Evaluating Immersive Approaches to Multidimensional Information Visualization

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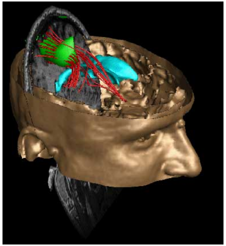
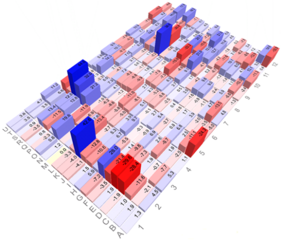
March 7, 2018

Motivation

- **3D representations** are known to offer advantages under many circumstances



Spatial data (OpenDX.org)



Abstract information (Brath, 2014)

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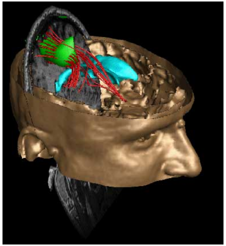

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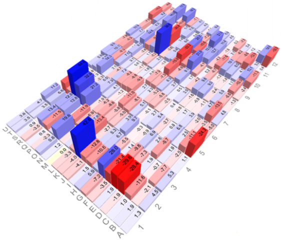

Abstract information (Brath, 2014)

- Nonetheless, their use has also been long **controversial**
  - **Perception** issues
  - **Interaction** issues

  → Data exploration is cumbersome and error-prone

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- Progressively explored alternative: **Immersive Analytics**
  - Stereoscopic displays + natural 3D interaction

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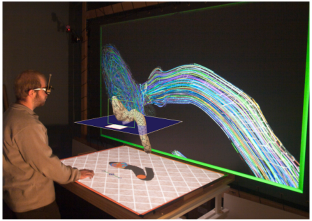
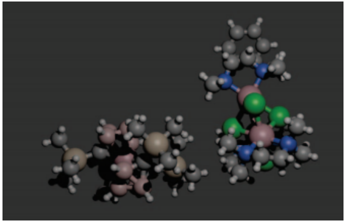
  - Stereoscopic displays + natural 3D interaction

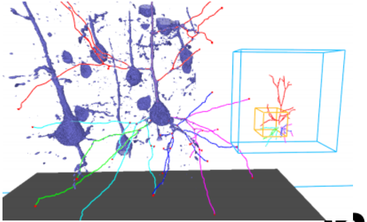
- Multiple favourable results for **spatial data**



Coffey et al., 2011



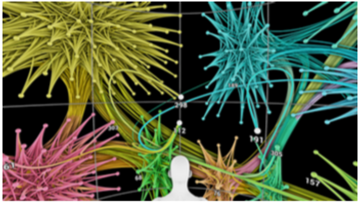
Drouhard et al., 2015



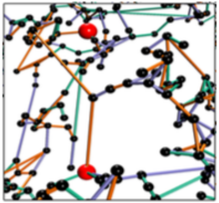
Usher et al., 2017

Motivation

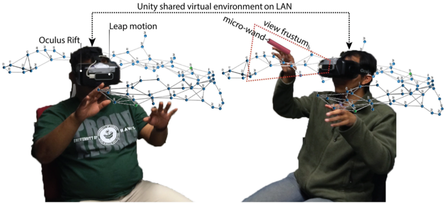
- **Immersive Analytics** of **abstract information**
  - New evaluations and guidelines are still needed
  - Some promising results have already been demonstrated (e.g. **graph visualization**)



Kwon et al., 2016



Zielasko et al., 2016



Cordeil et al., 2017

Main Goal

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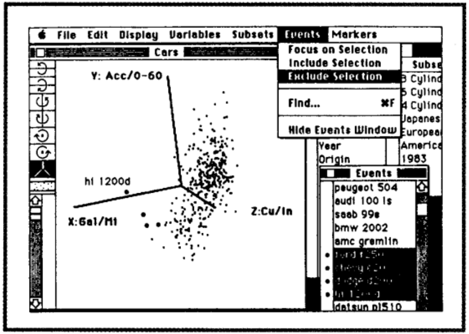
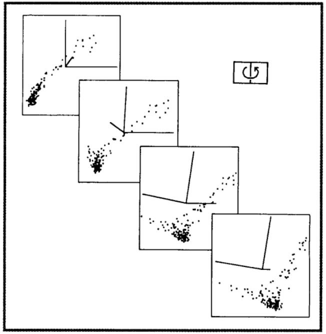
- Expand this discussion, taking into consideration a different representation: **3D scatterplots of dimensionally-reduced (DR) data**
  - Common approach to multidimensional data visualization
  - Potential advantage in transitioning from 2D to 3D
  - **Main hypothesis:** since this particular category of scatterplots is always analysed in terms of the distances between points, it could benefit from immersive setups

Context

- The use of **3D scatterplots** has been controversial for a long time





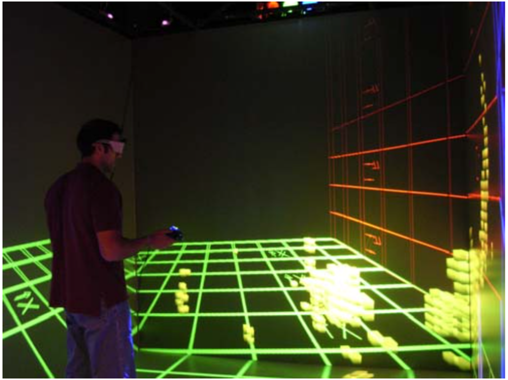
Donoho et al., 1988

Context

- The use of 3D scatterplots for the representation of **DR data** is also often discussed → **contradictory results**
  - Poco et al., 2011
  - Sedlmair et al., 2013
  - Gracia et al., 2016

Context

- Few studies on the impact of **immersion** and stereopsis
  - Most provided only preliminary results
  - Used technologies that have advanced enormously since
  - Used CAVE-style environments



Raja et al., 2004

Research Question

- **Could HMD-based immersive environments aid in the exploration of 3D DR data scatterplots?**

The Oculus Rift HMD (ArsTechnica.com)

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Immersive Analytics of Dimensionally-Reduced Data Scatterplots

Jorge A. Wagner Filho Marina F. Rey Carla M.D.S. Freitas Luciana Nedel

Institute of Informatics
Federal University of Rio Grande do Sul

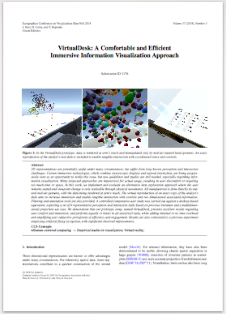
WIA @ IEEE VIS 2017

Outline

1. Methodology
2. User Study 1: Conventional Flying Approach Evaluation
3. VirtualDesk: Novel Proposed Approach
4. User Study 2: VirtualDesk Evaluation
5. Conclusion


Immersive Visualization of Abstract Information:
An Evaluation on Dimensionally-Reduced Data Scatterplots

IEEE VR 2018 (to appear)


VirtualDesk: A Comfortable and Efficient
Immersive Information Visualization Approach

EuroVis 2018 (2nd review round)

Key Questions

1. How do we assess the contribution of immersive approaches to the analysis of 3D DR data scatterplots?

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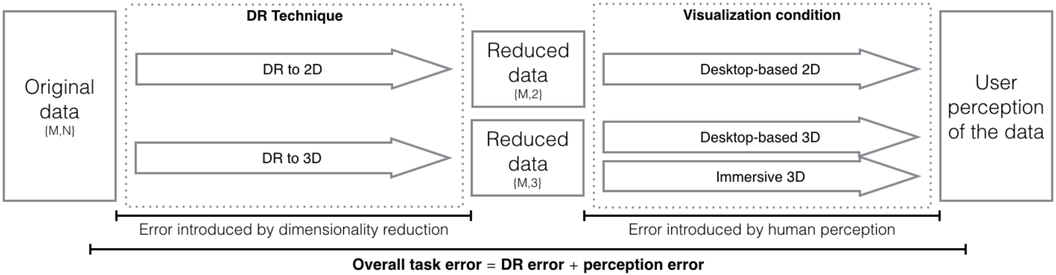
    1. What are the specific factors that vary between desktop-based (2D/3D) and HMD-based (3D) approaches?
    2. How to quantify each of these factors?

Problem Modelling



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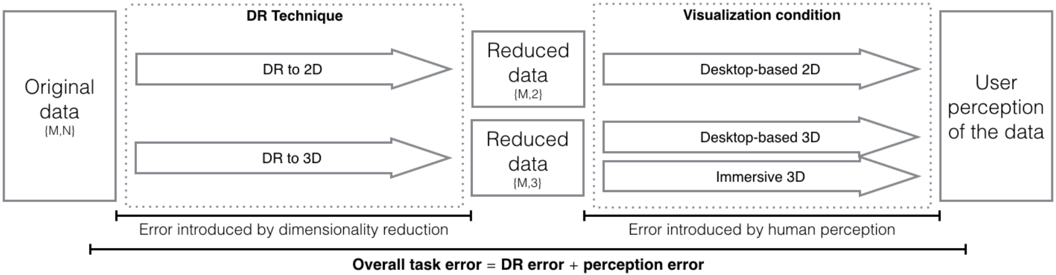

- Task-dependent
- Dataset-dependent

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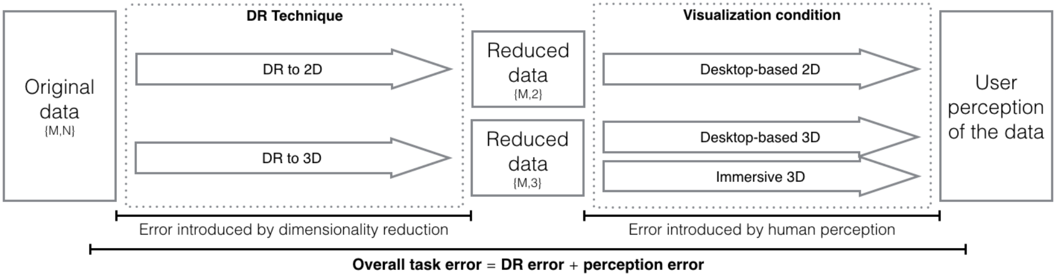

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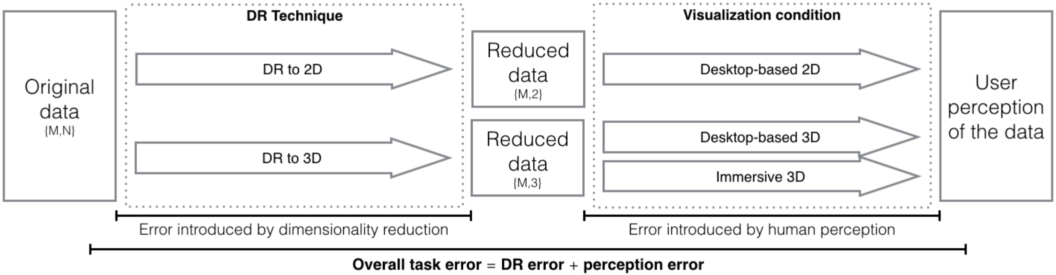

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→ **Two-step evaluation framework**

Targeted Use Case

- Multidimensional **roll call voting** data from the Brazilian Chamber of Deputies
  - Very high dimensionality (430-620)
  - Consistent application of DR techniques
  - Easy definition of semantically meaningful tasks
  - Appeal to the public

- Four legislature datasets: 52nd, 53rd, 54th and 55th

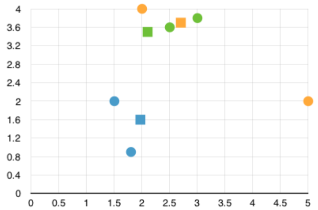
Targeted Use Case

	Roll call 1	Roll call 2	Roll call 3	Roll call 4	Roll call 5	...
Deputy A	Yes (1)	No (-1)	No (-1)	Yes (1)	Yes (1)	...
Deputy B	Absent (0)	Yes (1)	No (-1)	No (-1)	Absent (0)	...
Deputy C	Yes (1)	No (-1)	Yes (1)	No (-1)	Absent (0)	...
Deputy D	No (-1)	No (-1)	No (-1)	No (-1)	No (-1)	...
Deputy E	No (-1)	Yes (1)	Yes (1)	Yes (1)	No (-1)	...
Deputy F	Yes (1)	No (-1)	Yes (1)	Yes (1)	Yes (1)	...
Party A	Yes (1)	No (-1)	Yes (1)	No (-1)	No (-1)	...
Party B	No (-1)	No (-1)	No (-1)	Yes (1)	Yes (1)	...
Party C	Yes(1)	No (-1)	Yes (1)	No (-1)	No (-1)	...
...	...	...	...	...	...	...

(a)

	PC1	PC2
Deputy A	1.5	2
Deputy B	1.8	0.9
Deputy C	3	3.8
Deputy D	2	4
Deputy E	2.5	3.6
Deputy F	5	2
Party A	2	1.6
Party B	2.7	3.7
Party C	2.1	3.5
...	...	...

(b)



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  - Tasks should assess different competencies in distance judgements
- Designed to be simple and atomic

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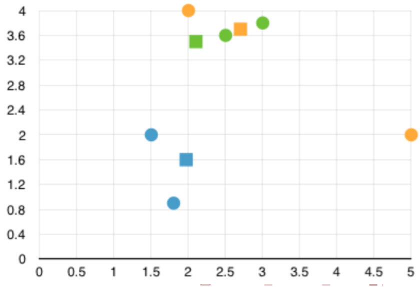
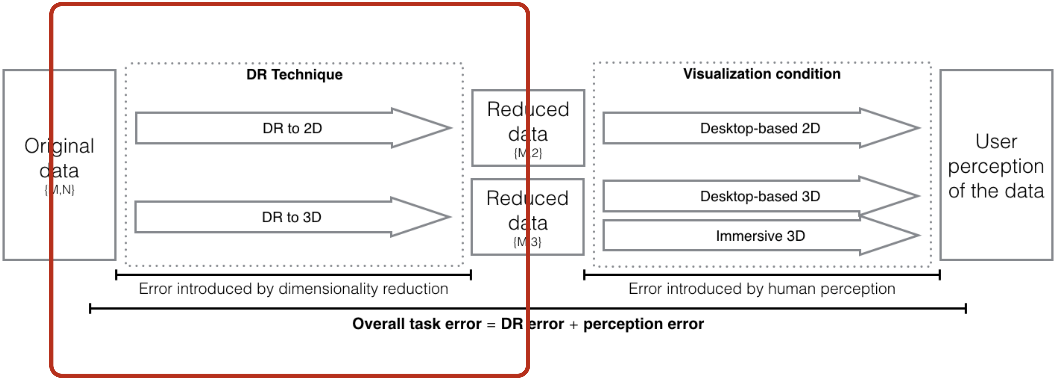
Point-based distance perception tasks

- T1 *Selection of a deputy's closest deputy*
- T2 *Selection of a deputy's closest party*
- T3 *Selection of a party's furthest member*
- T4 *Selection of a party's closest party*



Step 1: Task-based DR Error Estimation



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- Current approaches to DR information loss estimation
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- Our approach
  - Empirical, task-based
  - **Maximum potential performance** concept
  - **Simulation** of the *minimum error* a user could achieve in each scenario (2D/3D)
    - Assuming absolute accuracy in perceiving the presented information
    - Averaged over all possible instances of a task

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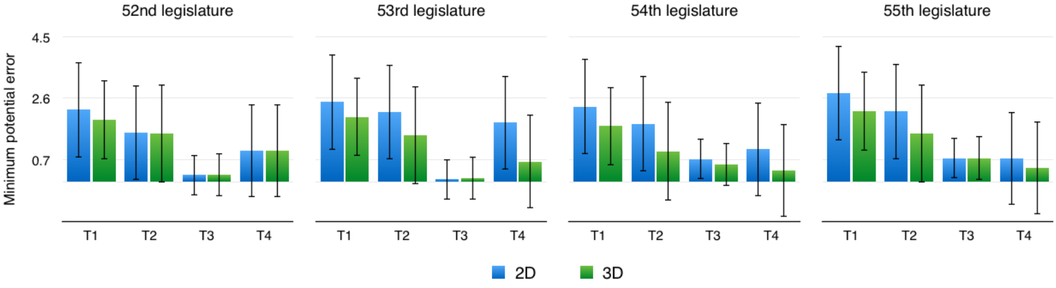

- Two particular scenarios identified
  - 54th legislature: all tasks appear to benefit from 3D $\rightarrow$ **D1**
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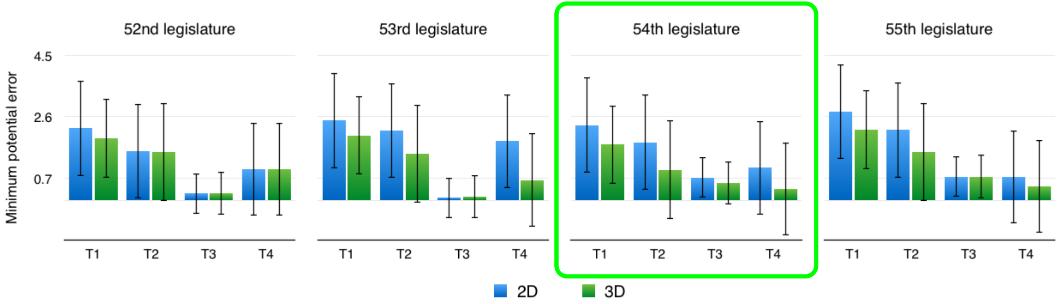

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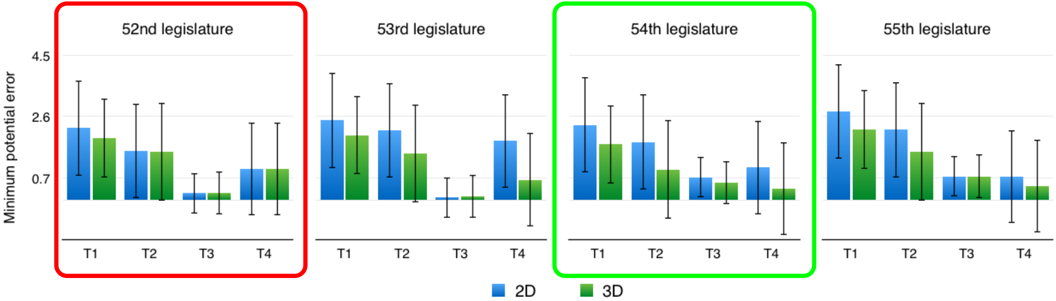

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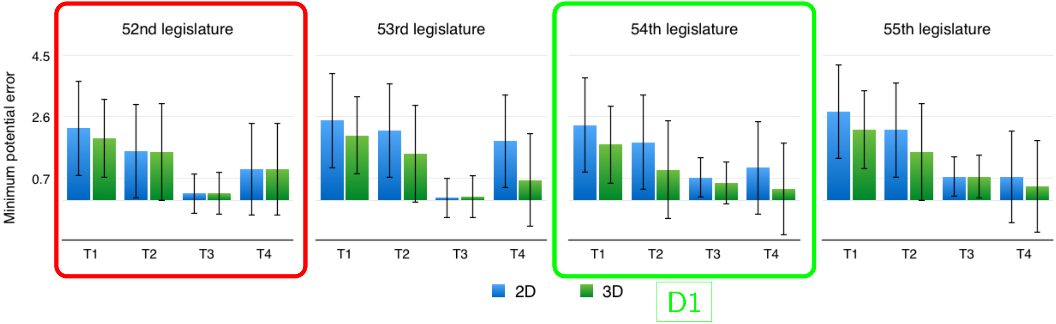

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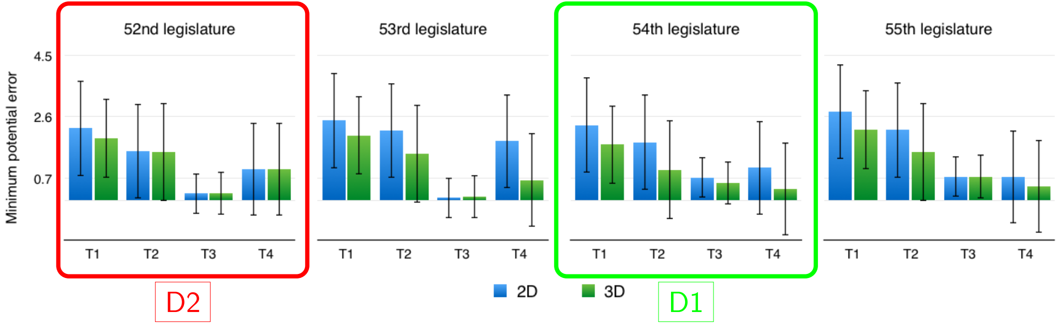

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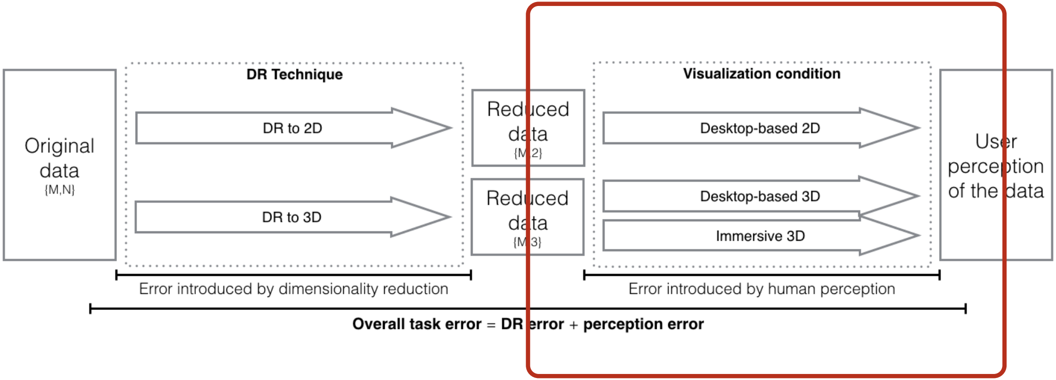

Step 2: Perception and Overall Error Assessment

- Evaluation approach: **controlled comparative user studies**
  - Within-subjects protocols
  - Standardized questionnaires (SUS, Nasa TLX, SSQ, IPQ)

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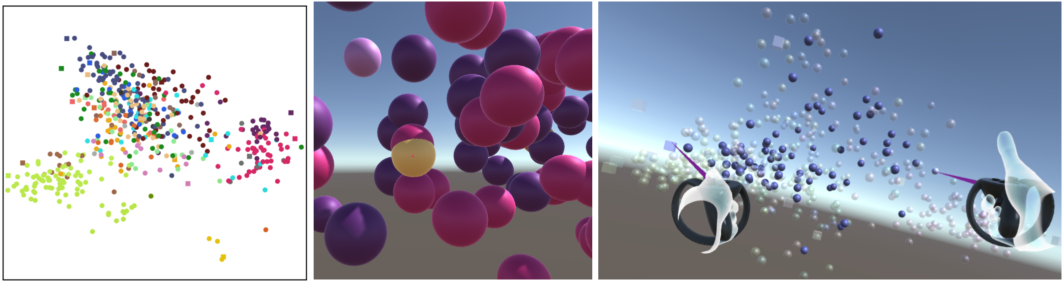
First User Study

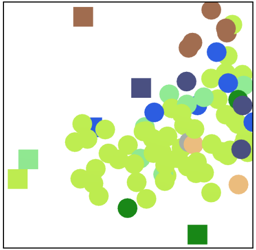
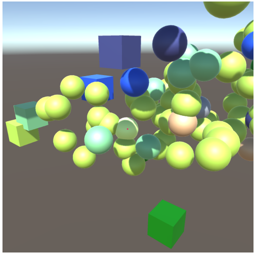
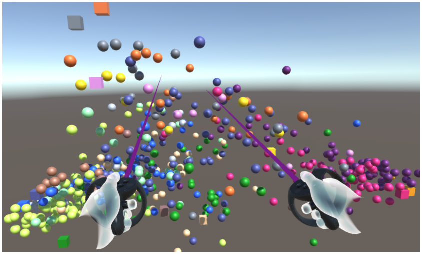
- 30 subjects (20 male/10 female)
- Comparison between **three conditions**
  - Desktop-based 2D (*2D*)
  - Desktop-based 3D (*3D*)
  - HMD-based 3D (*IM*)
- Immersive approach: **Gaze-directed Flying**
  - Conventional metaphor
  - Simple to learn
  - Places the user inside the representation

Visualization Conditions – Interaction



- Possible actions:
  - **Select** point
  - **Highlight** whole party

Visualization Conditions – Selection & Navigation

			
	2D	**3D**	**IM**
Selection	Mouse cursor	Reticle cursor	Pointer rays
Navigation	Zooming + Panning	Flying + Strafing	

Hypotheses

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- H4 *2D* will be the quickest, given its smaller navigation and interaction costs.
- H5 The benefits provided by immersion will be reflected on the subjective evaluations.

Experiment Design

- For each of the *3 visualization conditions*
  - Familiarization phase on a separate dataset
  - For each of the *4 tasks*
    - 3 executions in one dataset
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- Participants asked to be accurate
- Question sets repeated only once per condition
  - Maximized sampling and *cross-validation*
- Total time: ∼45 min (incl. questionnaires)

Results: Perception Errors

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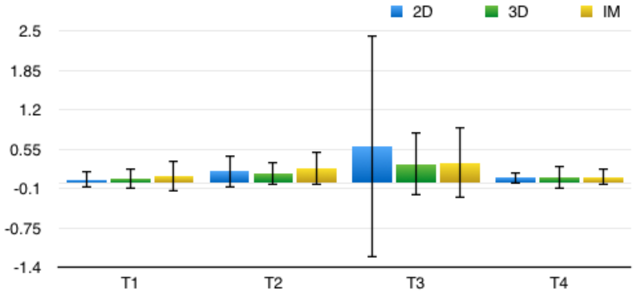
- Difference in Euclidean distances, **in two or three dimensions**, to the given answer and to the correct one **in the representation**
- In this analysis, we do not differentiate between datasets
- Surprisingly, no significant differences were observed (**H1**)



Average perception errors per task (meters)

Results: Overall Task Errors

- Differences in Euclidean distances, **in the original vote matrix**, to the given answer and to the correct one **in the real multidimensional data set**

(*) for $p < .05$, (**) for $p < .01$ and (***) for $p < .001$

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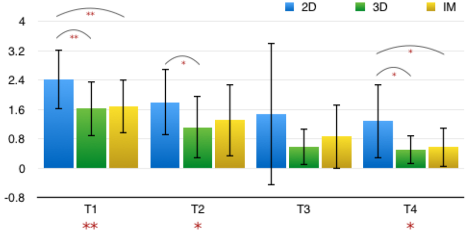
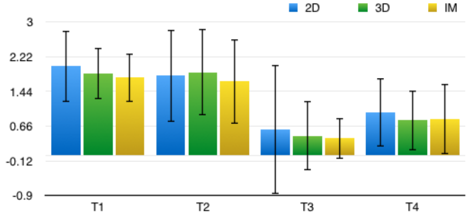


(a) D1



(b) D2

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Results: Task Completion Time

- *2D* allowed consistently faster task completion (**H4**)

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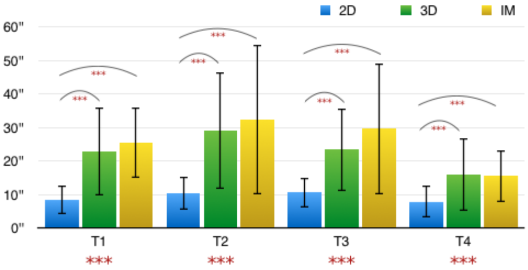
Results: Task Completion Time

- *2D* allowed consistently faster task completion (**H4**)
- *3D* and *IM* did not show significant differences in any case
  - **Despite** slower navigation in *IM*
  - Explanation: **navigation** was larger in Desktop *3D* (up to 38%)



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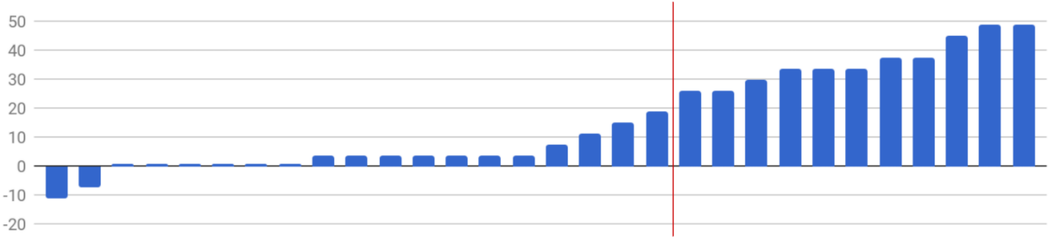
Results: Simulator Sickness

- Around 60% of the participants reported only minor symptoms



Participants' SSQ scores in increasing order

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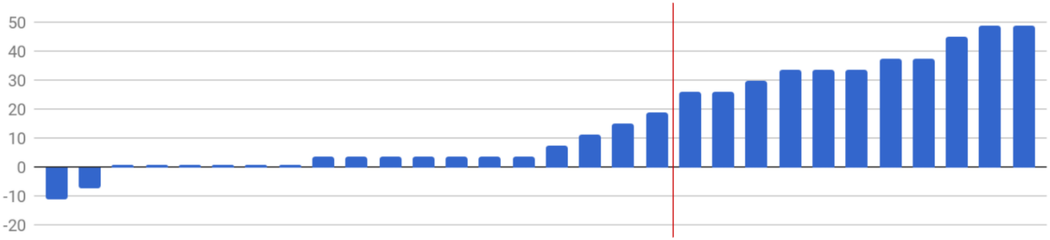
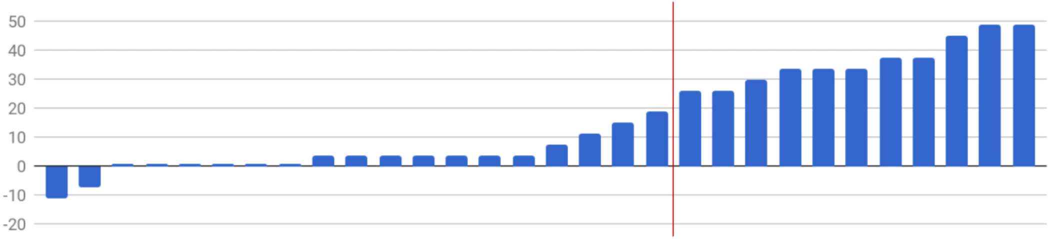


Participants' SSQ scores in increasing order

Results: Simulator Sickness

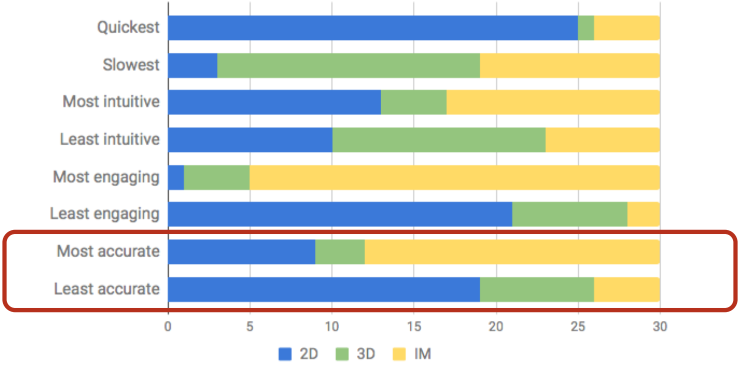
- Around 60% of the participants reported only minor symptoms
- Others, however, presented quite significant discomfort levels
- Perception results did **not** appear to be impacted (-0.1 correlation)



Participants' SSQ scores in increasing order

Results: User Feedback – Ranking Question

- Subjective **perception of accuracy** in *IM* was much larger than in *3D* (**H5**)



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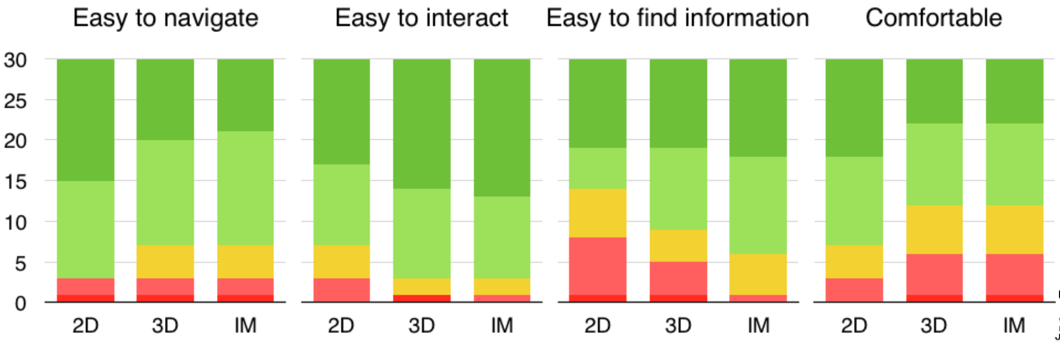
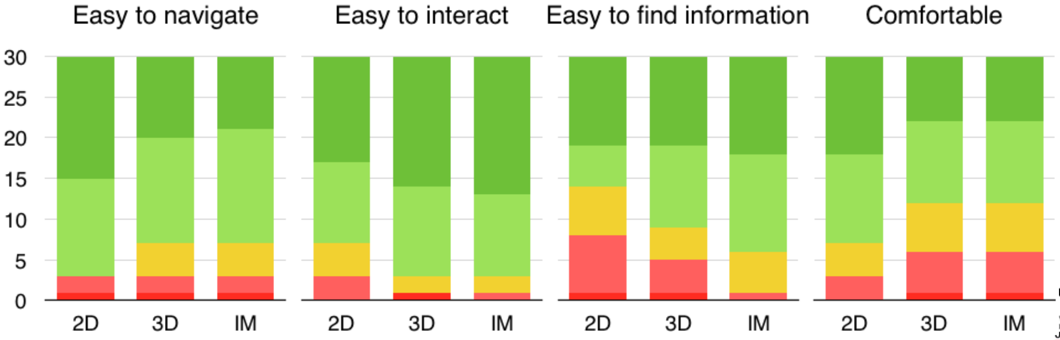
- All techniques were well rated in terms of ease of navigation and interaction



Results: User Feedback – Likert-scale Agreements

- All techniques were well rated in terms of ease of navigation and interaction
- *IM* was better rated in terms of **ease to find information**, and performed as well as *3D* for comfort



Hypotheses Recap

- H1 The perception error will be smaller in *IM* than in *3D*.
- H2 For **D1**, the overall task error in *IM* will be smaller than in *3D* or *2D*.
- H3 For **D2**, the overall task error in *IM* will be at least as good as in *3D* or *2D*.
- H4 *2D* will be the quickest, given its smaller navigation and interaction costs.
- H5 The benefits provided by immersion will be reflected on the subjective evaluations.

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- Game-like *desktop 3D* with multiple depth cues may explain absence of perception differences to *IM* (**H1** and **H2**)

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  - An equivalent performance appears to have taken considerable less effort and navigation in the immersive scenario
  - Subjectively perceived accuracy was also much larger for *IM*
- −
  - Times were around 3x slower in *IM* than in *2D*
  - Simulator sickness was still a major issue

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- Many proposed approaches are **impractical** for actual usage
  - Flying $\rightarrow$ time-consuming and high simulator sickness
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  - Flying $\rightarrow$ time-consuming and high simulator sickness
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- Goal: **propose**, **implement** and **evaluate** an alternative data exploration approach to circumvent the observed limitations

The *VirtualDesk* Exploration Metaphor

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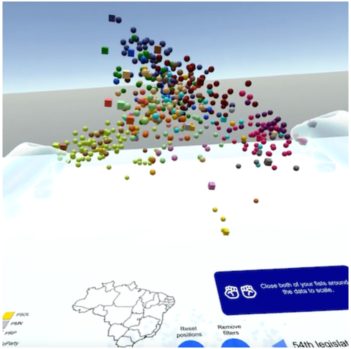
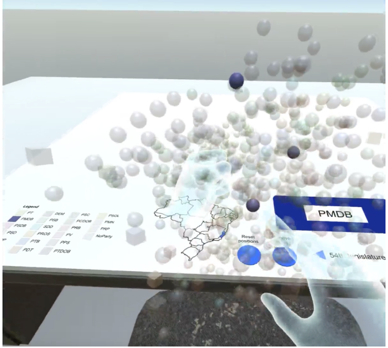
  - Higher precision and stronger stereopsis and parallax cues (Mine et al., 1997)
- Direct data manipulation through natural mid-air gestures
  - Spatio-data coordination (Cordeil et al., 2017)
- Reproduces an exact copy of the analyst's desk (Zielasko et al., 2017)
  - Enable display of two-dimensional associated views
  - Enable interaction with tangible controls

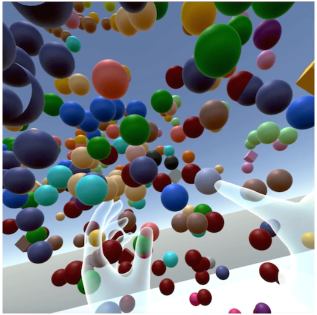
The *VirtualDesk* Prototype

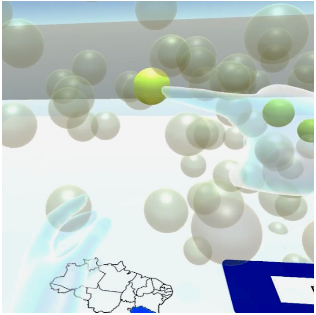




- **Grabbing** action
  - Translation
  - Rotation
  - Scaling

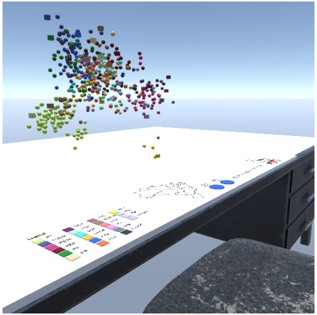
The *VirtualDesk* Prototype

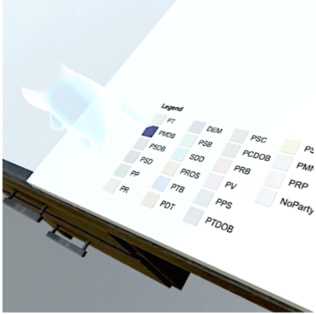




- **Double tapping** action
  - Left hand: highlight
  - Right hand: select
  - Haptic feedback

The *VirtualDesk* Prototype



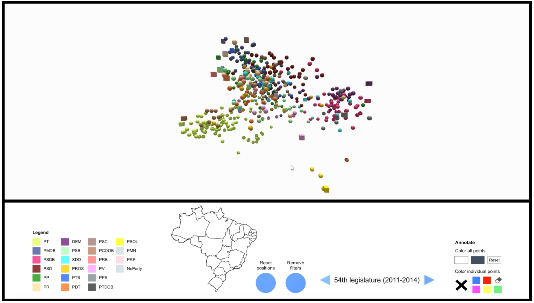


- **Tabletop** interaction
  - Combinable filters
    - Legend (categorical)
    - Map (spatial)
  - Annotations
  - Control buttons

Second User Study

- 24 subjects (20 male/4 female)
- Comparison between **two 3D conditions**
  - New desktop-based 3D
  - Immersive VirtualDesk
- Evaluated in terms of **perception** only

Comparable condition



- More representative of a typical 3D visualization tool
- *Rotate-Pan-Dolly* paradigm
- **Two panels interface**

Extended Task Set

Point-based distance perception tasks

- T1 *Selection of a deputy's closest deputy*
- T2 *Selection of a deputy's closest party*
- T3 *Selection of a party's furthest member*
- T4 *Selection of a party's closest party*

Extended Task Set

Class-based density perception tasks

T5 *Density comparison between two parties*

T6 *Density comparison over time*

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Clustering task

T7 *Estimation of the number of clusters in a given point cloud*

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Interaction tasks

- T8a *Filtering of a party-state combination*
- T8b *Selection of all remaining deputies*

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Experiment Design

- For each of the *2 visualization conditions*
  - Tutorial phase
  - For each of the *9 tasks*
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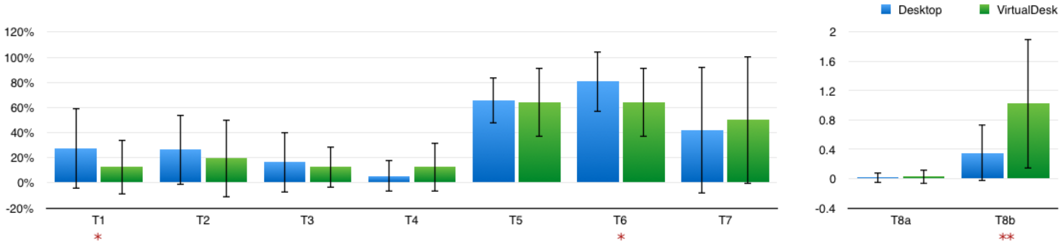
- For T1-T4, same question points from the previous study
- Total time: ~40 min (incl. questionnaires)

Results: Error Rates

- **Perception** tasks always performed equally or better in VirtualDesk (**H1**)



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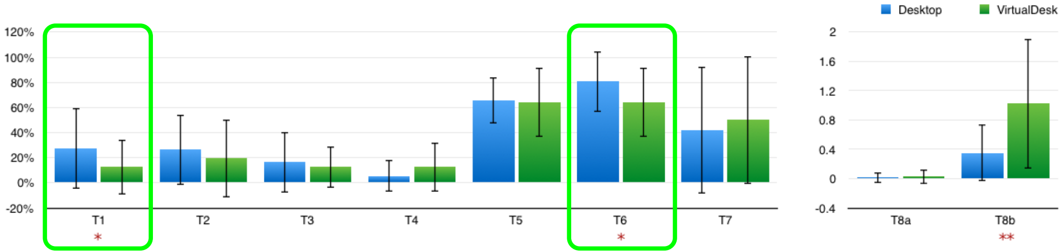
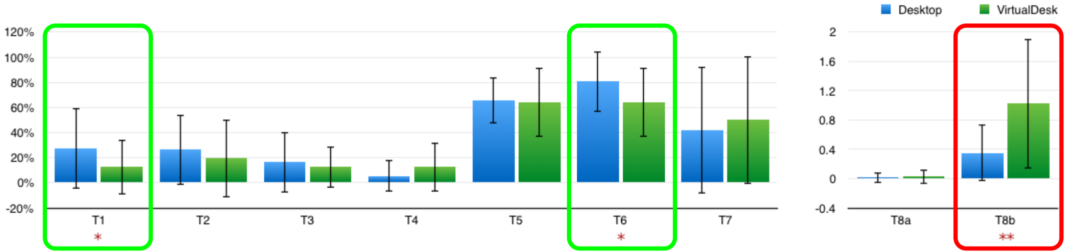


Results: Error Rates

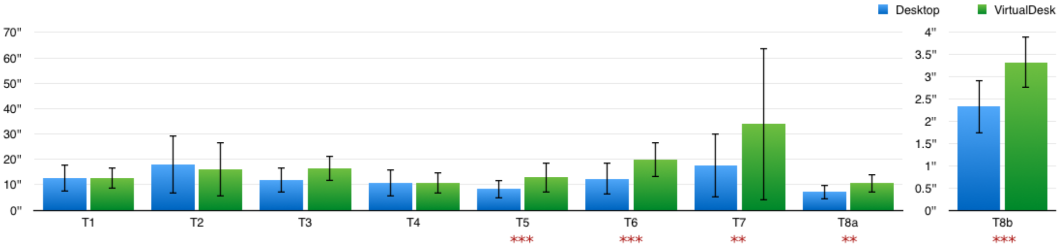
- **Perception** tasks always performed equally or better in VirtualDesk (**H1**)
- Desktop more accurate for point **selection** (**H2**)



(*) for $p < .05$, (**) for $p < .01$ and (***) for $p < .001$

Results: Task Completion Time

- VirtualDesk slower for T5-T8
  - Required interaction w/ tabletop controls



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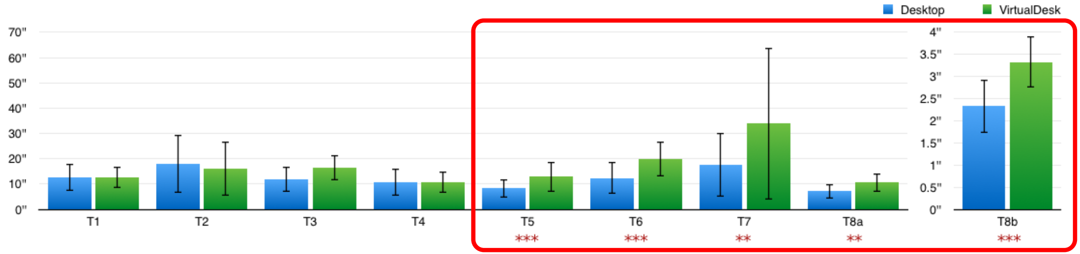

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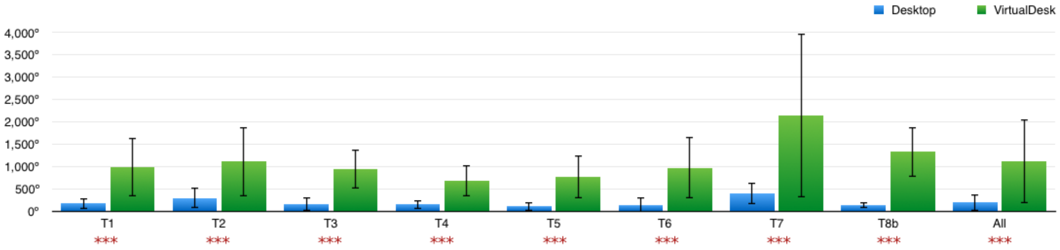
T8b times normalized per selected point

Results: Data Exploration

- Interesting difference observed in terms of **dataset rotations**
  - Performed **5.8x more** in the immersive condition



Accumulated dataset rotations per task (degrees)

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Results: Workload

- Higher task load score (NASA) in VirtualDesk (*)
  - 30.9 (SD 14.7) vs 23.2 (SD 15.4)

- Especially influenced by two components
  - **Physical Workload** (37.4 vs 9.7) (***)
  - **Effort** (36.1 vs 23.6) (*)

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  - **Effort** (36.1 vs 23.6) (*)
- **Mental Workload** was also higher but without significance (**H3**)
  - 26.3 (SD 16.2) vs 22.2 (SD 20)

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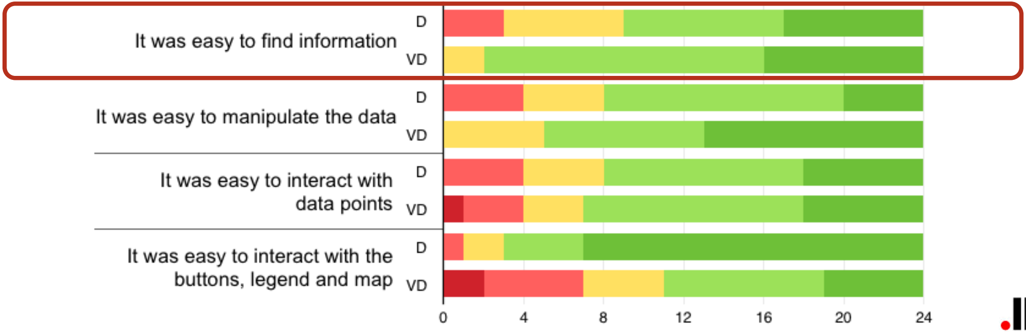
Results: User Feedback – Likert-scale agreements

- 46% more participants agreed that it was easy to **find information** in VirtualDesk



D: Desktop / VD: VirtualDesk

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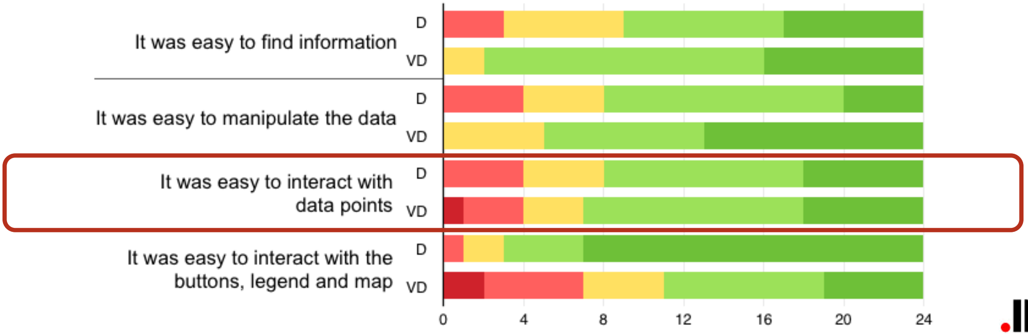

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- Difficulties with the **tabletop interaction** were the main prototype weakness

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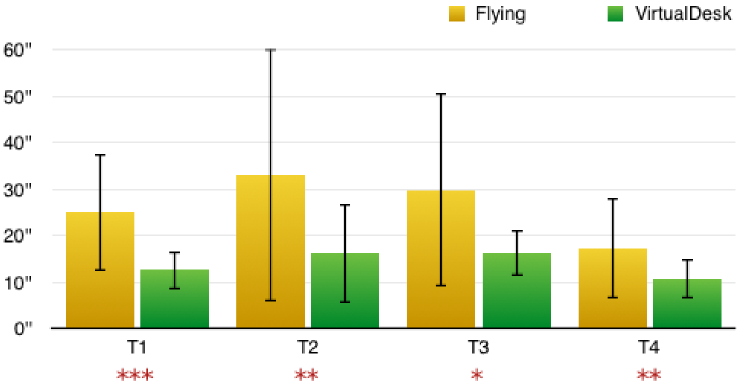
- 12 selected each condition as most accurate
  - Many reported that Desktop was most accurate for selection, but VirtualDesk for manipulation

Comparison with Flying: Time

- As expected, VirtualDesk was more **time-efficient**
  - **All tasks** were executed significantly faster (up to 51%)

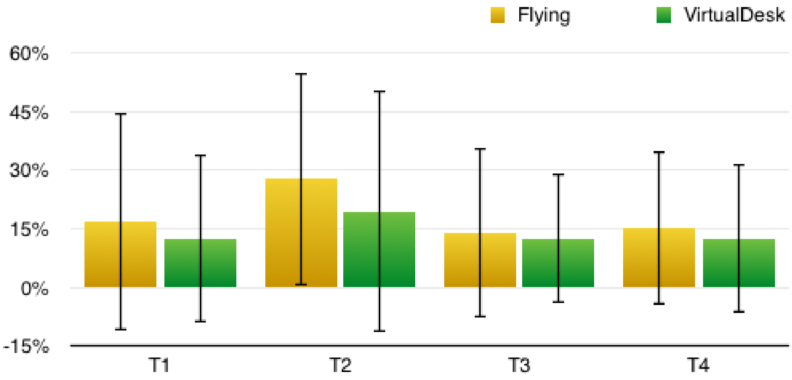


(*) for $p < .05$, (**) for $p < .01$ and (***) for $p < .001$

Considers only the first 24 participants from US1

Comparison with Flying: Error Rates

- VirtualDesk also achieved lower error rates, but without statistical significance



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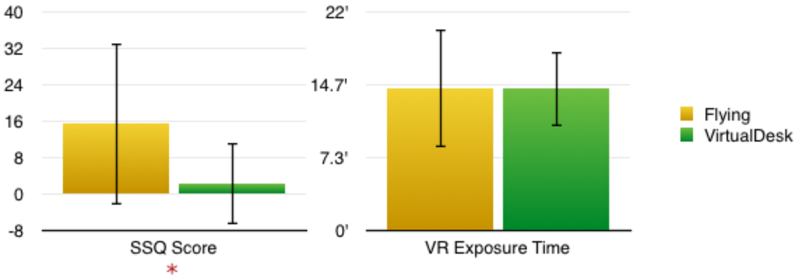
Comparison with Flying: Simulator Sickness

- **7x smaller** SSQ score than the previous Flying approach (**H4**)
  - Despite very similar VR exposure times



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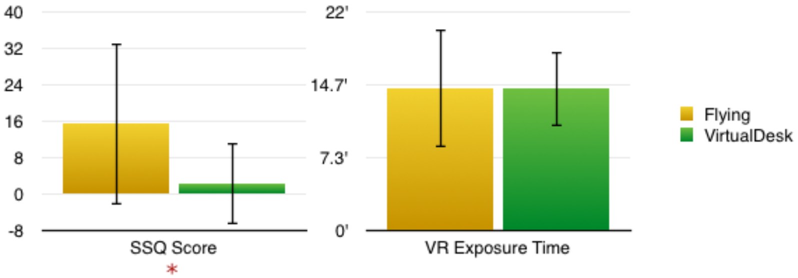
- **No user reported discomfort during or after the tasks**



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  - Highly realistic and precise modelling of the hands and gestures
  - **But:** hand models must be adjusted according to real size
- **Long term evaluations** are still needed
  - Interaction times and errors should decrease w/ more training
  - Comfort could vary for longer exposures

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- In an effort to **extend discussions** about *Immersive Analytics* to new contexts, we presented, in this work, evaluations on a particular representation for **multidimensional data**
- Our main objective was to demonstrate that current off-the-shelf VR technologies may effectively aid in analytical tasks for **abstract information visualization**
- We believe VirtualDesk is one of the first implementations for immersive exploration of abstract information actually convenient for **real world usage**, requiring only minor improvements

Summary of Contributions

1. An improved **modelling** of the problem in hand
2. A task-based evaluation **framework**
3. The identification of a complete set of relevant **tasks**
4. Results from two comparative **user studies**
5. The recommendation of a so-far atypical data **exploration metaphor**
6. **Baseline results** to be used in future work and paths pointed for improvement

Future Work

- Improvement of the VirtualDesk prototype based on participants' feedback
- Further testing under different conditions, including different **datasets** and **representations**
  - Strong candidates: *node-link diagrams* and *space-time cubes*
- Combination with the non-immersive counterpart could be an interesting approach

Evaluating Immersive Approaches to Multidimensional Information Visualization

Jorge Alberto Wagner Filho

Advisor: Prof. Luciana Nedel
Co-advisor: Prof. Carla Freitas

Graduate Program in Computer Science
Federal University of Rio Grande do Sul

March 7, 2018

Publications


Immersive Analytics of Dimensionally-Reduced Data Scatterplots

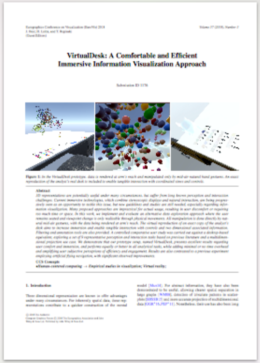
Jorge A. Wagner Filho* Marina F. Rey† Carla M.D.S. Freitas‡ Luciana Nedel§

WIA @ IEEE VIS 2017


Immersive Visualization of Abstract Information: An Evaluation on Dimensionally-Reduced Data Scatterplots

Jorge A. Wagner Filho* Marina F. Rey† Carla M.D.S. Freitas‡ Luciana Nedel§

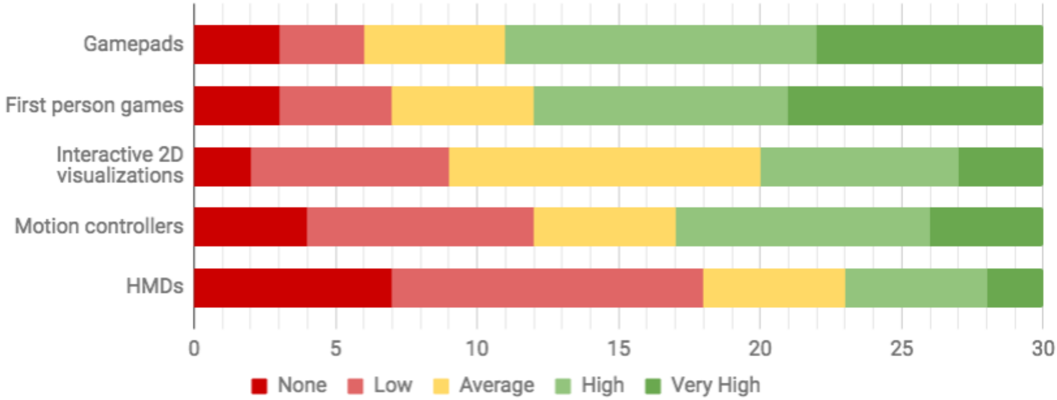
IEEE VR 2018 (to appear)


VirtualDesk: A Comfortable and Efficient Immersive Information Visualization Approach

EuroVis 2018 (accepted for 2nd review round)

User Study 1 - Participants

- 30 subjects (20 male/10 female)
- Mean age 25.2, ranging from 17 to 50



User Study 2 - Participants

- 24 subjects (20 male/4 female)
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