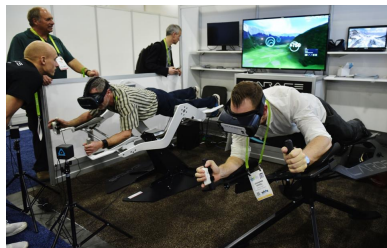


Computational Methods for Natural Walking in Virtual Reality

Dr. Niall L. Williams
niallw.phd@gmail.com
University of Zaragoza
April 23, 2026

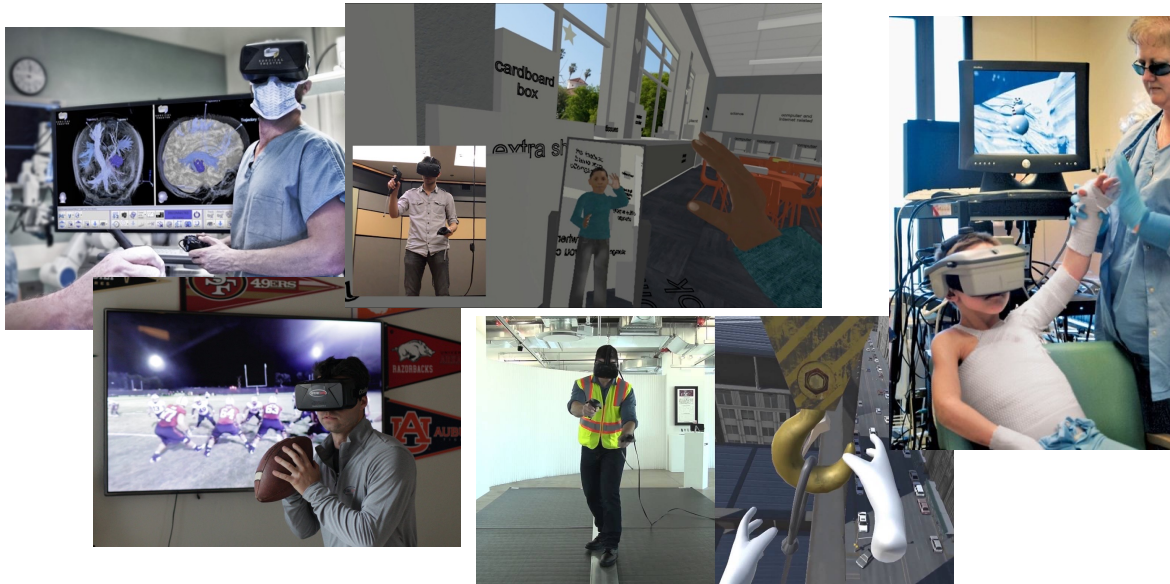
1

Virtual Reality



2

Virtual Reality



3

3

Navigation

- Navigation consists of two components
 - Wayfinding: Refers to cognitive processes of navigation (route planning)
 - Locomotion: Refers to the motor control and mechanics of moving from point A to point B (travel)

4

4

Wayfinding

5

5

Wayfinding

- Depends on wayfinding cues
 - Fewer cues → wayfinding is harder

6

6

Wayfinding

- Depends on wayfinding cues
 - Fewer cues → wayfinding is harder
- Cognitive map: How the brain builds and learns knowledge and relative positions of objects in an environment

7

7

Wayfinding

- Depends on wayfinding cues
 - Fewer cues → wayfinding is harder
- Cognitive map: How the brain builds and learns knowledge and relative positions of objects in an environment
 - Landmark knowledge



8

Wayfinding

- Depends on wayfinding cues
 - Fewer cues → wayfinding is harder
- Cognitive map: How the brain builds and learns knowledge and relative positions of objects in an environment
 - Landmark knowledge
 - Route knowledge

Department of Computer Science
 Brendan Iribe, Center for Computer Science and Engineering 8125, 8125 Paint Branch Dr, College Park, MD 20742

↑ Head west toward Paint Branch Dr
 180 ft

↪ Turn right onto Paint Branch Dr
 0.1 mi

↶ Turn left onto Stadium Dr
 Destination will be on the right
 213 ft

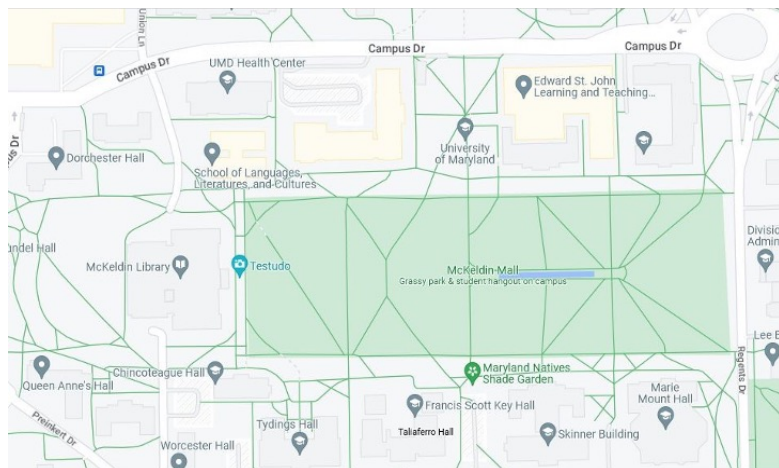
E.A. Fernandez IDEA Factory
 4462 Stadium Dr, College Park, MD 20740

9

9

Wayfinding

- Depends on wayfinding cues
 - Fewer cues → wayfinding is harder
- Cognitive map: How the brain builds and learns knowledge and relative positions of objects in an environment
 - Landmark knowledge
 - Route knowledge
 - Survey knowledge (map!)



10

Wayfinding

- Depends on wayfinding cues
 - Fewer cues → wayfinding is harder
- Cognitive map: How the brain builds and learns knowledge and relative positions of objects in an environment
 - Landmark knowledge
 - Route knowledge
 - Survey knowledge (map!)
- User-centered cues
 - FoV, body, motion cues (path integration)
- Environment-centered cues Landmarks, maps, signs

11

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Locomotion

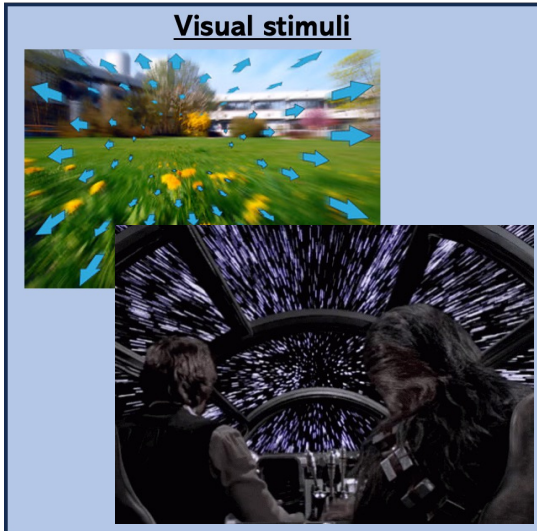
- Motor control and mechanics of travelling to a location
- Tightly coupled with perception

12

12

Locomotion

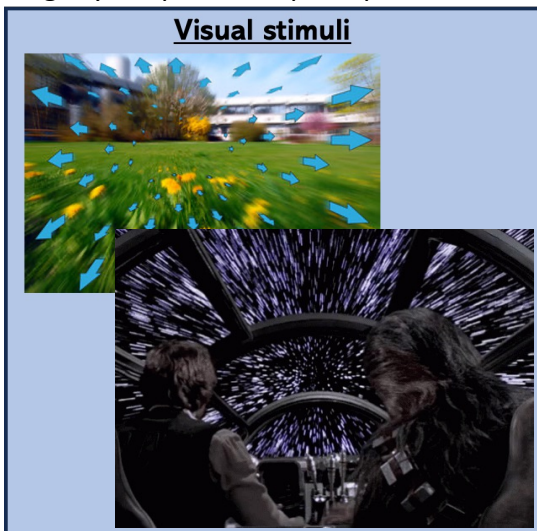
- Motor control and mechanics of travelling to a location
- Tightly coupled with perception



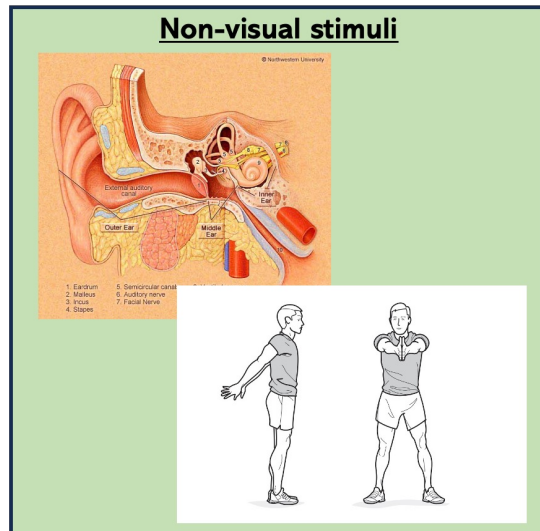
13

Locomotion

- Motor control and mechanics of travelling to a location
- Tightly coupled with perception



+



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Locomotion

- Motor control and mechanics of travelling to a location
- Tightly coupled with perception

15

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Exploration of Virtual Environments

Virtual Environment



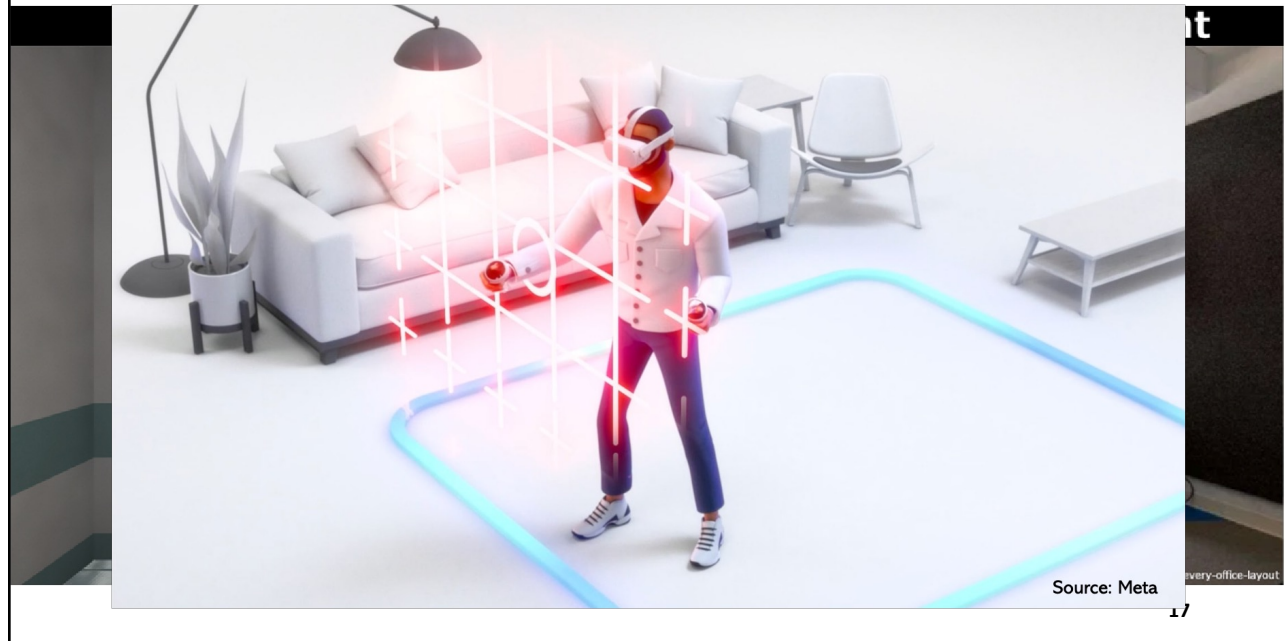
Physical Environment



16

16

Exploration of Virtual Environments



17

VR Locomotion

Bozgeyikli, Evren, et al. "Point & teleport locomotion technique for virtual reality." *Proceedings of the 2016 annual symposium on computer-human interaction in play*



Lee, Juyoung, Sang Chul Ahn, and Jae-In Hwang. "A walking-in-place method for virtual reality using position and orientation..."

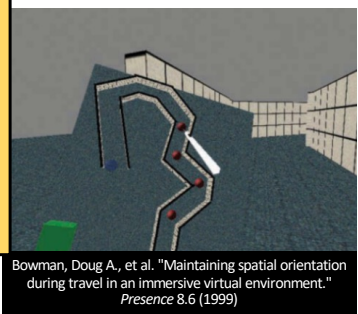
And many, many more...

Ground Level Scaling	Moving Platforms	Gravity Well	Head Bowling	Redirected Portal	Grab and Pull
Indirect wheelchair	Casts	Left Hand Right Hand	Control Theater	Tunneling	TV Screen
Haptic Feedback	Galvanic stimulation	Freedom Locomotion	Natural Locomotion	Astral Body	Charge Float Jump
Sliding Joystick	Sliding Pointing	Finger Run	Hand Close	LazyNav	Climbing

Di Luca, Massimiliano, et al. "Locomotion vault: the extra mile in analyzing vr locomotion techniques." *Proceedings of the 2021 CHI conference on human factors in computing systems*. 2021.

Von Kapri, Anette, Tobias Rick, and Steven Feiner. "Comparing steering-based travel techniques for search tasks in a cave." *2011 IEEE Virtual Reality Conference*. IEEE, 2011.

Kulkarni, Sandip D., et al. "Combined wind speed and angle control in a virtual environment using a static observer." *IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2008.



Bowman, Doug A., et al. "Maintaining spatial orientation during travel in an immersive virtual environment." *Presence* 8,6 (1999)

18

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Natural Walking in VR

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Natural Walking Interfaces

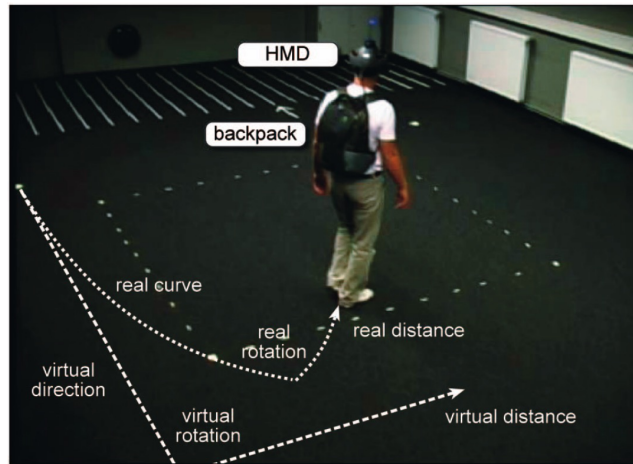
- Redirected walking (RDW) is a natural walking interface for VR locomotion.

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Natural Walking Interfaces

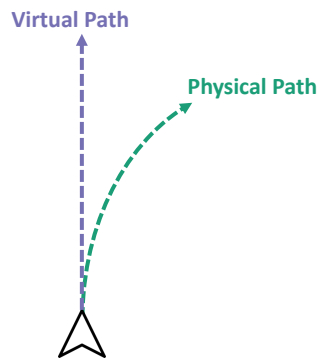
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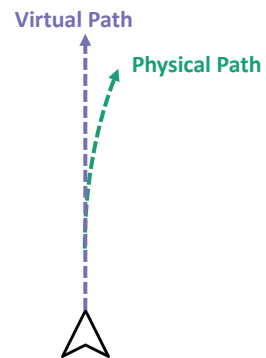
Steinicke, Frank, et al. "Estimation of detection thresholds for redirected walking techniques." *IEEE transactions on visualization and computer graphics* 16.1 (2009)

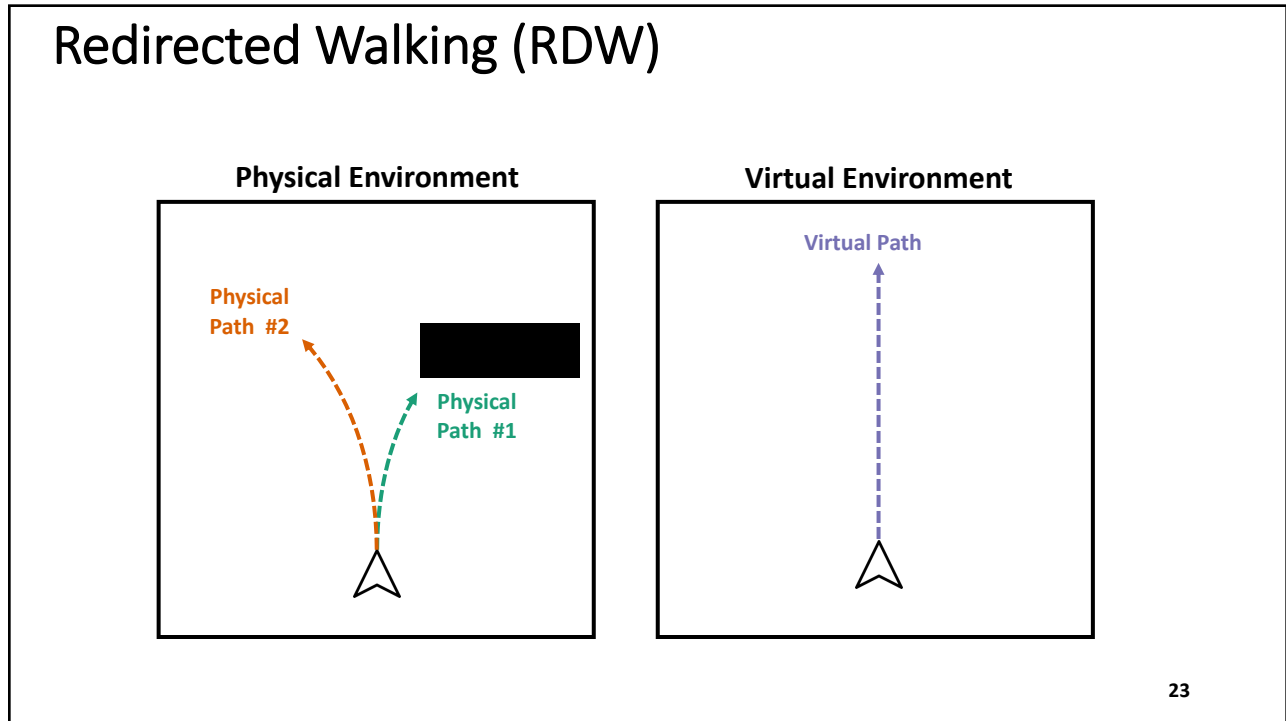
Redirected Walking (RDW)

Strong redirection gains

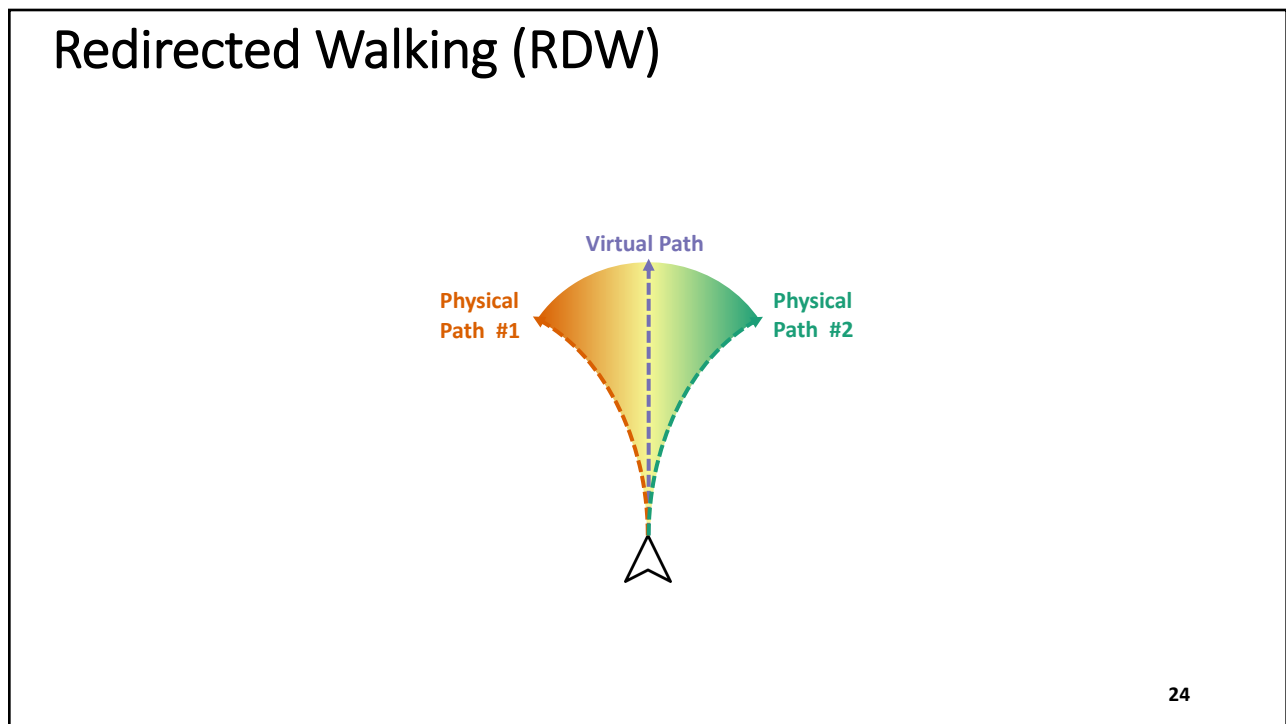


Weak redirection gains





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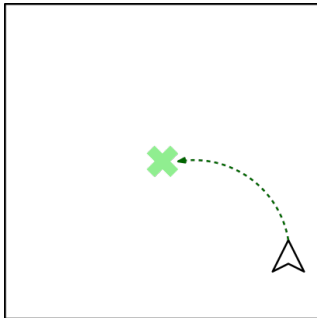


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Redirection Controllers

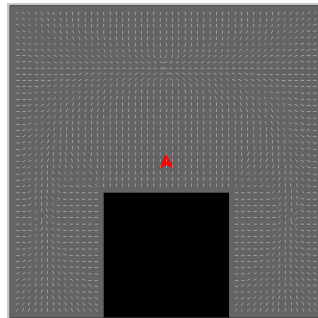
- Redirection controller applies redirected walking to avoid physical obstacles.

Steer-to-Center



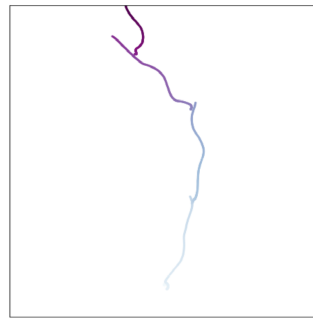
Razzaque, Sharif, Zachariah Kohn, and Mary C. Whitton. *Redirected walking*. Chapel Hill: University of North Carolina at Chapel Hill, 2005.

Artificial Potential Fields



Thomas, Jerald, and Evan Suma Rosenberg. "A general reactive algorithm for redirected walking using artificial potential functions." *2019 IEEE VR*

Reinforcement Learning



Strauss, Ryan R., et al. "A steering algorithm for redirected walking using reinforcement learning." *IEEE transactions on visualization and computer graphics* 2020

and many more...

25

25

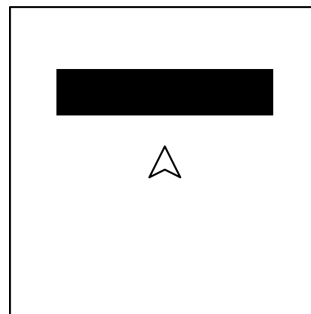
RDW Algorithm Design Assumptions

- One user, physical and virtual environments.
- Can apply rotation, translation, or curvature gains.
- Only have information available at time of computation.
 - No prediction.

Prior work:

- Assume the virtual environment is empty and infinite.

Physical Environment

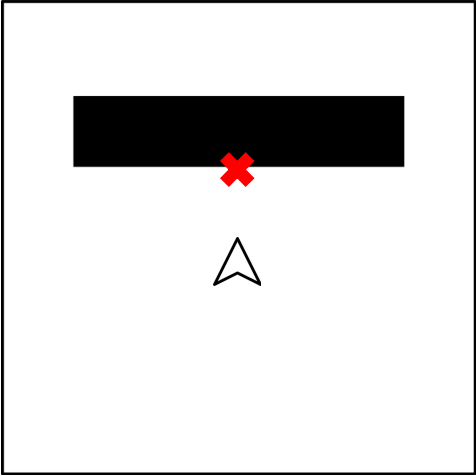
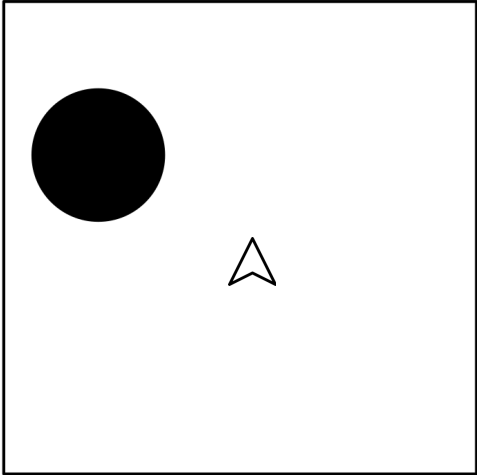


Virtual Environment



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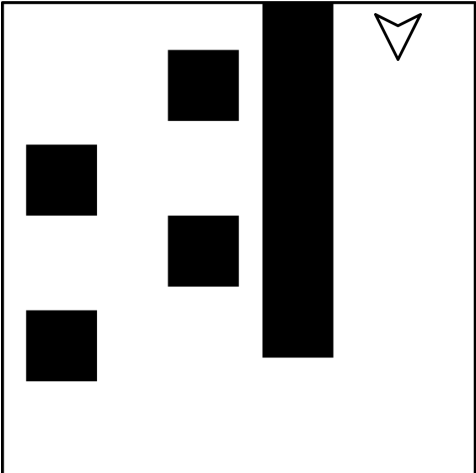
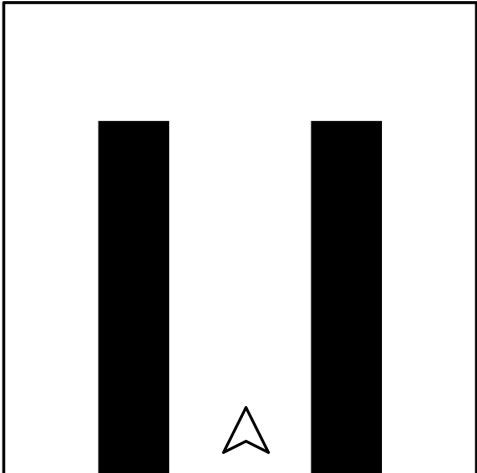
VR Locomotion: Key Observation

Physical Environment	Virtual Environment
	

28

28

VR Locomotion: Key Observation

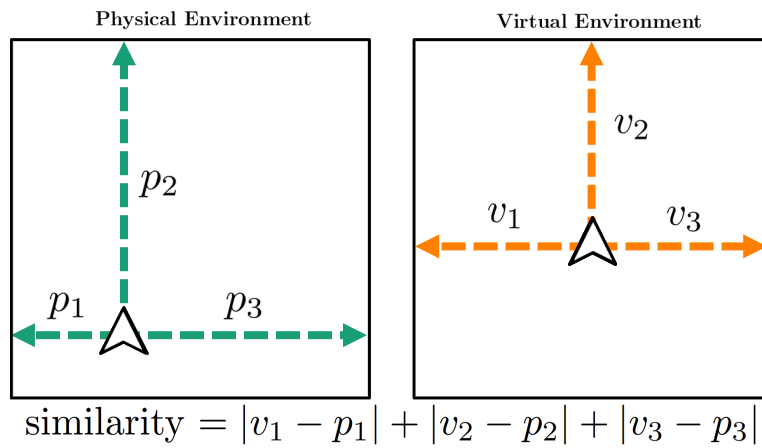
Physical Environment	Virtual Environment
	

29

29

Alignment-Based Redirection Controller (ARC)

- Compare the layout of the physical and virtual environments.
- Steer the user towards locally similar positions.

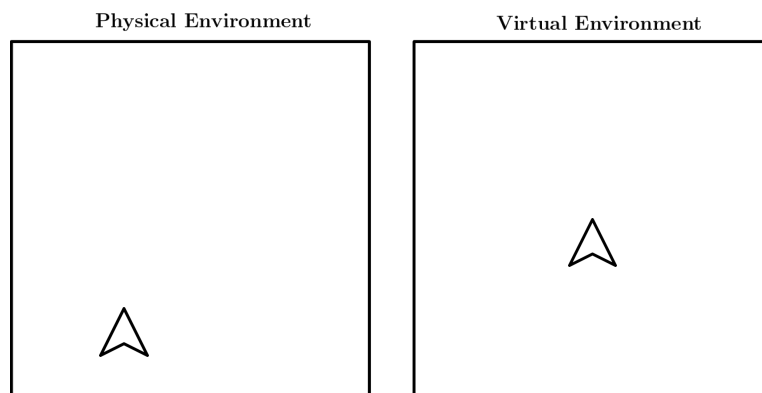


[1] Thomas, Jerald, Courtney Hutton Pospick, and Evan Suma Rosenberg. "Towards physically interactive virtual environments: Reactive alignment with redirected walking." *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*. 2020. **30**

30

Alignment-Based Redirection Controller (ARC)

- Compare the layout of the physical and virtual environments.
- Steer the user towards locally similar positions.

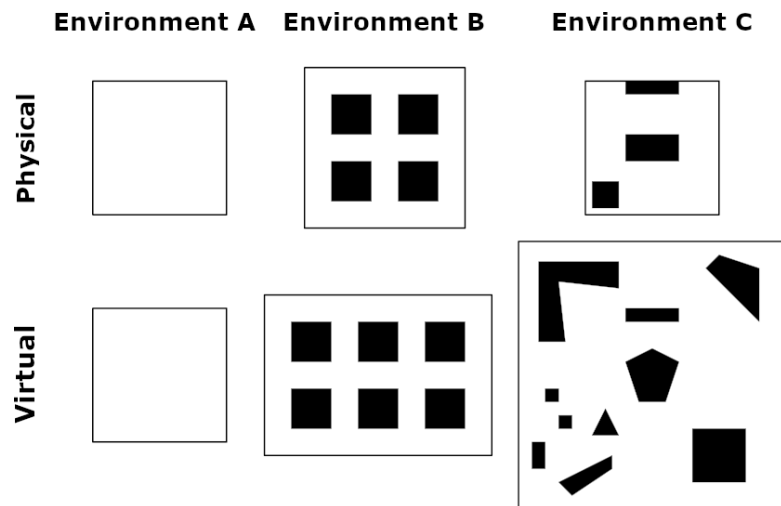


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Experiments

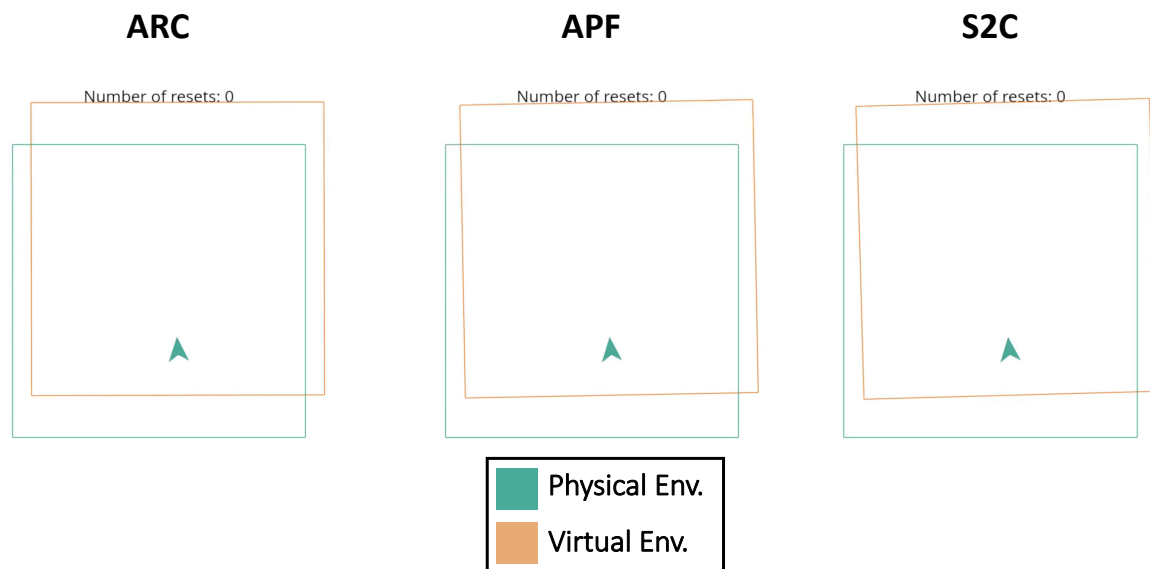
- Evaluated in 3 pairs of environments.
- Compared against steer-to-center (S2C) and potential fields (APF).



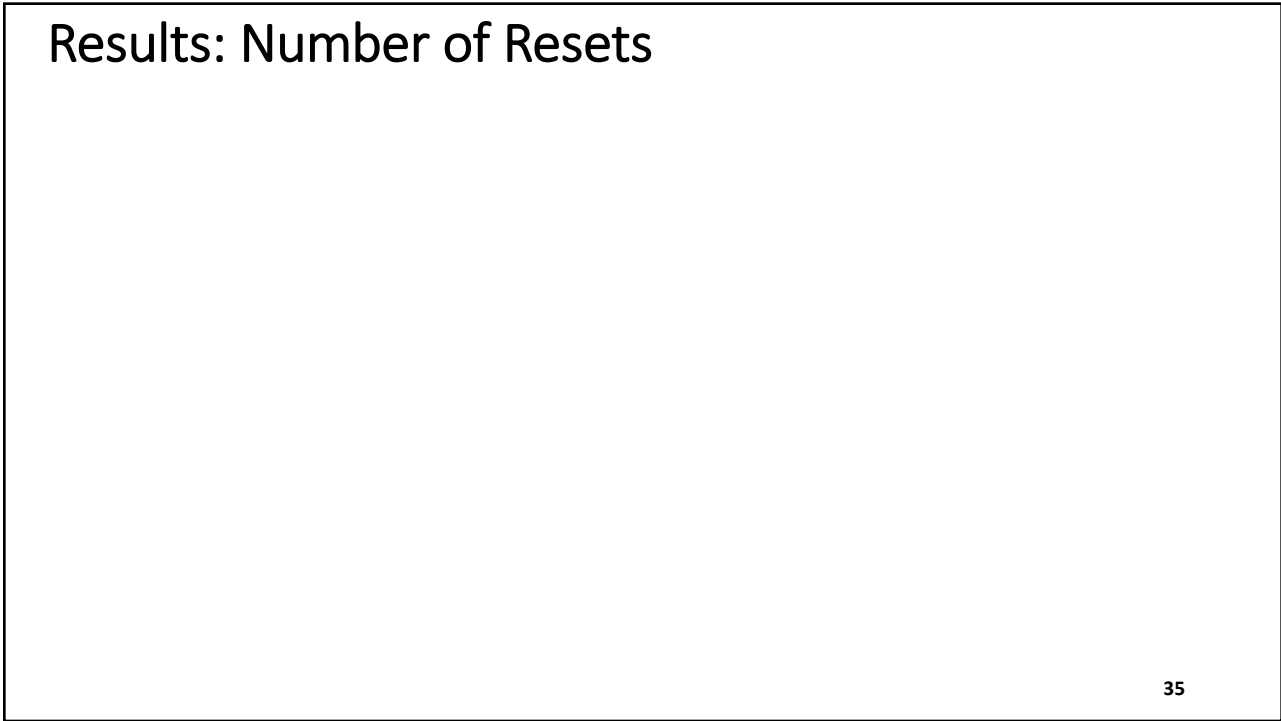
32

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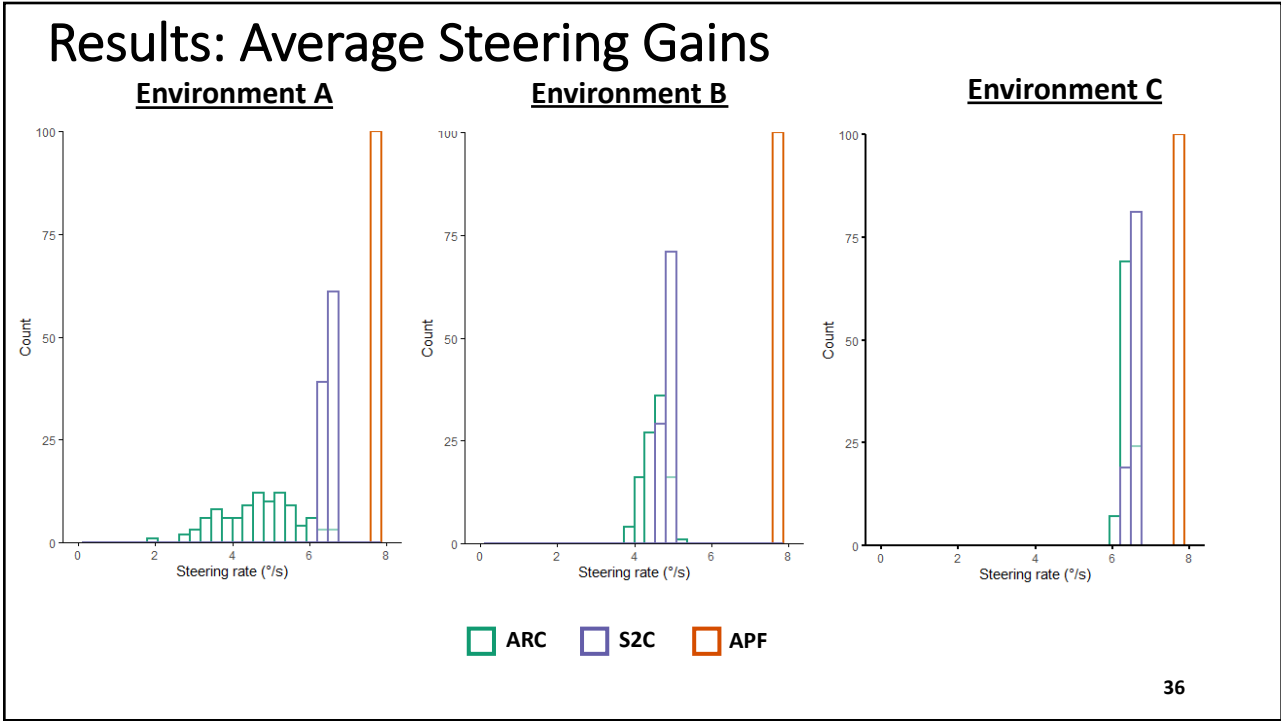
Results: Path Visualization



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Limitations

- Only compute alignment based on distance to objects in 3 directions.
- RDW gains only grant mild steering power.
 - Bigger environments yield bigger benefits.
- No live user study.

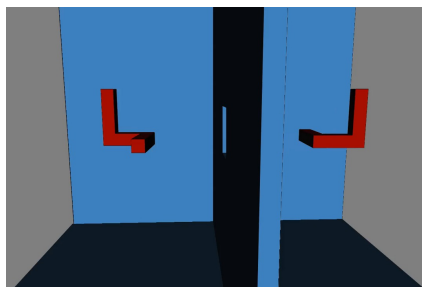
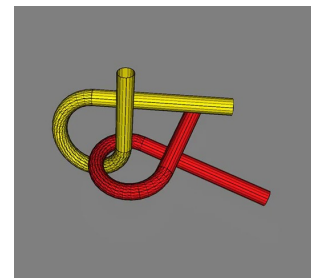
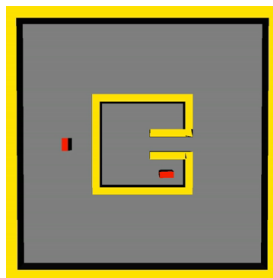
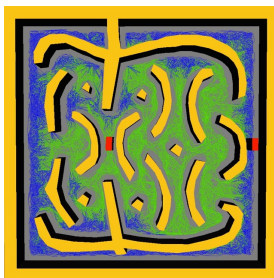
Conclusion & Takeaways

- Environments can be globally dissimilar **and** have local similarity.
- Local similarity can be useful for collision-avoidance in VR.

37

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Motion Planning



Open Motion Planning Library: ompl.kavrakilab.org

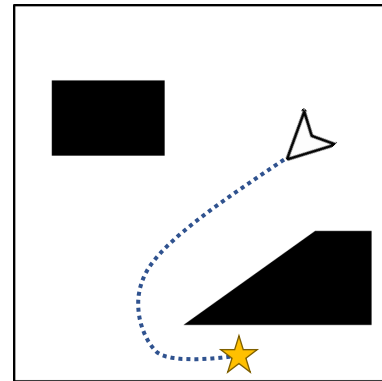
39

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Motion Planning

- Configuration describes the agent's state in an environment.
- C_{obs} = configurations that yield a collision
- C_{free} = configurations that don't yield a collision

Environment

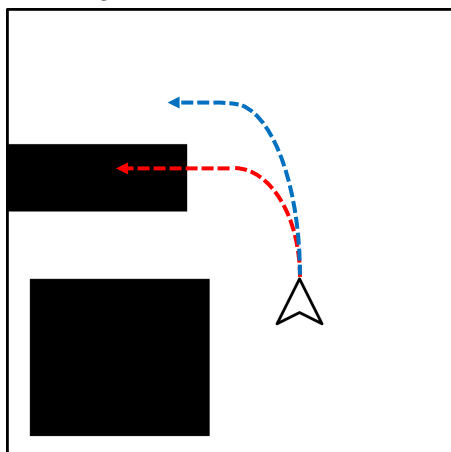


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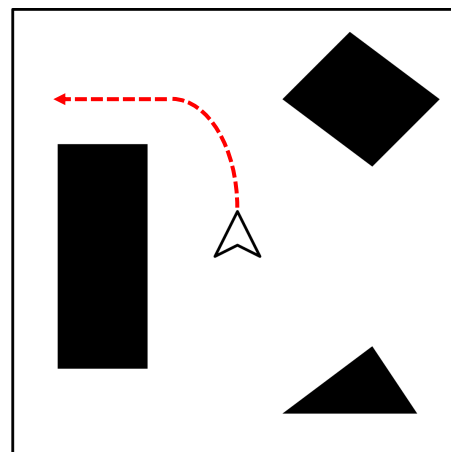
40

Motion Planning for RDW

Physical Environment



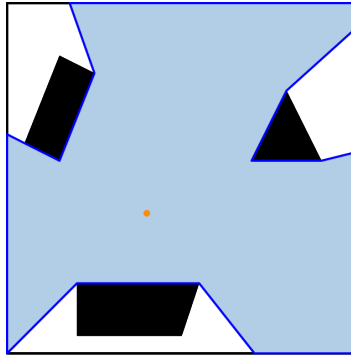
Virtual Environment



41

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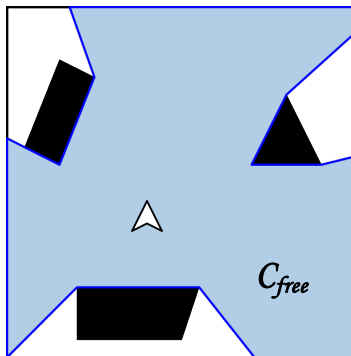
RDW Using Visibility Polygons



42

42

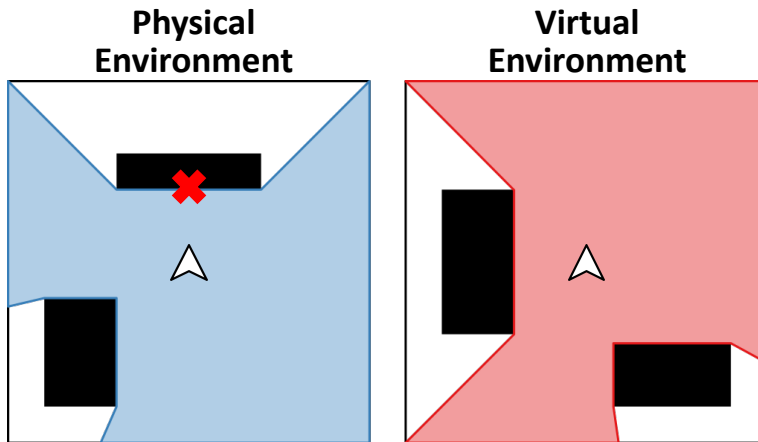
RDW Using Visibility Polygons



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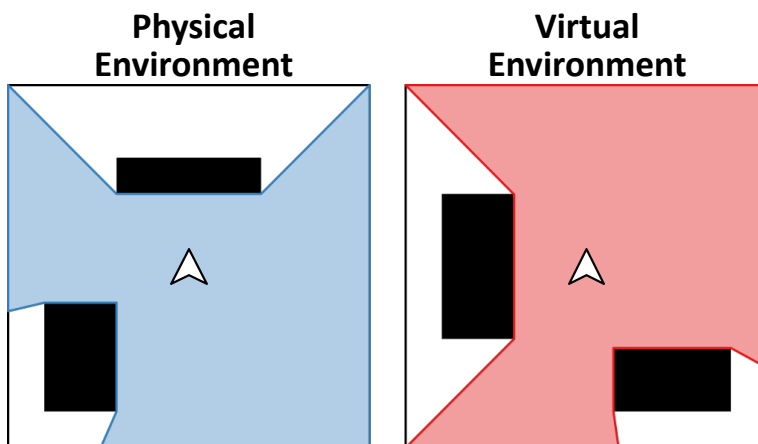
RDW Using Visibility Polygons



44

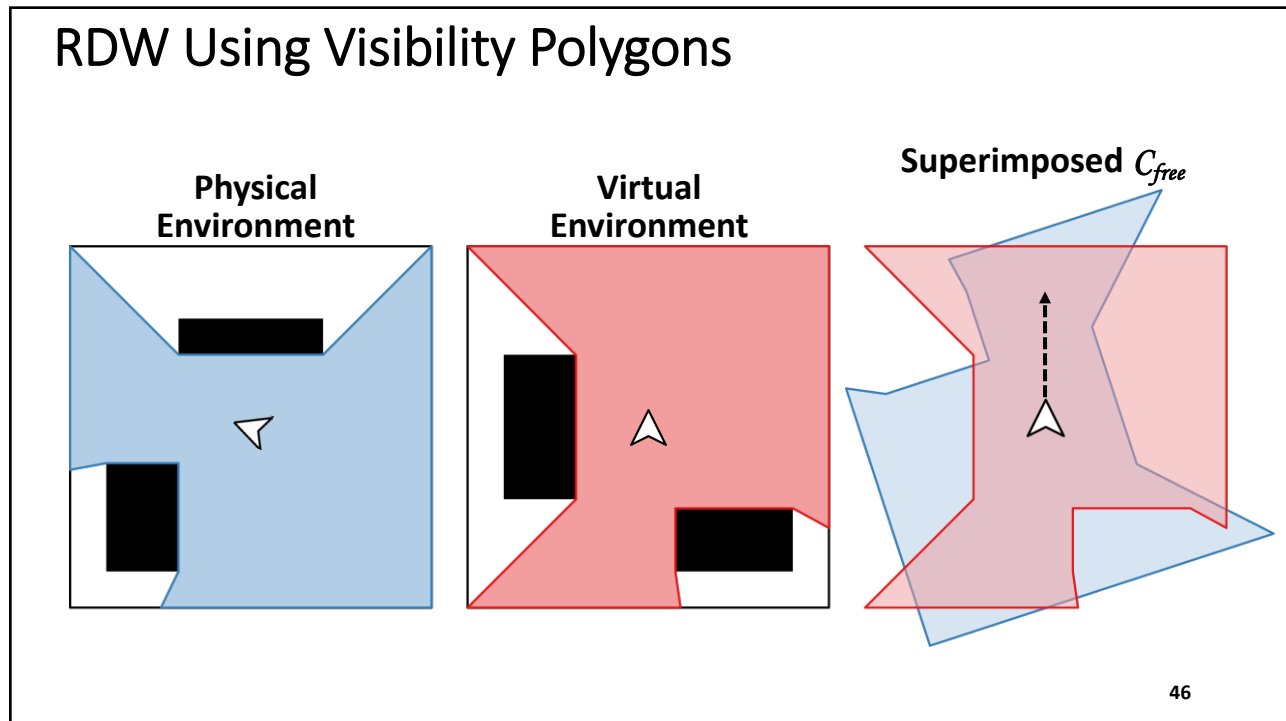
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RDW Using Visibility Polygons

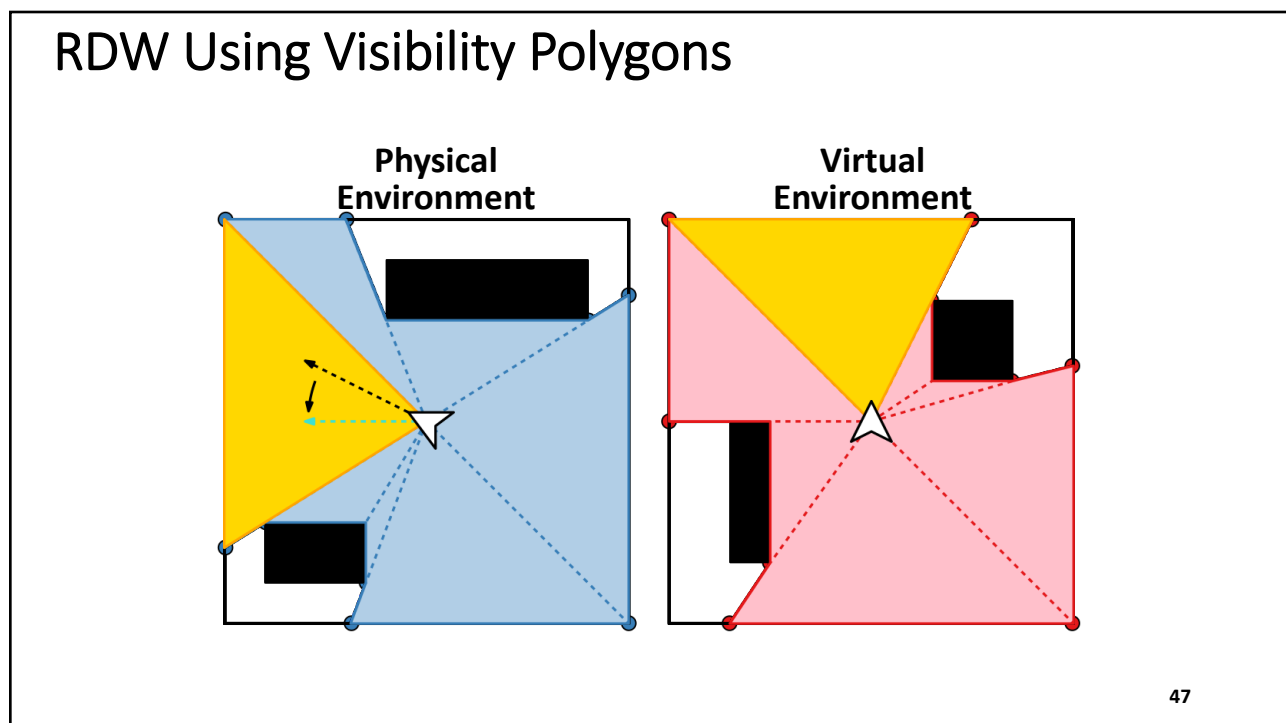


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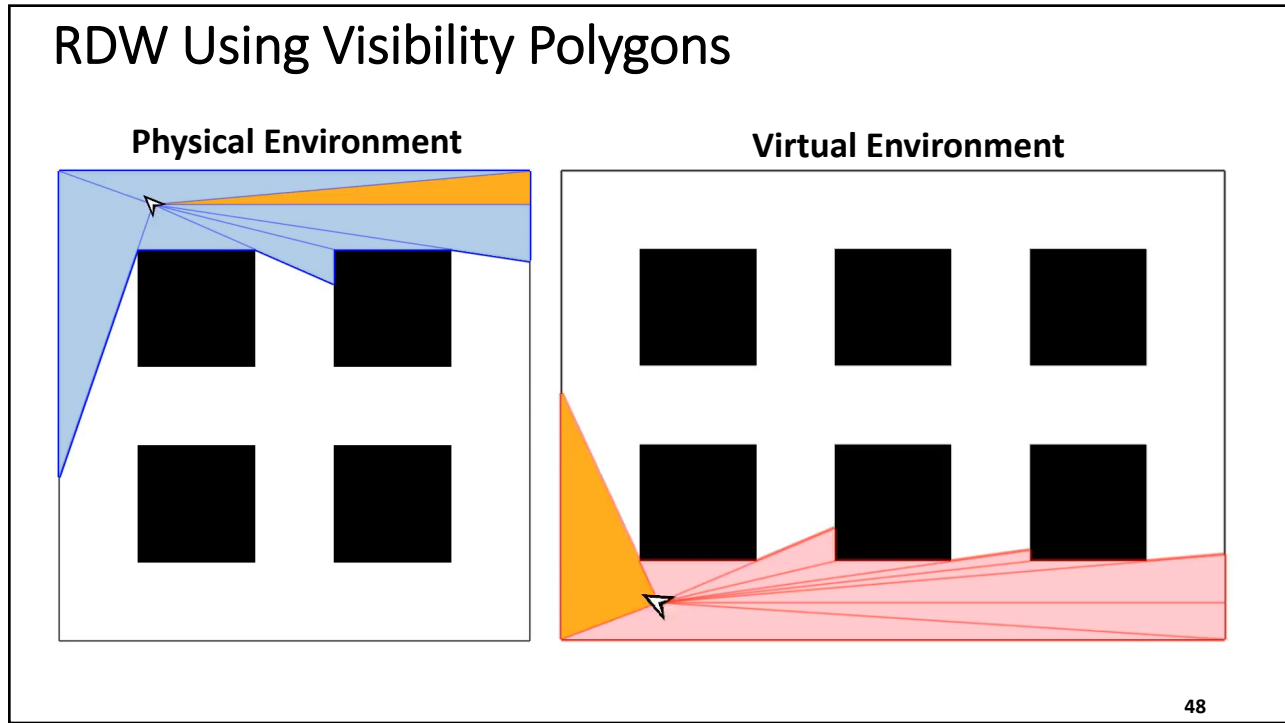
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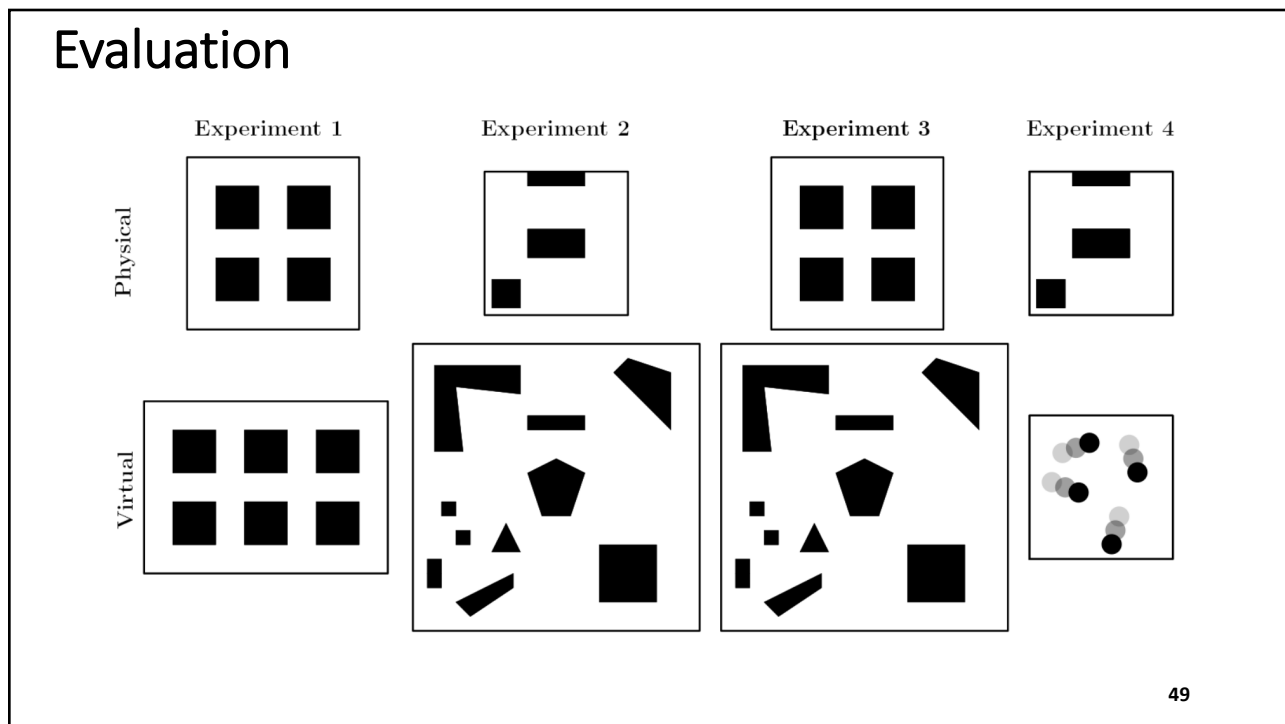
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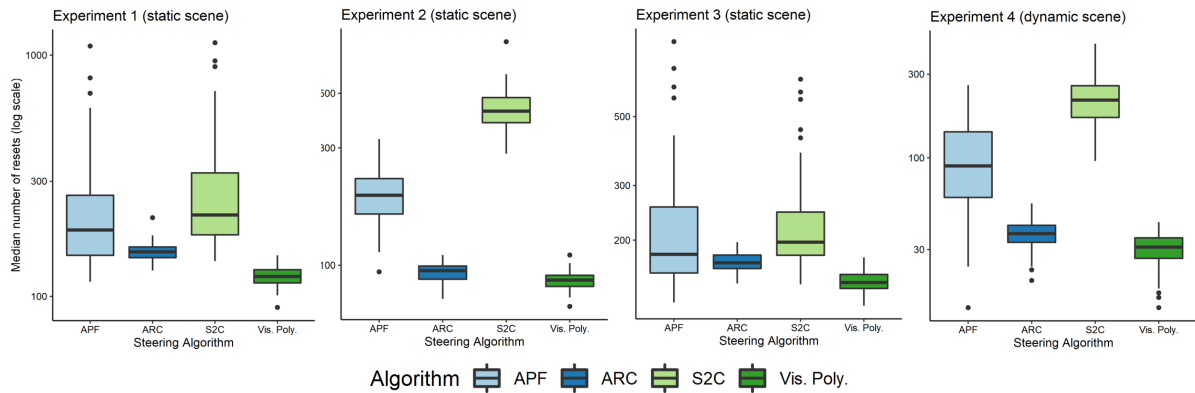


48



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Results: Number of Resets



50

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Limitations

- Area is a crude metric for “slice similarity”
- RDW gains only grant mild steering power.
 - Bigger environments yield bigger benefits.
- Single-user VR
- No live user study.

Conclusion & Takeaways

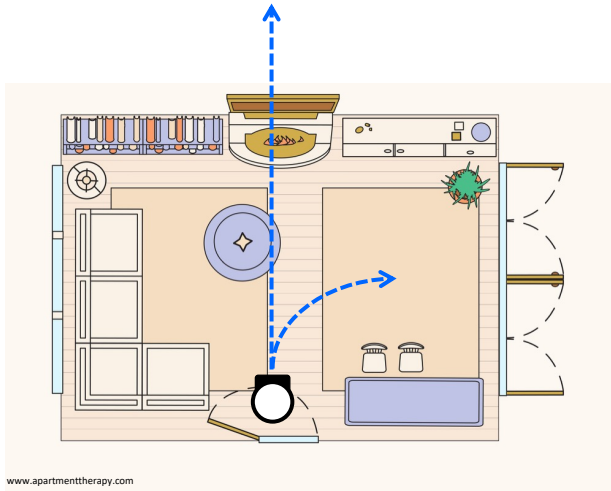
- RDW has many similarities to motion planning!
 - Lots of prior work in robot motion planning to leverage.
- Visibility polygons are well-suited for VR locomotion.

51

51

VR Locomotion

- How much natural locomotion is possible?
- Difficult to know without user studies.



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Environment Navigability

- Average distance walked before colliding with an obstacle in the physical space.

High navigability

Low navigability

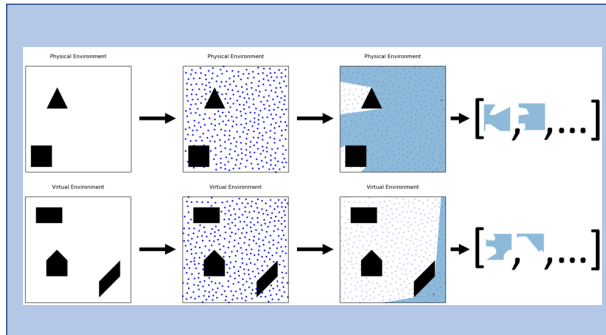


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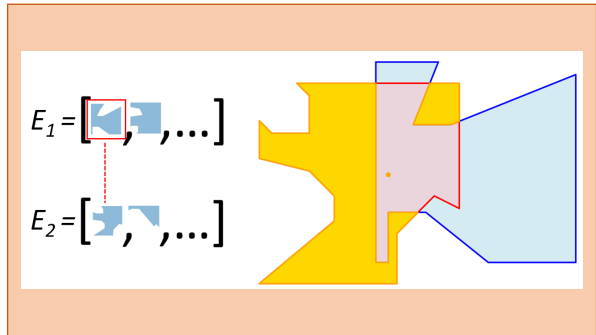
54

Algorithm Overview

Step 1: Quantify Salient Features



Step 2: Compare Salient Features



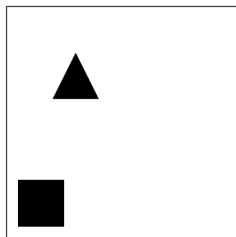
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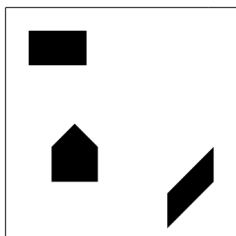
Step 1: Quantify Salient Features

Input geometry

Physical Environment



Virtual Environment



56

Step 2: Compare Salient Features

$$E_1 = [\text{feature 1}, \text{feature 2}, \dots]$$

$$E_2 = [\text{feature 1}, \text{feature 2}, \dots]$$

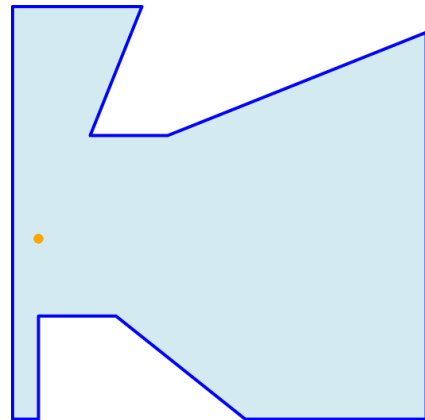
57

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Step 2: Compare Salient Features

$$E_1 = [\text{feature 1}, \text{feature 2}, \dots]$$

$$E_2 = [\text{feature 1}, \text{feature 2}, \dots]$$



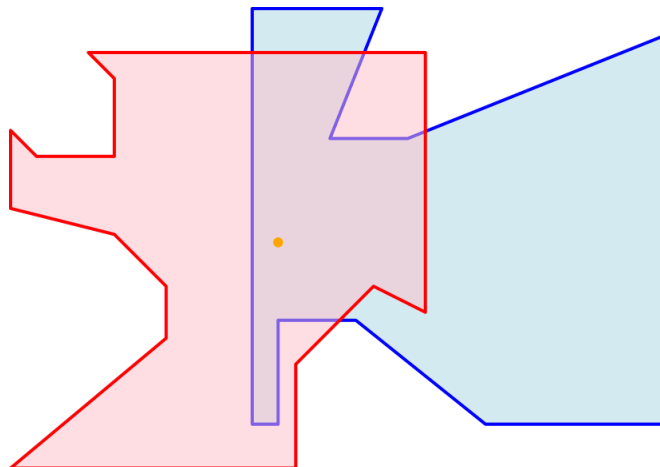
58

58

Step 2: Compare Salient Features

$$E_1 = [\text{left arrow}, \text{right arrow}, \dots]$$

$$E_2 = [\text{right arrow}, \text{down arrow}, \dots]$$



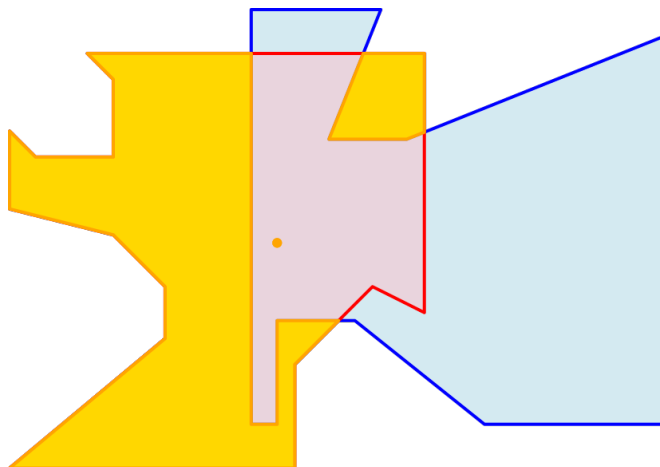
59

59

Step 2: Compare Salient Features

$$E_1 = [\text{left arrow}, \text{right arrow}, \dots]$$

$$E_2 = [\text{right arrow}, \text{down arrow}, \dots]$$



60

60

Step 2: Compare Salient Features

$$E_1 = [\text{◀}, \text{▶}, \dots]$$

$$E_2 = [\text{▶}, \text{◀}, \dots]$$



61

61

Step 2: Compare Salient Features

$$E_1 = [\text{◀}, \text{▶}, \dots]$$

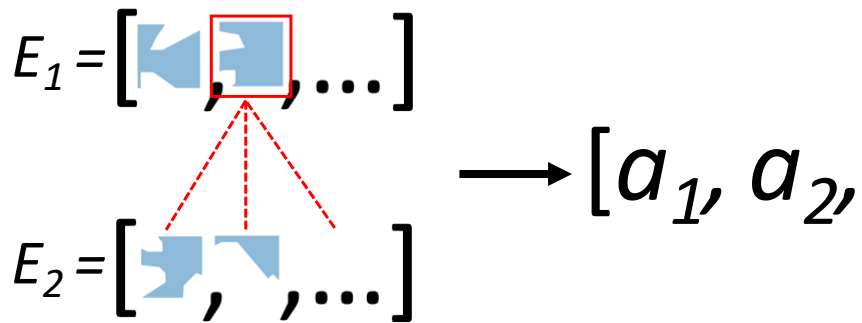
$$E_2 = [\text{▶}, \text{◀}, \dots]$$

 $\rightarrow [a_1,$

62

62

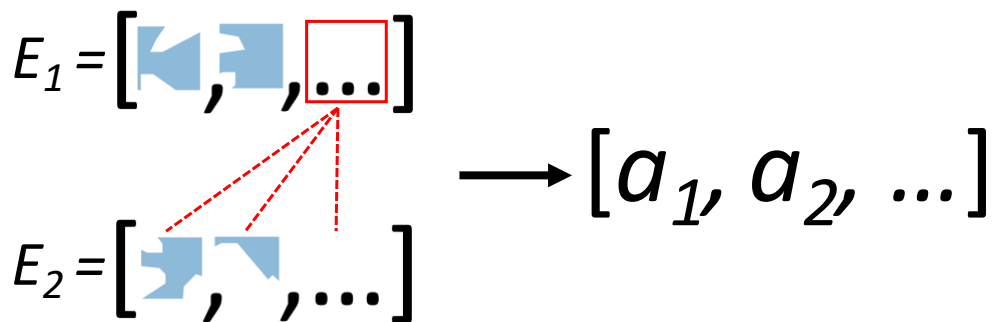
Step 2: Compare Salient Features



63

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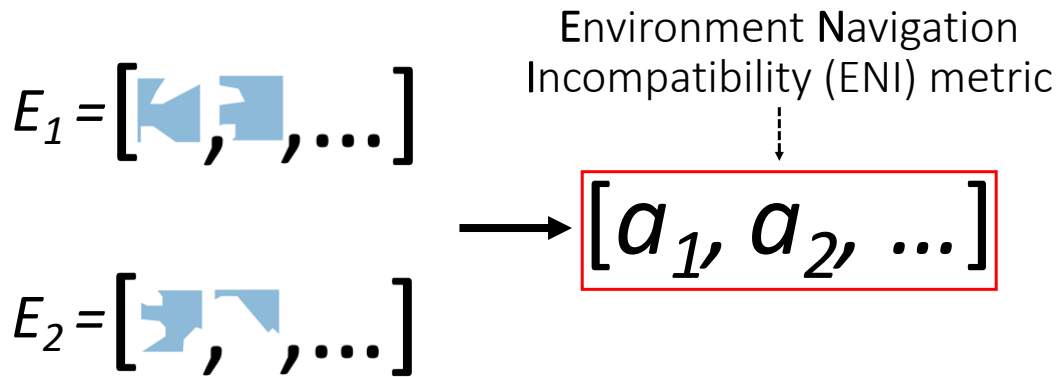
Step 2: Compare Salient Features



64

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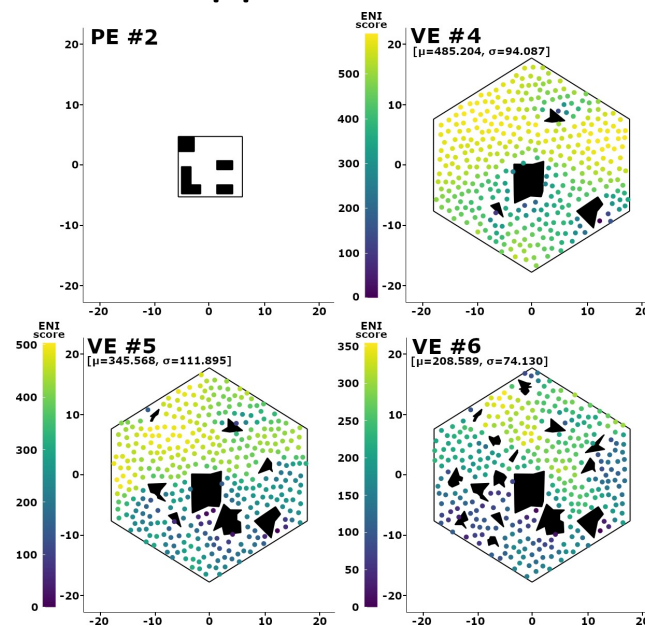
Step 2: Compare Salient Features



65

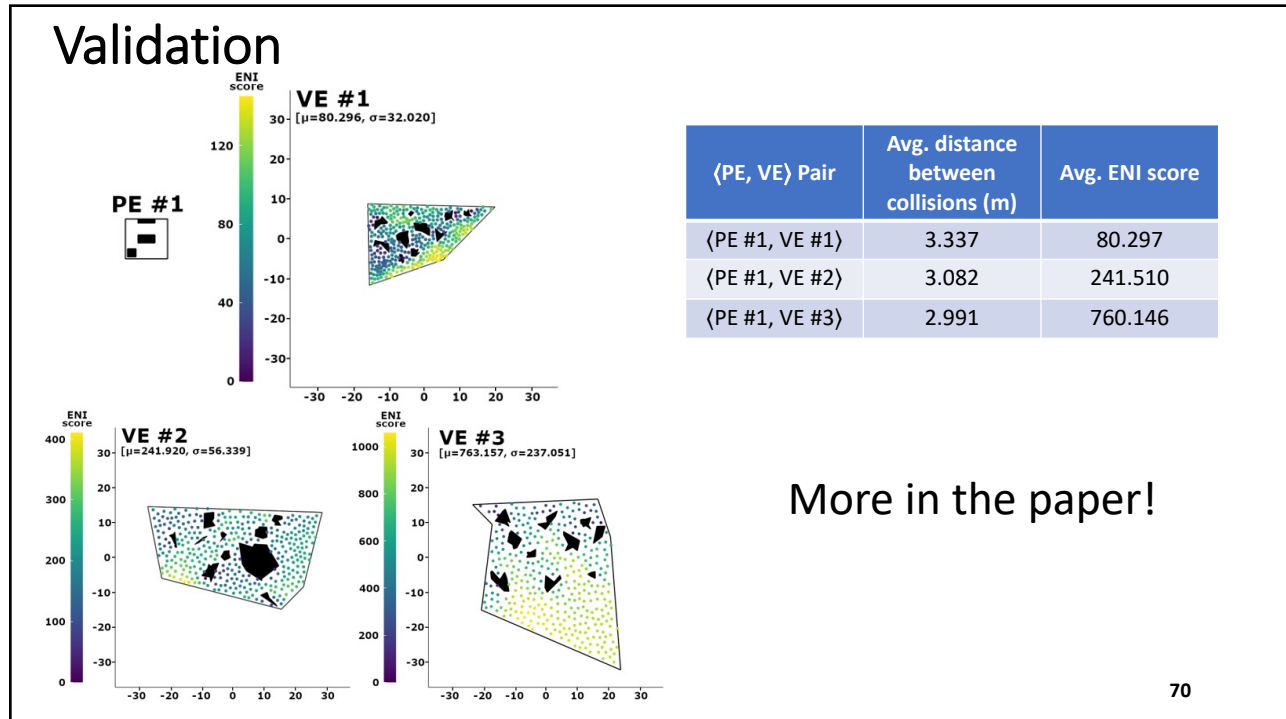
65

Interpretation and Applications



66

66



70

Limitations

- Computation can be slow.
- “Best-case mapping” between physical and virtual environments.
- Only considers the layouts of environments.
- More data!

Conclusion & Takeaways

- Comparing the similarity of physical/virtual environments is useful.
- Accurate estimates of similarity can help in the design of virtual environments.

72

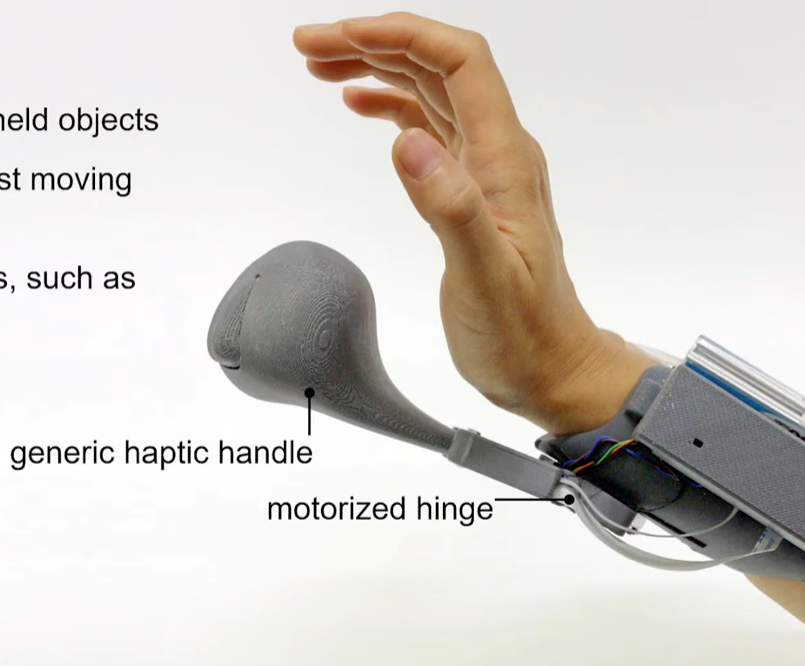
72



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PIVOT's (3) key features:

- (1) rendering grasp to handheld objects
- (2) catching and throwing fast moving objects
- (3) rendering dynamic forces, such as inertia or springiness



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Active haptic guidance

Render haptic forces to influence the user's behavior in mixed reality.

76

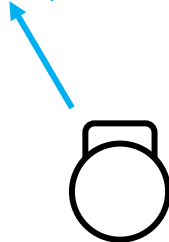
Active haptic guidance

Render haptic forces to influence the user's behavior in mixed reality.

Constraint #1: Influential haptics

Haptic forces should be compelling enough to reliably influence the user's behaviors.


Haptic force



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Active haptic guidance
Render haptic forces to influence the user's behavior in mixed reality.

Constraint #1: Influential haptics
Haptic forces should be compelling enough to reliably influence the user's behaviors.



A simple line drawing of a haptic device, possibly a ring or a small handheld controller, with a blue arrow pointing upwards and to the left from its top edge. The arrow is labeled 'Haptic force' in blue text above it.

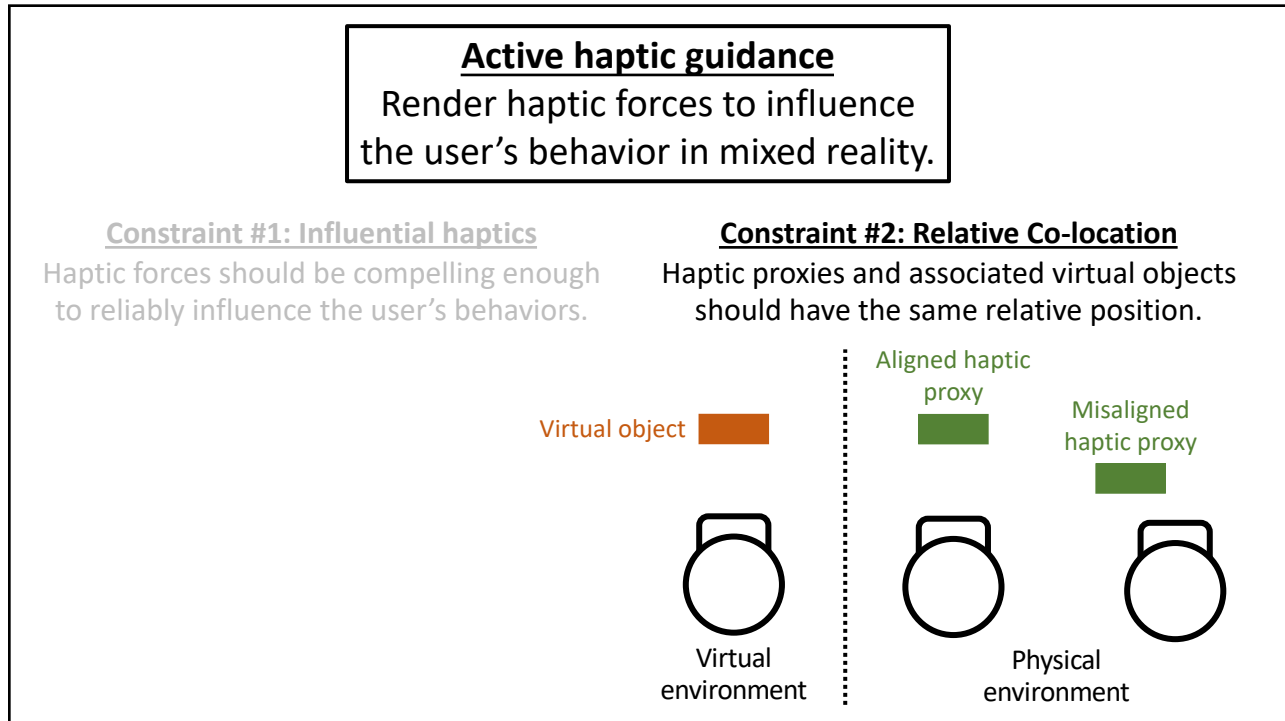
78

Active haptic guidance
Render haptic forces to influence the user's behavior in mixed reality.

Constraint #1: Influential haptics
Haptic forces should be compelling enough to reliably influence the user's behaviors.

Constraint #2: Relative Co-location
Haptic proxies and associated virtual objects should have the same relative position.

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<u>User Study Results</u>	
Haptics	
With	
Without	

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Limitations

- Only tested one bespoke application (walking a dog).
- Users can still choose to ignore the haptic forces.

Conclusion & Takeaways

- Locomotion is multisensory!
- Haptics can be used proactively to avoid collisions in VR.

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Sensitivity to RDW

- Sensitivity to redirection changes depending on user and system factors.
- Measuring sensitivity to RDW is expensive and time-consuming.

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Sensitivity to RDW

Questions:

1. How does sensitivity change depending on display luminance?
2. Can we use physiological signals to estimate sensitivity to RDW?

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Prior Work on Motion Perception + Luminance

- Prior work in vision science has shown that motion perception thresholds change depending on stimulus luminance [1, 2, 3, 4]
 - Participants were seated during those experiments!

1. Sara, Giovagnoli, et al. "The effect of luminance condition on form, form-from-motion and motion perception." *pathways* 8 (2017): 11.
2. Takeuchi, Tatsuto, and Karen K. De Valois. "Velocity discrimination in scotopic vision." *Vision research* 40.15 (2000): 2011-2024.
3. Hisakata, Rumi, and Ikuya Murakami. "The effects of eccentricity and retinal illuminance on the illusory motion seen in a stationary luminance gradient." *Vision Research* 48.19 (2008): 1940-1948.
4. Yoshimoto, Sanae, Katsunori Okajima, and Tatsuto Takeuchi. "Motion perception under mesopic vision." *Journal of Vision* 16.1 (2016): 16-16.

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Prior Work on Sensitivity to RDW

- A lot of existing work on measuring detection
 - Thresholds depend on field of view [1], cognitive load [1, 3], locomotion direction [4, 5], optical flow [2], gender [1, 3], and more...
- Correlations between simulator sickness and physiological signals
 - Postural stability [8], gaze stability [7], skin conductance [6]

1. Williams, Niall L., and Tabitha C. Peck. "Estimation of rotation gain thresholds considering fov, gender, and distractors." *IEEE transactions on visualization and computer graphics* 25.11 (2019): 3158-3168.
2. Lee, Jieun, et al. "Effect of optical flow and user VR familiarity on curvature gain thresholds for redirected walking." *Virtual Reality* 28.1 (2024): 35.
3. Nguyen, Anh, et al. "Effect of cognitive load on curvature redirected walking thresholds." *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*. 2020.
4. Steinicke, Frank, et al. "Estimation of detection thresholds for redirected walking techniques." *IEEE transactions on visualization and computer graphics* 16.1 (2009): 17-27.
5. You, Christopher, et al. "Strafing gain: Redirecting users one diagonal step at a time." *2022 IEEE international symposium on mixed and augmented reality (ISMAR)*. IEEE, 2022.
6. Islam, Rifatul, et al. "Automatic detection and prediction of cybersickness severity using deep neural networks from user's physiological signals." *2020 IEEE international symposium on mixed and augmented reality (ISMAR)*. IEEE, 2020.
7. Hemmerich, Wanja, Behrang Keshavarz, and Heiko Hecht. "Visually induced motion sickness on the horizon." *Frontiers in Virtual Reality* 1 (2020): 582095.
8. Chardonnet, Jean-Rémy, Mohammad Ali Mirzaei, and Frédéric Mérienne. "Features of the postural sway signal as indicators to estimate and predict visually induced motion sickness in virtual reality." *International Journal of Human-Computer Interaction* 33.10 (2017): 771-785.

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Experiment Design

- Participants completed an experiment to measure rotation gain sensitivity in different luminance levels.
 - We looked for correlations with physiological data.

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Experiment Design

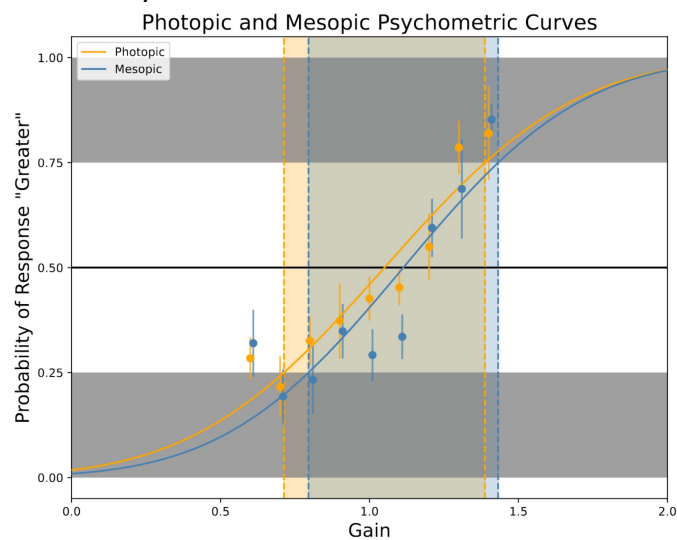
- Participants completed an experiment to measure rotation gain sensitivity in different luminance levels.
- 2 luminance conditions:
 - High (photopic) light level
 - Low (mesopic) light level
- 2 physiological signals collected:
 - Gaze data
 - Posture data (HMD position + orientation)
- 8 participants (4 male, 4 female)

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Results: Luminance

- No effect of luminance.
- Possibly due to multisensory nature of the task.

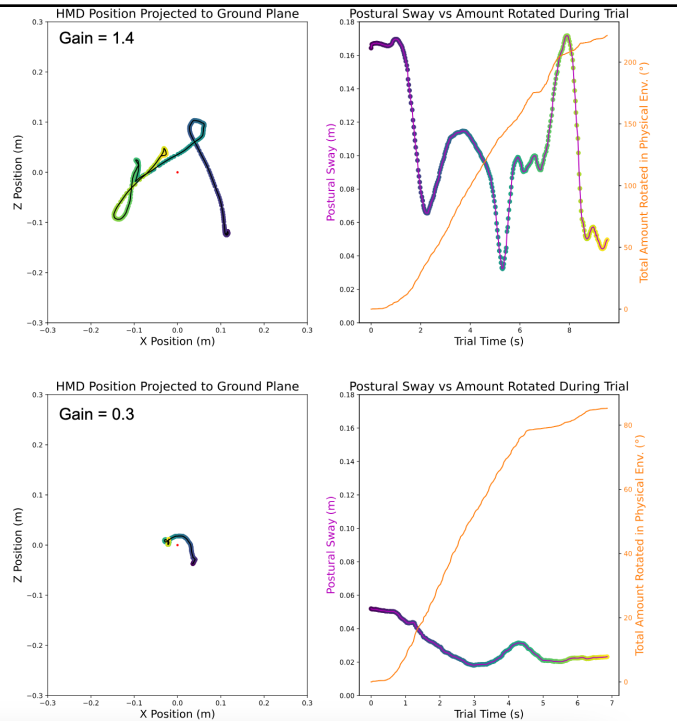


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Results: Posture Data

- Positive correlation between gain and postural instability
 - Higher gain → More postural instability
- Gain increase of 1 → Additional 6.08cm of postural sway (average)



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Results: Gaze Data

- Positive correlation between gain and saccade frequency

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Limitations

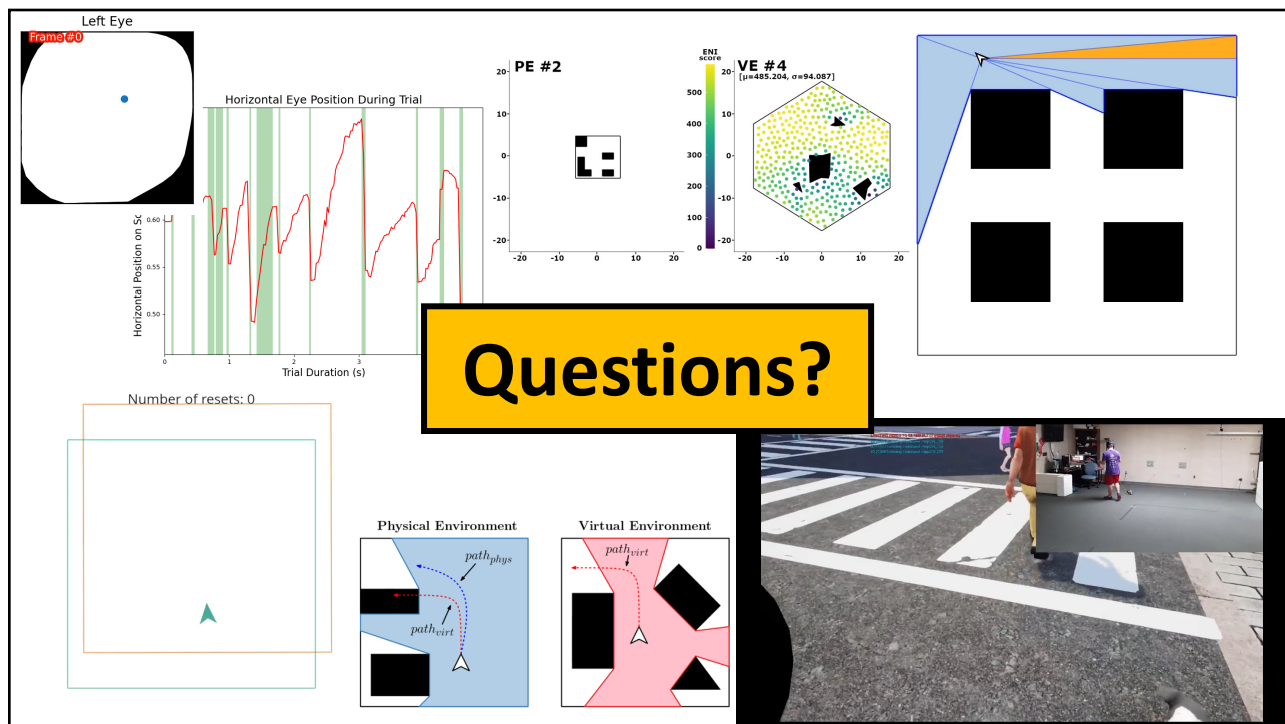
- Only tested rotation gains. Other redirection gains may yield different results.
- Hard to decouple effects of redirection and simulator sickness.
- Physiological signals:
 - Only tested a subset of possible signals.
 - Used a proxy measure for postural stability.

Conclusion & Takeaways

- There is evidence of correlations between redirection gain strength and physiological signals.
- Better understanding of the effects of redirection on physiology can likely lead to more efficient ways to estimate comfort during redirection.
- Effects of luminance are likely complicated by the multisensory nature of locomotion.

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