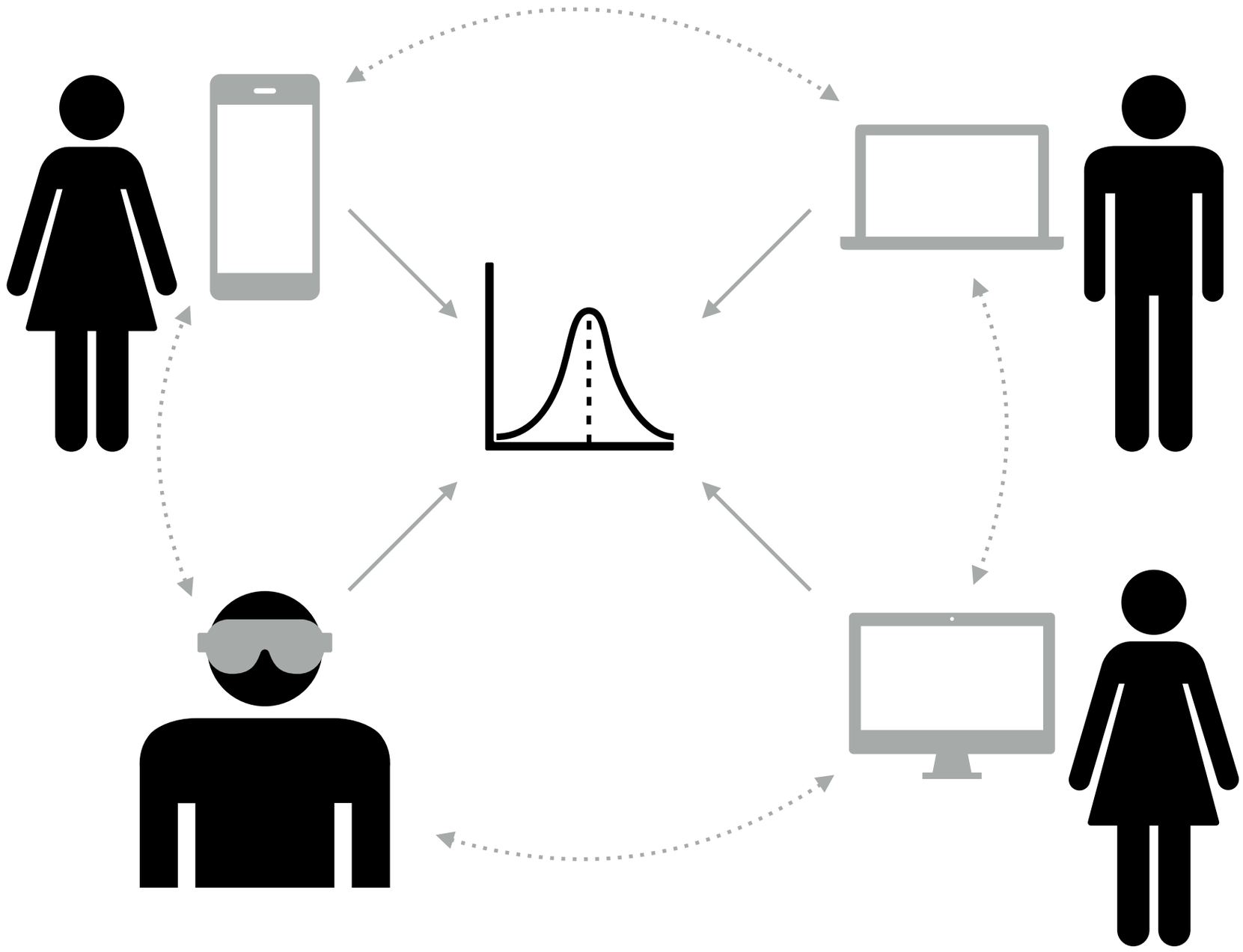
Reset [initialize]



Reset [completed]

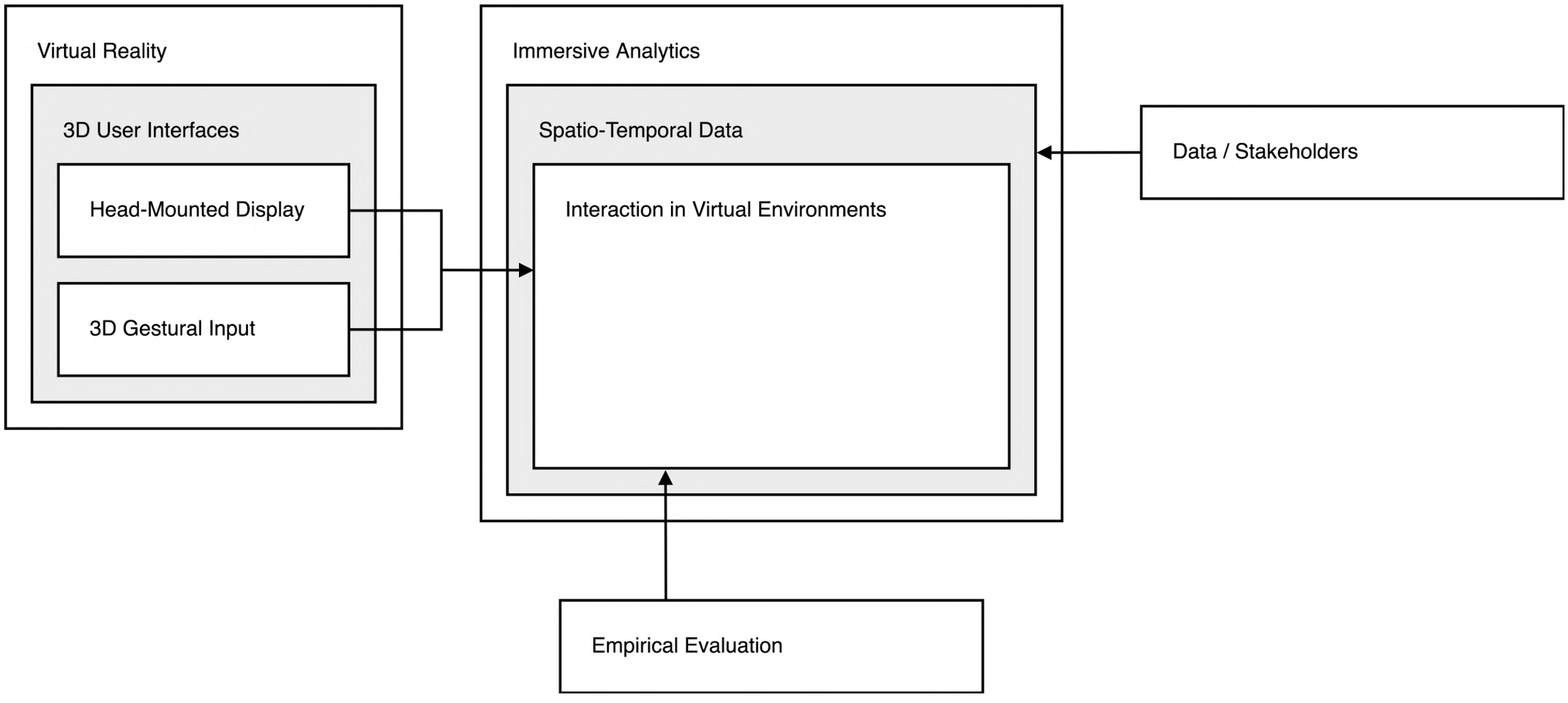




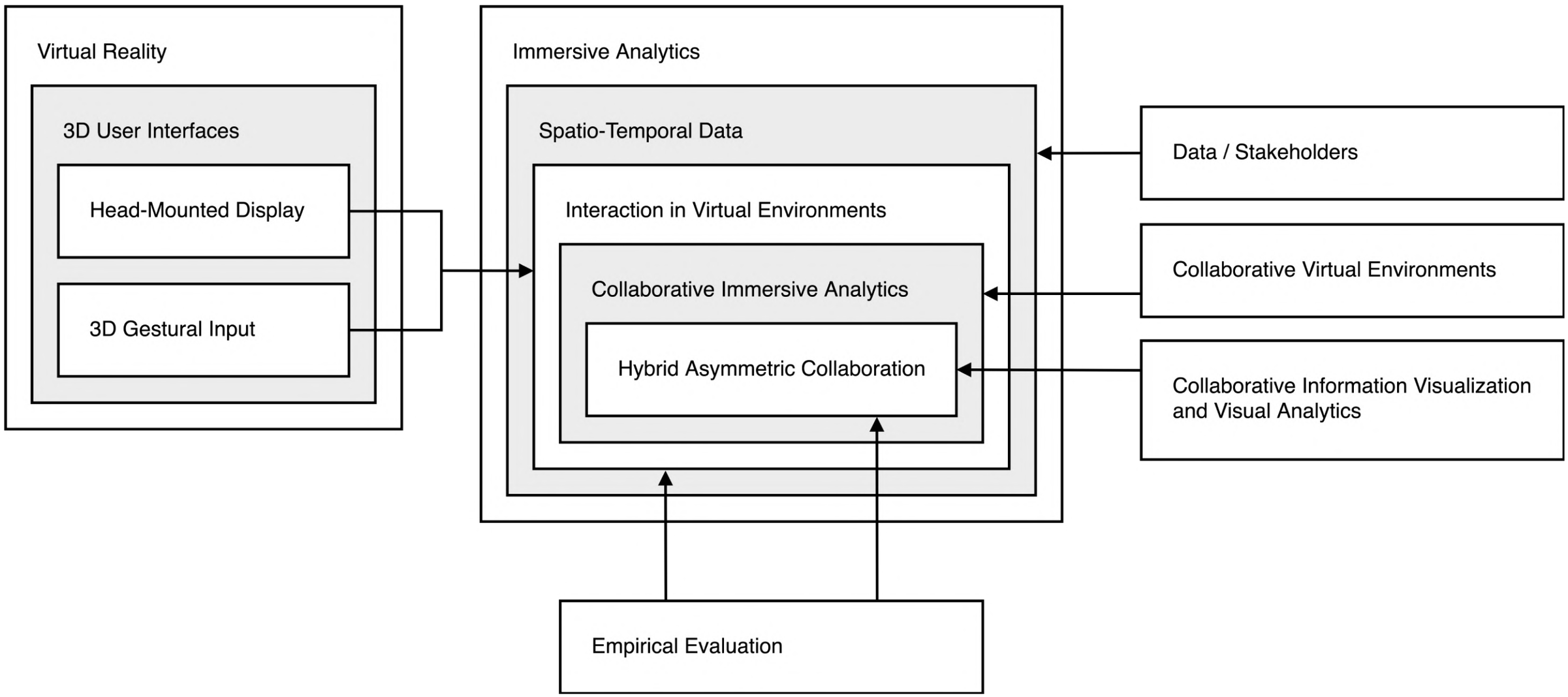


Hybrid Asymmetric Collaboration

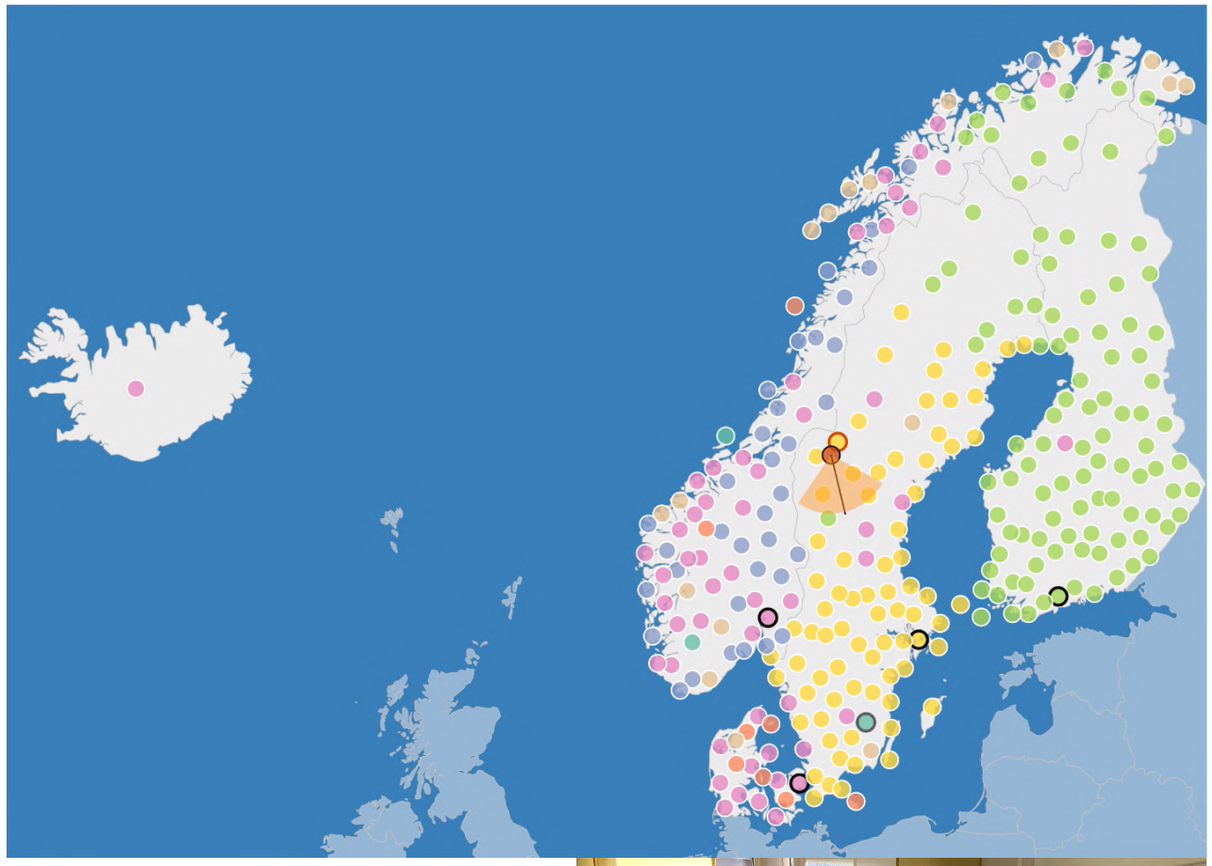
"Hybrid Asymmetric Collaboration is the use of immersive 3D and non-immersive 2D display and interaction technologies in a collaborative data analysis activity with two or more analysts where each individual analyst assumes a distinct role, based on their knowledge and facilitated by their respective technological interface, with the objective to equally contribute to the joint data interpretation and analytical reasoning."

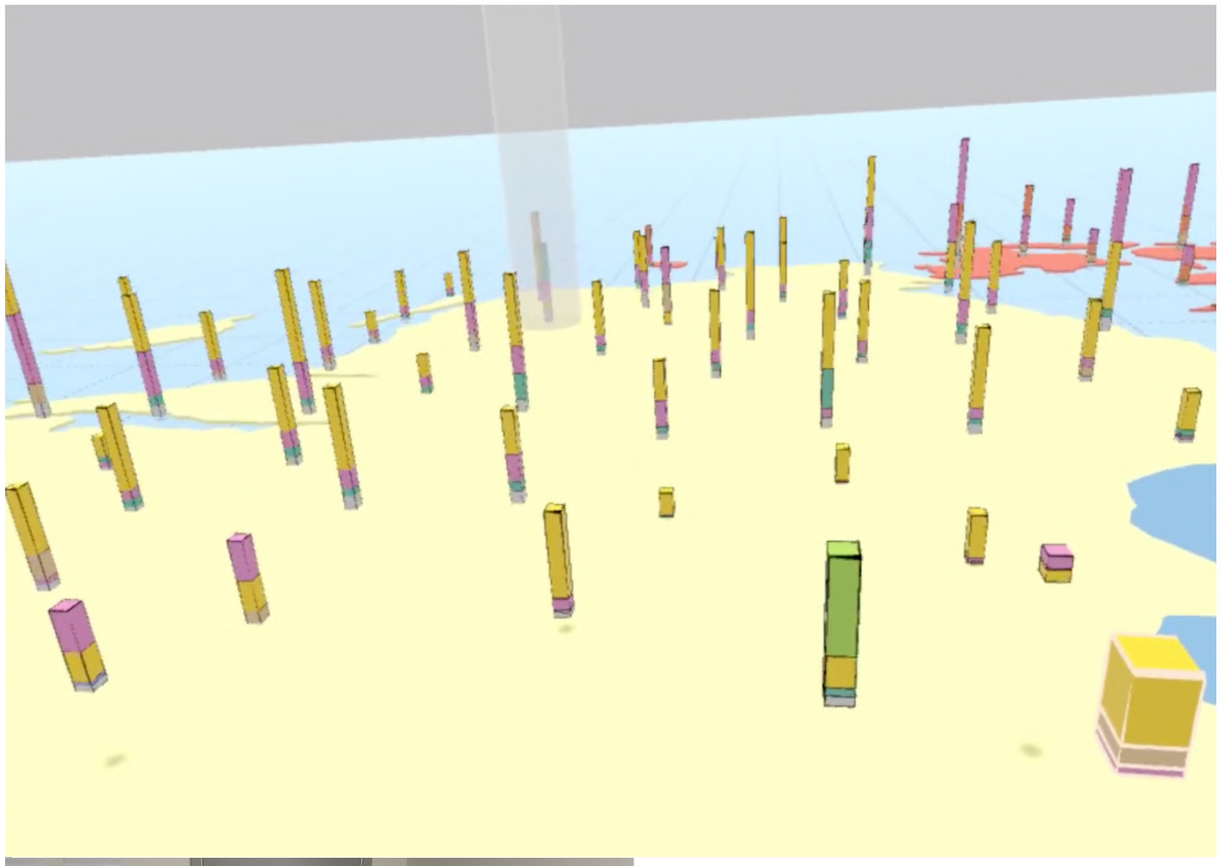

Virtual Reality
3D User Interfaces
Head-Mounted Display
3D Gestural Input
Immersive Analytics
Spatio-Temporal Data
Interaction in Virtual Environments
Data / Stakeholders
Empirical Evaluation

Thesis Design Space
(complete; interaction + collaboration; research objectives 2 + 3)



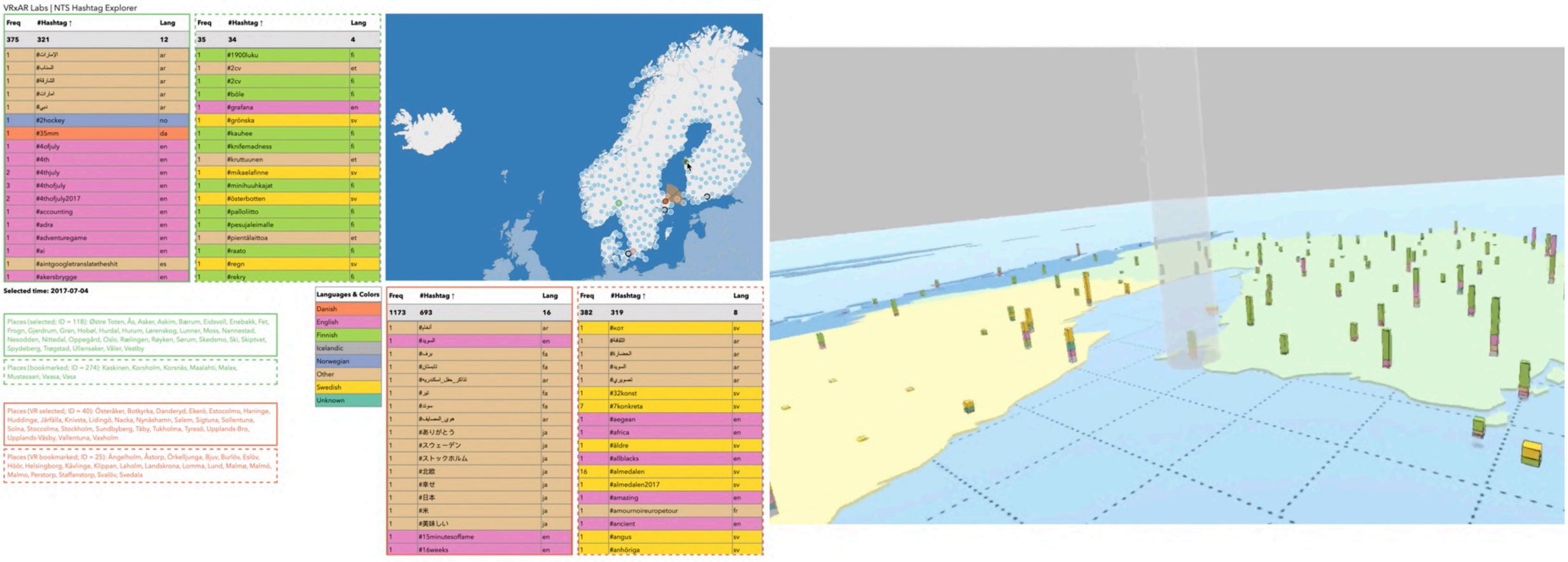
Collaboration in VE Iteration 2: Stacked Cuboids





Non-Immersive Setup Immersive Setup

Collaboration in VE Iteration 2: Stacked Cuboids



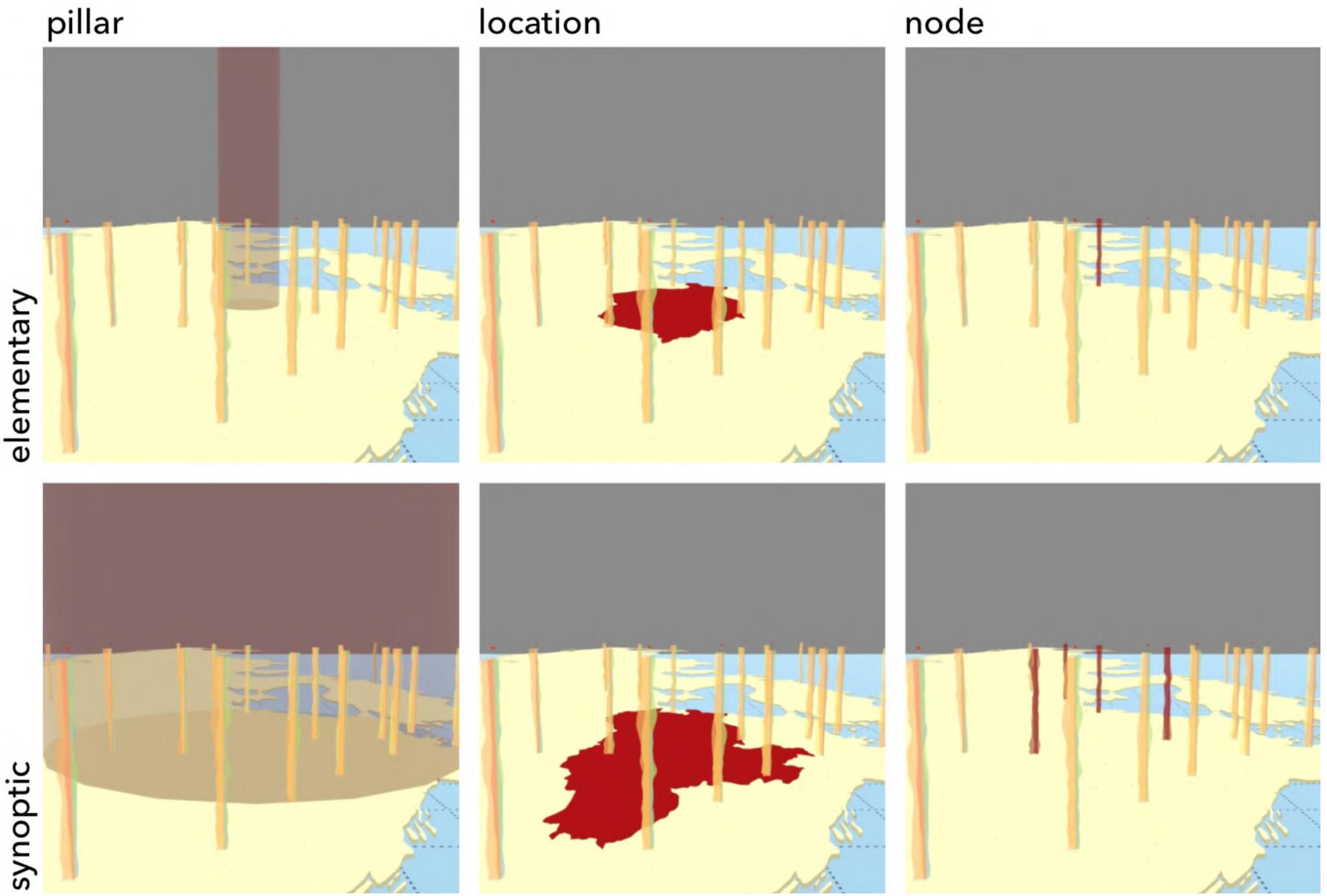
Non-Immersive Desktop Terminal

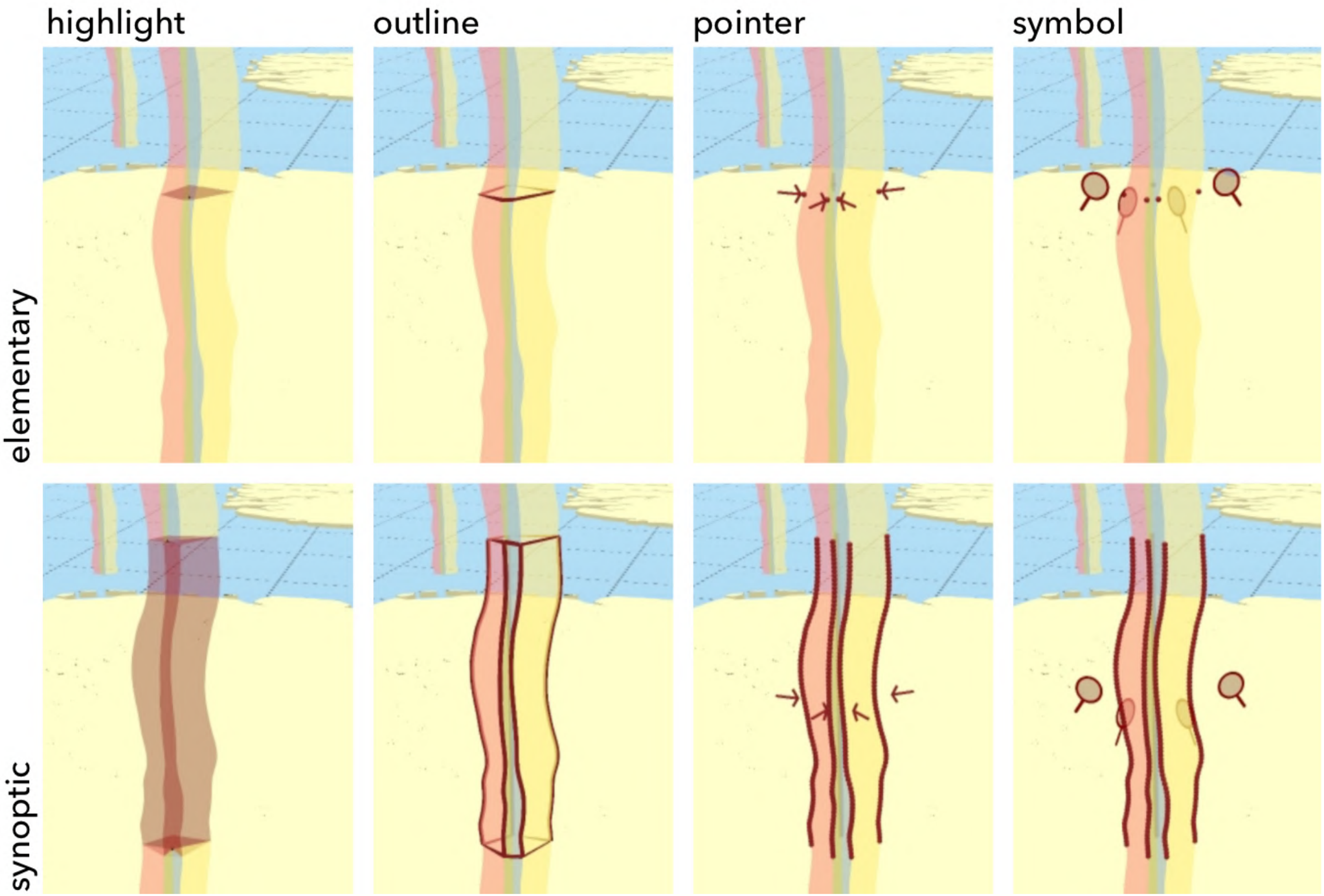
Immersive Virtual Environment

Modify Artifact
Modification of the visual appearance of the referred artifact.

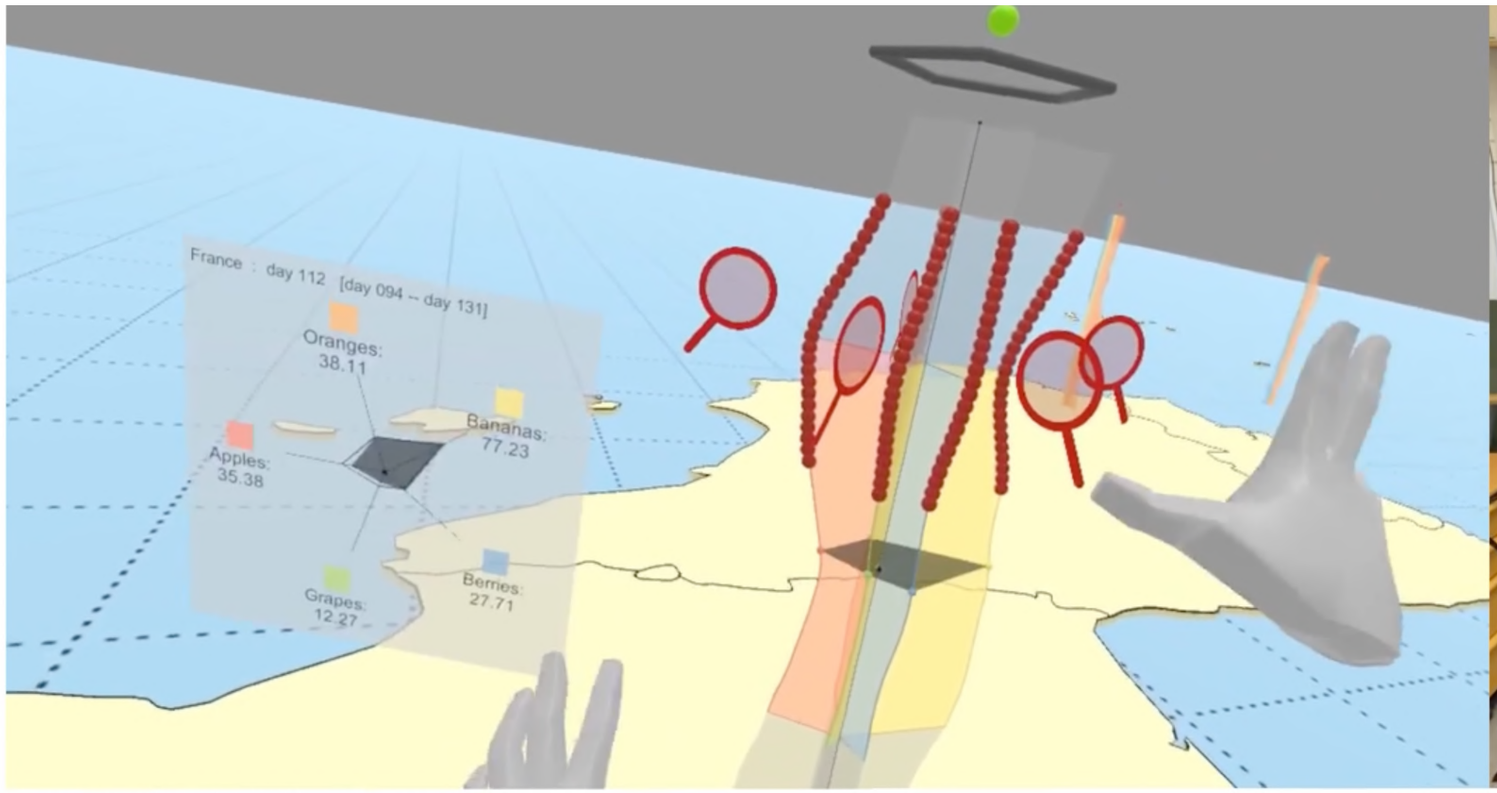
Add Artifact
Addition of a visual artifact in close proximity to the referred artifact.

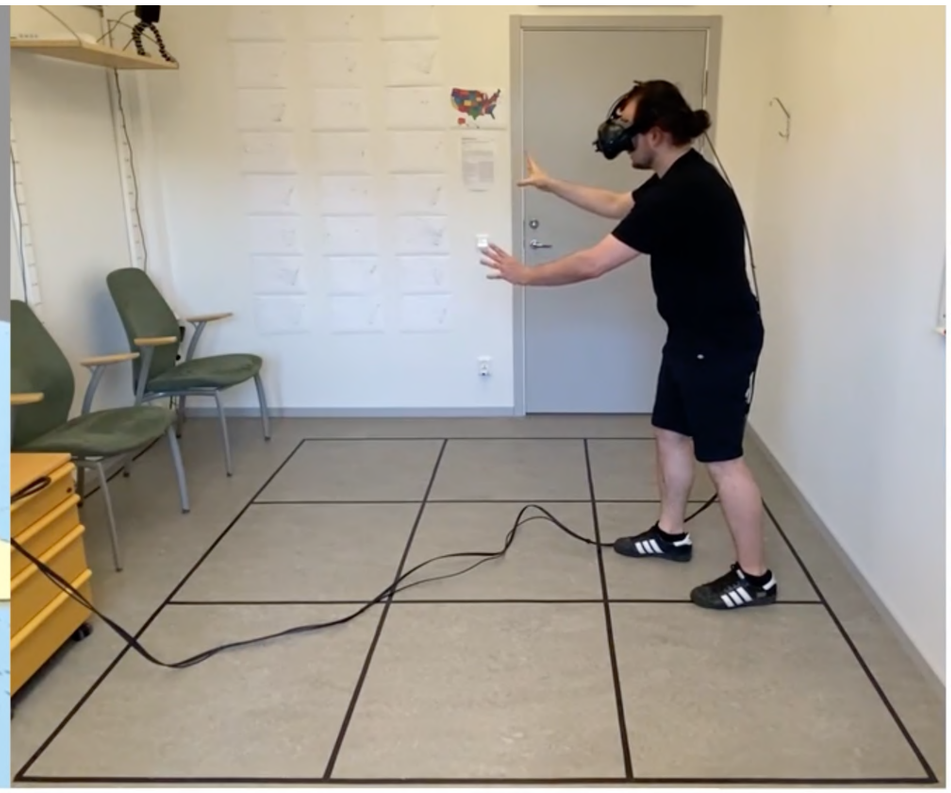
Modify Environment
Modification of the environment around the referred artifact.


pillar
location
node
elementary
synoptic
Add Artifact
Modify Environment
Modify Artifact


highlight
outline
pointer
symbol
elementary
synoptic
Modify Artifact
Modify Environment
Add Artifact
Add Artifact

Collaboration in VE Iteration 3:
3D Radar Charts



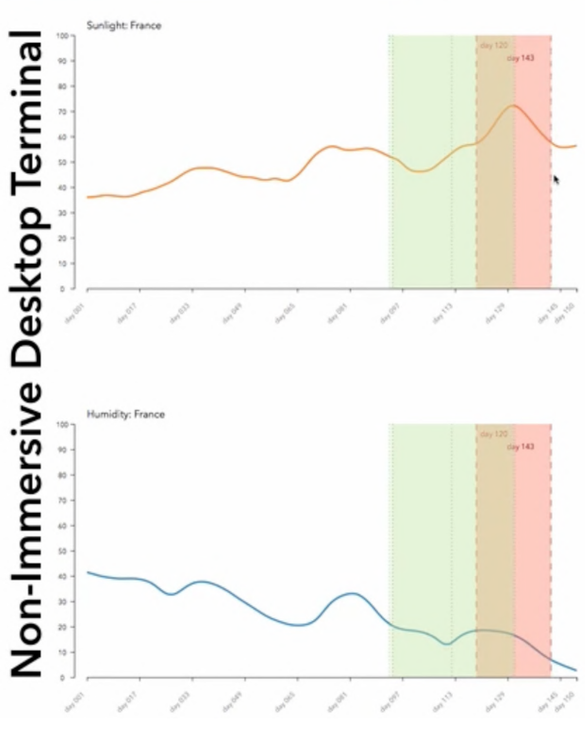


Immersive VR Environment

[Synchronous Collaborative Features]

- Spatial References
- Temporal References
  - Time Event
  - Time Range

Non-Immersive Desktop Terminal



Collaboration in VE Iteration 3:
3D Radar Charts

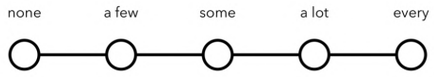




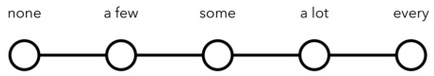



[TSIA] Transitions between Shared and Individual Activities: The interplay between individual and group efforts, including the ability to switch between these, within the scope of collaborative work.

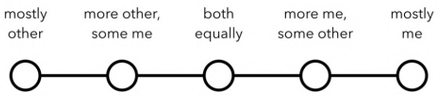
TSIA.1 How many of your efforts during this task would you consider to have been *individual* efforts?



TSIA.2 How many of your efforts during this task would you consider to have been *group* efforts?

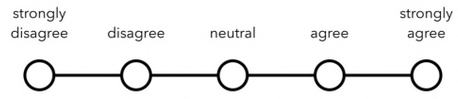


TSIA.3 According to your impression, who was more in a leading / directing role during the *group* efforts?

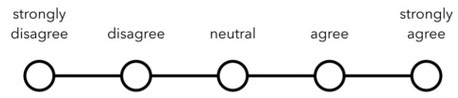


[SC] Sharing Context: Characteristics and features of the shared space that facilitate and support focused and unfocused collaborative work, leading to shared understandings.

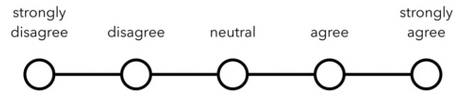
SC.1 The collaborative features of the system allowed me to focus on the same subject as my partner.



SC.2 The collaborative features of the system allowed me to establish a dialog with my partner.

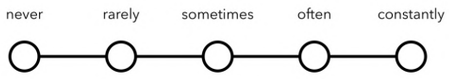


SC.3 The collaborative features of the system distracted me from my *individual* efforts.

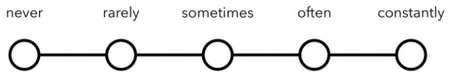


[NC] Negotiation and Communication: Verbal conversation (i.e., talk) facilitated through the ability of utilizing nonverbal information cues in order to discuss and interpret any task-related aspects of the activity (e.g., findings in the data, roles and structure of task approach, and so on).

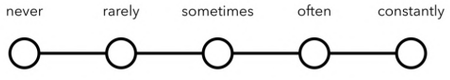
NC.1 According to your impression, how often did you communicate *verbally* to your partner?



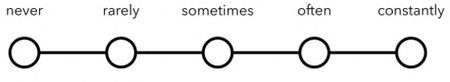
NC.2 According to your impression, how often did you communicate *nonverbally* to your partner?



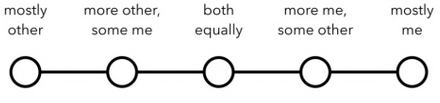
NC.3 How often would you consider did *dialog* take place?



NC.4 How often would you consider did *negotiation* take place?

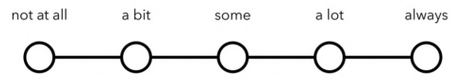


NC.5 Who would you say mostly initiated the *negotiations*?

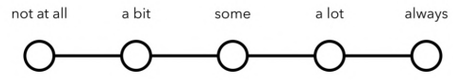


[AO] Awareness of Others: The ability to understand your partner's activity during times of (1) focused collaboration and active communication (i.e., *group* efforts), as well as (2) more independent and *individual* work.

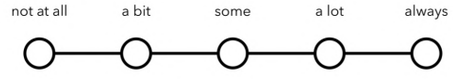
AO.1 During your *group* efforts, how much were you aware of your partner's activities?



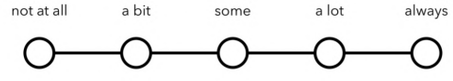
AO.2 During your *group* efforts, how much were you aware of your partner's location in space?



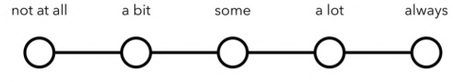
AO.3 During your *group* efforts, how much were you aware of your partner's time reference (time point / interval)?



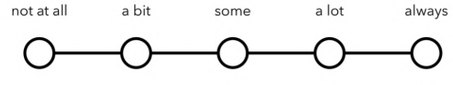
AO.4 During your *individual* efforts, how much were you aware of your partner's activities?



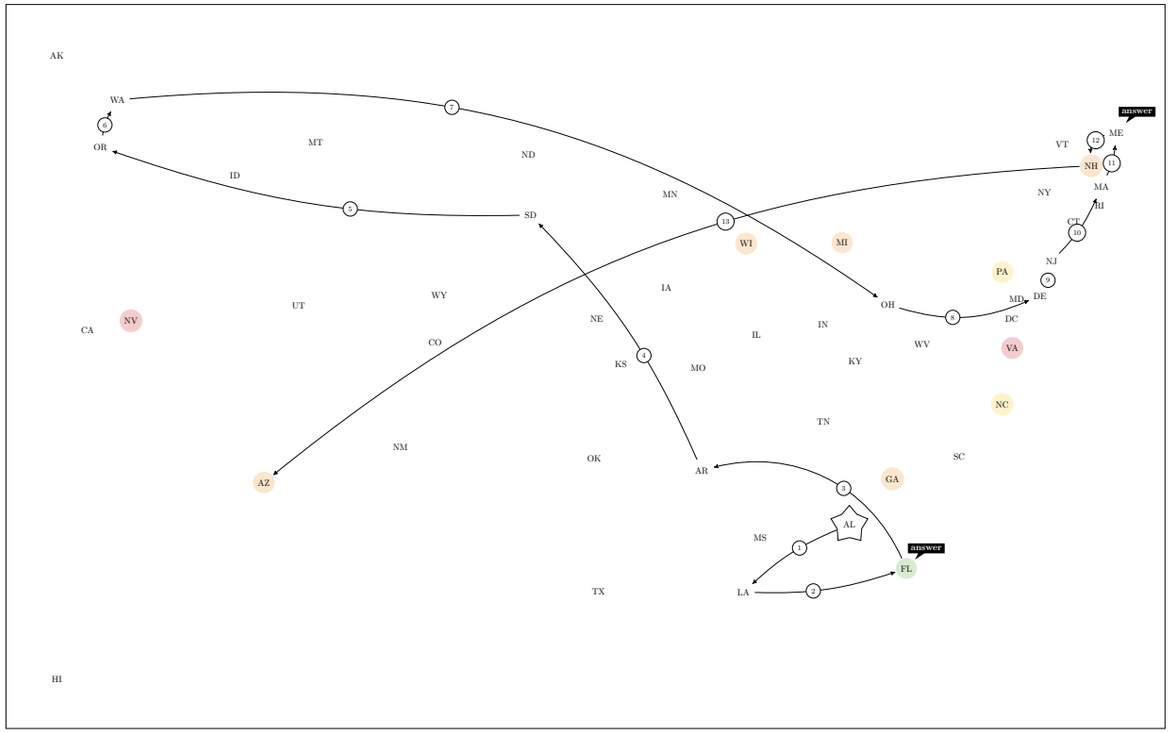
AO.5 During your *individual* efforts, how much were you aware of your partner's location in space?



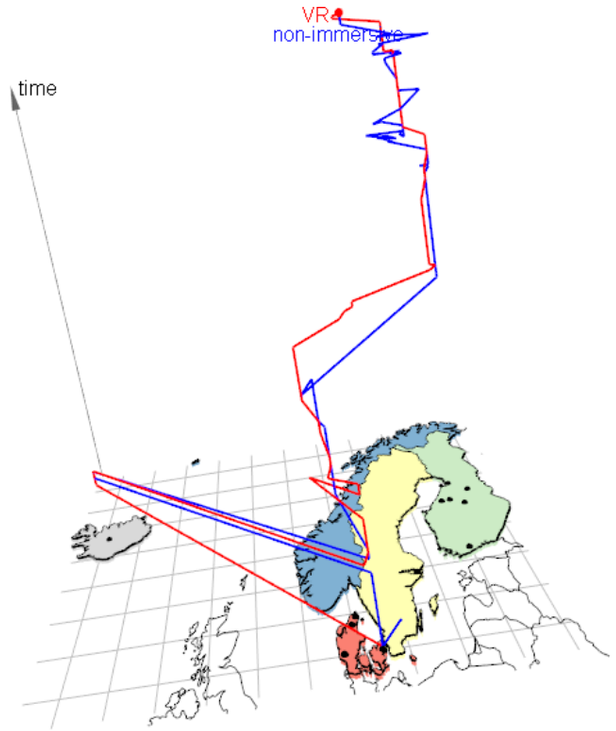
AO.6 During your *individual* efforts, how much were you aware of your partner's time reference (time point / interval)?



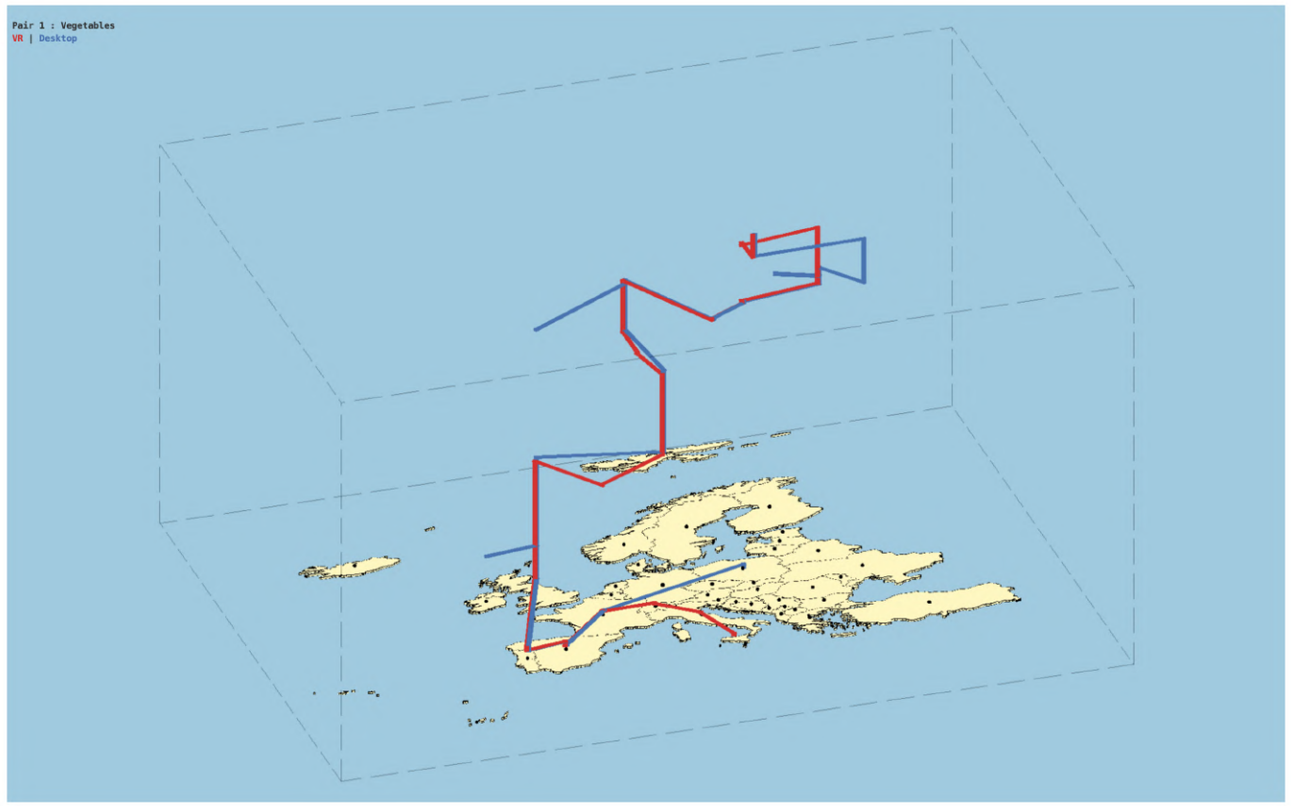
Study Data Analysis:
Pathway Visualizations



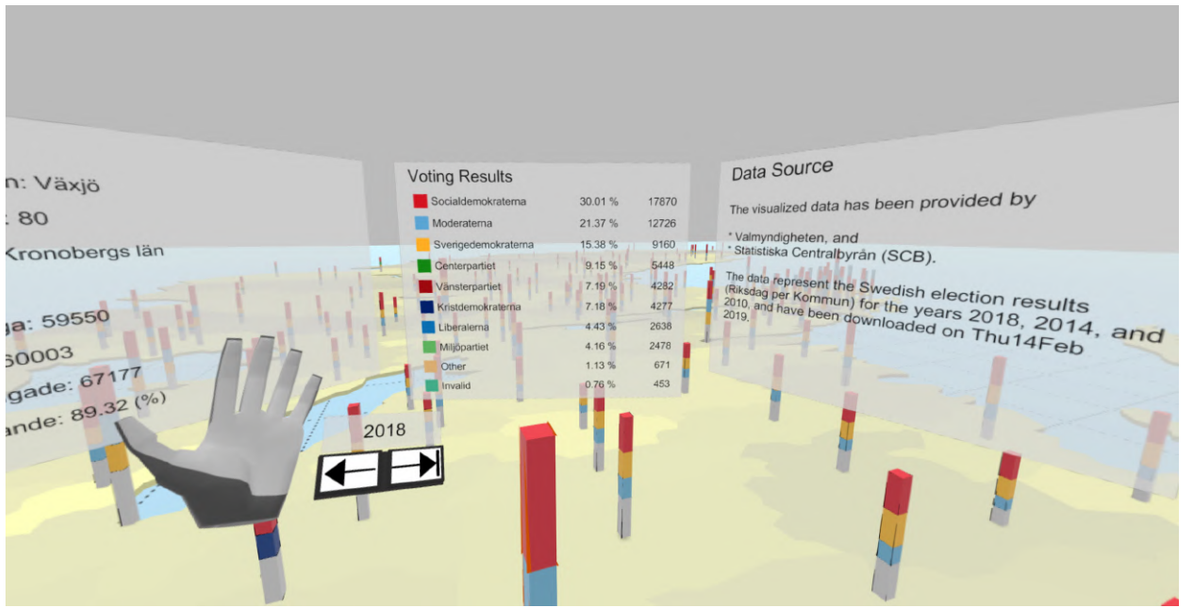
VE Iteration 1



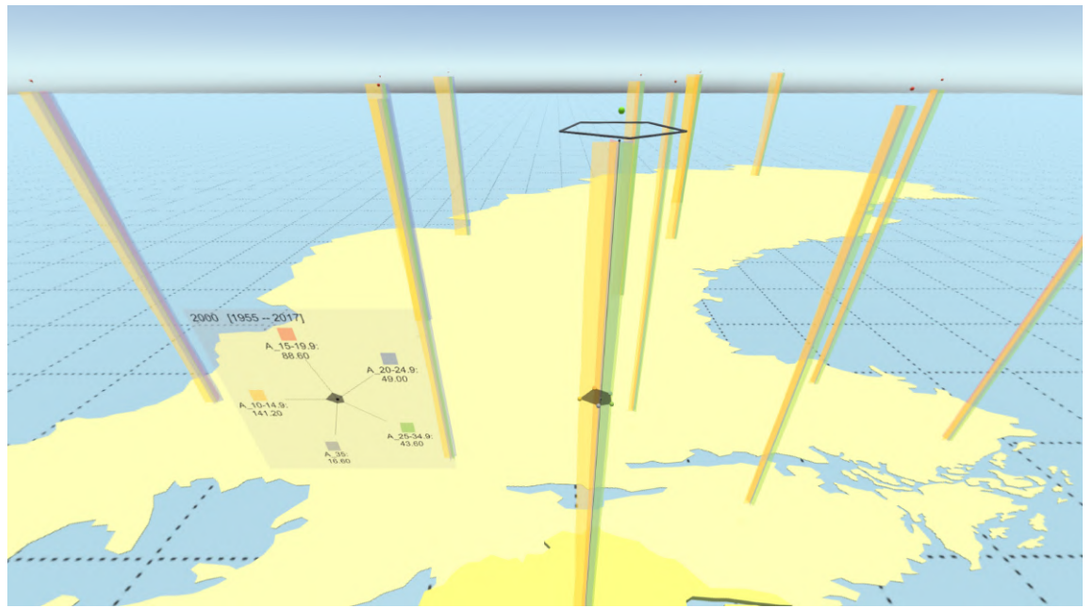
Collaboration in
VE Iteration 1



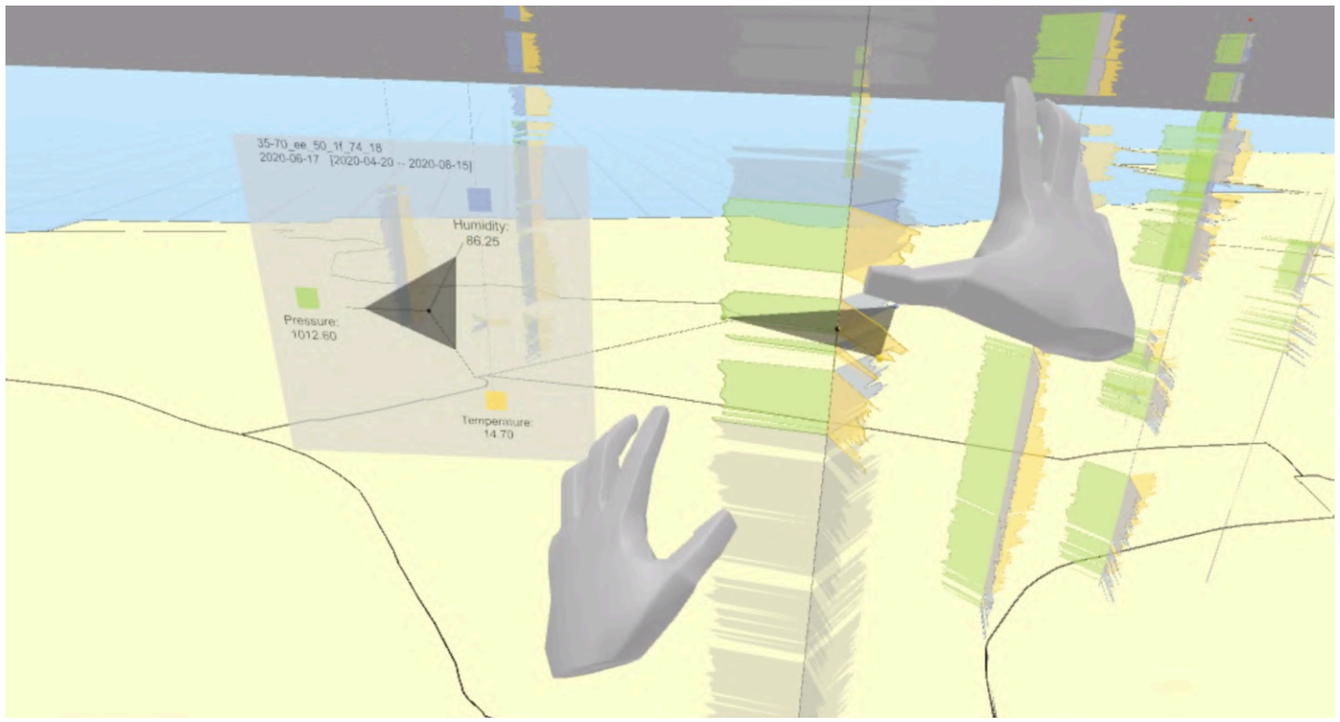
Collaboration in
VE Iteration 3
[vrxar.lnu.se/apps/2021-frivr/]



Swedish Election (VE 2)



Forestry Data (VE 3)



Urban Climate Data (VE 3)

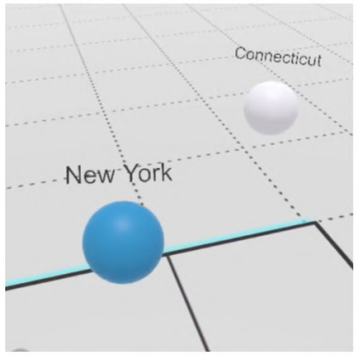
Design Guideline 1

Consider providing supporting artifacts that facilitate orientation and interpretation of the spatial data context.

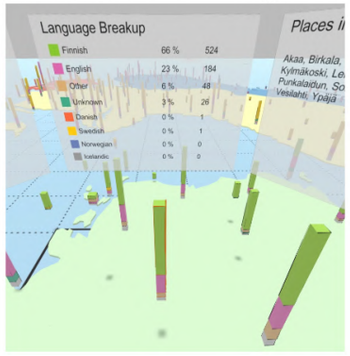
Design Guideline 2

Consider the visual mapping for the integration of the temporal data variables into each data entity.

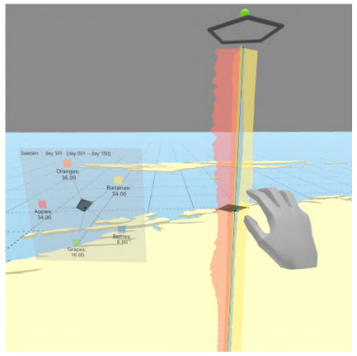
Geolocation Encoding
No Temporal Encoding



Geolocation Encoding
Time Event Encoding



Geolocation Encoding
Time Series Encoding

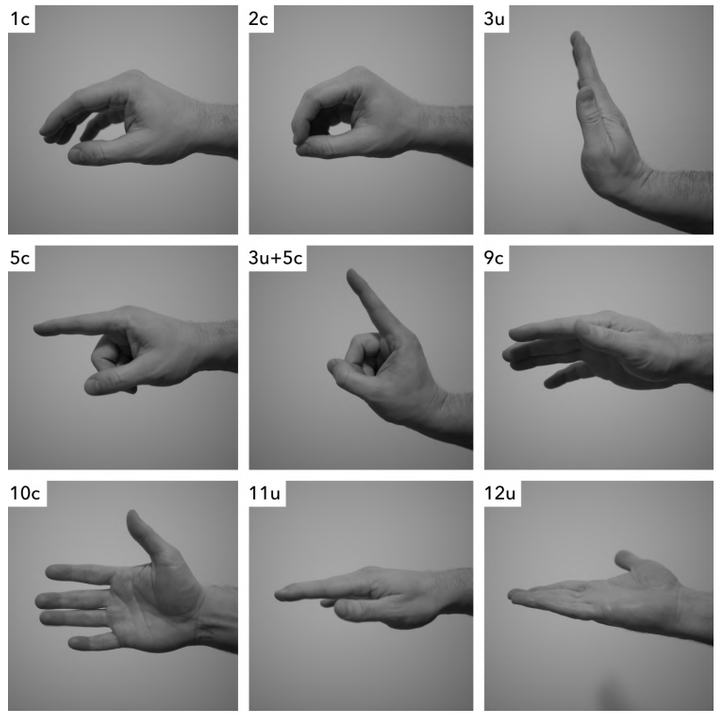


Design Guideline 3

Design for hand interaction.

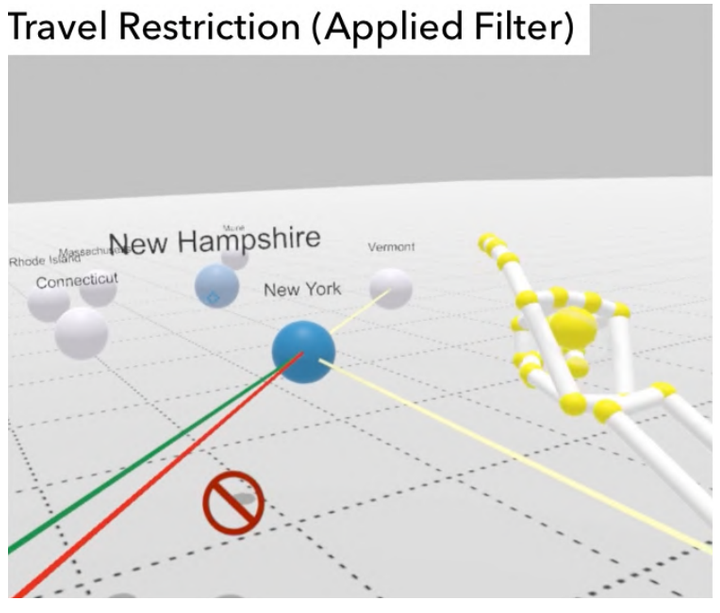
Design Guideline 4

Design with hand posture complexity in mind; utilize simple unimanual techniques for frequent tasks, and more complex bimanual techniques for less frequent ones.



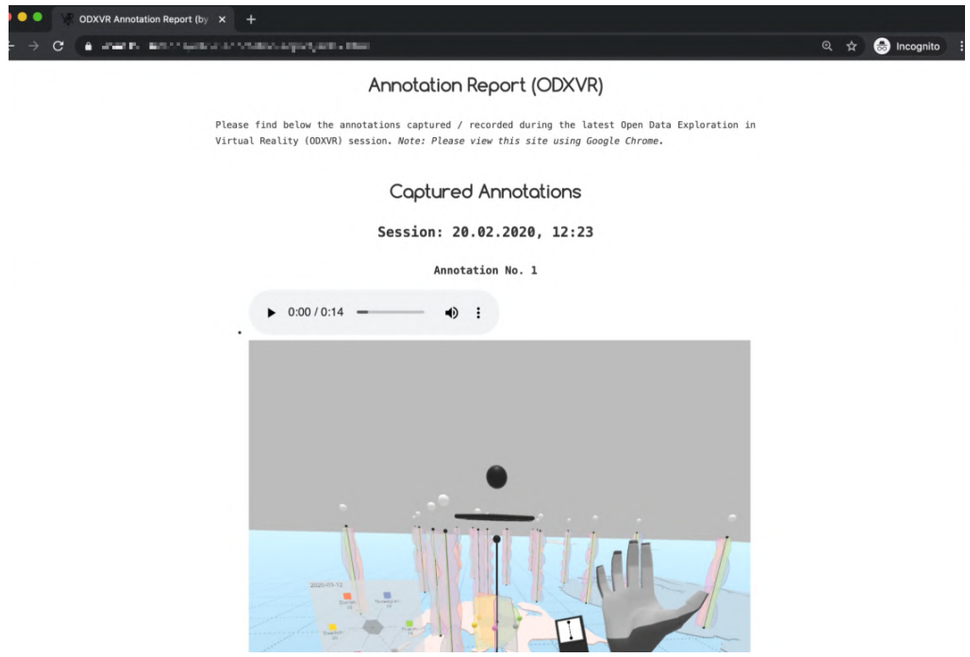
Design Guideline 5

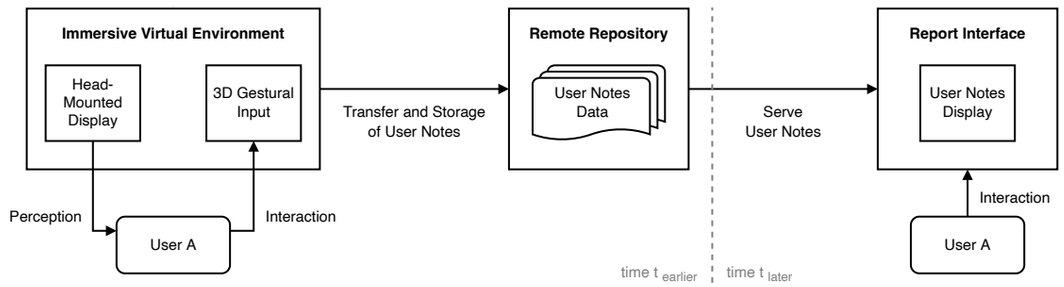
Limit available interactions based on the user's in-situ context.



Design Guideline 6

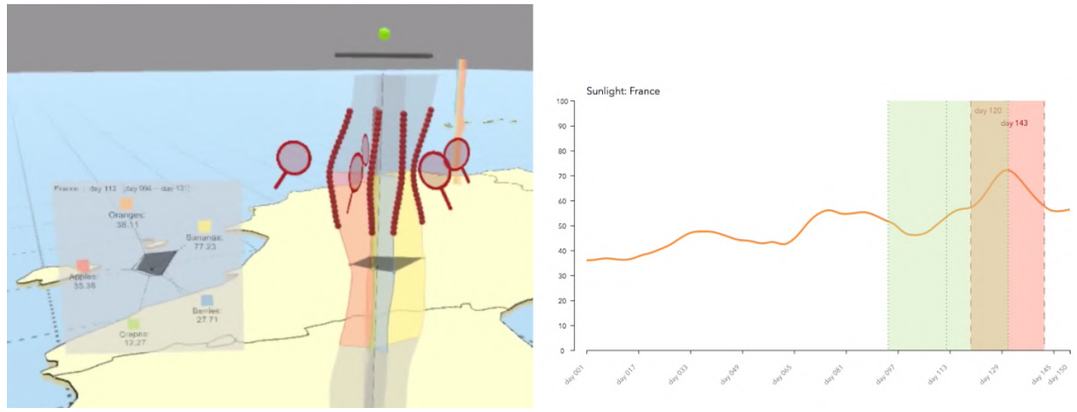
Consider workflow integration with non-immersive tools.





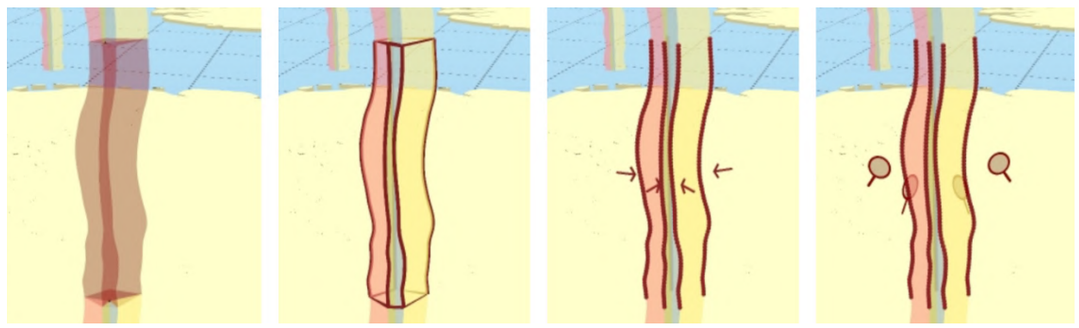
Design Guideline 7

Facilitate collaboration by enabling multimodal communication using a mixture of verbal and nonverbal tools.



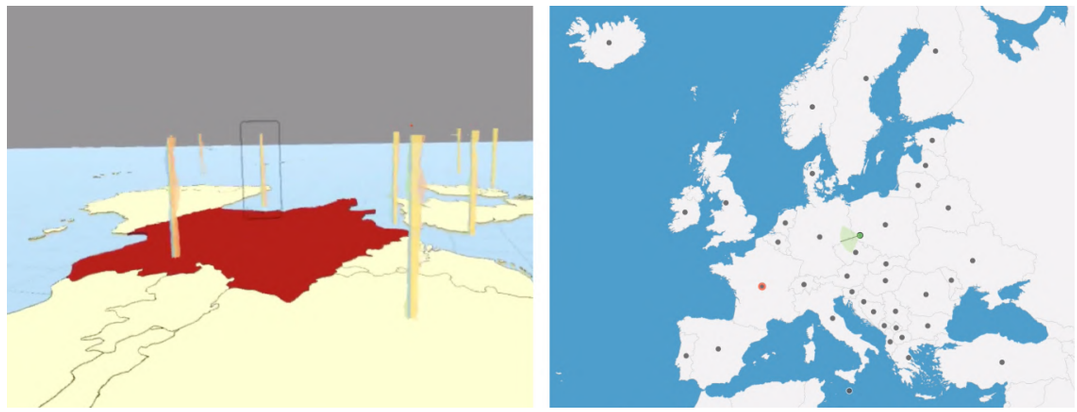
Design Guideline 8

Consider the design of the nonverbal collaborative information cues; modify or add artifacts to a data entity, or modify its environment.



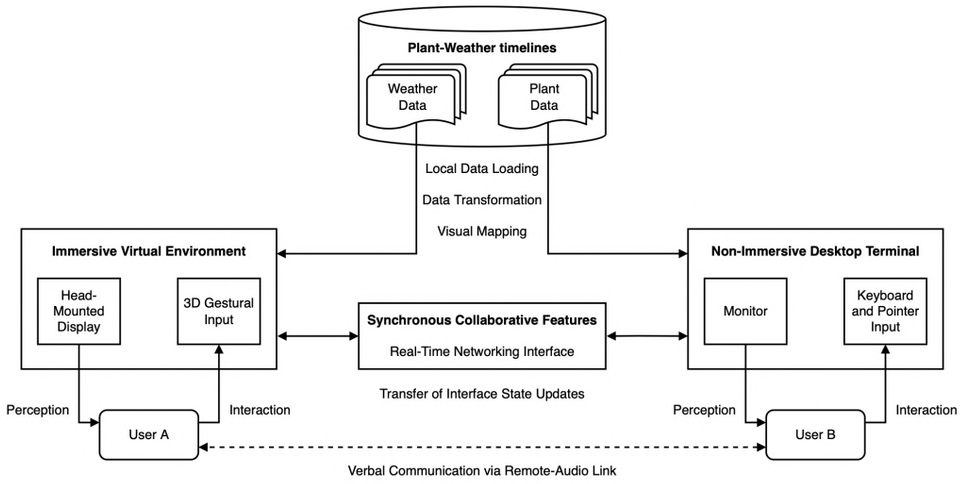
Design Guideline 9

Consider the update frequency of the nonverbal collaborative information cues; utilize continuous updates to allow for fluent collaboration, and on demand updates for focused ad hoc group efforts.



Design Guideline 10

Consider the classification of the collaborative data analysis experience; take into account data context, scenario, tasks, technologies, and user roles.



Thank you for listening!