THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY | DEPARTMENT OF COMPUTER SCIENCE & ENGINEERING

A Survey on Evaluation Practices of Immersive Visualization for Abstract 3D Data

PhD Qualifying Exam

Qian Zhu

Supervisor: Prof. Xiaojuan Ma

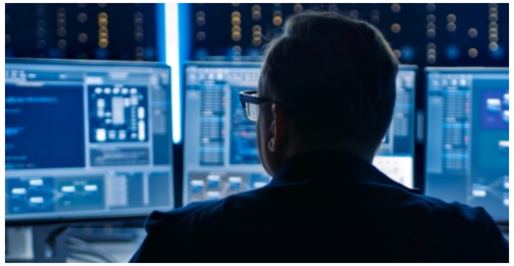
2022.04.27

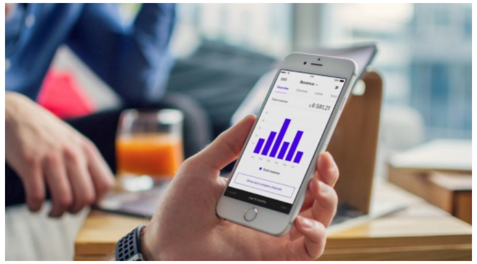
Outline

Data visualization is needed everywhere

Data is ubiquitous, **far surpass our ability** to understand or use it in our decisions[1].

Data visualization plays a critical role in helping people make decisions with data.





Data analysis:

Not only for scientists and experts,

also for ordinary users (e.g., personal data analysis)

1. Marriott, Kim, et al., eds. Immersive analytics. Vol. 11190. Springer, 2018.

Emerging display devices for data analysis

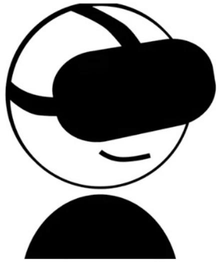
Different displays have **different capabilities** for data visualization

(1) how the data can **be visually represented,**

(2) how people can **interact** with visual representations.

→ Affect **user experience: engagement** and **productivity**[1].

Dominant 2D screen display devices (e.g., desktop, phones)



High-quality VR/AR head-mounted displays (HMDs): more **affordable and accessible** than before

Immersive visualization: The use of immersive devices for visualization (extended from the definition of immersive analytics[1])

Question: Why do we need to use immersive devices, like VR/AR, when the 2D displays work well?

1. *Marriott, Kim, et al., eds. Immersive analytics. Vol. 11190. Springer, 2018.*

2D displays work well most of time, **but...**

Visualizing 3D data in 2D screen may have some problems...

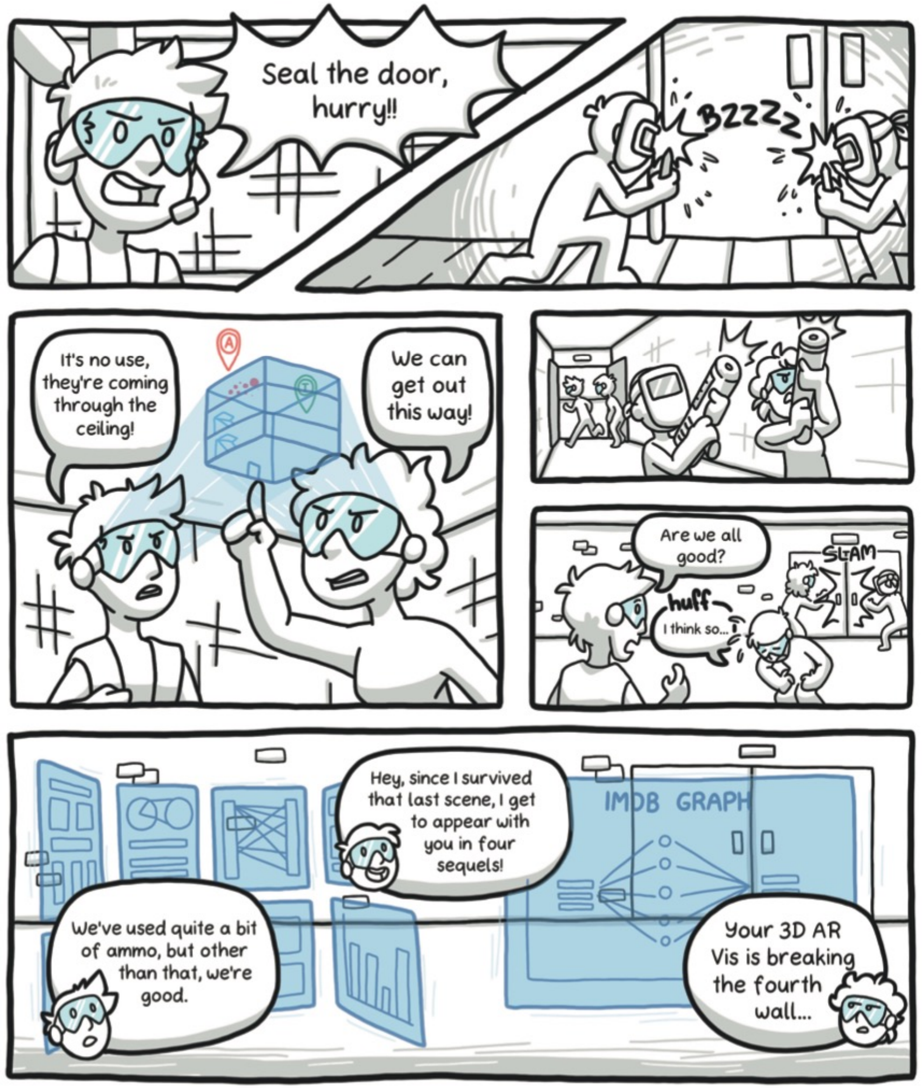
"A high-consequence failure of a mobile visualization device to **correctly convey the 3D structure of data**"
—from the film *Aliens*.

3D Mobile Data Visualization. *Lonni Besançon, Wolfgang Aigner, Magdalena Boucher, Tim Dwyer, Tobias Isenberg. 2021. Chapter of Book Mobile Data Visualization.*

Sometimes, **we may need a 3D display**

Reimagined scenario (Wearing AR headsets).

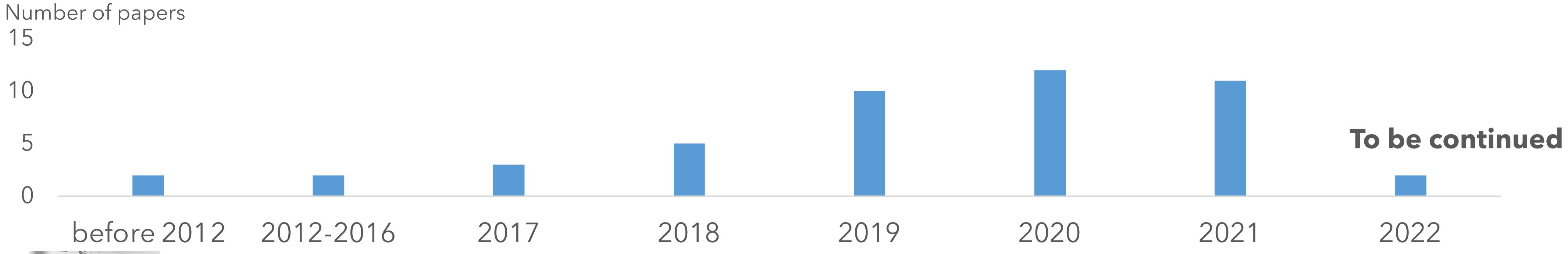
- Becoming aware of the problem in advance and **accurately firing** at the Aliens through the ceiling.
- Using **their shared view** of the facility to plan their escape route.



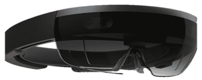
3D Mobile Data Visualization. *Lonni Besançon, Wolfgang Aigner, Magdalena Boucher, Tim Dwyer, Tobias Isenberg. 2021. Chapter of Book Mobile Data Visualization.*

The general benefits of immersive visualization are **not clear**

A growing body of work has used VR/AR to present and interact with data to explore the **potential advantages** of immersive visualization.




Oculus Rift


Hololens AR

...


Hololens2 AR


all-in-one VR

However, these works **empirically explore the benefits** of immersive visualization in **specific scenarios**, which can not be easily extended to other tasks of data analysis.

Evaluation practice

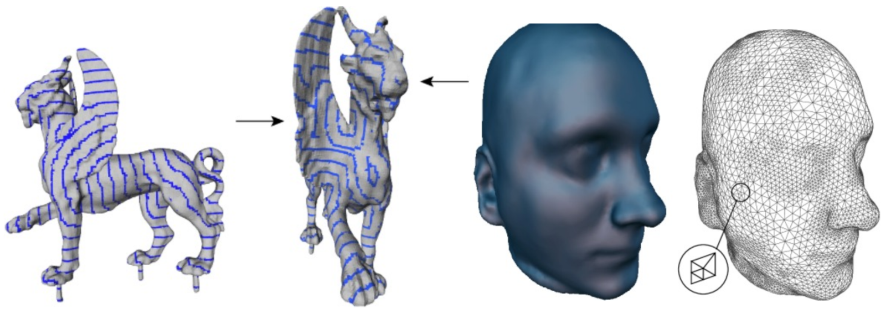
How did previous works evaluate their design to explore the benefits of immersive visualizations?

- **Q1**: How do previous works evaluate the visualization with immersive HMDs?
- **Q2**: How do previous designs work in general? (General benefits)

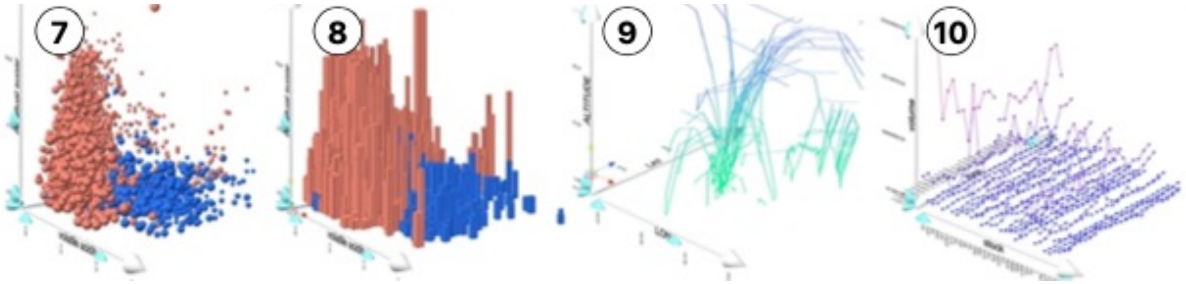
Scope: 47 papers on immersive visualization (two criteria for collecting papers)

- **Data type**: abstract 3D data (the benefits of displaying this data type in 3D remain controversial)
- **Immersive devices**: VR/AR HMDs

Non-abstract 3D data:



Abstract 3D data:



General Taxonomy

Evaluation Focus[1]

1. Visualization:

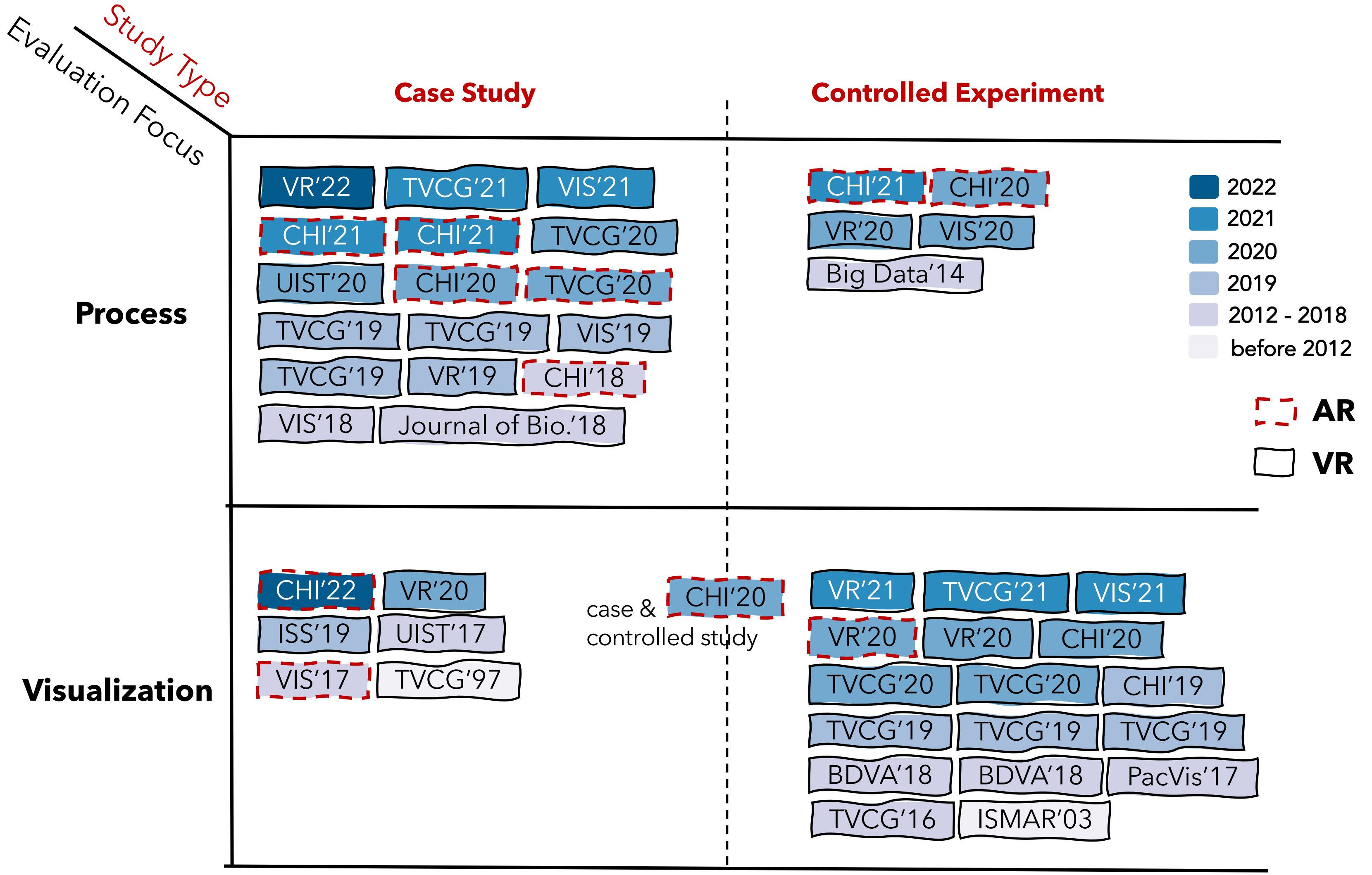
Test design decisions, evaluate a design space, or discover usability issues.

→Evaluating the visualization itself

2. Process:

Understand the underlying process and the roles played by visualizations.

→Capture a holistic view of user experience



1. Lam, H., Bertini, E., Isenberg, P., Plaisant, C., & Carpendale, S. (2011). Empirical studies in information visualization: Seven scenarios. IEEE TVCG, 18(9), 1520-1536.

Outline

Taxonomy of this Section

Evaluation Goals

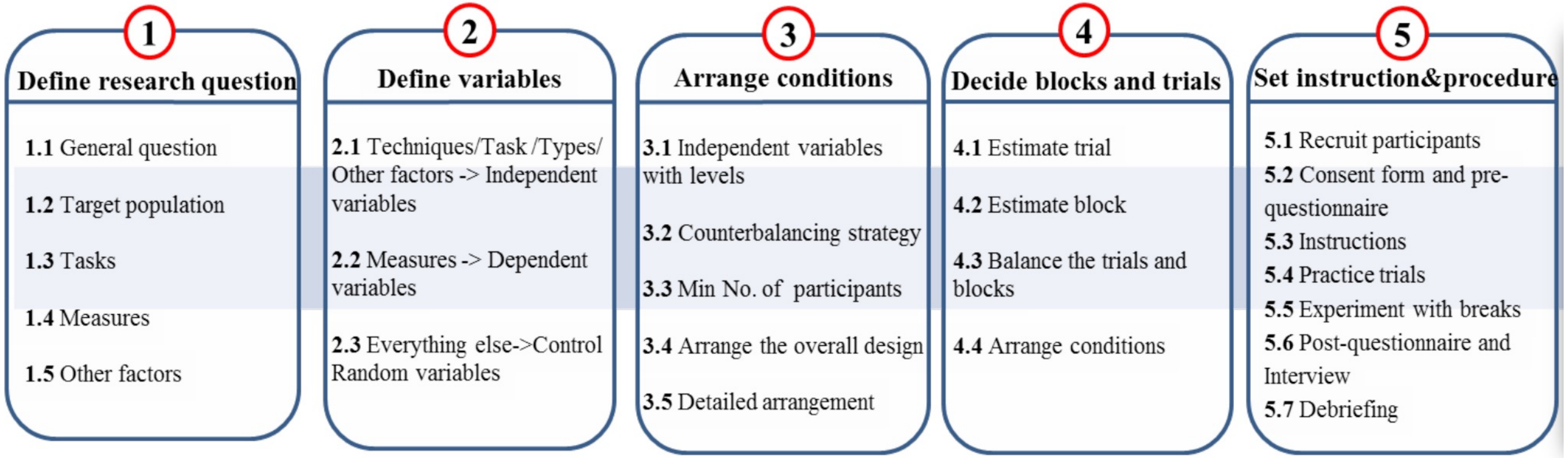
	Evaluation Goals	Papers
Visualization	**Compare** desktop **(2D)** and VR HMD **(3D)**	VIS'21, CHI'20, TVCG'19, TVCG'19, ISMAR'03
	Evaluate **interaction** design of immersive visualization	CHI'20, VR'21, CHI'19, BDVA'18, PacVis'17
	Evaluate stereoscopic **3D display** of immersive visualization	VR'20, BDVA'18
	Evaluate **both** interaction design and display design	TVCG'21, VR'20, TVCG'20, TVCG'20, TVCG'19, TVCG'16
Process	Evaluating **V**isual **D**ata **A**nalysis and **R**easoning (VDAR)[1]	CHI'21, CHI'20
	Evaluating **C**ommunication **T**hrough **V**isualization (CTV)[1]	VR'20
	Evaluating **C**ollaborative **D**ata **A**nalysis(CDA)[1]	VIS'20, Big Data'14

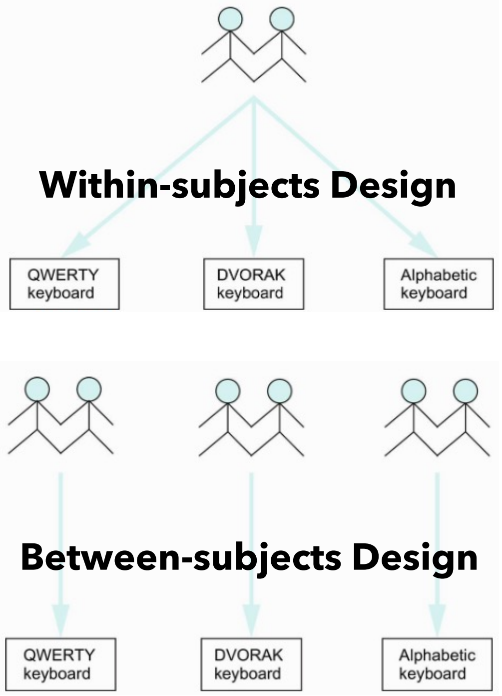
1. Lam, H., Bertini, E., Isenberg, P., Plaisant, C., & Carpendale, S. (2011). Empirical studies in information visualization: Seven scenarios. IEEE TVCG, 18(9), 1520-1536.

Controlled Experiment

Controlled experiment is an important, widely-used research method **in HCI to evaluate** user interfaces, styles of interaction, and to understand cognition in the context of interactions with systems[1]

The **5-step approach** for **controlled experiment design** for HCI[2]





1. *Jonathan Lazar, Jinjuan Heidi Feng, and Harry Hochheiser. 2017. Research methods in human-computer interaction 2nd Edition. John Wiley & Sons.*
2. *Meng, Xiaojun et al. (2017, September). Nexp: A beginner friendly toolkit for designing and conducting controlled experiments. In IFIP Conference on Human-Computer Interaction*

Visualization
Compare desktop (2D) and VR HMD (3D) CHI'20
...

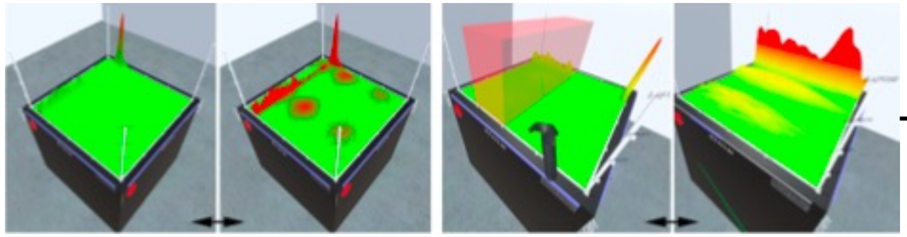
Kraus, M. et al. (CHI'20)

2D Heatmaps: density distributions, **[color or brightness]** → **Inaccurate** in reading and comparing numeric data values

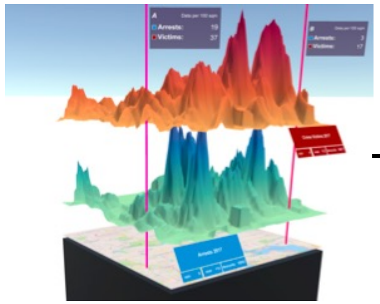
3D heatmaps: value perception **[height]** as a third dimension → **Drawbacks:** occlusion, perceptual distortion

1 **How to balance the advantages and disadvantages of 3D heatmaps?**

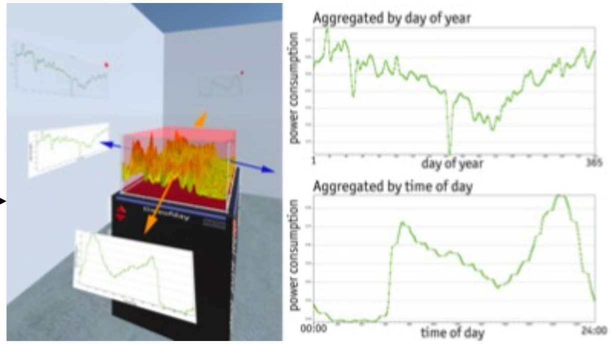
Goal: Understanding the **design space** of 3D heatmaps:



(1) Base Visualization



(2) Comparison of Multiple Heatmaps



(3) Transformation & Projection from 3D to 2D

Kraus, M., Angerbauer, K., Buchmüller, J., Schweitzer, D., Keim, D. A., Sedlmair, M., & Fuchs, J. Assessing 2d and 3d heatmaps for comparative analysis: An empirical study. 2020 CHI.

Visualization

Compare desktop **(2D)** and VR HMD **(3D)** CHI'20

...

Kraus, M. et al. (CHI'20)

2 **IVs:** 2D/3D, Screen/VR

DVs: error rate, time, memory; task load, usability, perceived difficulty, immersion and certainty of answers.

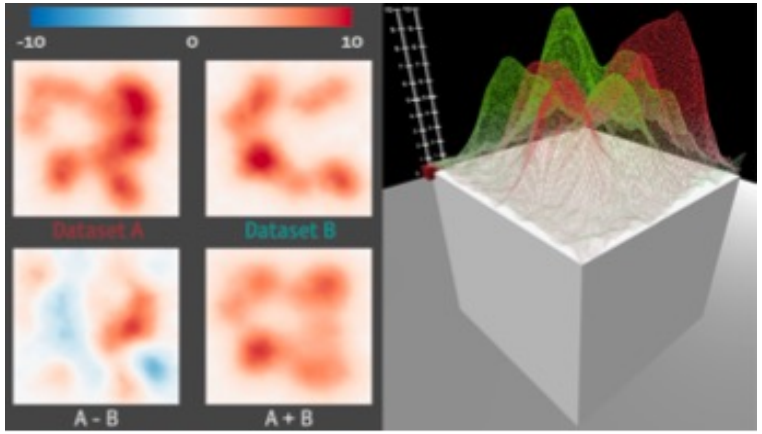
Screen2D	VR2D
Screen3D	VR3D

3 **Overall: Between-subjects** design with 48 participants

Comparative Tasks: *Lookup, Locate, Overview.*

4 Each participant **42 trails** (4 training + 10 test for each task) + free exploration & discussion

5 **Procedure:** introduction → training → formal test tasks → memorization tasks → Questionnaire



2D 3D

Result: 3D (lookup & locate), 2D (overview); **Limitation:** Screen resolution & difference in 2D and 3D

Kraus, M., Angerbauer, K., Buchmüller, J., Schweitzer, D., Keim, D. A., Sedlmair, M., & Fuchs, J. Assessing 2d and 3d heatmaps for comparative analysis: An empirical study. 2020 CHI.

Prouzeau, A. et al. (CHI'19)

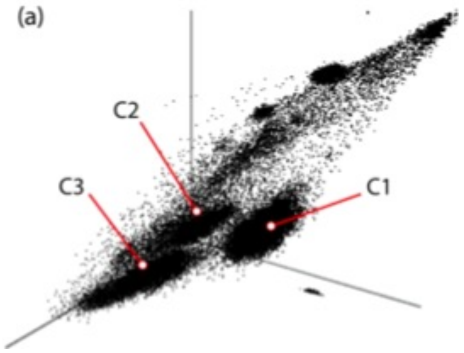
Visualization

...

Evaluate **interaction** design of immersive visualization

CHI'19

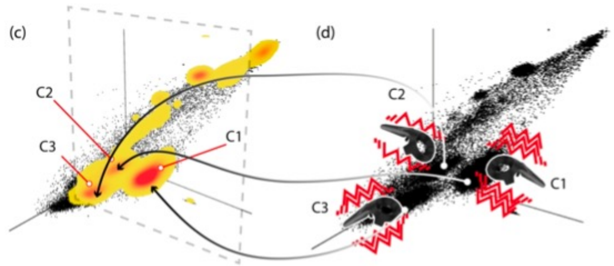
...



3D Scatterplots: **overplotting and occlusion** issues

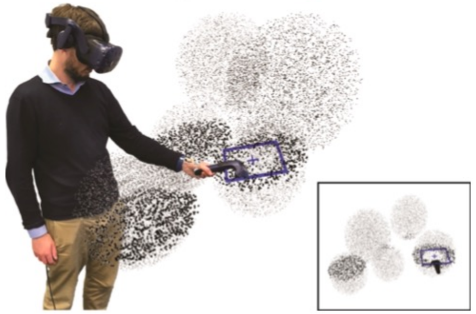
How to leverage the **new** sensory modalities of VR/AR → **help perceive** and **interact** with 3D scatterplots

① **What is the benefit of applying new interactive techniques in immersive environment?**



- Scaptics **(S)**: a density-based **haptic** vibration technique
- Highlight-Plane **(H)**: an adaptation of a **cutting plane** for 3D scatterplots

Goals: Evaluate two techniques for **density perception**



Prouzeau, A., Cordeil, M., Robin, C., Ens, B., Thomas, B. H., & Dwyer, T. (2019, May). Scaptics and highlight-planes: Immersive interaction techniques for finding occluded features in 3D scatterplots. 2019 CHI.

Prouzeau, A. et al. (CHI'19)

Visualization

...

Evaluate **interaction** design of immersive visualization | CHI'19

...

2 **IVs:** interactive techniques provided (**visual only** & Scaptics **(S)** & Highlight-Plane **(H))**

DVs: completion time, error rate; confidence, physical and cognitive demand, preference.

3 **Overall: Within-subjects** design with 15 participants;

Tasks: finding high- (clusters) and low- (void) density areas

4 Each participant **72 study trials**:

2 Tasks × **3** Techniques × **2** Density (Low and High) × **2** Diff. Den. (Low and High) × **3** repetitions

5 **Procedure**: introduction → training → tasks → questionnaire + demographic information

Result: Both are beneficial for density perception (S: faster, H: prefer), complementary. **Limitation:** the baseline

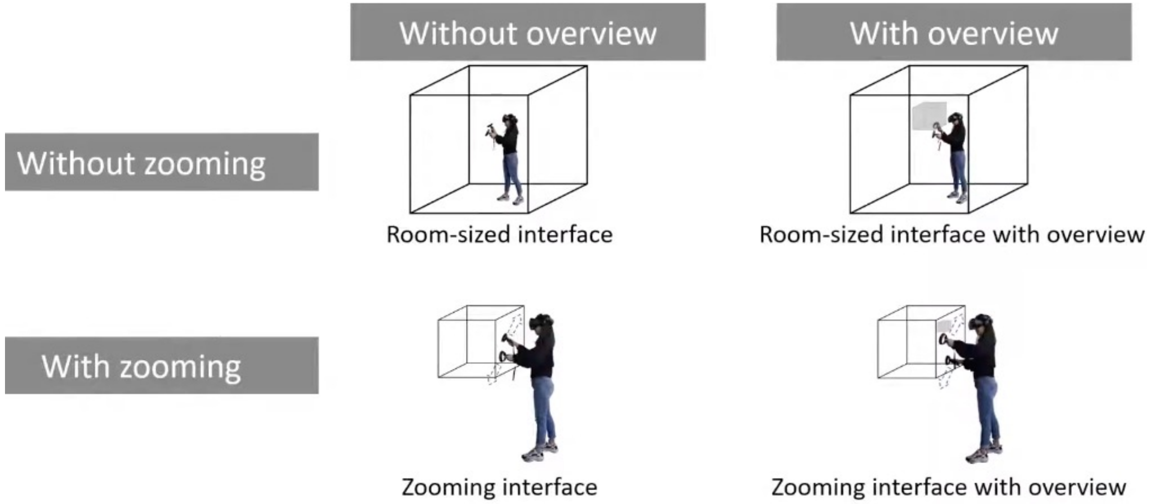
Prouzeau, A., Cordeil, M., Robin, C., Ens, B., Thomas, B. H., & Dwyer, T. (2019, May). Scaptics and highlight-planes: Immersive interaction techniques for finding occluded features in 3D scatterplots. 2019 CHI.

Visualization

...

Evaluate **both** interaction design and display design TVCG'20

Yang et al. (TVCG'20)



Interactive navigation:

- freely **re-scale** the visualization
- **change viewpoint**

1 **How effective these navigation techniques are in immersive environment?**

3 **Overall**: **Within-subject** design with 20 participants

2 **IVs** (independent variables): Overview, Zooming techniques

DVs (dependent variables): error rate, time, moving distance, No. of interactions, subjective preference.

4 Each participant **40 study trials**: 4 VR conditions × (3 Distance-Close + 3 Distance-Far + 4 Count)

5 **Procedure**: introduction → training → tasks → questionnaire + demographic information

Result: no one-fits-all, overview for room-sized, not for zooming;

Yang, Y., Cordeil, M., Beyer, J., Dwyer, T., Marriott, K., & Pfister, H. (2020). Embodied navigation in immersive abstract data visualization: Is overview+ detail or zooming better for 3D scatterplots?. *IEEE Transactions on Visualization and Computer Graphics*, *27*(2), 1214-1224.

Process

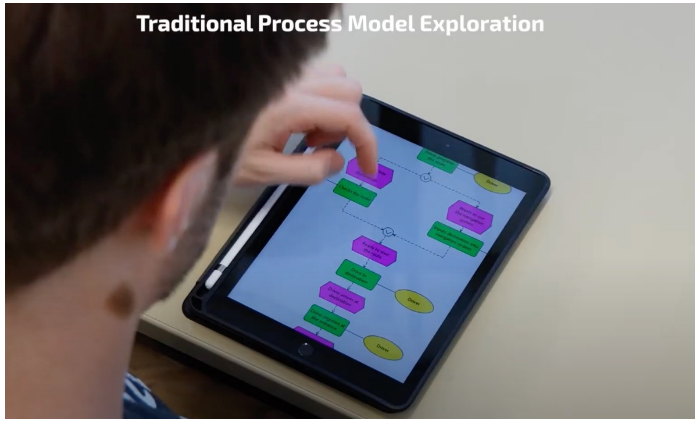
...

Evaluating Communication Through Visualization (CTV)[1] VR'20

...

Zenner, A. et al. (VR'20)

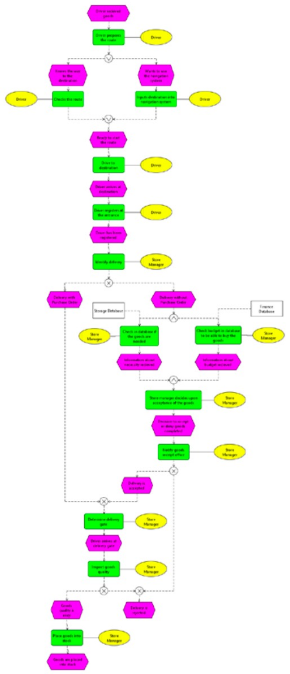
Process models data: a process or some rules (e.g., how to operate a machine, the rules of a company)



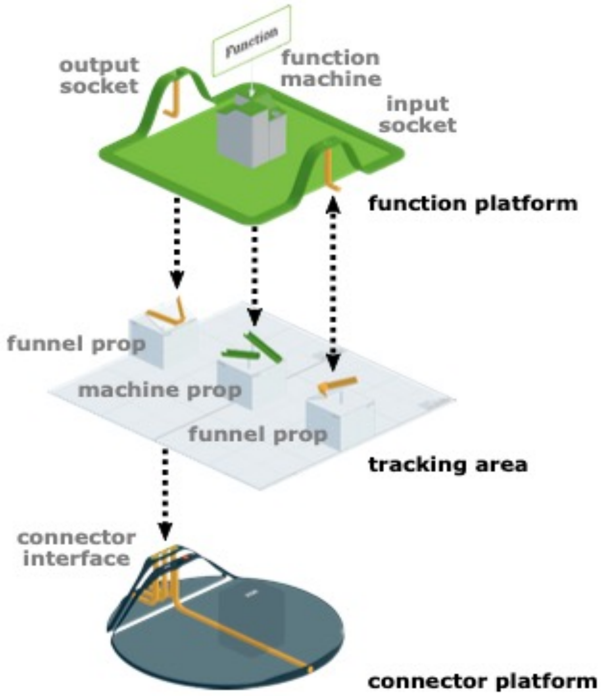
Complex data:

memory, interaction

1 **What is the benefits of displaying it in immersive environment?**



Mapping



Zenner, A., Makhsadov, A., Klingner, S., Liebemann, D., & Krüger, A. (2020). Immersive process model exploration in virtual reality. IEEE VR.

Zenner, A. et al. (VR'20)

② **IVs:** Mediums for display process model data, feedback (controller or passive haptic)

DVs: time, error rate, user experience, cognitive load, sickness, user preference, usability

Goal: 2D Exploration vs. Immersive Exploration **|** Controller Feedback vs. Passive Haptic Feedback

③ **Overall: Between-subject** study with **27 participants**

Tasks: Understanding process model data (no determined trails)

⑤ **Procedure:** Introduction → free exploration → testing Qs → Questionnaire

Results: similar performance, virtual: more time, props: preference

Zenner, A., Makhsadov, A., Klingner, S., Liebemann, D., & Krüger, A. (2020). Immersive process model exploration in virtual reality. IEEE VR.

Observations of Controlled Experiments

DVs: user performance and experience

Motivations (not mutually exclusive):

1. Evaluating 3D visualizations on **different mediums** (2D vs. 3D)
2. Evaluating the **novel techniques** to support the **the traditional** visualization tasks in 3D
3. Evaluating the **potentially effective channels in 3D** for encoding data

Potential Trends:

- Testing **diverse data types, traditional tasks**
- Exploring more **possibilities** of immersive visualization based on the **limitations** (or imperfections) **of 2D**
- Mining more **characteristics of immersive devices** to design **novel techniques**

Outline

Taxonomy of this Section

Evaluation Focus	Evaluation Goals		
Visualization	Evaluate **U**ser **E**xperience (UE)[1] **of the Design Space**		CHI'22, ISS'19, UIST'17
	Evaluate **U**ser **E**xperience (UE)[1] of **Novel Techniques**		VR'20, VIS'17, TVCG'97
Process	**U**nderstand Environments and **W**ork **P**ractices (UWP)[1]	Sports	TVCG'21, VIS'21
		Economy	TVCG'19
		Biology	Journal of Bio.'18
	Visual **D**ata **A**nalysis and **R**easoning (VDAR)[1]	Novel Applications	VR'22, UIST'20, TVCG'19, VIS'19, VIS'18
		Toolkits	CHI'21, CHI'20, TVCG'20, TVCG'19, VR'19
	Evaluate **U**ser **E**xperience (UE)[1] of novel **combinations**	Mobile	CHI'21
		Large screen	TVCG'20, CHI'18

1. Lam, H., Bertini, E., Isenberg, P., Plaisant, C., & Carpendale, S. (2011). Empirical studies in information visualization: Seven scenarios. IEEE TVCG, 18(9), 1520-1536.

Case Study

Four key aspects of HCI **Case Studies**[2]

- in-depth investigation of a small number of cases;
- examination in context;
- multiple data sources;
- emphasis on qualitative data and analysis.

The **goals** of HCI **case studies**[1]**:** exploration | explanation | description

Four Components of a case study design:

C1: Questions; **(study goal)**

C2: Hypotheses or propositions; (what you expect to find)

C3: Units of analysis (granularity of study)

C4: A data analysis plan **(data collection)**

1. *Jonathan Lazar, Jinjuan Heidi Feng, and Harry Hochheiser. 2017. Research methods in human-computer interaction 2nd Edition. John Wiley & Sons*
2. *J. R. Feagin, A. M. Orum, and G. Sjoberg, A case for the case study. UNC Press Books, 1991.*

Visualization

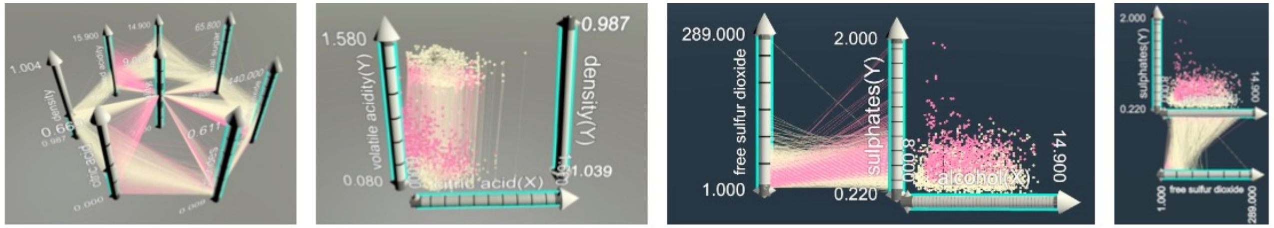
Evaluate **U**ser **E**xperience (UE)[1]
of the Design Space

...

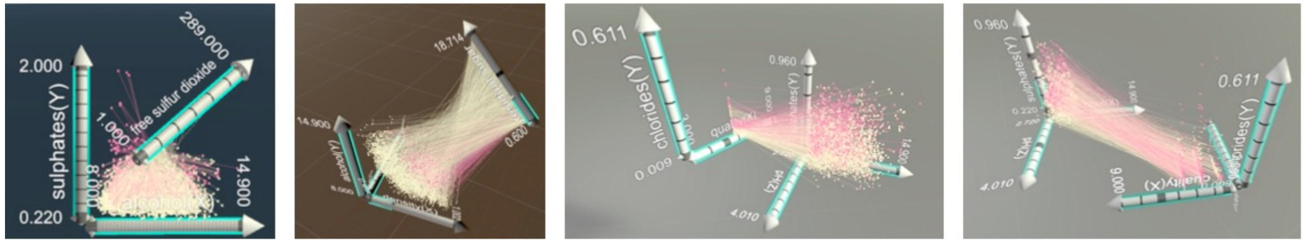
UIST'17

Cordeil, M. et al. (UIST'17)

ImAxes, an immersive system for exploring multivariate data (3D axis grammar in space)



(a) Circular 1 to many PCP (b) Overlaid SPLOM (c) Linking to Y-axis (d) X-axis link



A **use case** to demonstrate *ImAxes*

C1. Goal: describing a context of how the *ImAxes* can be used by experts

C2. Hypotheses: The design of *ImAxes* can support data analysts' multi-dimensional data analysis

C3. Units of analysis: *ImAxes (fluid interaction and expressive design)* | an individual expert | multivariate data

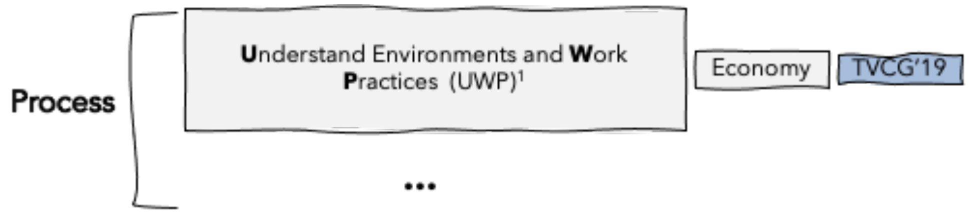
C4. Data collection: Think-aloud style, video recording.

Result: novel experience, freedom, fluid;

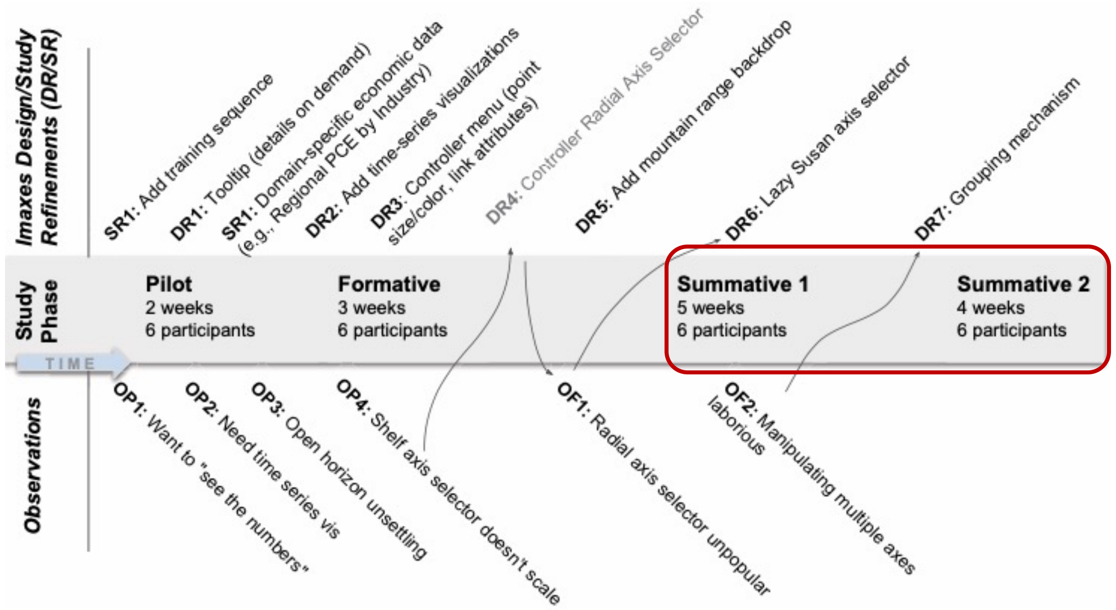
Limitation: no comprehensive evaluation

Cordeil,. M. et al. ImAxes: Immersive Axes as Embodied Affordances for Interactive Multivariate Data Visualisation. UIST. 2017

Batch, A. et al. (TVCG'19)



[A design study[2]]: A problem-driven visualization research. (real-world cases)



A **case study** with 12 professional **economists**

C1. Study goal: Utility of *ImAxes* for domain experts

C2. Hypotheses: *ImAxes* might benefit experts' data exploration and presentation process

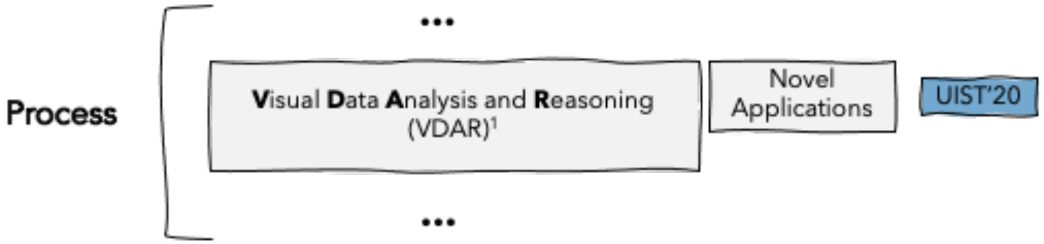
C3. Units of analysis: an individual expert | exploration and presentation | utilize the physical space

C4. Data collection: video recordings, participant position and view direction, interview and survey

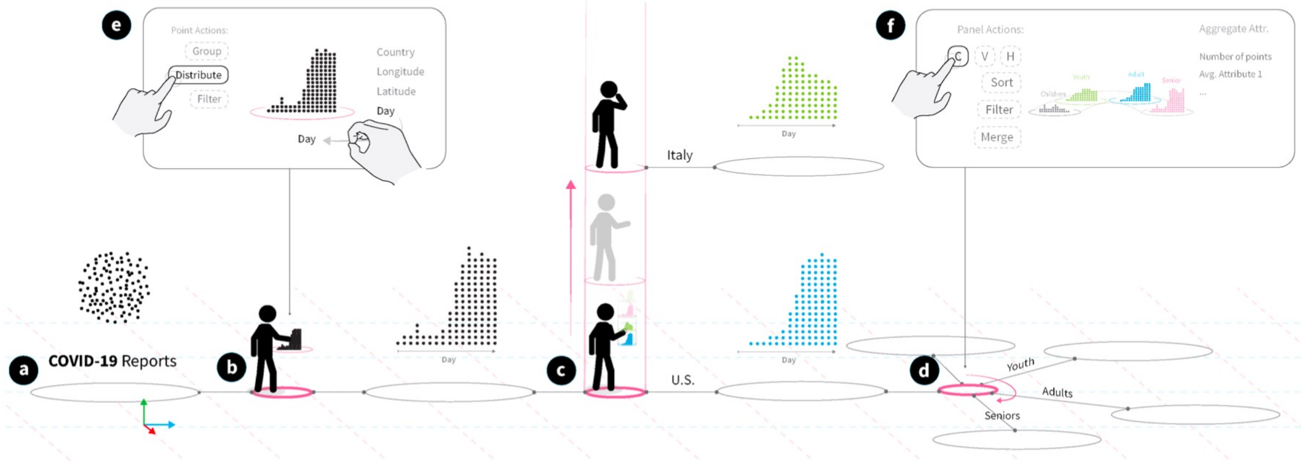
Result: engaged, organize views; **Limitation:** use of space

1. *Batch, A.,et al. There is no spoon: Evaluating performance, space use, and presence with expert domain users in immersive analytics. IEEE TVCG 2019.*
2. *M. Sedlmair, M. D. Meyer, and T. Munzner. Design study methodology: Reflections from the trenches and the stacks. IEEE TVCG. 2012.*

Devamardeep, H. et al. (UIST’20)



DataHop: an immersive visualization system → **lay out their data analysis steps** in VR.



A case study with six VR users

C1. Study goal: usability, affordances and performance of DataHop

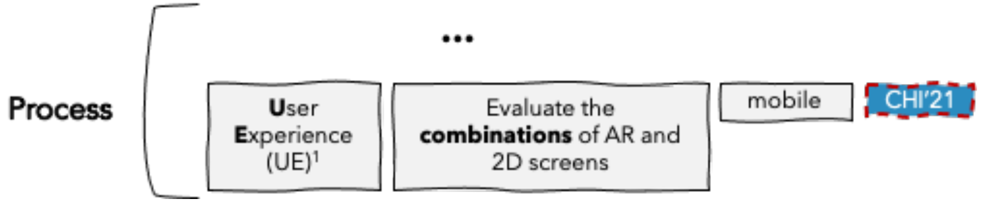
C2. Hypotheses: Spatially mapping one’s workflow in immersive environment → beneficial

C3. Units of analysis: an individual VR user | understanding and exploring multidimensional datasets

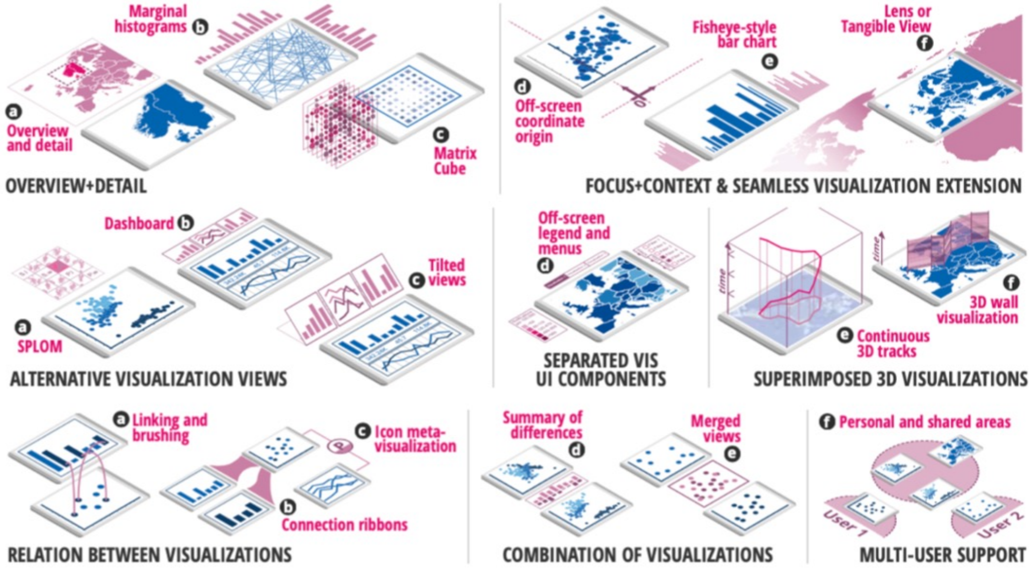
C4. Data collection: Interview: underlying features and metaphors | Questionnaire: usability and usefulness

Result: sensemaking, spatial cues **Limitation:** no cues for the start

Hayatpur, D., Xia, H., & Wigdor, D. (2020, October). DataHop: spatial data exploration in virtual reality. UIST.



Langner, R. et al. (CHI'21)



A conceptual **framework**: combination of **mobile** devices and **AR** HMDs for data analysis.

Six use cases with **seven experts;**

C1. Study goal: Evaluate the concepts and early prototype.

C2. Hypotheses: These two devices can be **complementary** for data analysis.

C3. Units of analysis: an individual data analyst | data analysis

C4. Data collection (think-aloud style): Verbally reported advantages & disadvantages;

Take notes -> thematic analysis

(**Themes:** *#successful design, #design issues, #alternatives, #missing functionality, etc.).*

Result: novel, alternative views **Limitation:** without AR input

Langner, R., Satkowski, M., Büschel, W., & Dachselt, R. Marvis: Combining mobile devices and augmented reality for visual data analysis. CHI 2021.

Observations of Case Studies

Motivations:

1. Evaluating user experience under the **novel work practices** with immersive visualization
2. Evaluating user experience of **interacting with data** by **novel techniques**

Potential Trends:

- Exploring **diverse real-world application scenarios**;
- Designing **novel immersive systems** to support data analysis
- Testing **novel combination** of traditional and immersive devices (complementary instead of comparative)

Outline

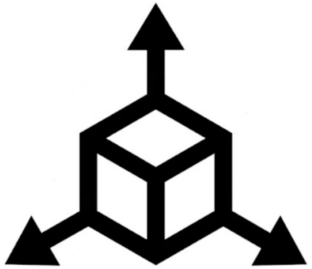
1. Introduction
2. Controlled Experiment
3. Case Study
4. Summary of Evaluation
5. Discussion & Future Work

Summary of General Benefits

Q1: "How did these works evaluate the visualization with immersive HMDs?"

→ scenario-based or tasks-based (ad-hoc)

The general benefits of immersive visualization for 3D abstract data **(Q2)**



3D rendering: Intuitive display of 3D visualization

- Improve user performance of relevant tasks
- Improves the perception of 3D data

Examples:

3D graph (Zenner, A. et al. 20), 3D maps (Yang et al. 20), 3D trajectories (Wolfgang, B. et al.21),

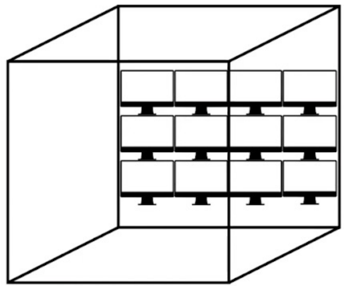
3D flows (Yang et al. 19) and 3D scatterplots (Matt, W. et al. 19)

Summary of General Benefits

Embodied interaction:

Flexible/fluid interaction design of interaction

- Novel experience (learning effects and memory)
- Natural interaction: people's spatial ability
- Feedback of data (haptic)



Large display space:

- Freedom: display and manipulate data
- Sensemaking and reasoning process
- Extended memory
- Collaborative data analysis (improved presence and awareness)

Summary of Common Setting

	Controlled experiments	Case studies
Participants	Avg. **20.6** (86.9% are ordinary users)	**1-5** experts (45.8%), 6-12 experts (20.8%)
• **Prior experience**	VR/AR, 3D games, 3D modeling; normal vision, VR sickness; familiarity of visualization, color-blind	Experts' domains, **background** (years)
Physical Setting	VR(87.5%), AR (12.5%); Room-scale	VR (66.7%), AR (29.2%), MR(8.3%); Room-scale
Study Process	a pilot study (47.8%), **training** (73.9%); 1.3h	Training session (30.4%), not measure time
Measures	**Questionnaire** (91.3%), user interaction data (47.8%);	**Interview** , video recording (think aloud)

Pros and Cons

	Controlled experiments	Case studies
Pros	A high level of control (cause-and-effect) Duplicated results Objective evidence	Real-world scenarios Unexpected insights In-depth investigation
Cons	Artificial situations Affected by small errors Lack of in-depth qualitative feedback	Limit to a specific industry or type of idea Highly subjective due to limited samples Inability to Replicate

Outline

Discussion & Future Work

Unsolved Questions for Current Evaluation Practice

Target Users

Domain experts or ordinary users

1. What are the effects of **their prior** VR/AR or relevant **experience**?
2. How about their data **visualization literacy** or **spatial abilities**?

Evaluation Process

Controlled conditions or free exploration

1. How to evaluate the effectiveness of **training session** before the study?
2. How to reduce the impact of potential **confounding factors** (devices, individuals, data) during the study?
3. How to infer **users' intent** based on the tracked users' behavior?

Discussion & Future Work

Unsolved Questions for Current Evaluation Practice

Evaluation Results

Measures and Analysis

1. How to identify **user preference**? (due to the **novelty** of immersive devices or their **real feelings** of 3D visualization)

2. What other **high-level user perception** needs to be measured (engagement, aesthetics)?

3. How to conduct effective **qualitative** analysis?

Discussion & Future Work

Human perceives different visual channels differently: **effectiveness**

Previous research has figured out the **effectiveness** among **different channels** based on human perception for 2D visualization.

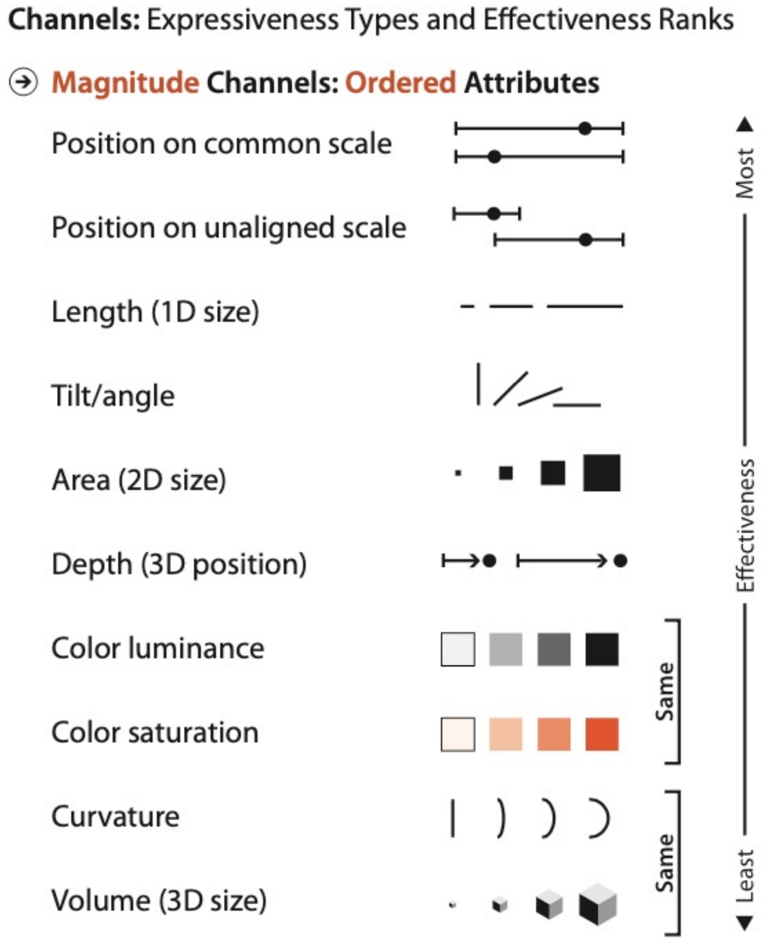
We may need similar guidelines for more **complicate** situations:

- Multivariate visualization
- Social Perspective

More studies are required to understand **human factors** in more complicated scenarios

- Human's spatial ability to interact with 3D visualization
- Human perception of 3D visualization

Guidelines for basic situations[1]



1. Munzner, T. (2014). Visualization analysis and design. CRC press.

Thank you
Q & A