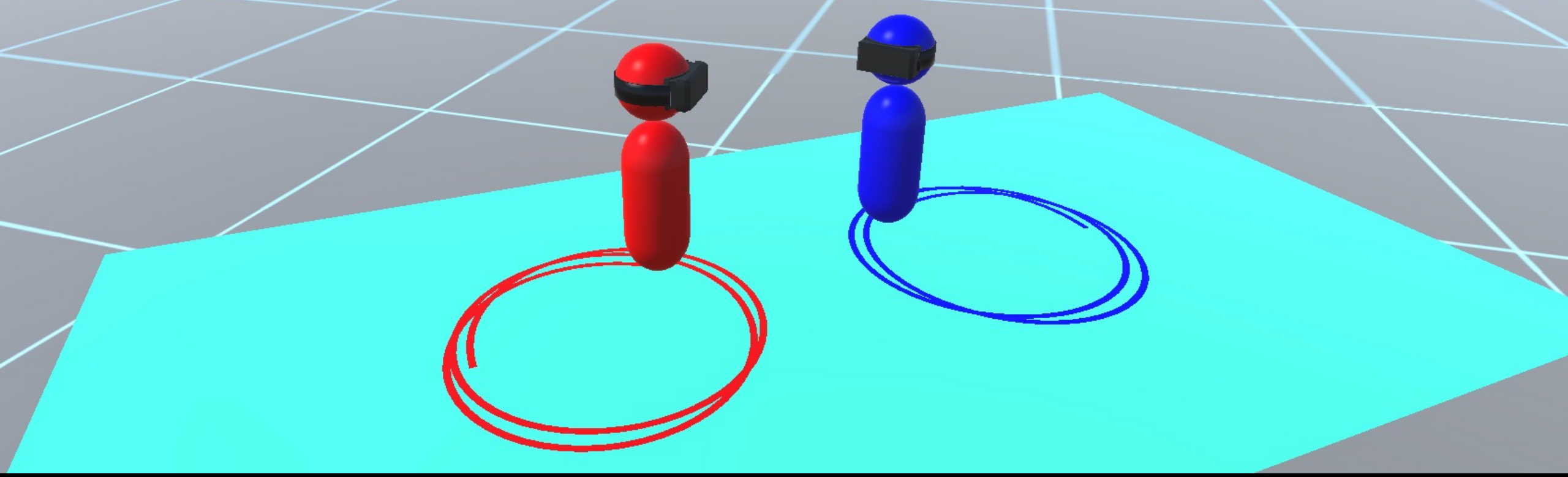


Redirected Walking

Reading: *15 Years of Research on Redirected Walking in Immersive Virtual Environments*

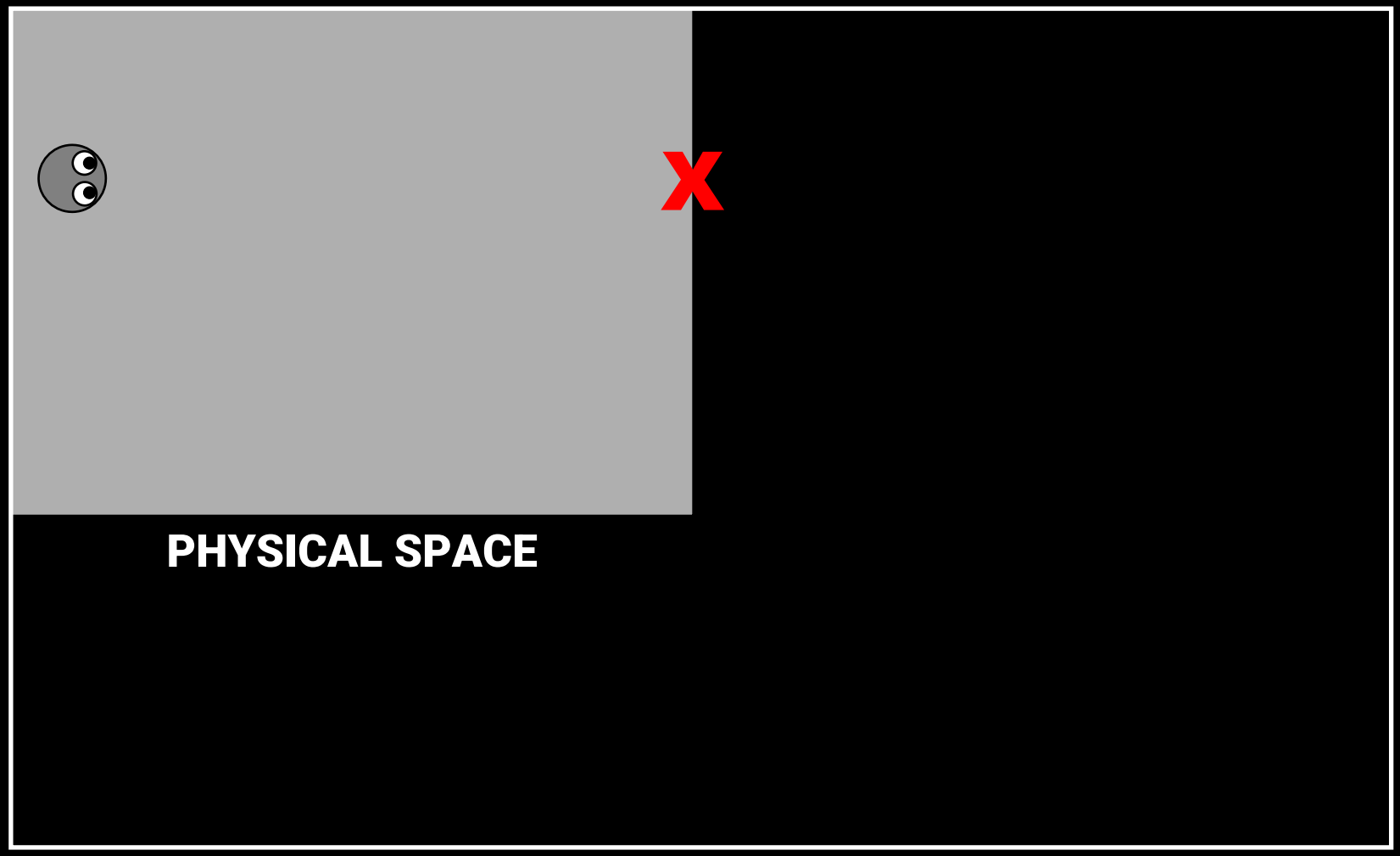
Slides adapted from Evan Suma Rosenberg's material

STRESS LEVEL ZERO

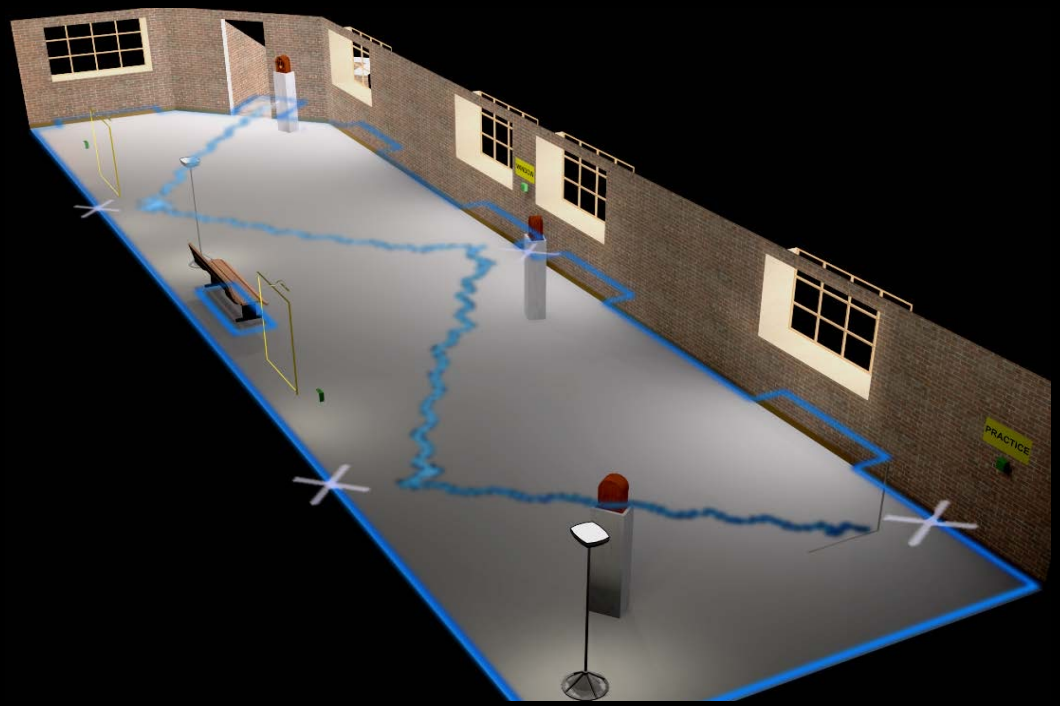
Every controller position is still being tracked

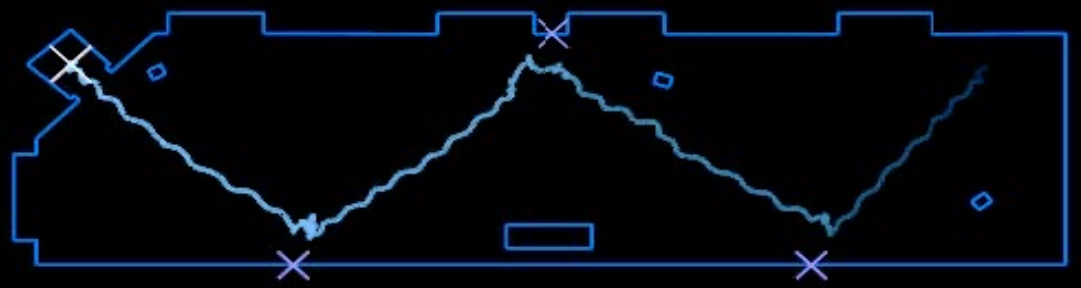
orange volume is our Primary hard bounds

The Locomotion Problem



Redirected Walking



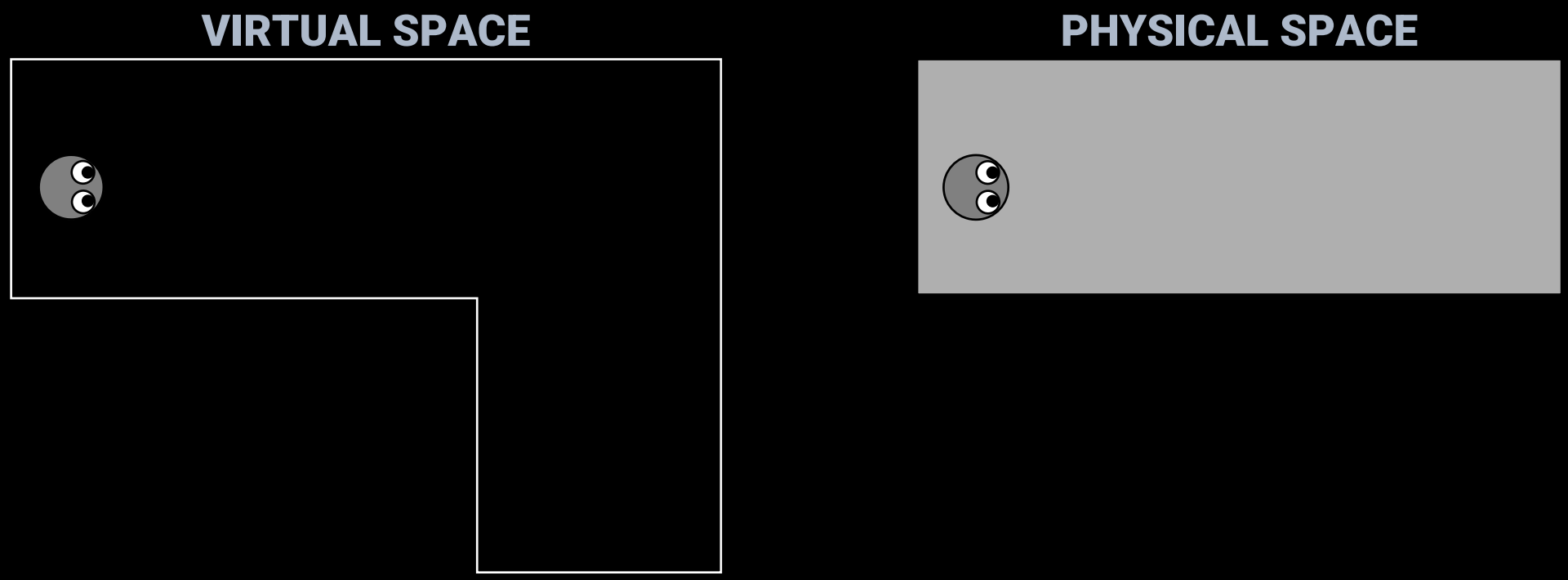


Virtual World Path

Real World Path

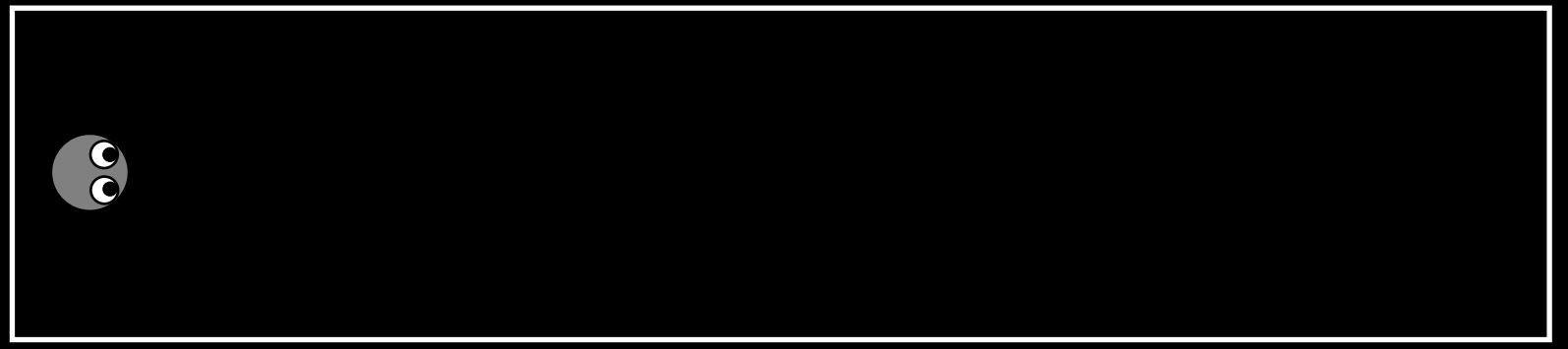
S. Razzaque, Z. Kohn, and M. Whitton. Redirected Walking, Eurographics 2001.

Rotation Gain



Translation Gain

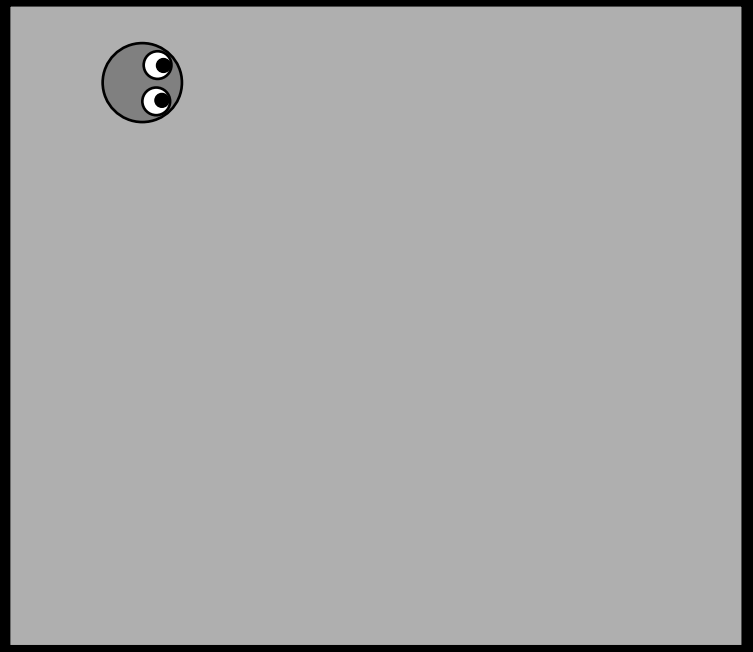
PHYSICAL SPACE



VIRTUAL SPACE

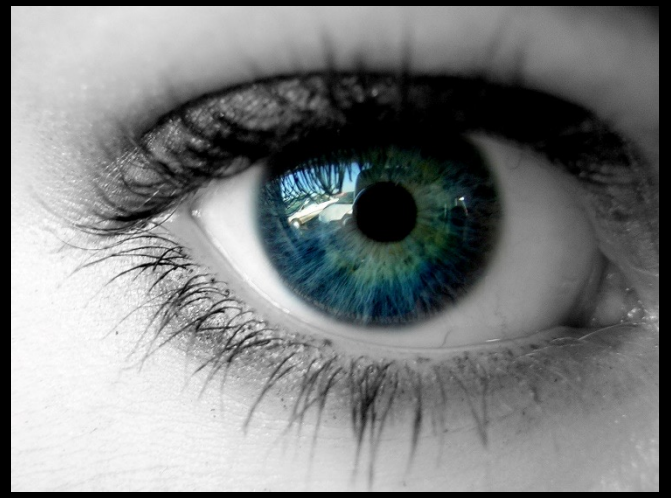
Curvature Gain

VIRTUAL SPACE



PHYSICAL SPACE

Why does redirection work?



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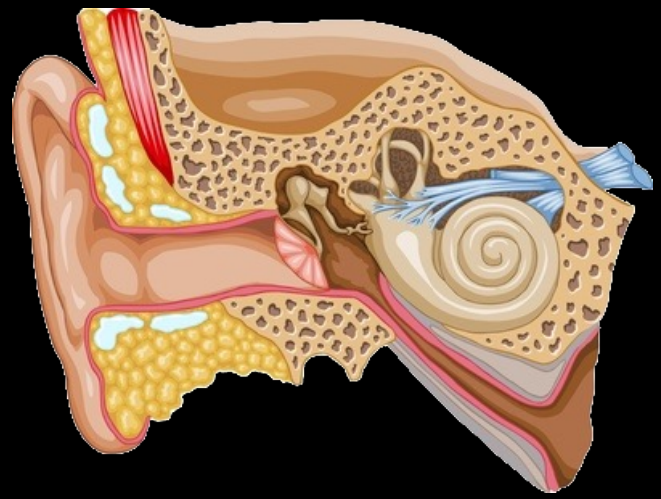
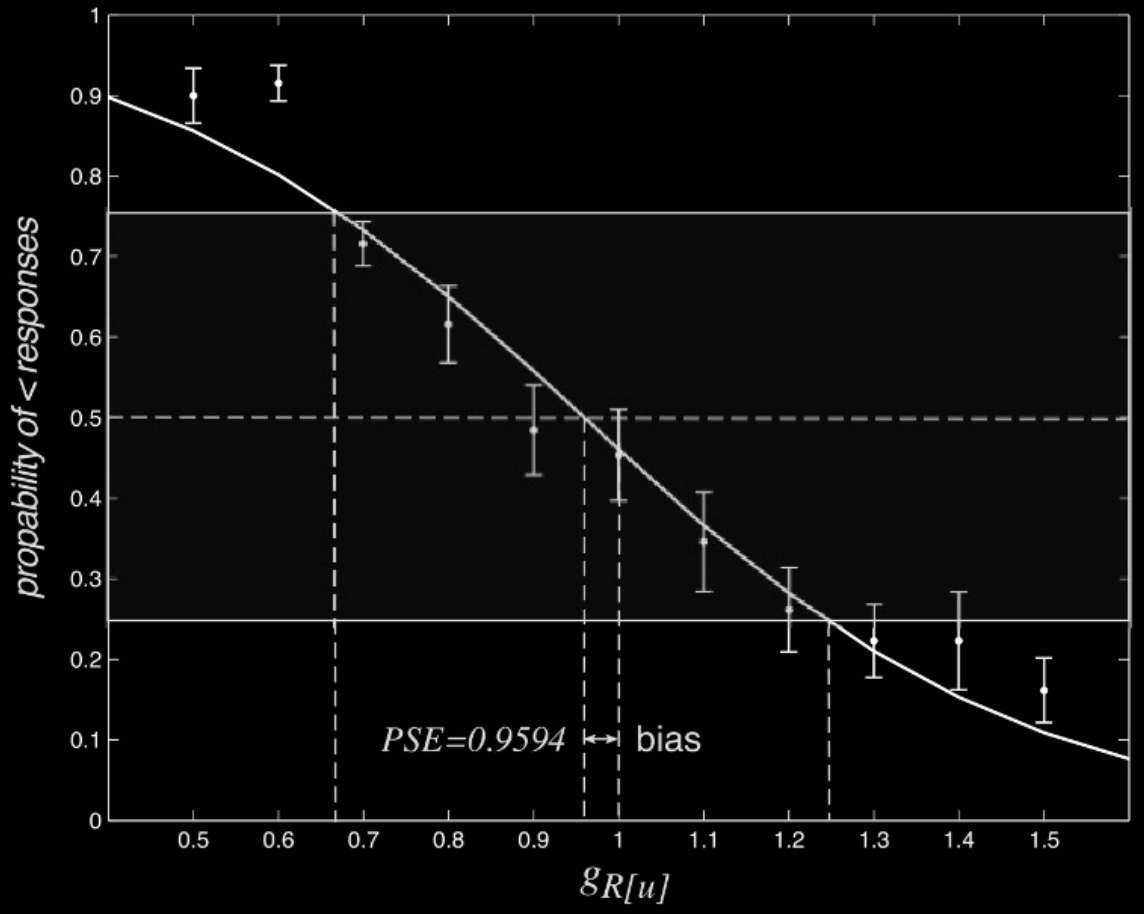


Vision tends to dominate over **vestibular** sensation.

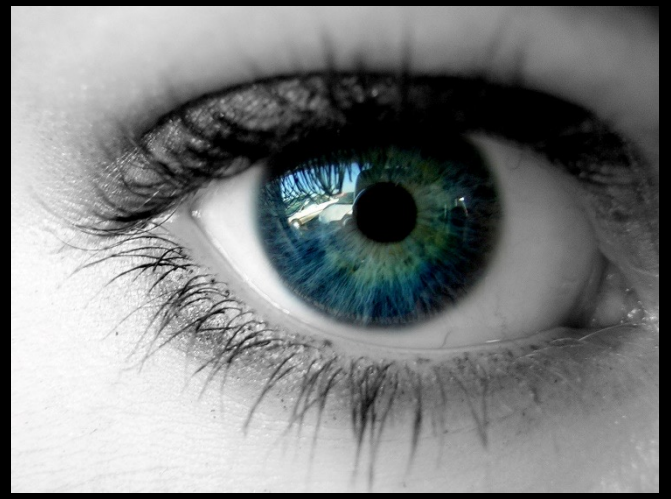
Measuring Detection Thresholds

- Two alternative forced choice task (2AFC)
- User repeatedly presented with a stimulus of varying level and asked to detect it
- Compute pooled probability of response (forced choice, no neutral option)
- Fit a psychometric function (sigmoid)
- Point of subjective equality (PSE) at 50%
- Detection thresholds at 25% and 75%



F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of Detection Thresholds for Redirected Walking Techniques, IEEE TVCG 2010.

Detection Thresholds for Redirected Walking



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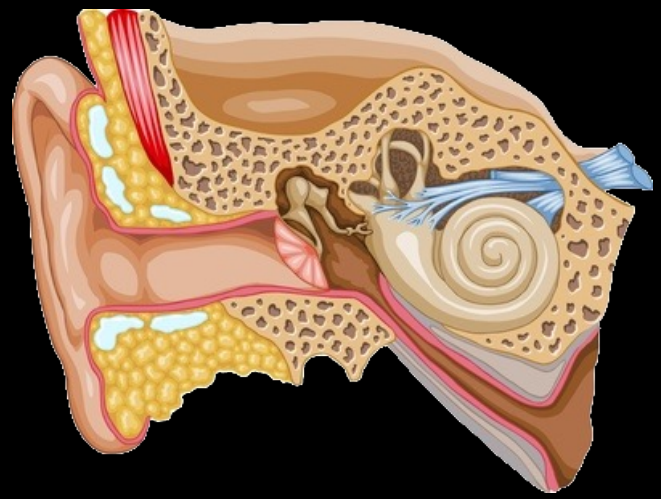
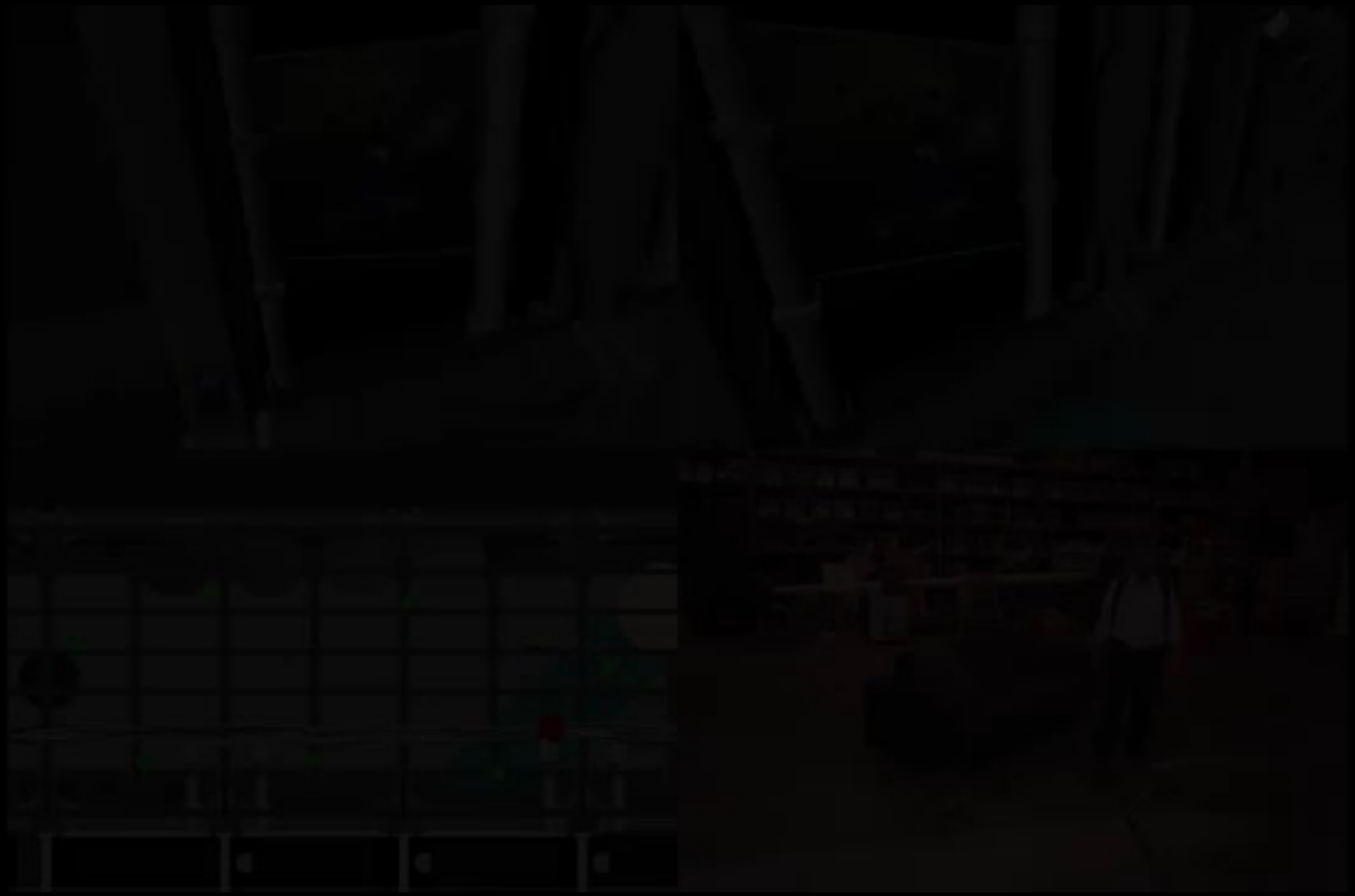


Rotation Gains
49% amplification
20% dampening

Curvature Gains
arc radius >= 20 meters

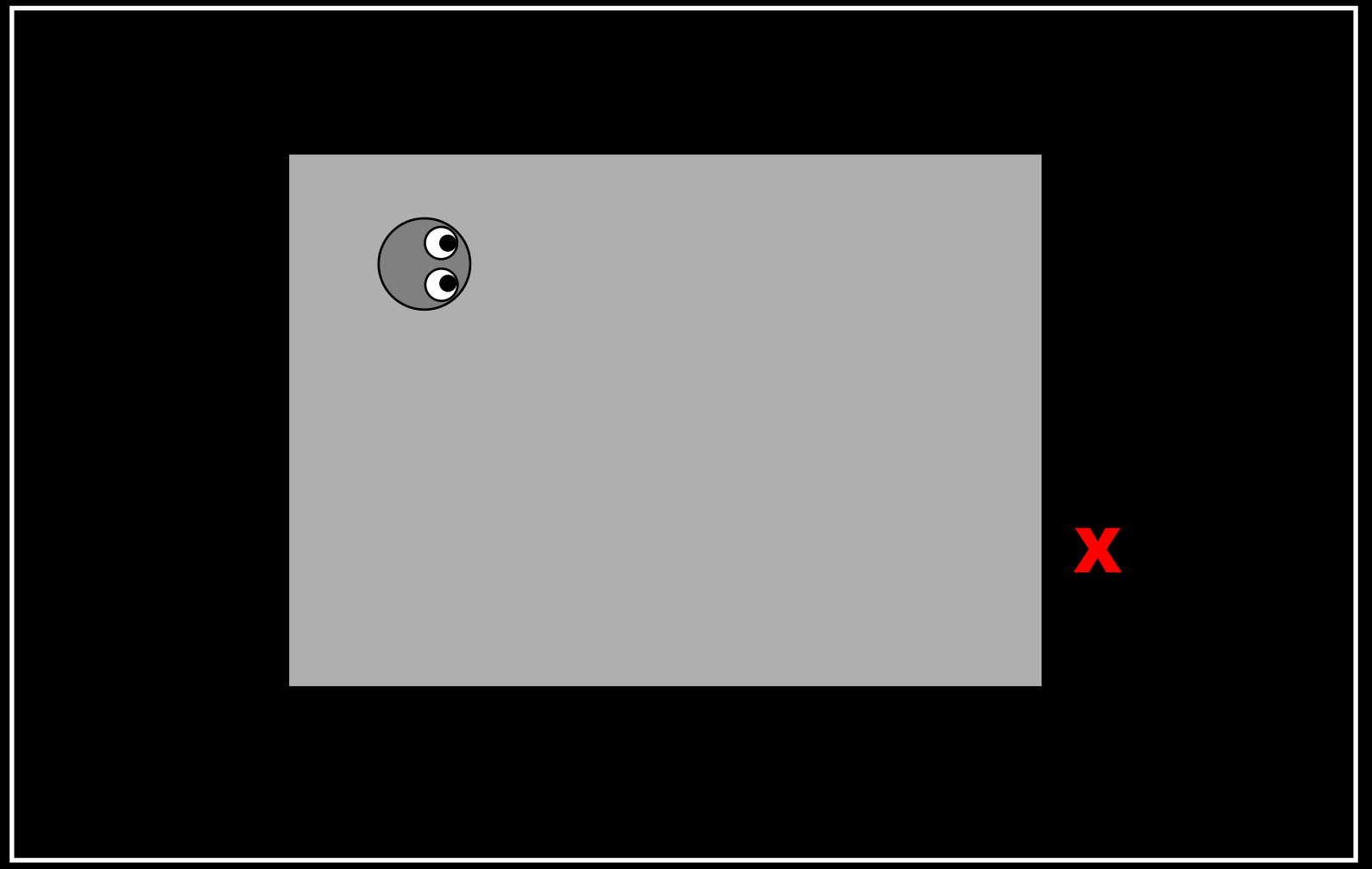
Translation Gains
26% upscale
14% downscale

F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of Detection Thresholds for Redirected Walking Techniques, IEEE TVCG 2010.

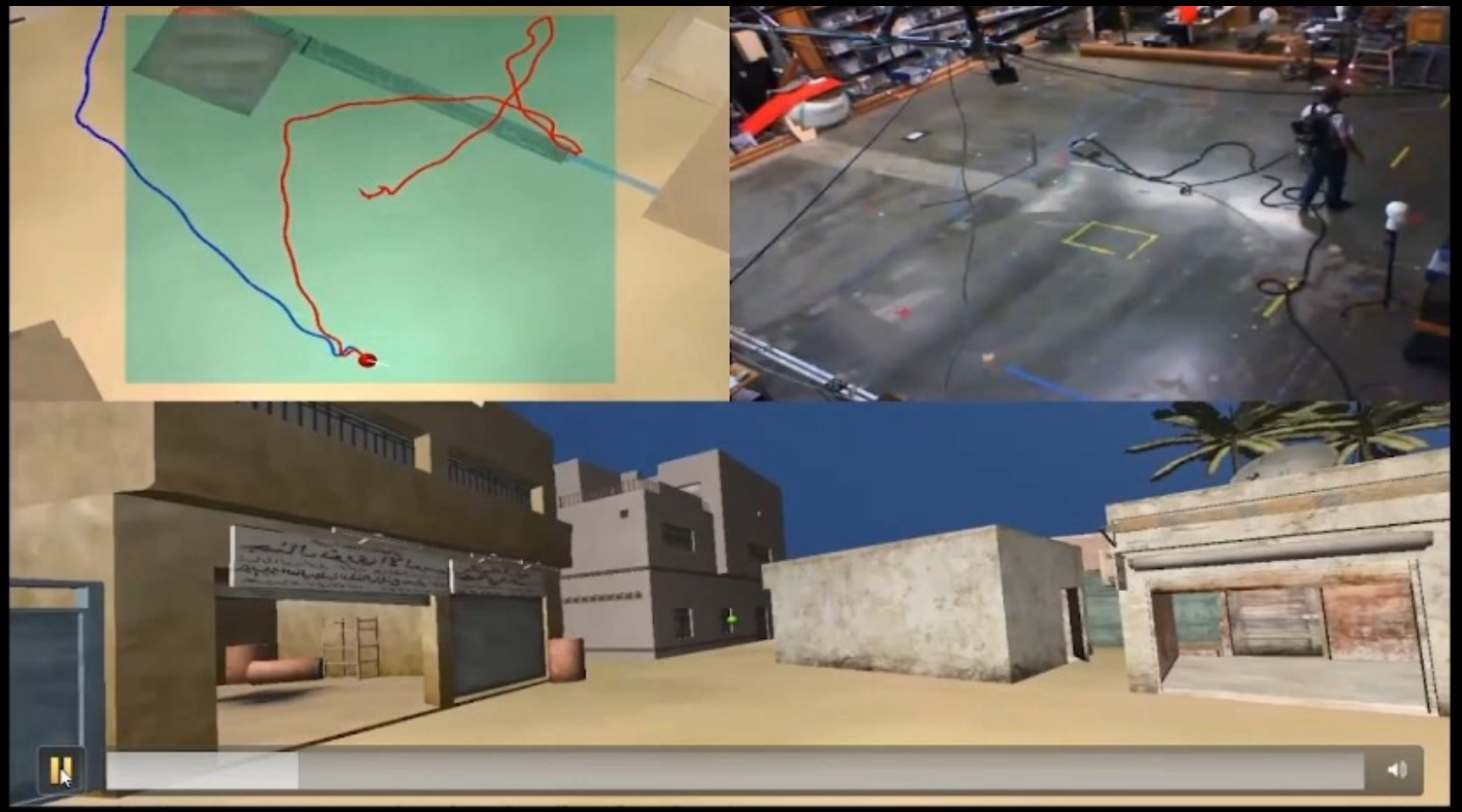


Discovering Near-Field VR: Stop Motion with a Touch of Light-Fields and a Dash of Redirection, 2015 SIGGRAPH AR/VR Contest Winner

Reorientation Events (Resets)

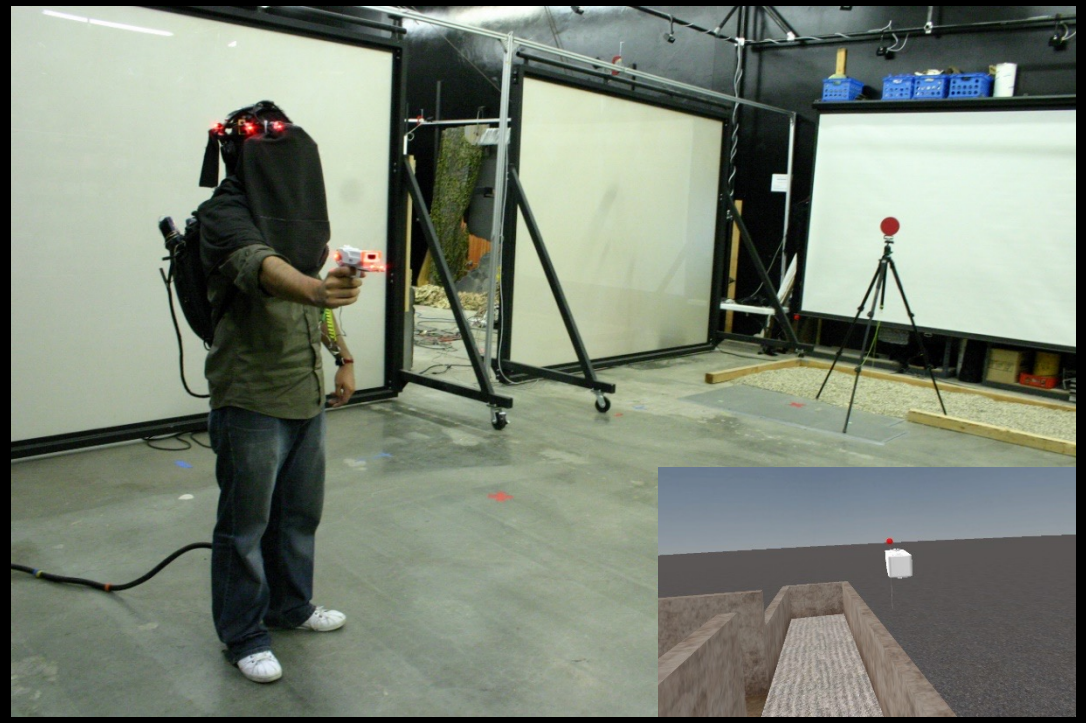


Reorientation Events (Resets)

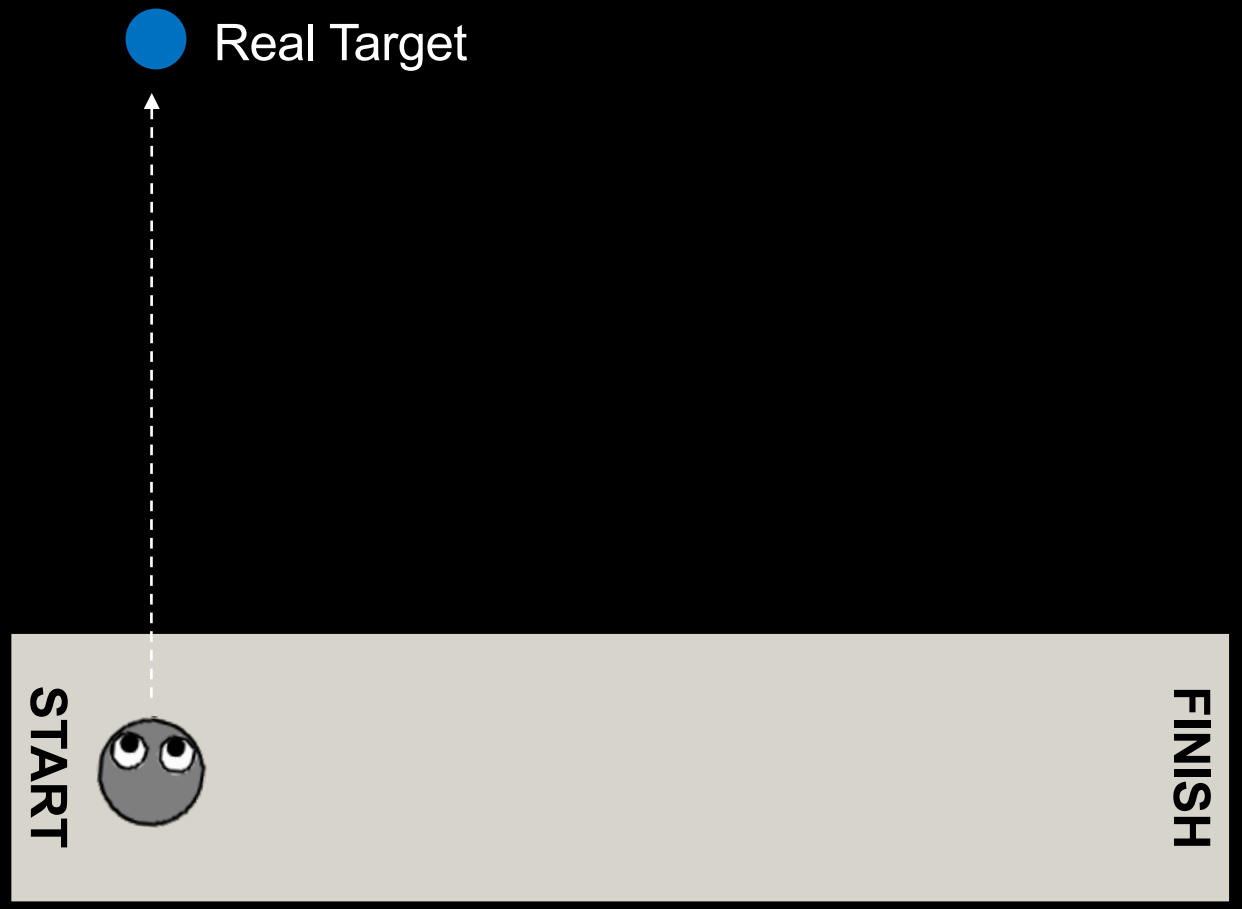


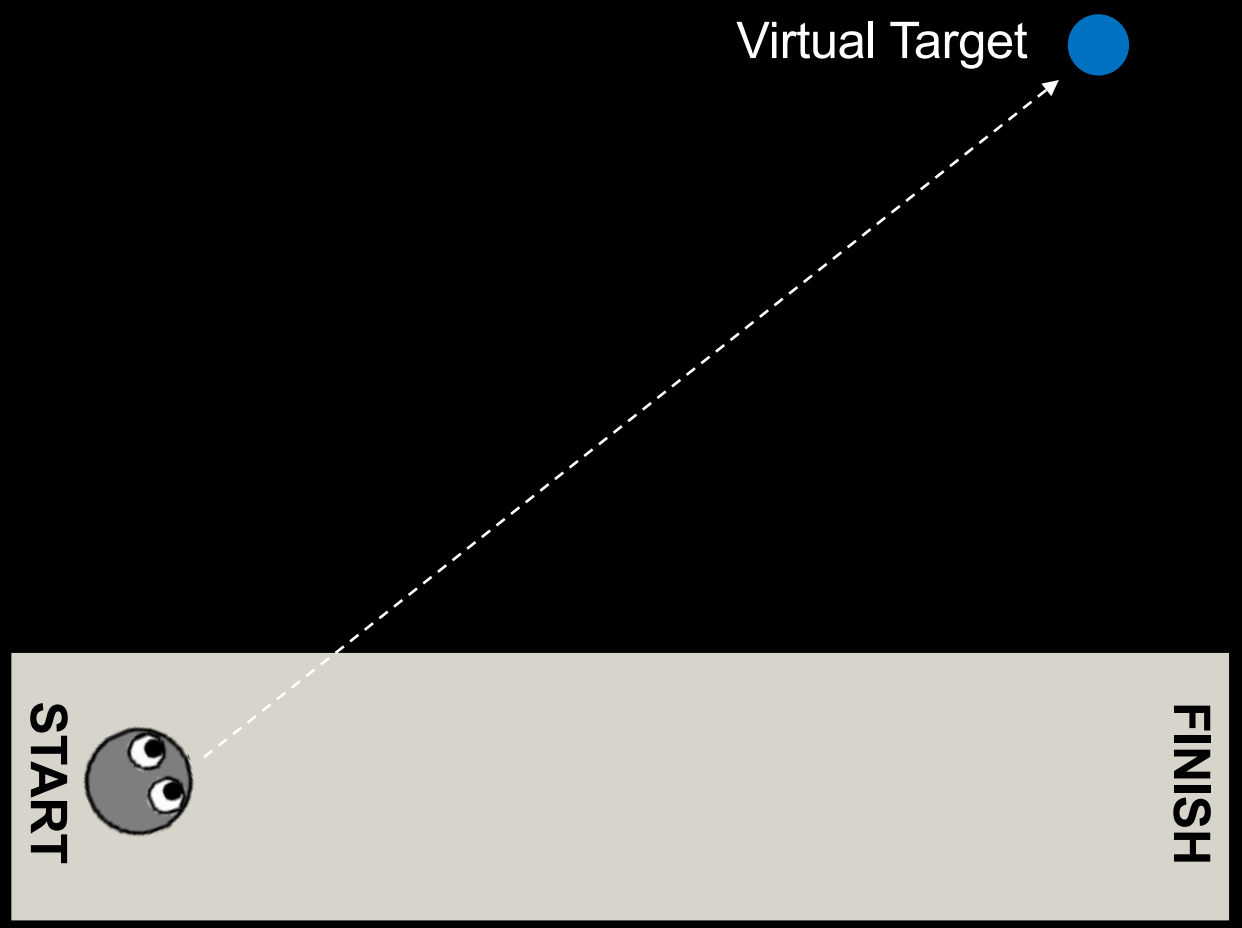
T. Grechkin, M. Azmandian, M. Bolas, and E. Suma. Towards Context-Sensitive Reorientation for Real Walking in Virtual Reality, IEEE VR 2015.

Spatial Orientation Experiment



E. Suma, D. Krum, S. Finkelstein, and M. Bolas. Effects of Redirection on Spatial Orientation in Real and Virtual Environments, IEEE 3DUI 2011.

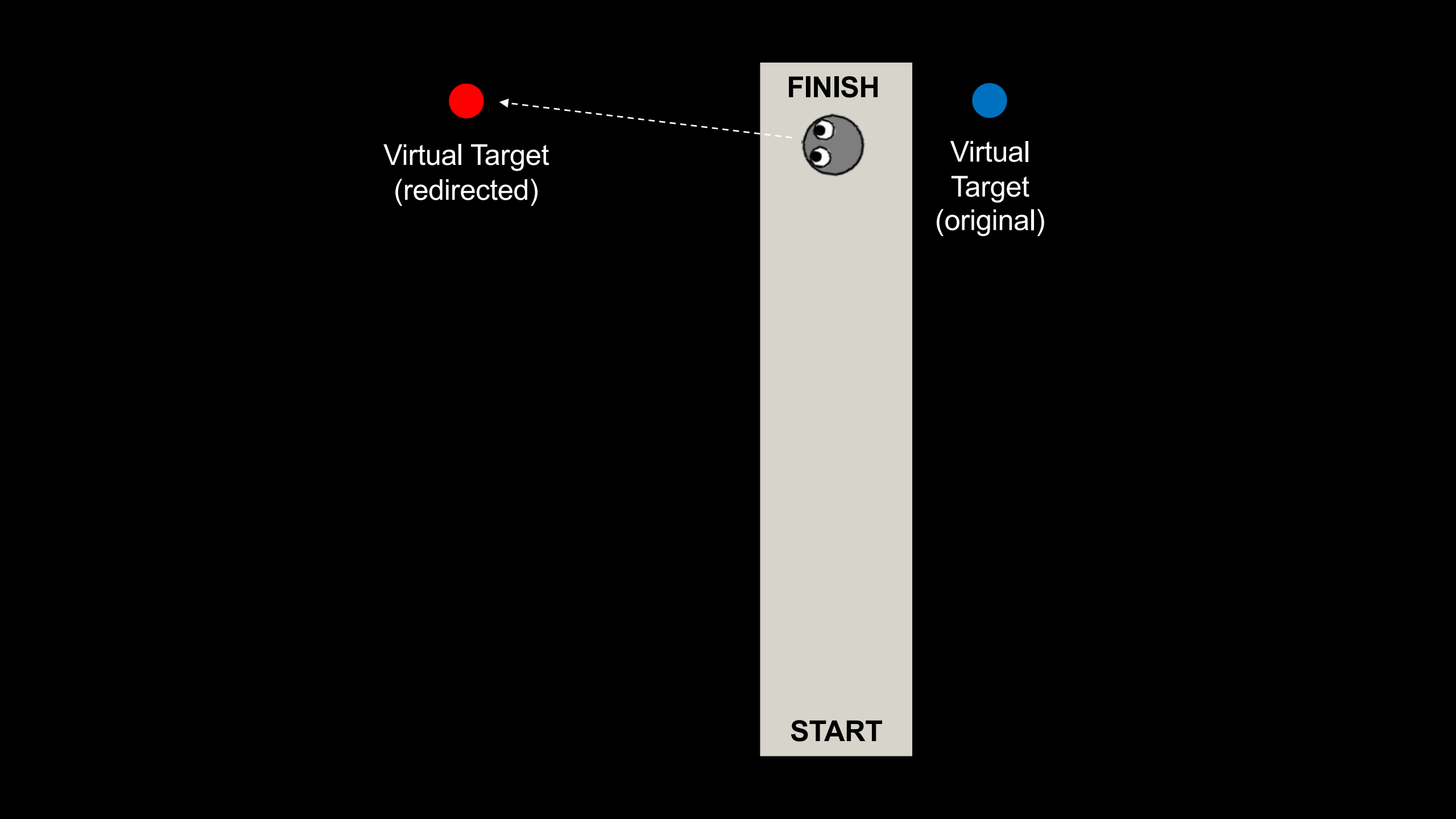

Real Target
START
FINISH


Virtual Target
START
FINISH

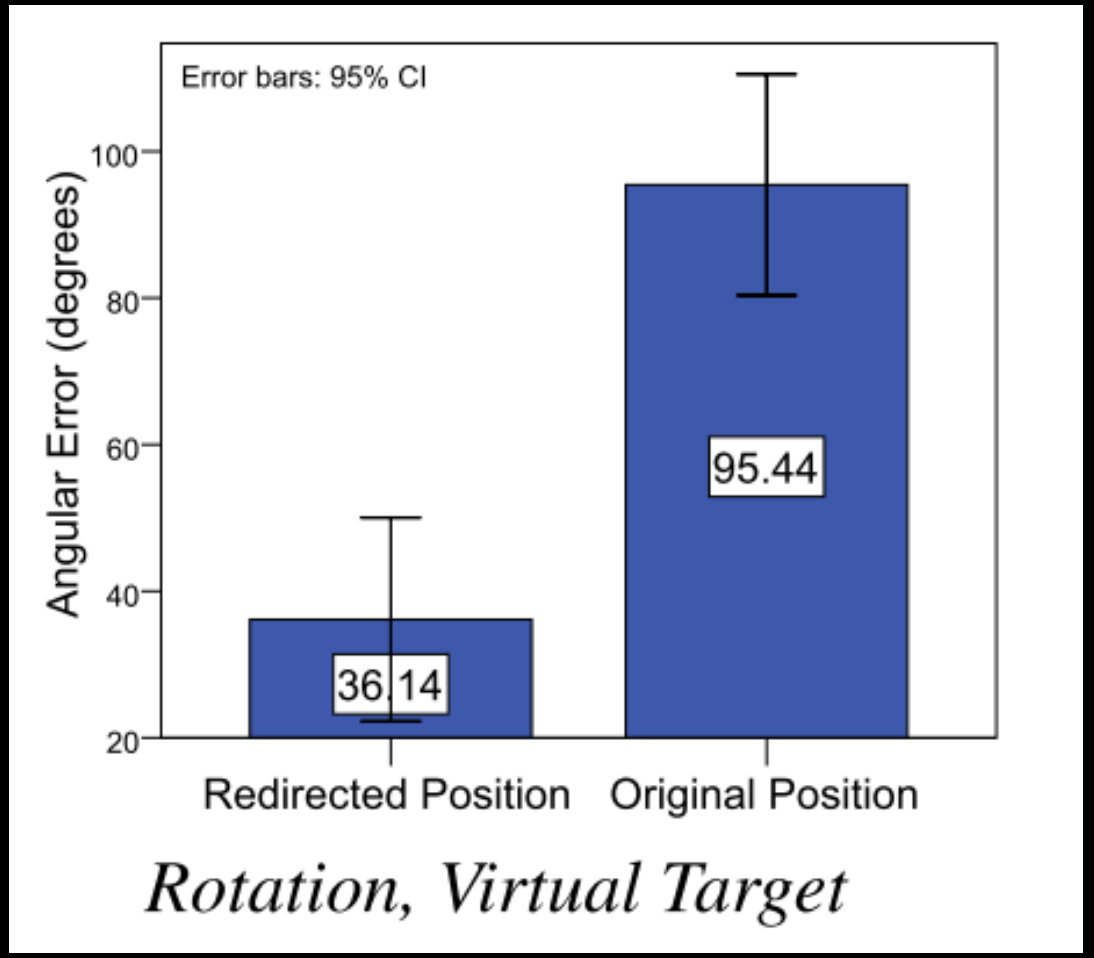
FINISH

START

Virtual
Target
(original)
START
FINISH


FINISH
Virtual Target
(redirected)
Virtual
Target
(original)
START

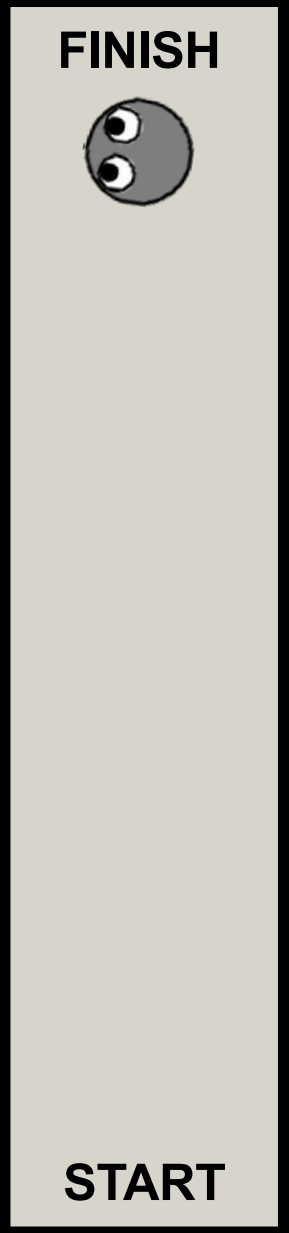
Angular Pointing Error

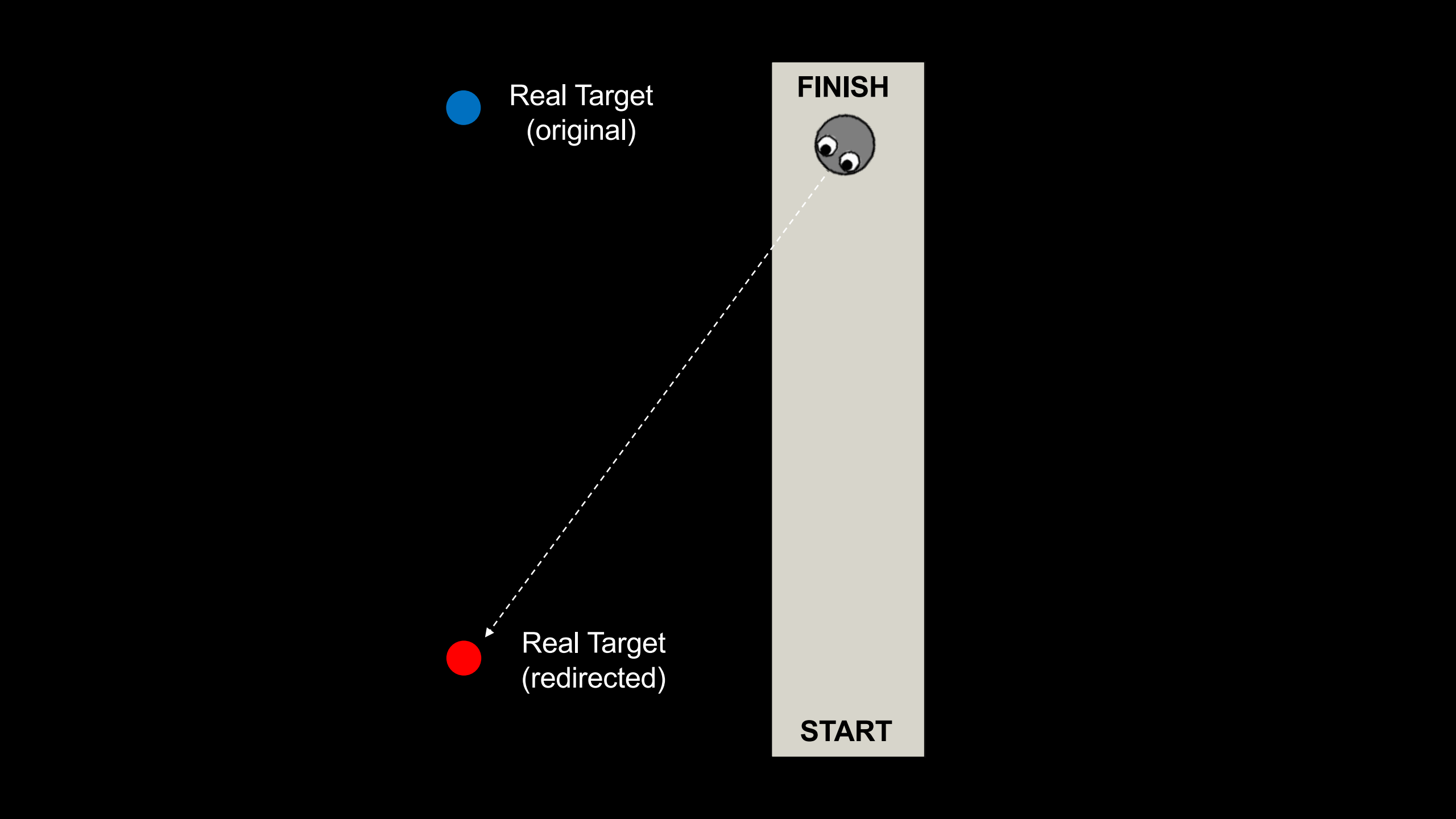


FINISH

START

Real Target
(original)

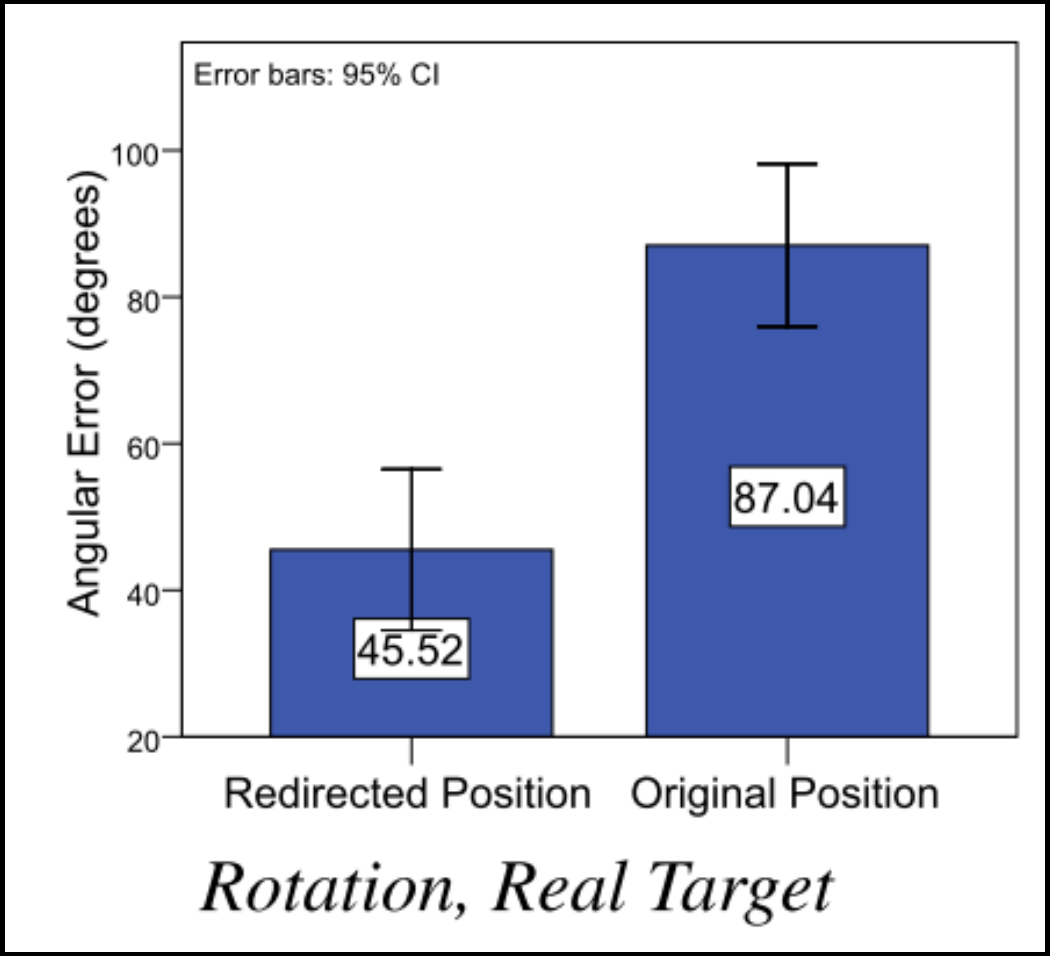



Real Target
(original)
FINISH
Real Target
(redirected)
START

How does redirection influence the user’s **real world** orientation?

Can we maintain both spatial **reference frames** at the same time?

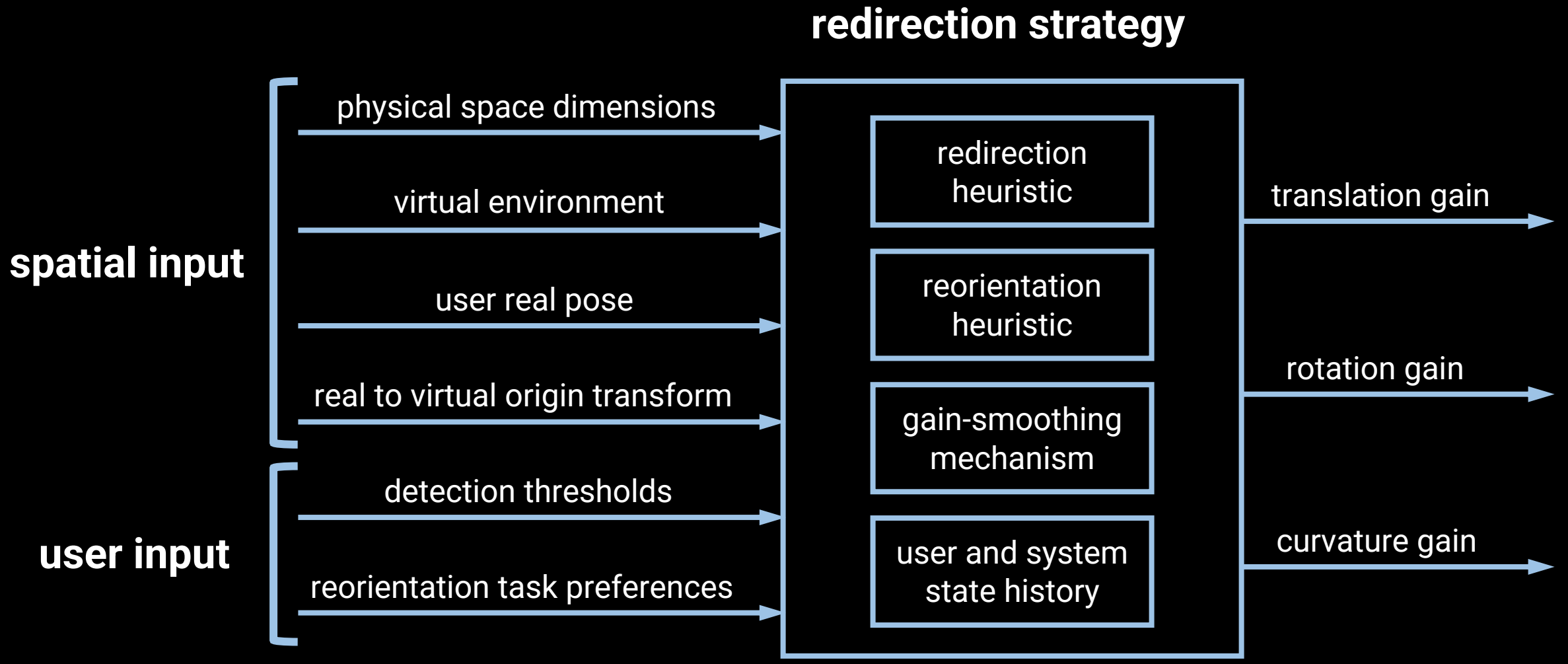
Angular Pointing Error



Research Questions

- How much redirection can we apply before it becomes **perceptible?**
  - *Answer: quite a bit!*
- How much redirection can we apply before it becomes **noticeable?**
  - *Answer: even more!*
- How does redirection impact the **user experience?**
  - spatial cognition
  - user behavior
  - task performance
- **Optimal steering direction** that minimizes # of resets?

Redirected Walking Systems



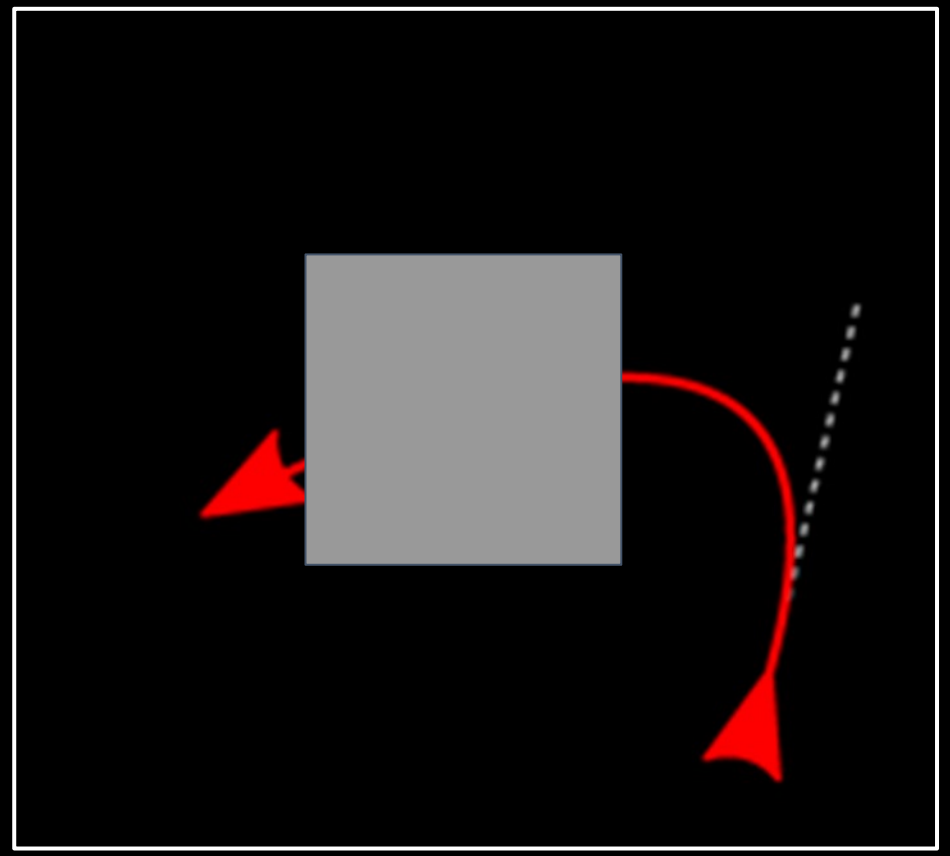
How much can we predict the user?

Linear Route	Branching Pathways	Open World
Static Planning	**Dynamic Planning**	**Reactive Algorithms**

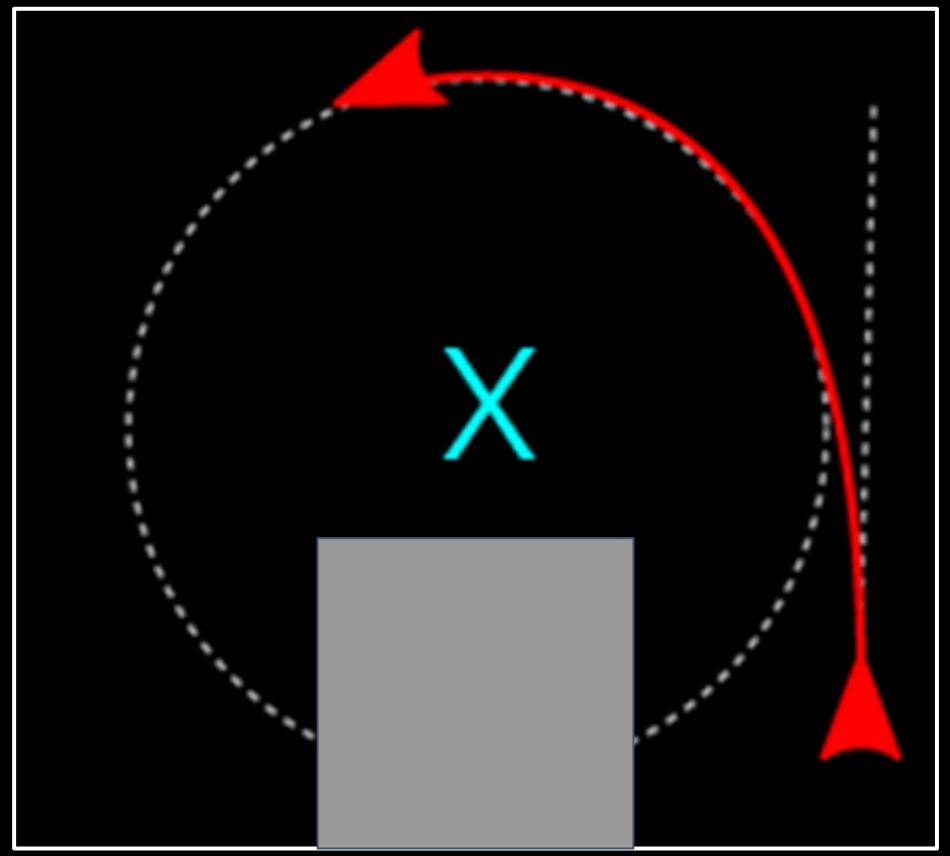
How much can we predict the user?

Linear Route	Branching Pathways	Open World
Static Planning	**Dynamic Planning**	**Reactive Algorithms**

Reactive Algorithms

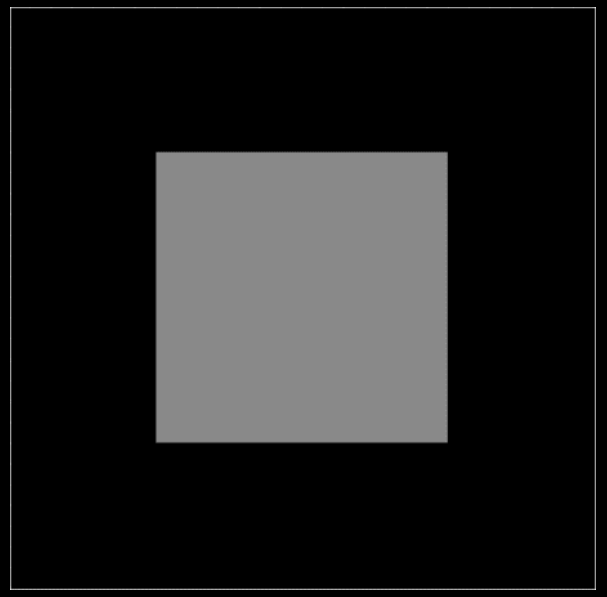


Steer to Center (S2C)

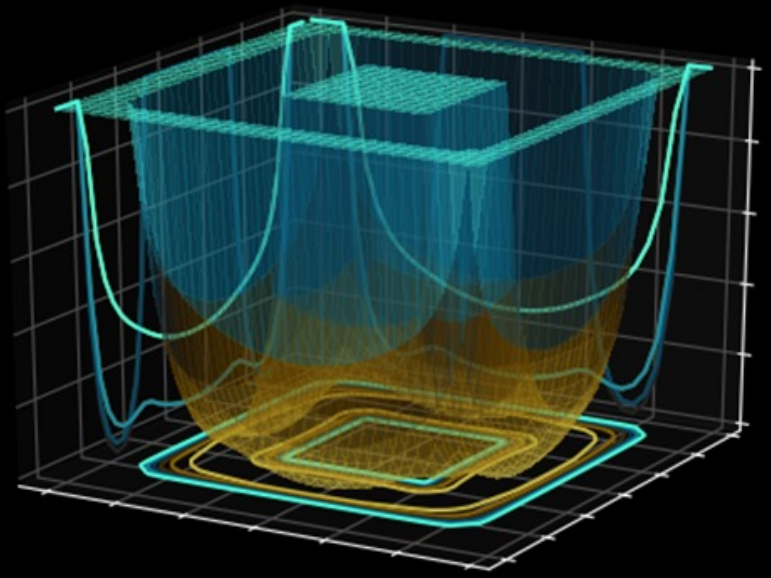


Steer to Orbit (S2O)

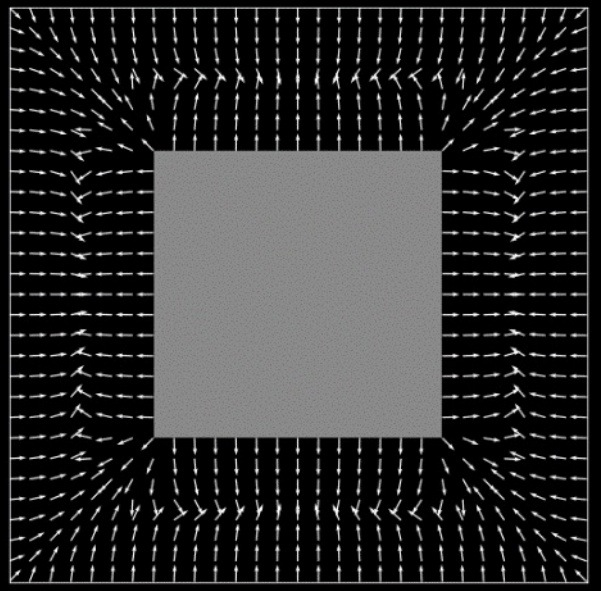
Push / Pull Reactive (P2R) Algorithm



Physical Environment



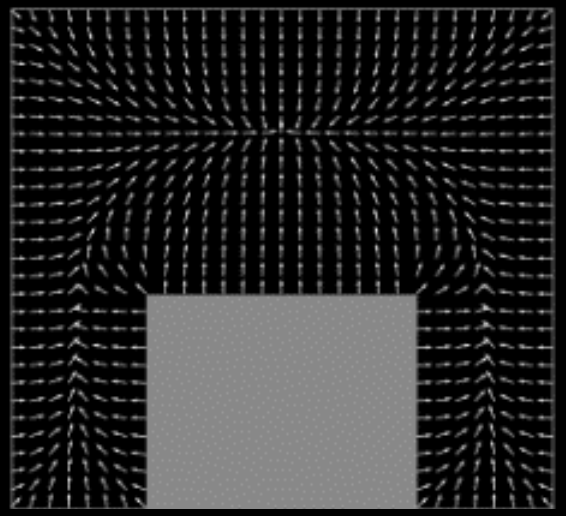
Artificial Potential Function

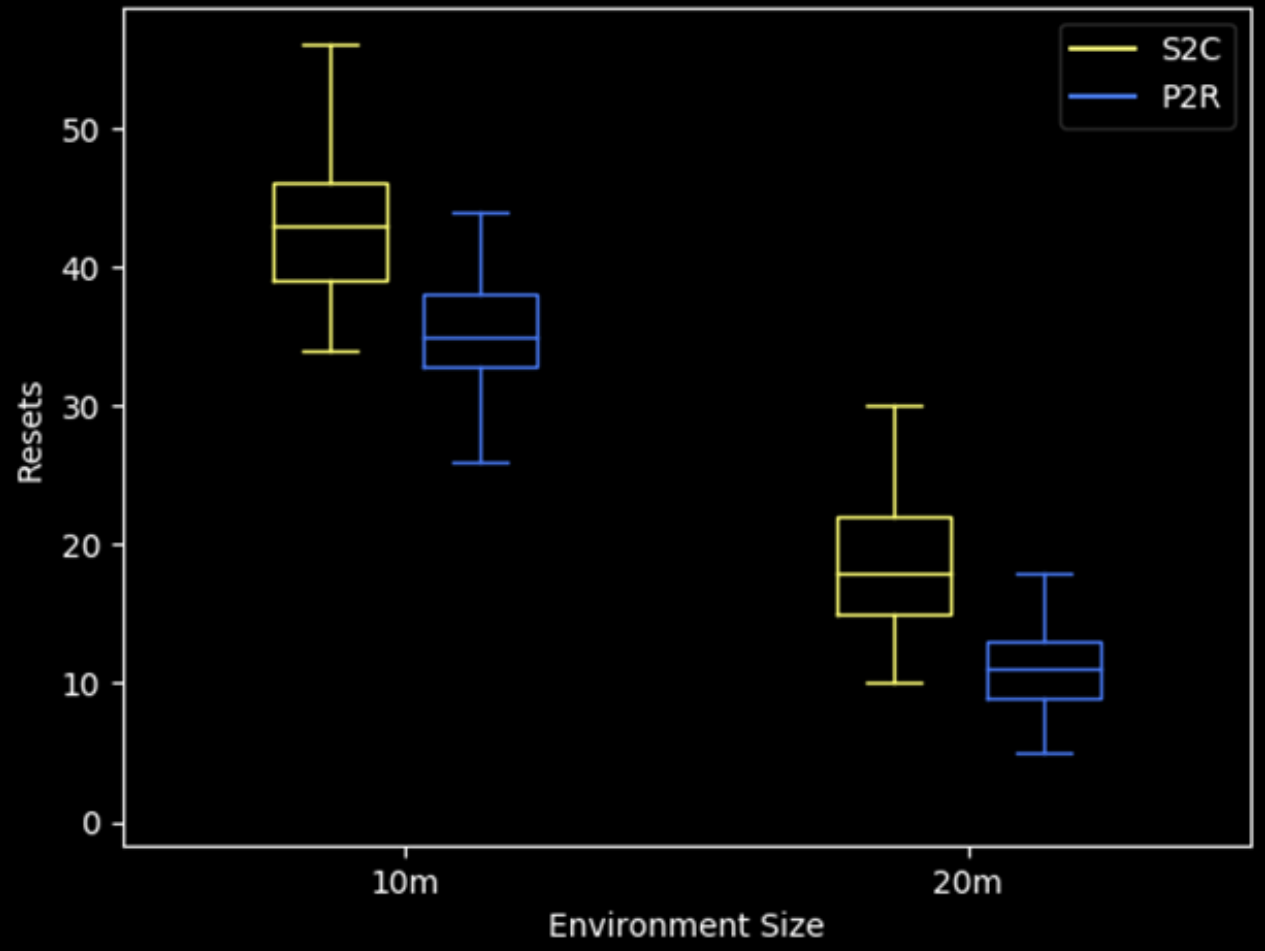


Gradient Field

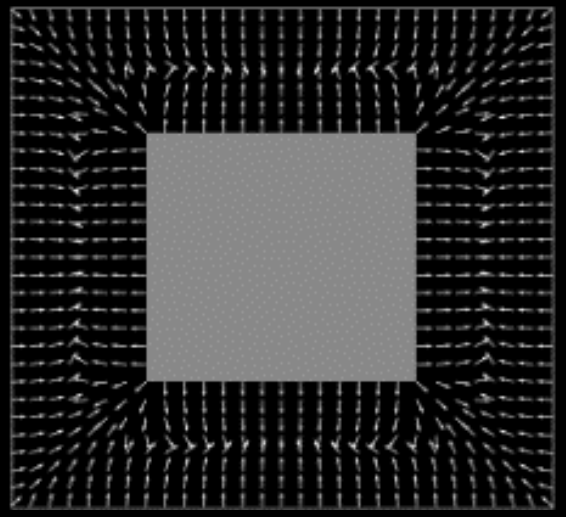
J. Thomas and E. Suma Rosenberg. A General Reactive Algorithm for Redirected Walking using Artificial Potential Functions, IEEE VR 2019.

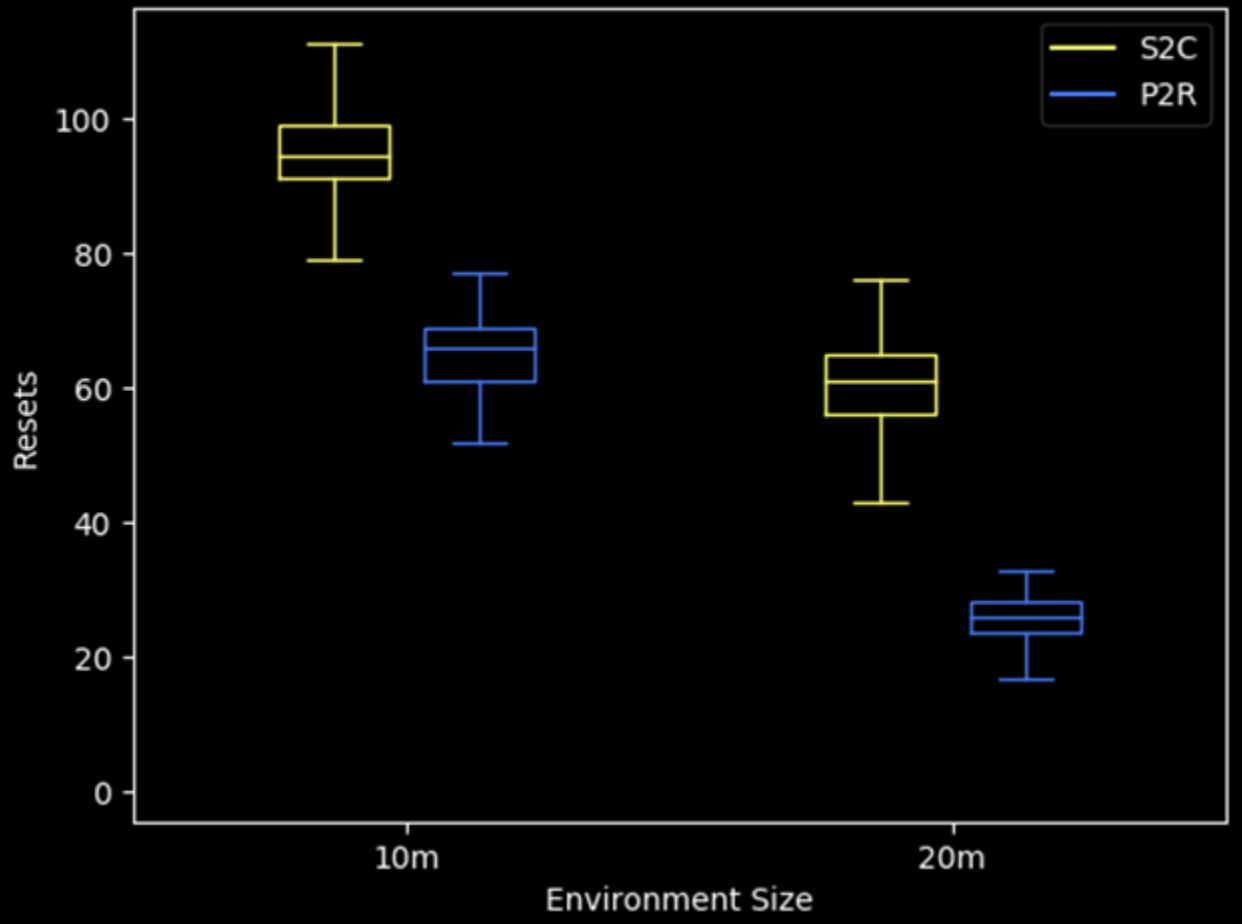
P2R Results: Non-Convex Boundaries





P2R Results: Interior Obstacles

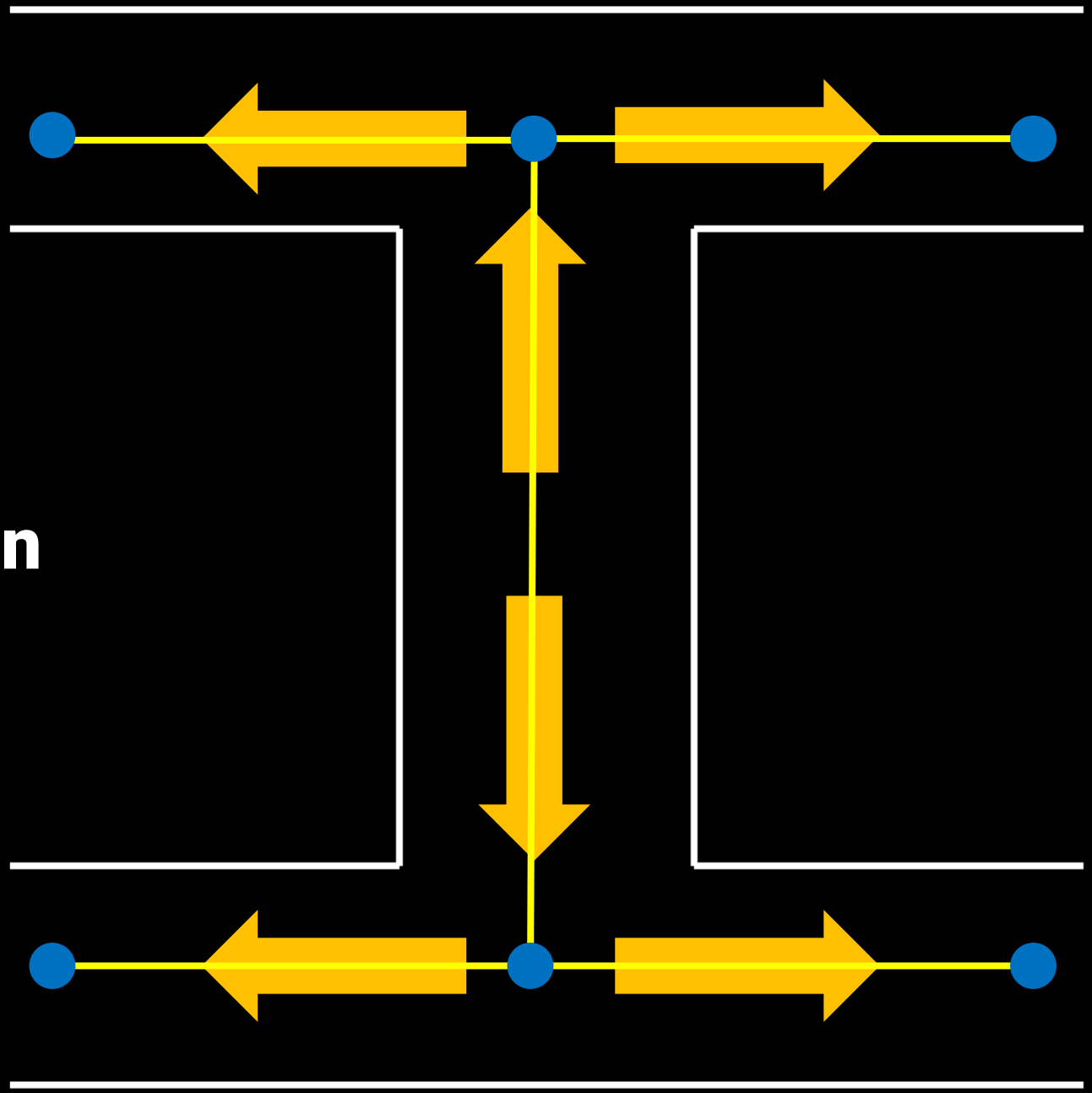


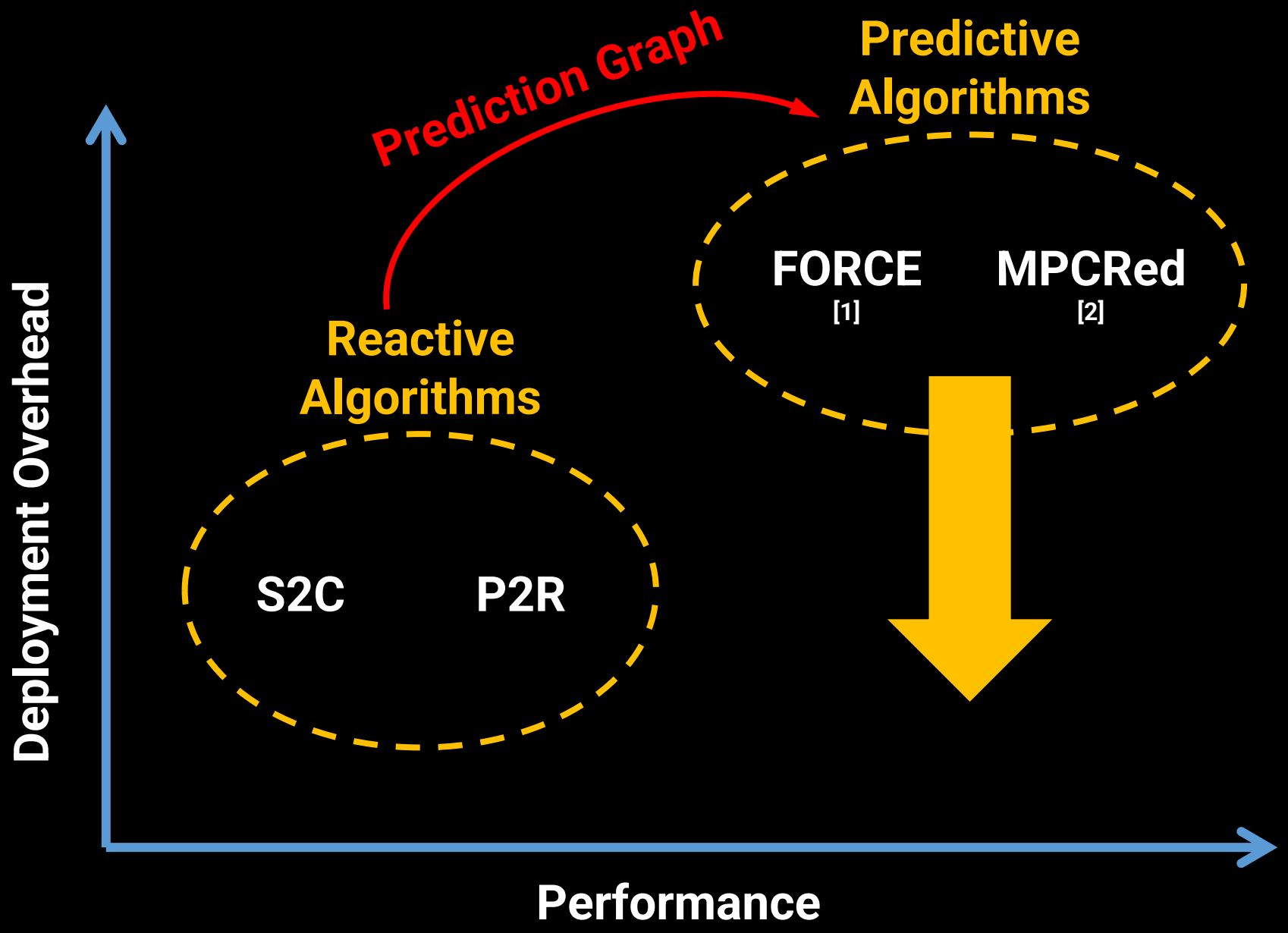


How much can we predict the user?

Linear Route	Branching Pathways	Open World
Static Planning	**Dynamic Planning**	**Reactive Algorithms**

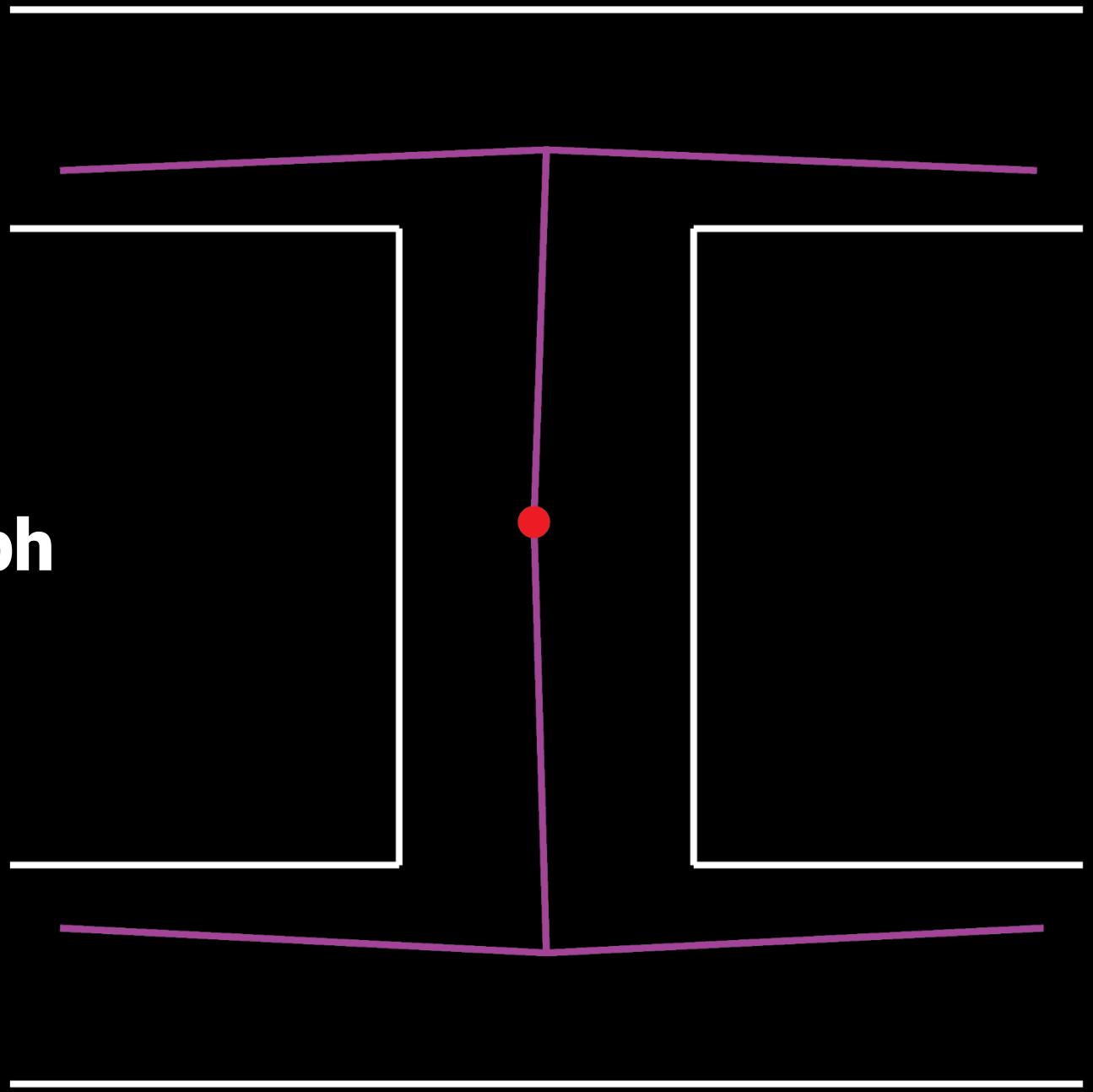
user prediction



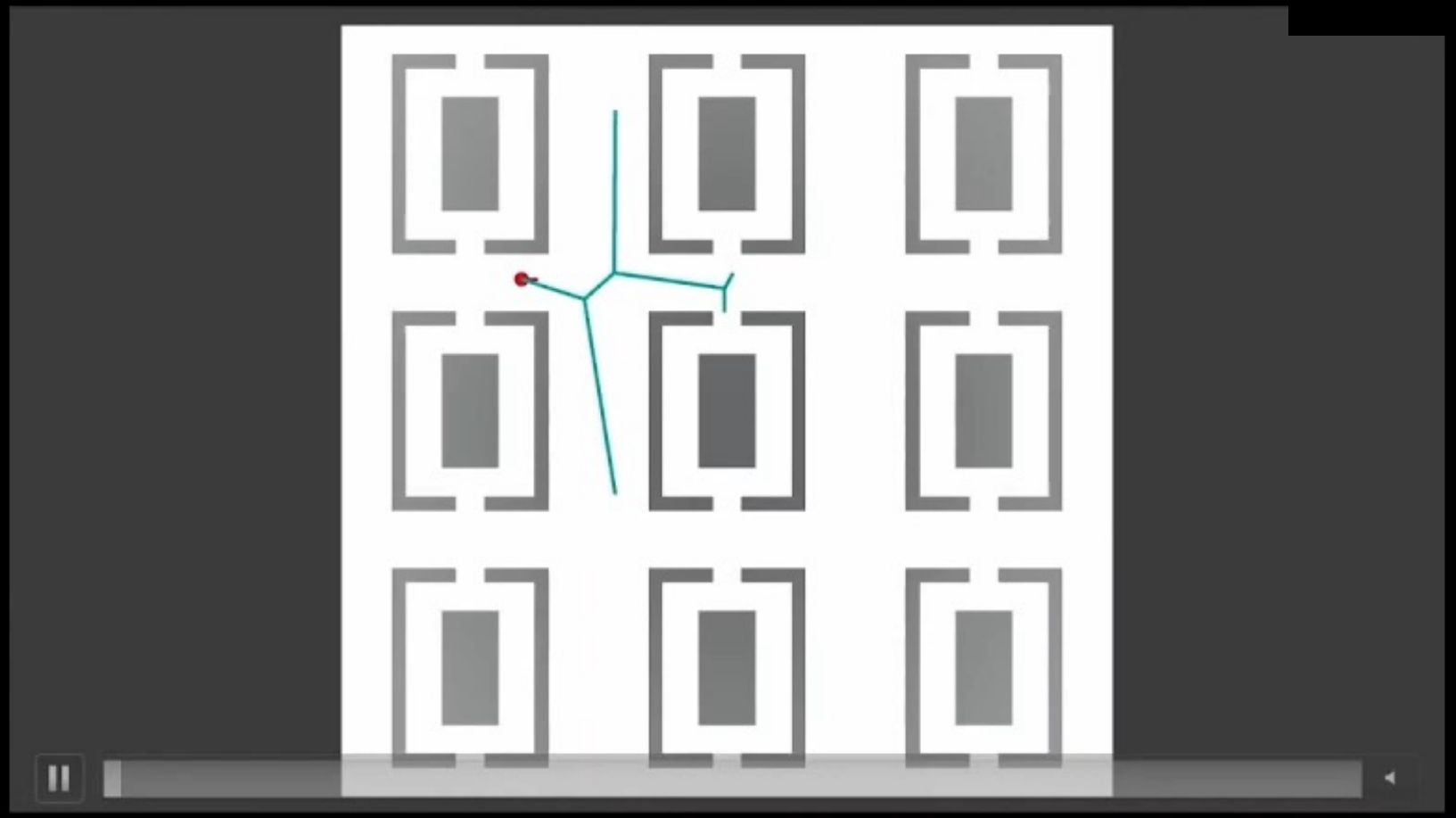


[1] M. Zmuda, J. Wonser, E. Bachmann, and E. Hodgson. Optimizing constrained-environment redirected walking instructions using search techniques, IEEE TVCG 2013.
[2] T. Nescher, Y. Huang, and A. Kunz. Planning Redirection Techniques for Optimal Free Walking Experience Using Model Predictive Control, IEEE 3DUI 2014.

prediction graph



Prediction Graph Generation

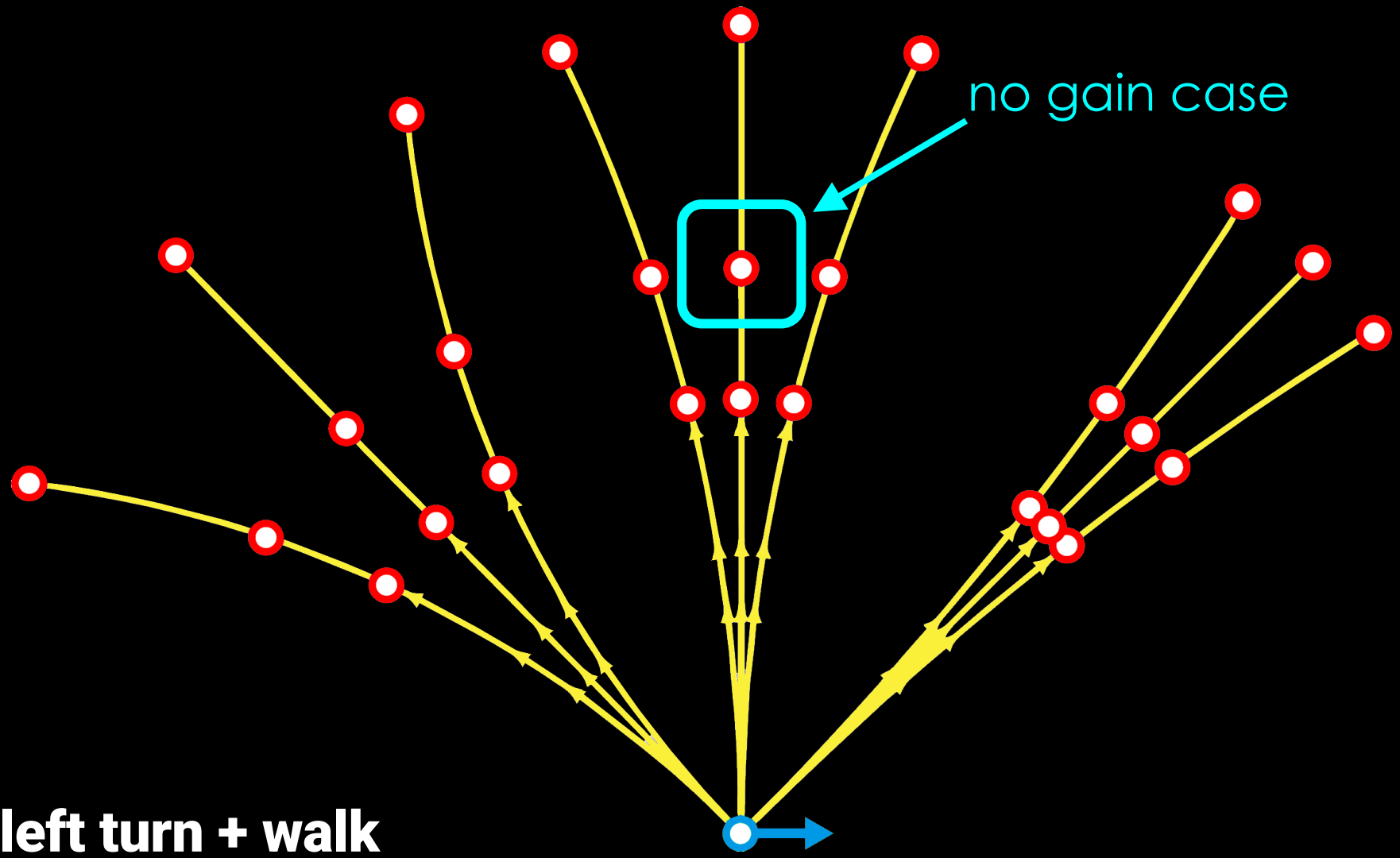


M. Azmandian, T. Grechkin, M. Bolas, and E. Suma. Automated path prediction for redirected walking using navigation meshes, IEEE 3DUI 2016.

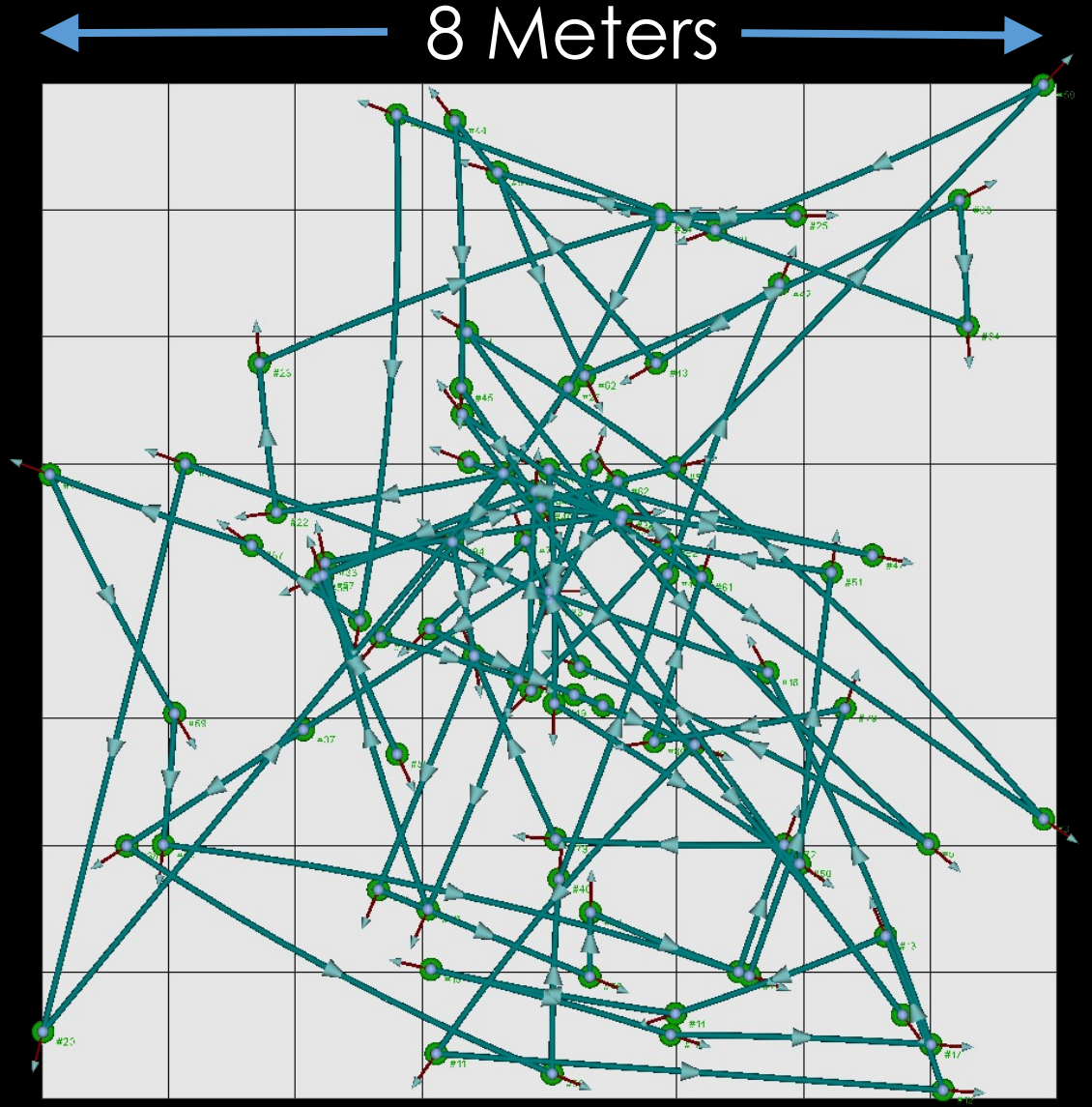
How much can we predict the user?

Linear Route	Branching Pathways	Open World
Static Planning	**Dynamic Planning**	**Reactive Algorithms**

Combinatorial Optimization

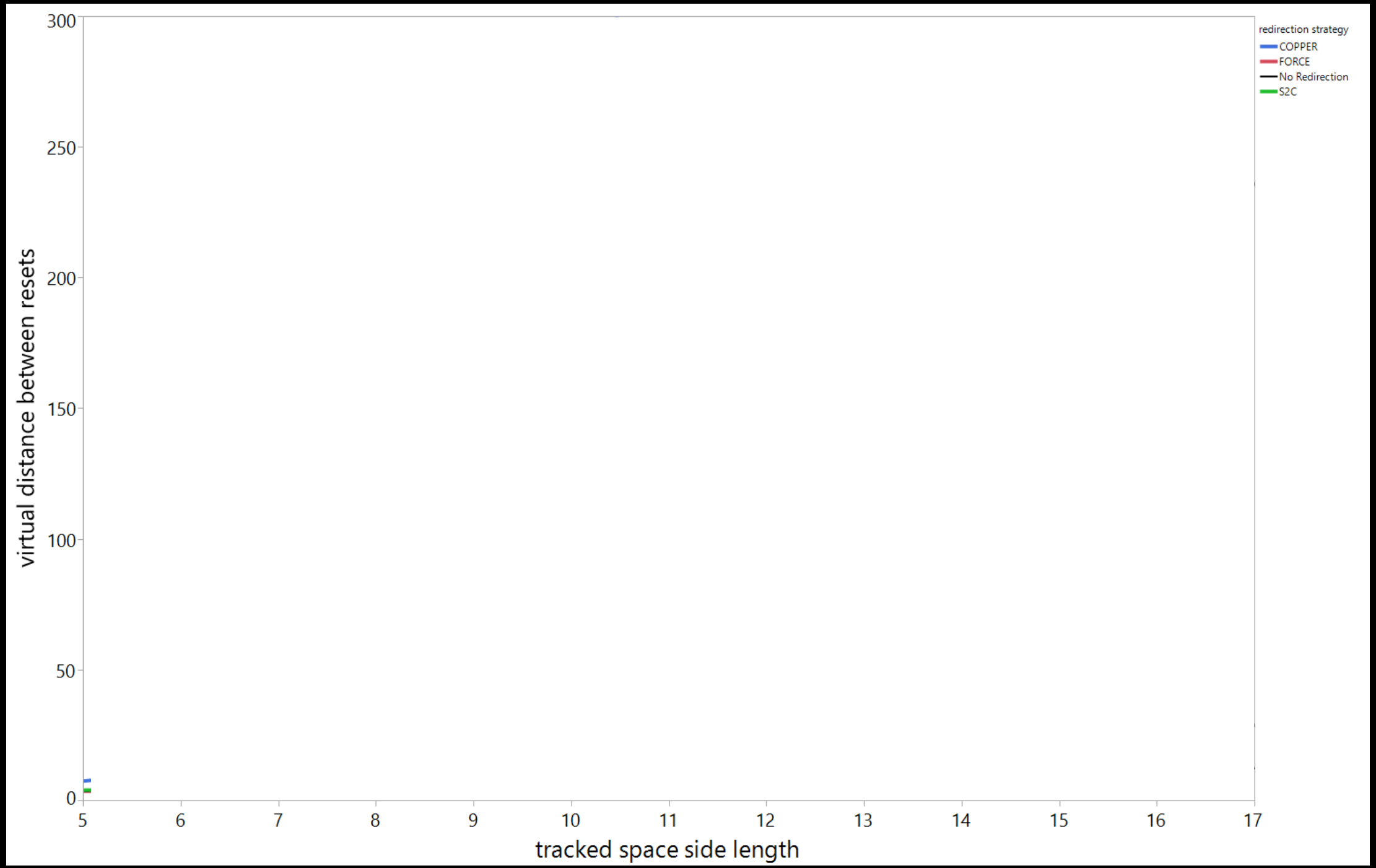


90 degree left turn + walk



M. Azmandian. Design and Evaluation of Adaptive Redirected Walking Systems, Ph.D. Thesis, University of Southern California, 2018.

IEEE VGTC Virtual Reality Best Dissertation Award Honorable Mention.

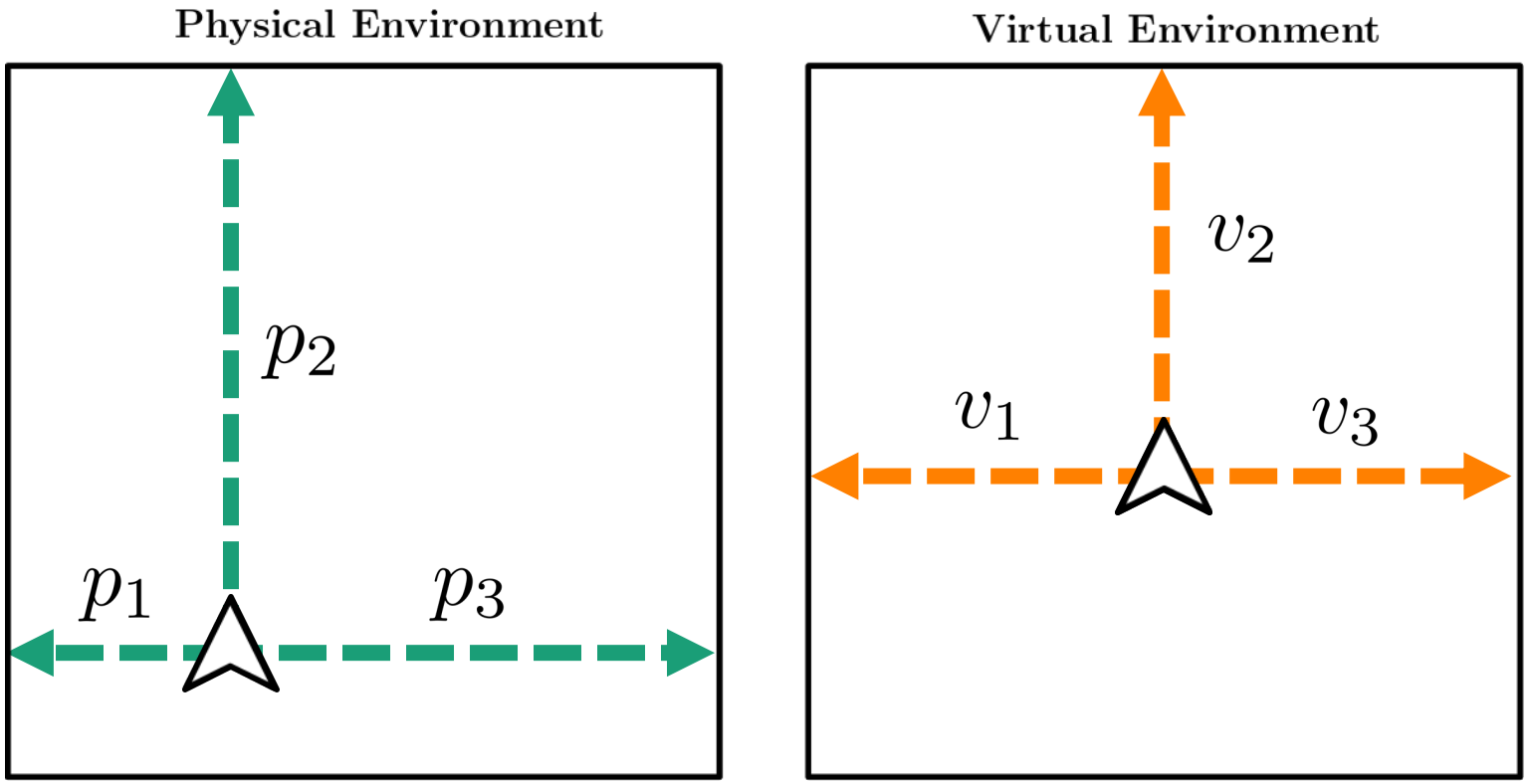

redirection strategy
COPPER
FORCE
No Redirection
S2C
virtual distance between resets
300
250
200
150
100
50
0
5
6
7
8
9
10
11
12
13
14
15
16
17
tracked space side length

Alignment-based Redirection

Similarity of physical and virtual environments!

Alignment-based Redirection

How to measure similarity?

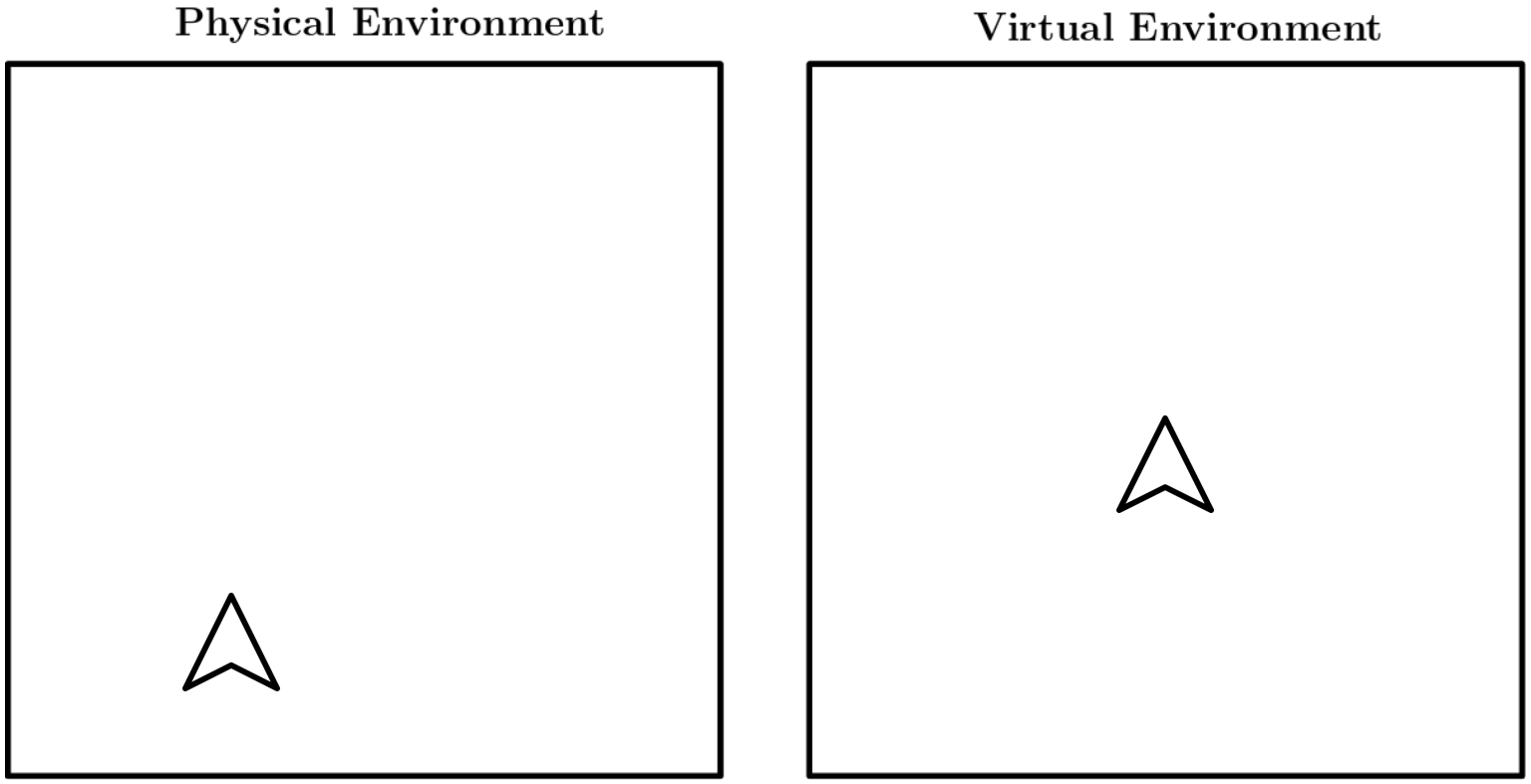


$$\text{similarity} = |v_1 - p_1| + |v_2 - p_2| + |v_3 - p_3|$$

1) J. Thomas, C. Hutton Pospick, and E. Suma Rosenberg. Towards Physically Interactive Virtual Environments: Reactive Alignment with Redirected Walking, ACM VRST 2020.
2) Williams, Niall L., Aniket Bera, and Dinesh Manocha. "Arc: Alignment-based redirection controller for redirected walking in complex environments." *IEEE Transactions on Visualization and Computer Graphics* 27.5 (2021): 2535-2544.
3) Williams, Niall L., Aniket Bera, and Dinesh Manocha. "Redirected walking in static and dynamic scenes using visibility polygons." *IEEE transactions on visualization and computer graphics* 27.11 (2021): 4267-4277.

Alignment-based Redirection

How to measure similarity?



1) J. Thomas, C. Hutton Pospick, and E. Suma Rosenberg. Towards Physically Interactive Virtual Environments: Reactive Alignment with Redirected Walking, ACM VRST 2020.
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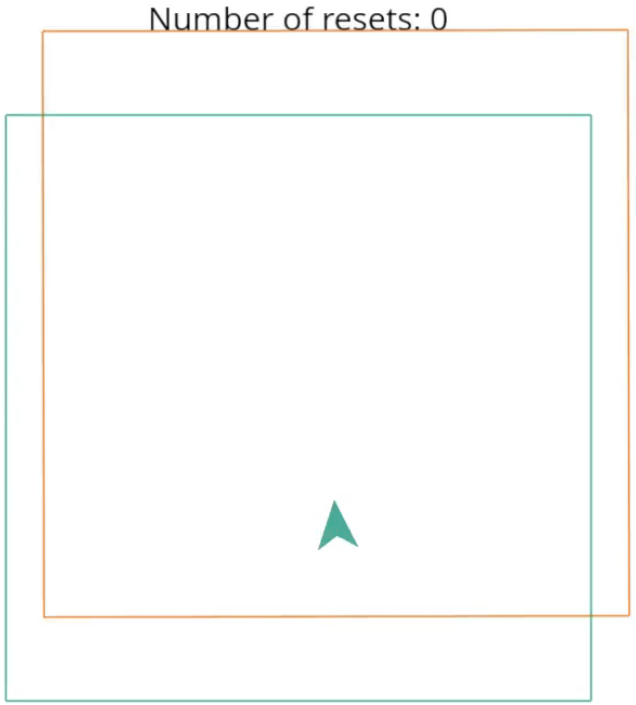
3) Williams, Niall L., Aniket Bera, and Dinesh Manocha. "Redirected walking in static and dynamic scenes using visibility polygons." *IEEE transactions on visualization and computer graphics* 27.11 (2021): 4267-4277.

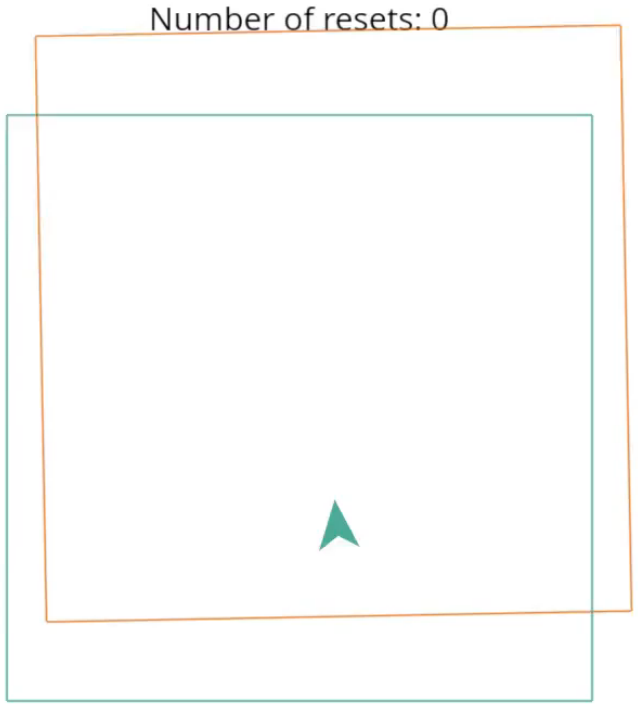
Alignment-based Redirection

How good is it?

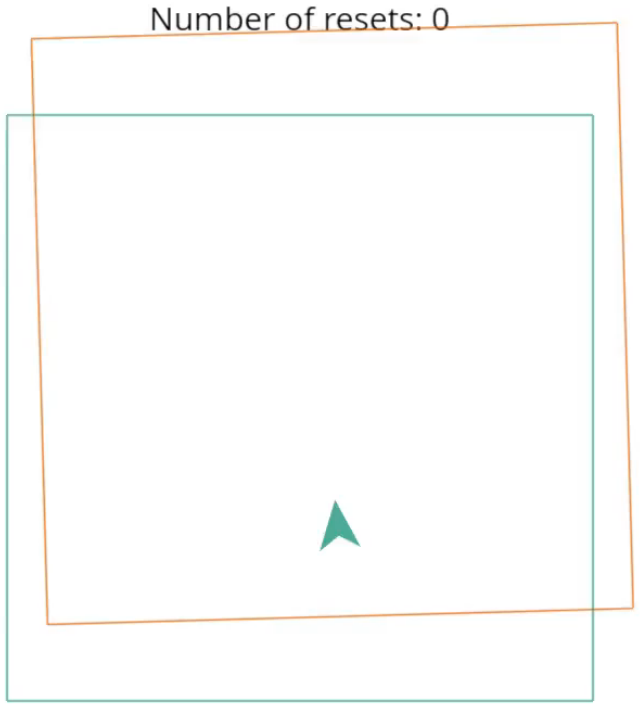
Alignment



Potential Fields

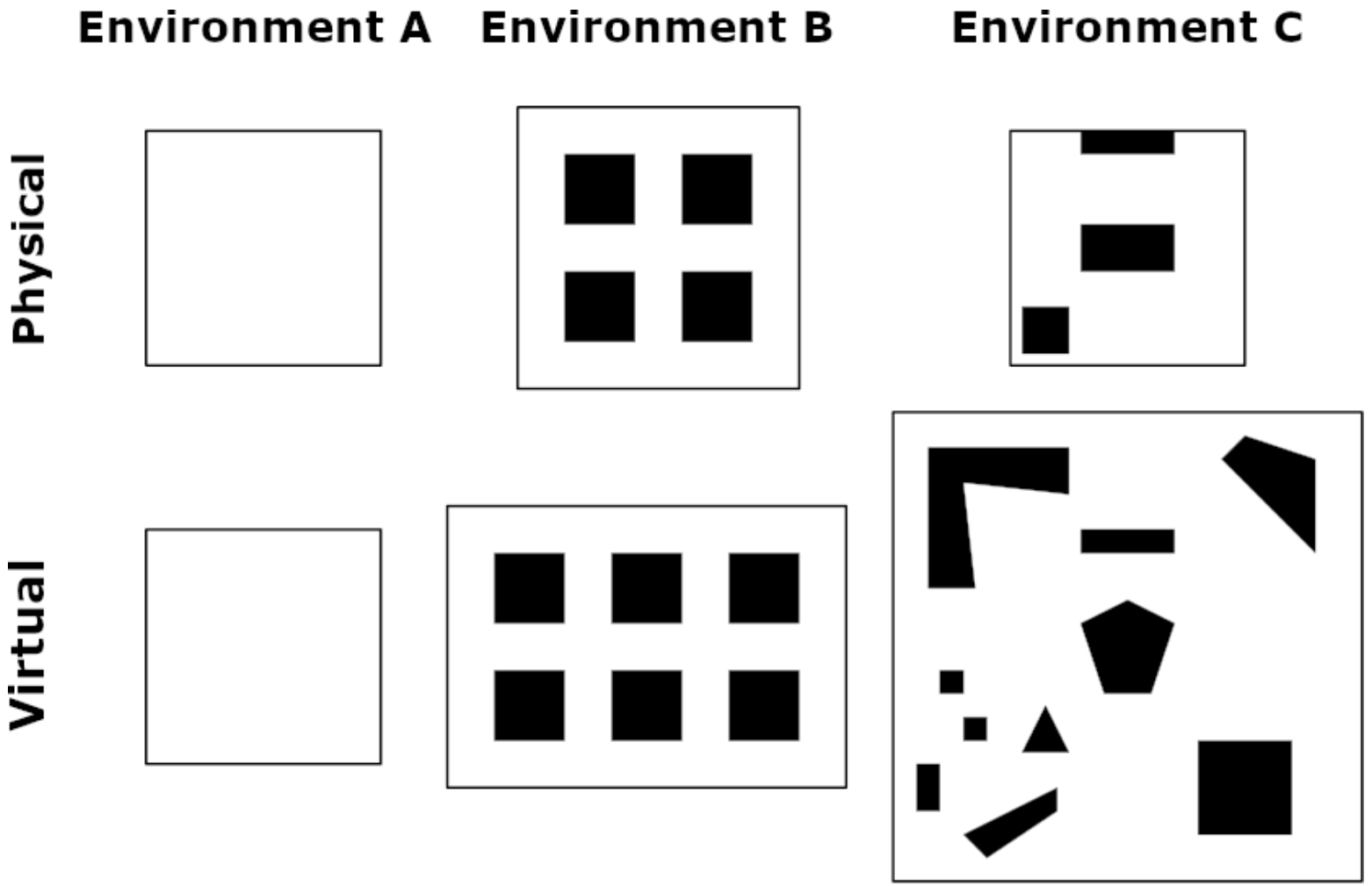


S2C



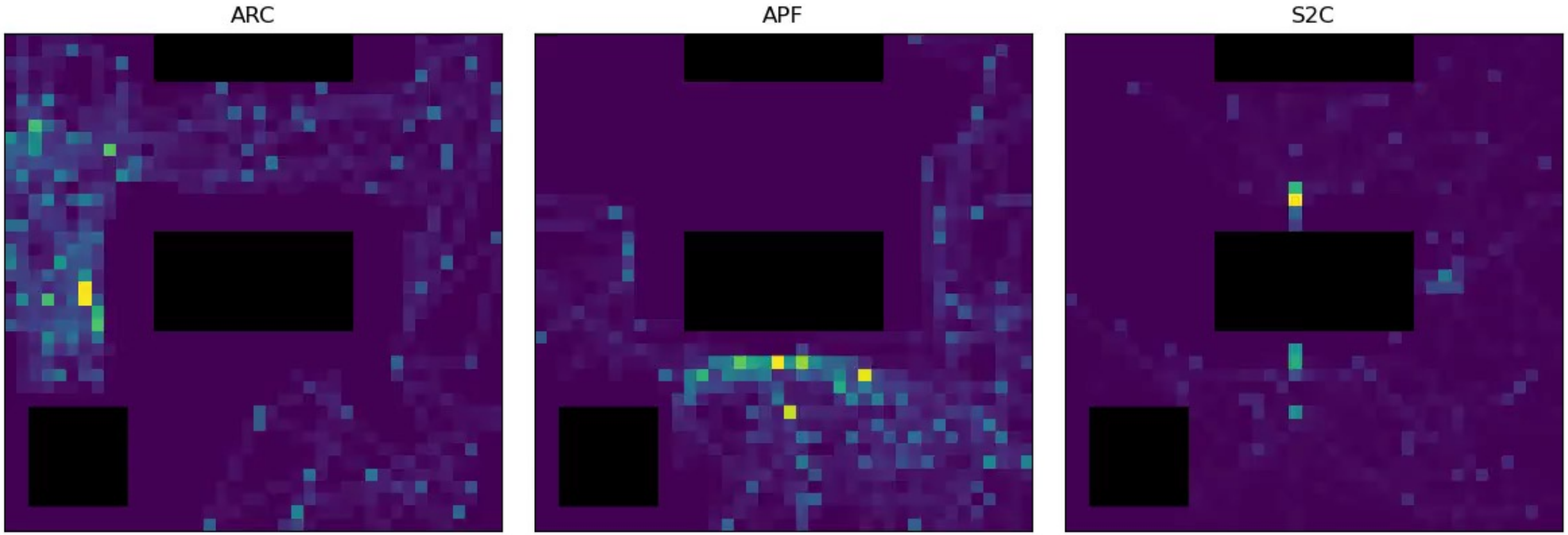
Alignment-based Redirection

How good is it?

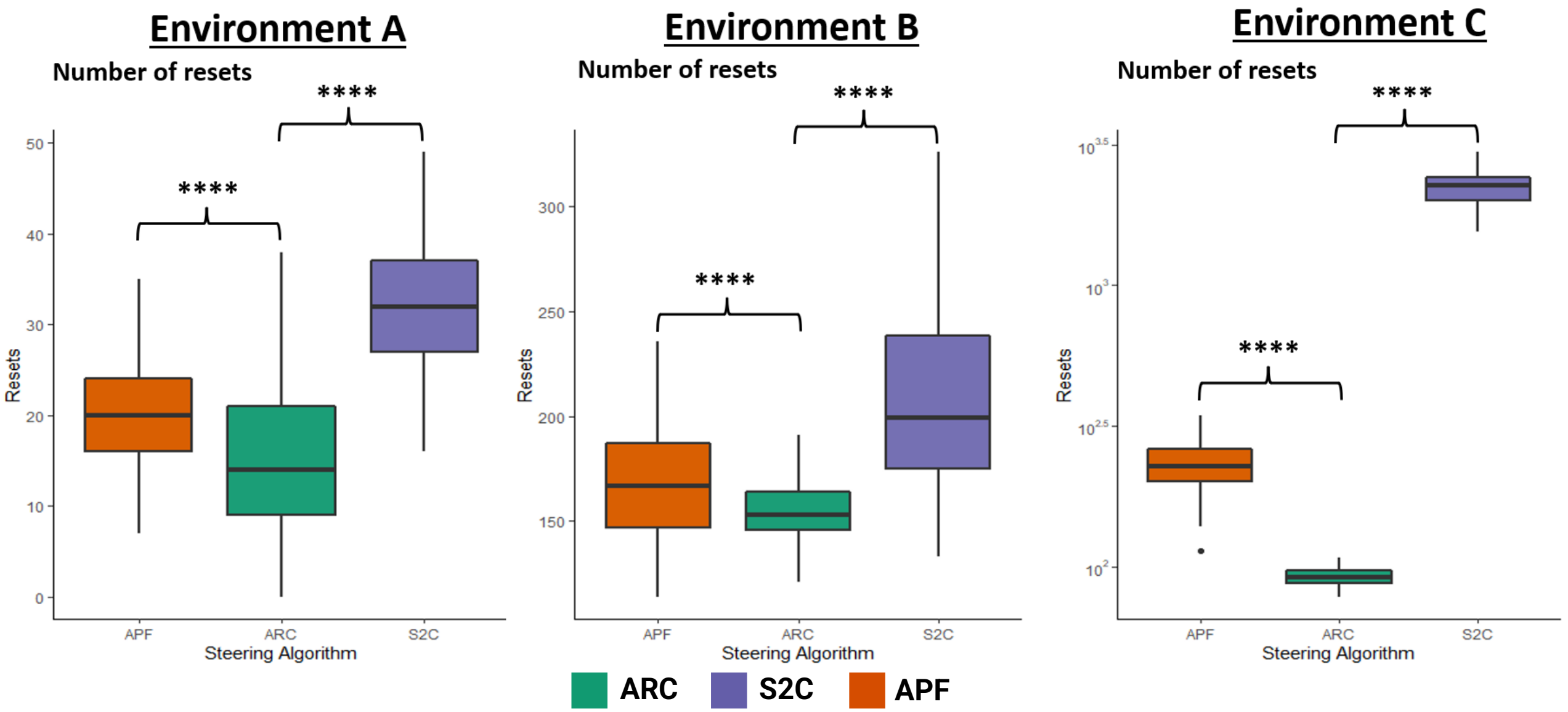


Alignment-based Redirection

How good is it?

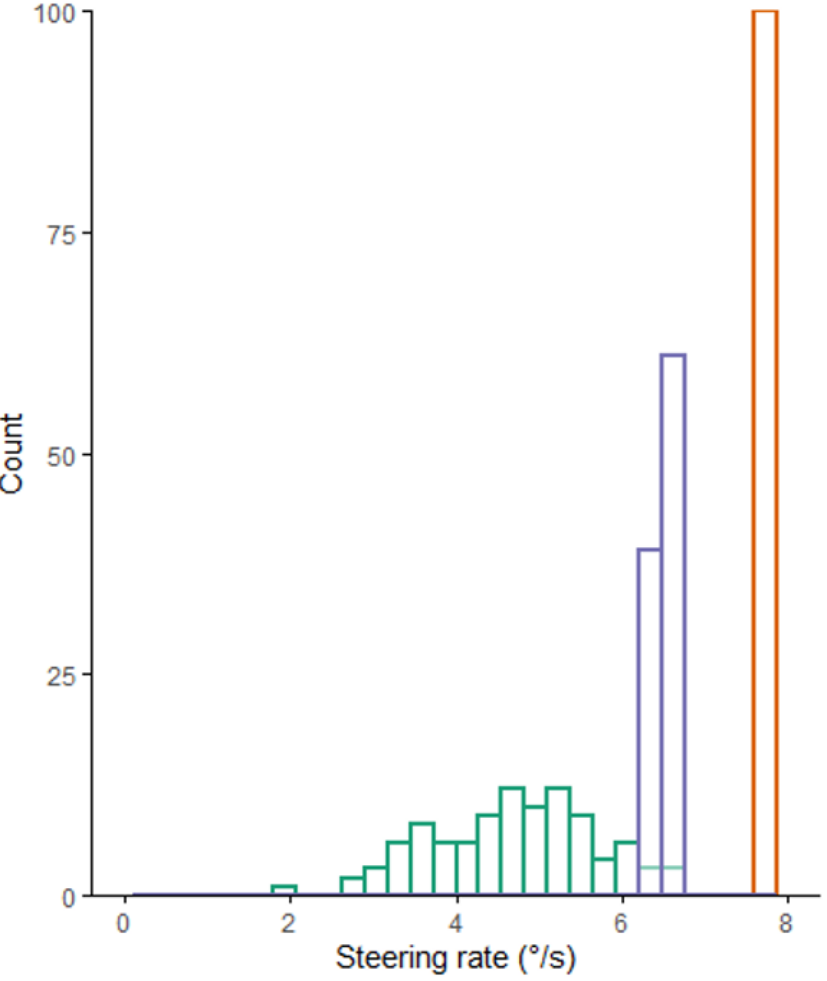


Alignment-based Redirection

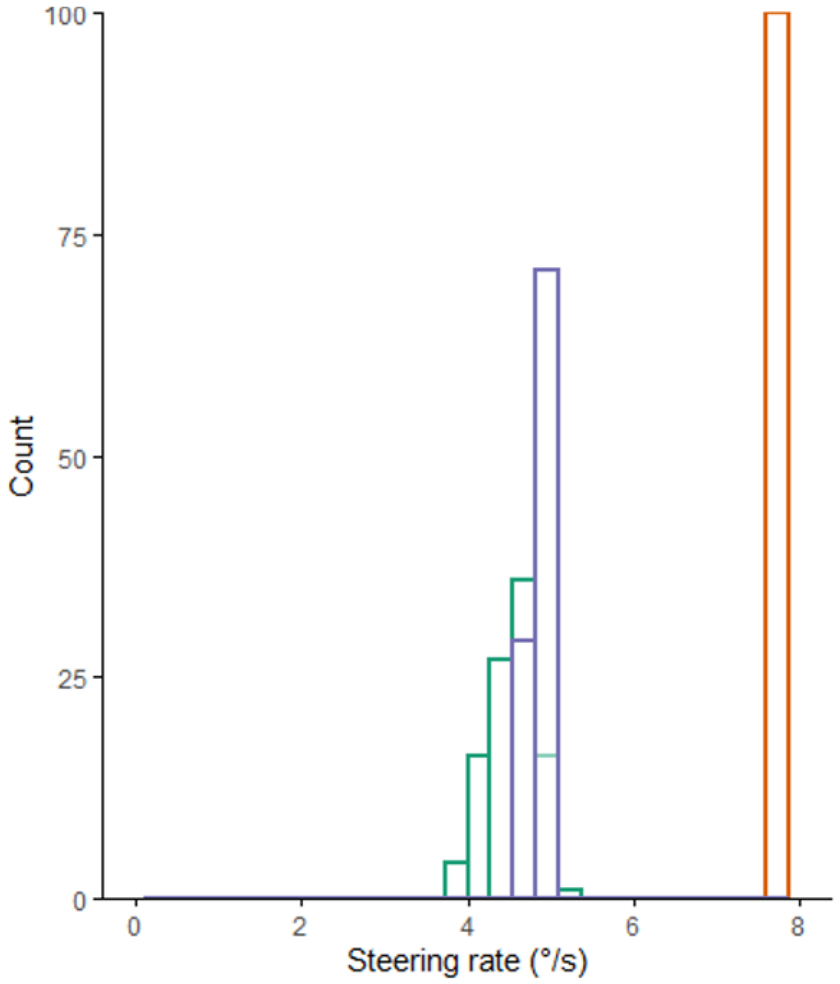


Alignment-based Redirection

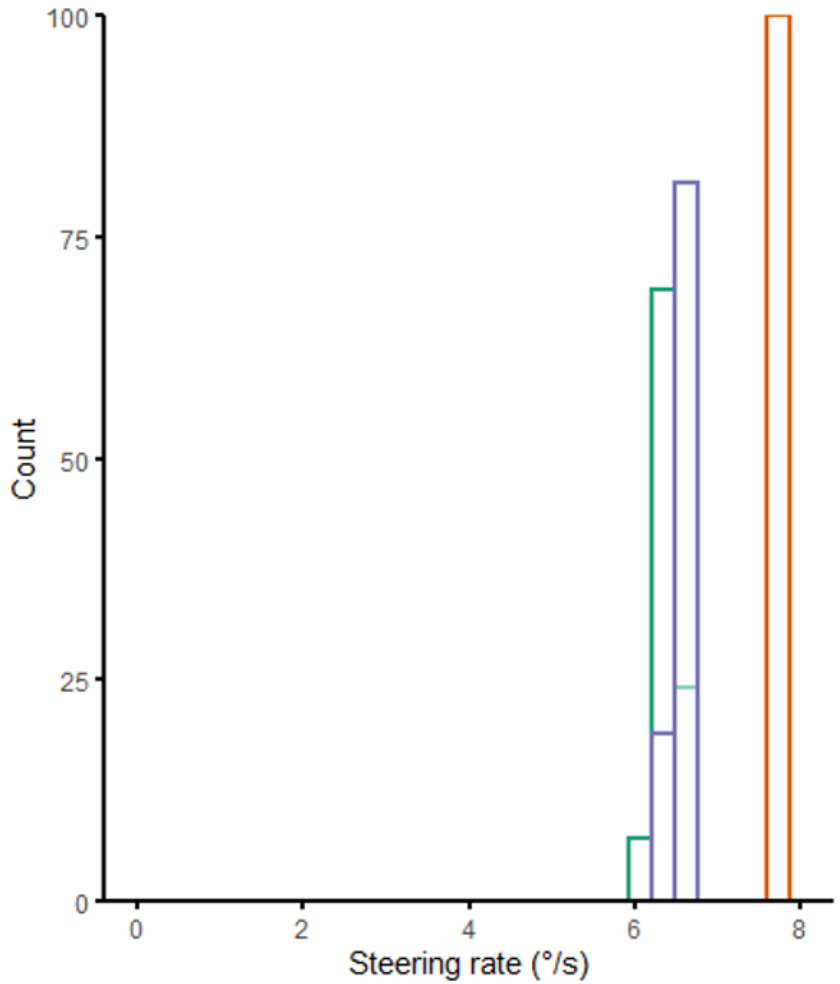
Environment A



Environment B



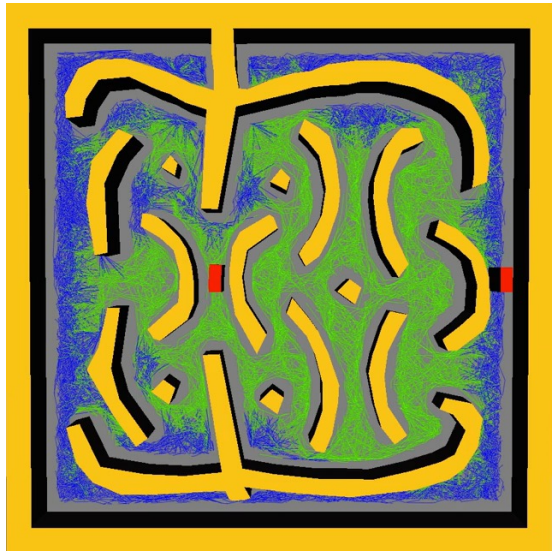
Environment C

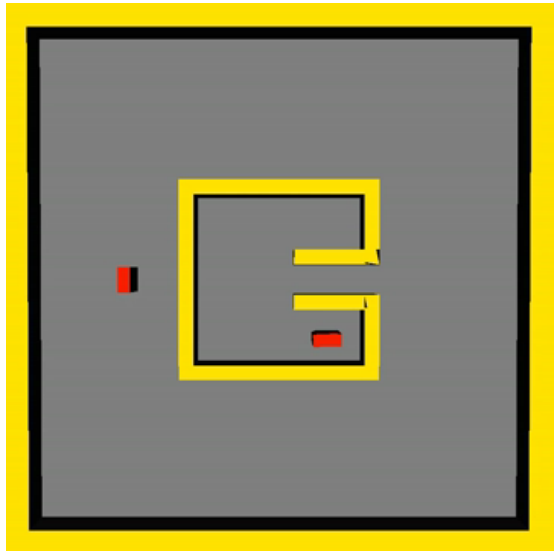


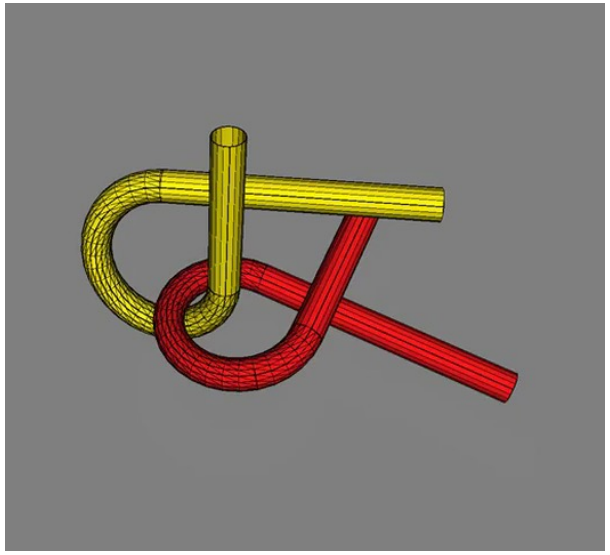
ARC S2C APF

Motion planning for Redirected Walking

- VR locomotion is a path planning problem!
- Robotics community is very good at path planning





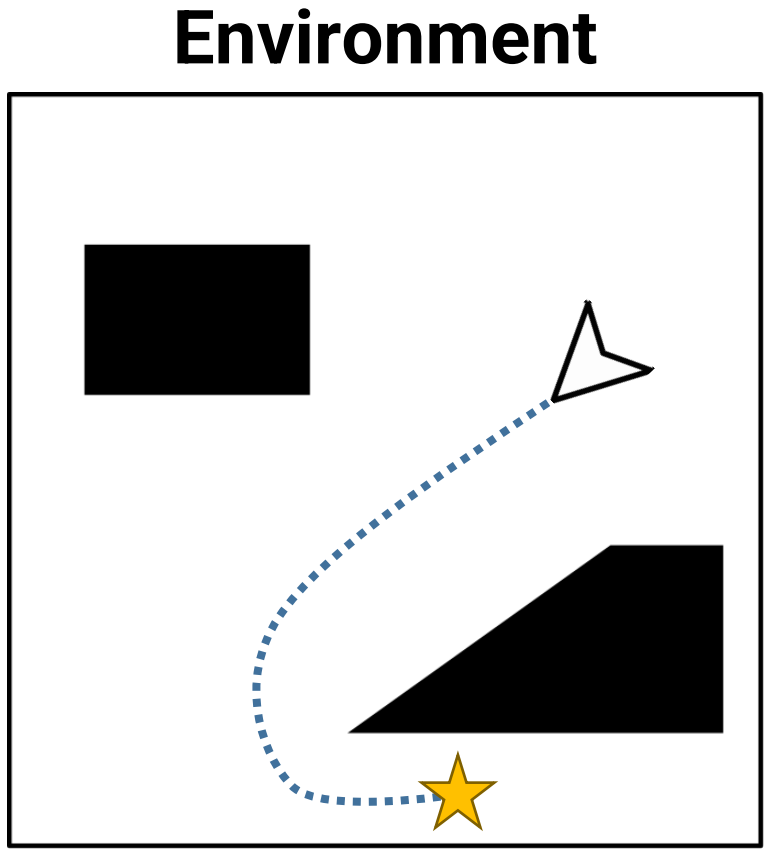


Open Motion Planning Library: *ompl.kavrakilab.org*

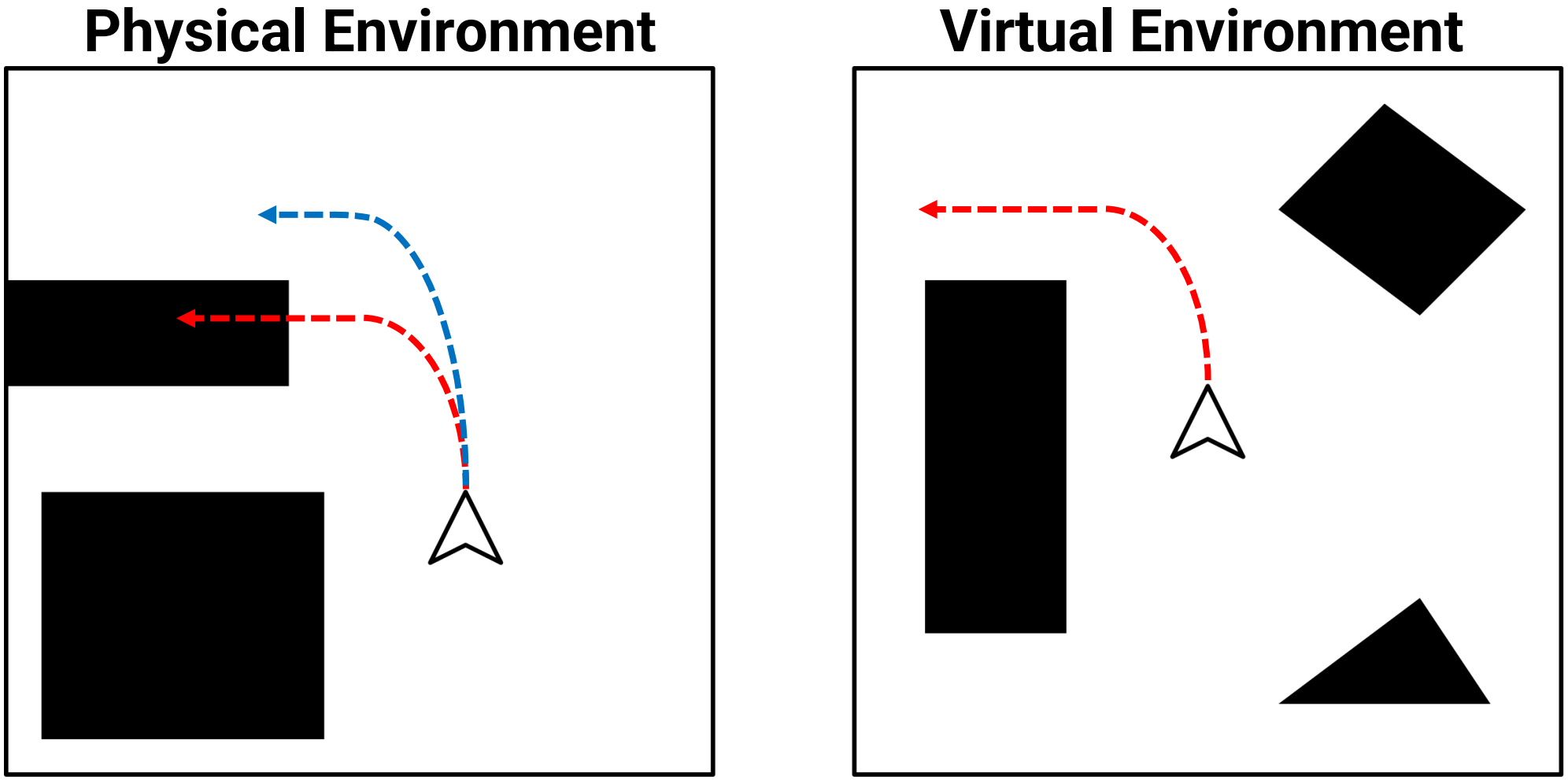
Motion planning for Redirected Walking

- 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



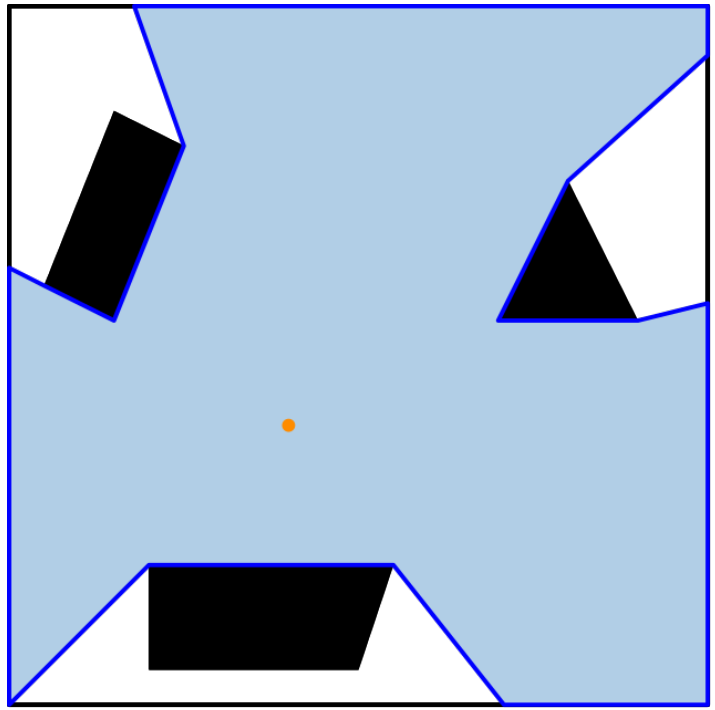
Motion planning for Redirected Walking



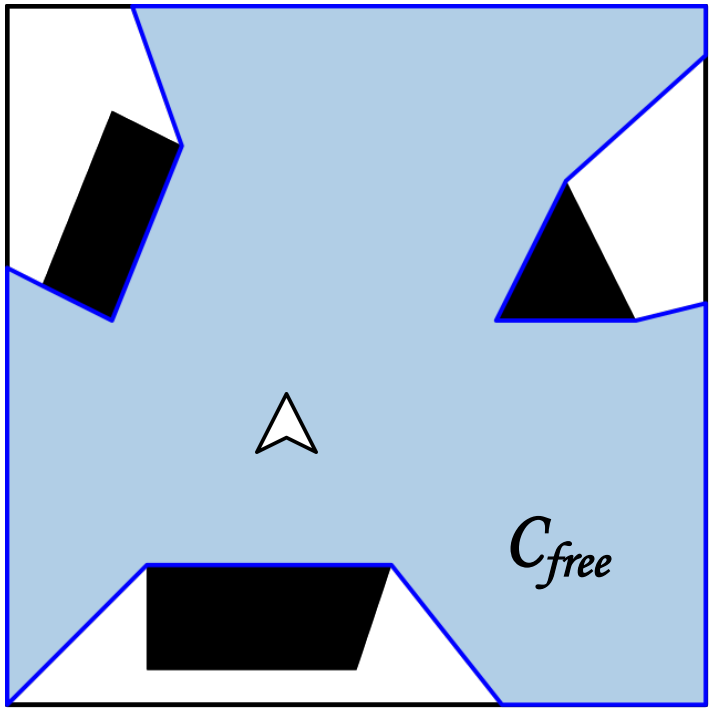
Motion planning for Redirected Walking

- Perform some reasoning about the environment structure
- Use insights to plan a path more intelligently
- Local similarity is important, so only do reasoning about the local surroundings!
  - Visibility polygon

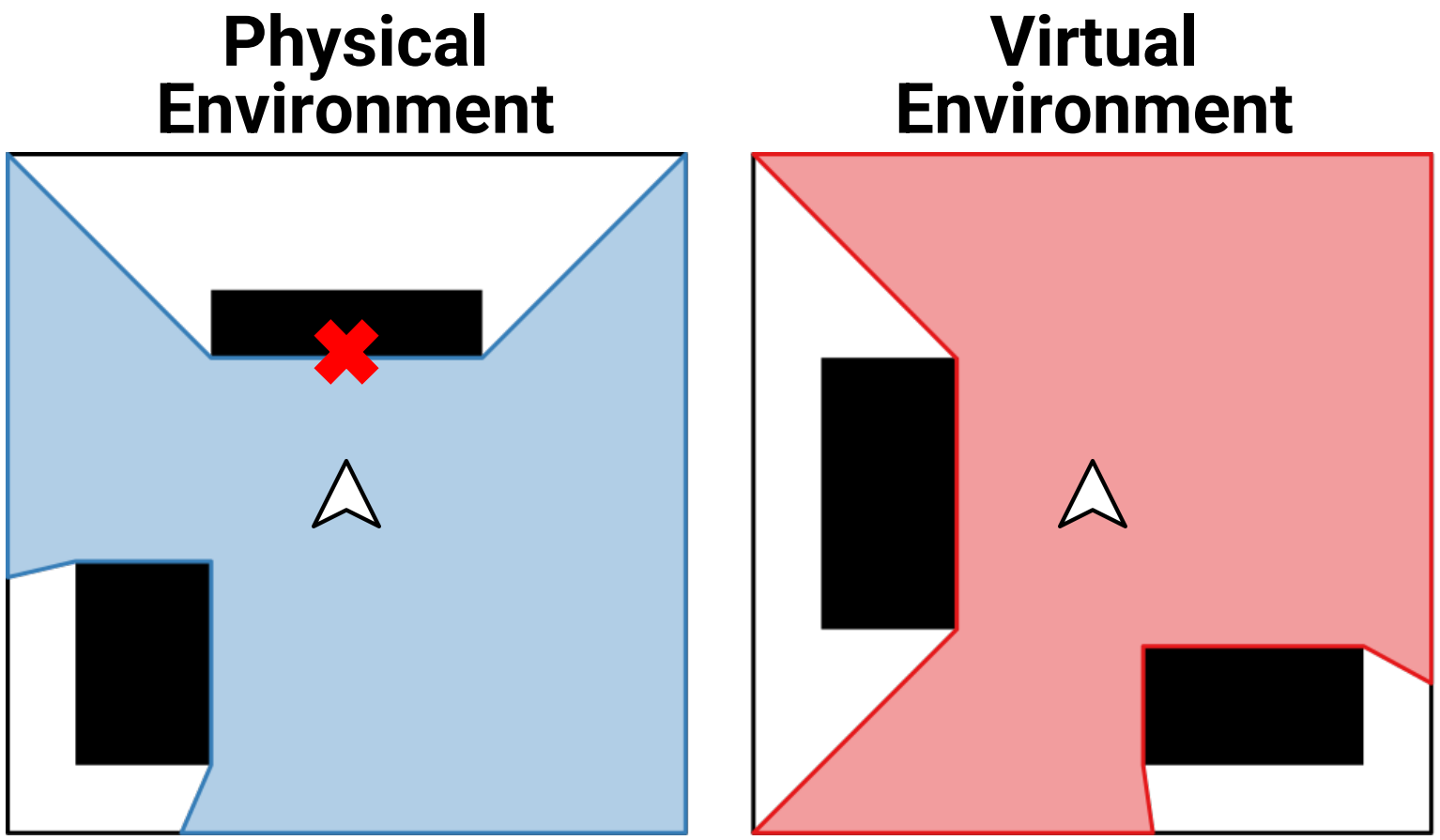
Motion planning for Redirected Walking



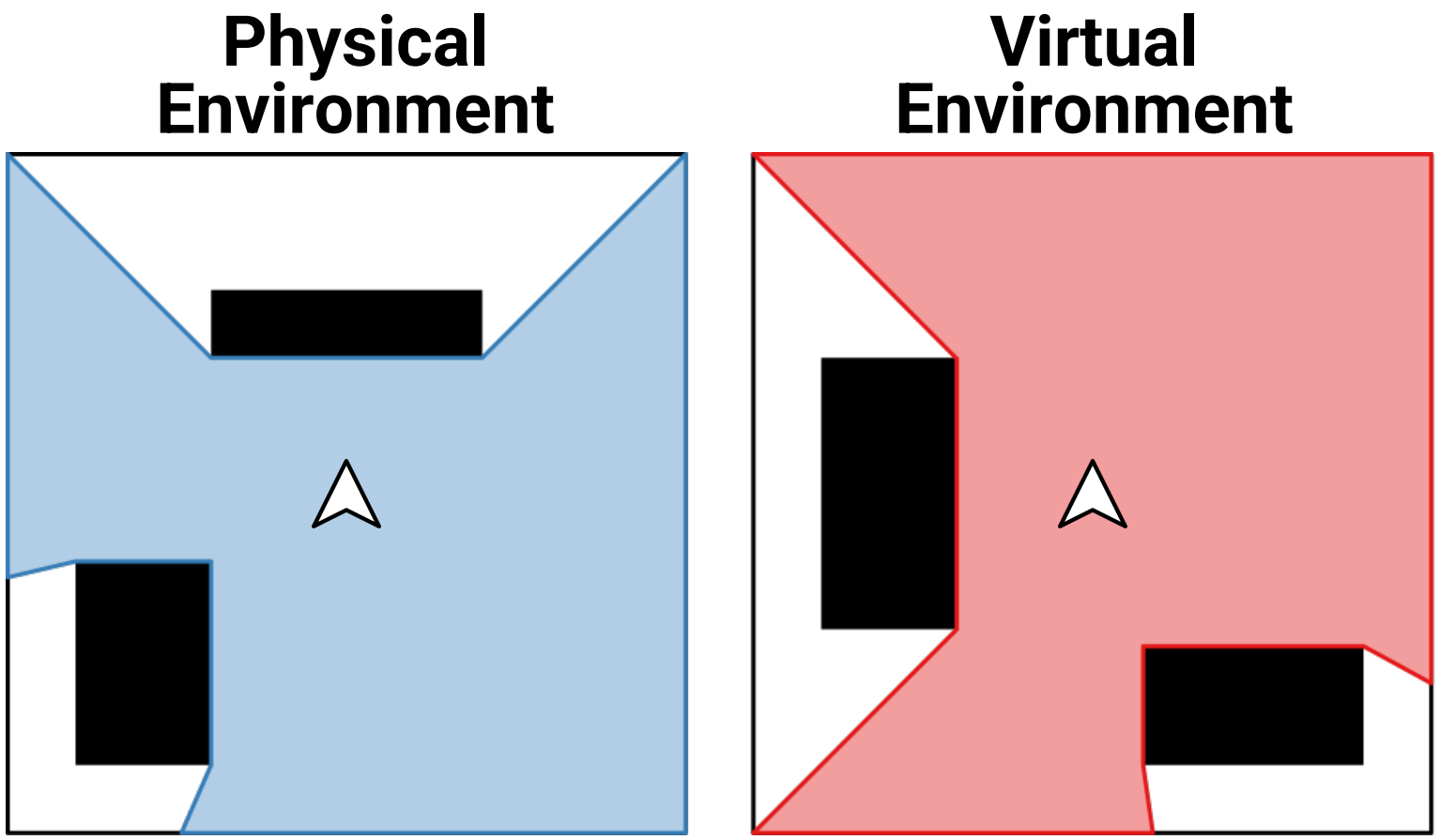
Motion planning for Redirected Walking



Motion planning for Redirected Walking

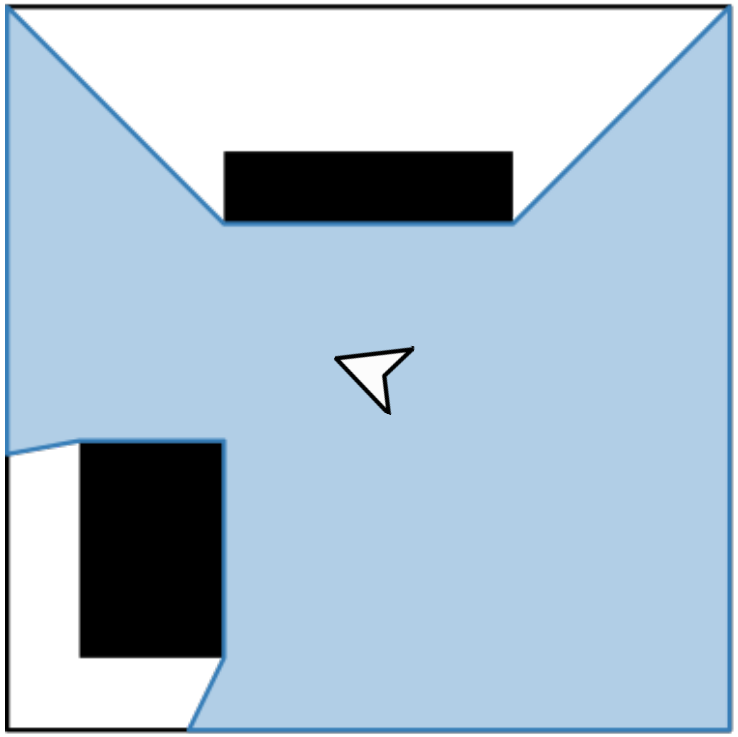


Motion planning for Redirected Walking

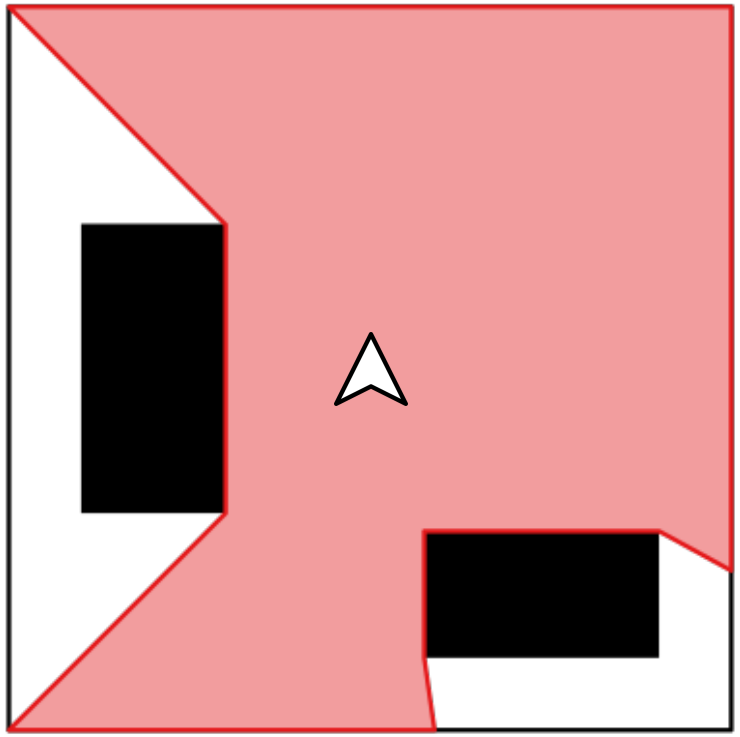


Motion planning for Redirected Walking

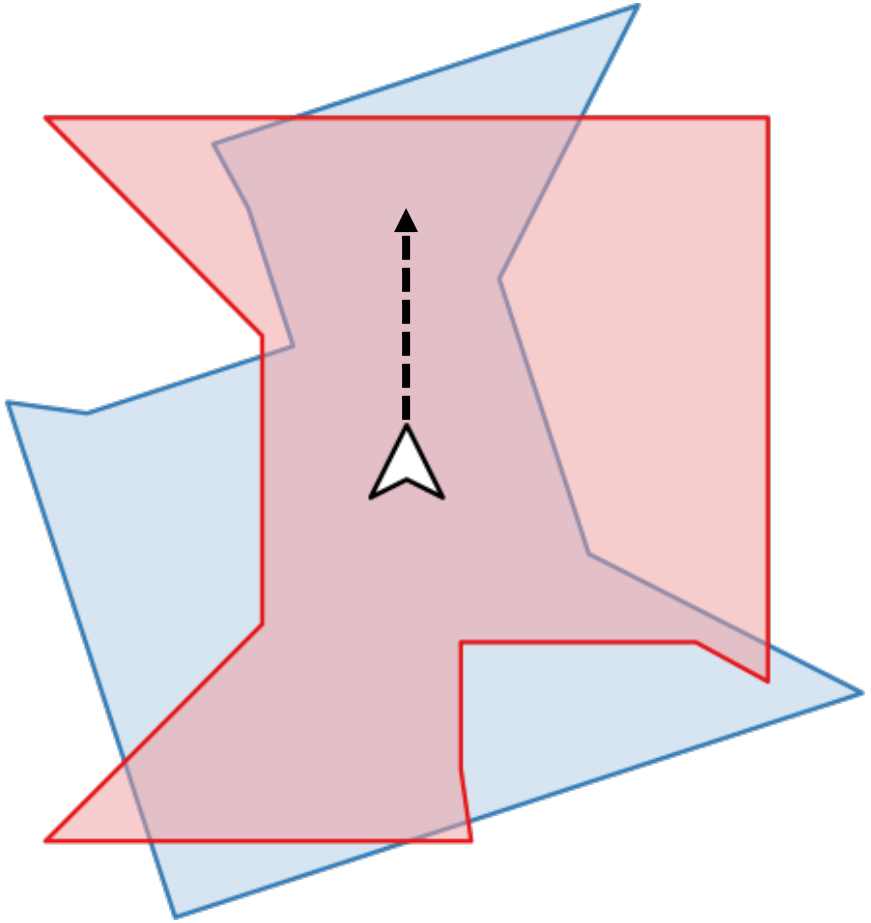
Physical Environment



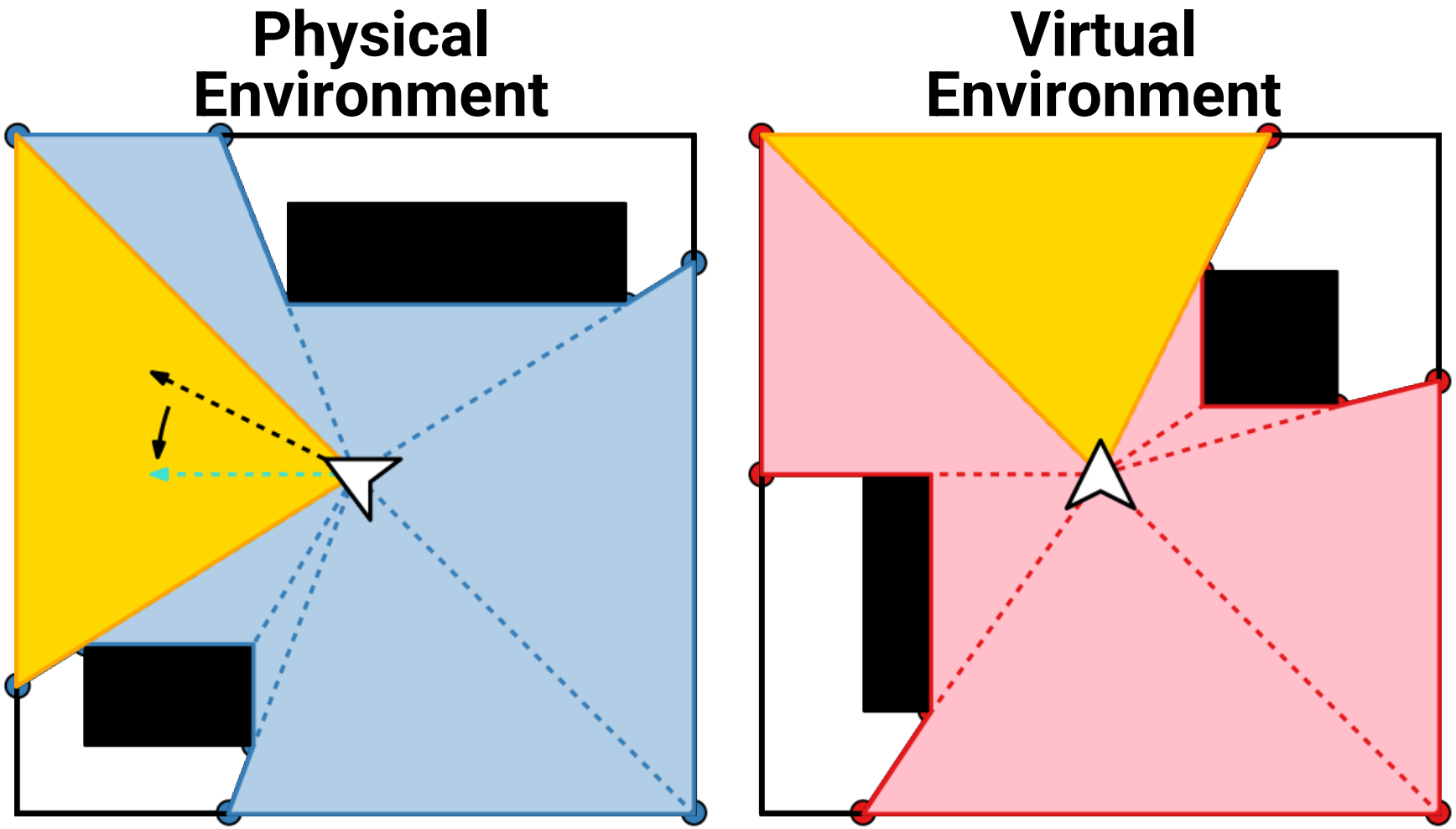
Virtual Environment



Superimposed C_{free}

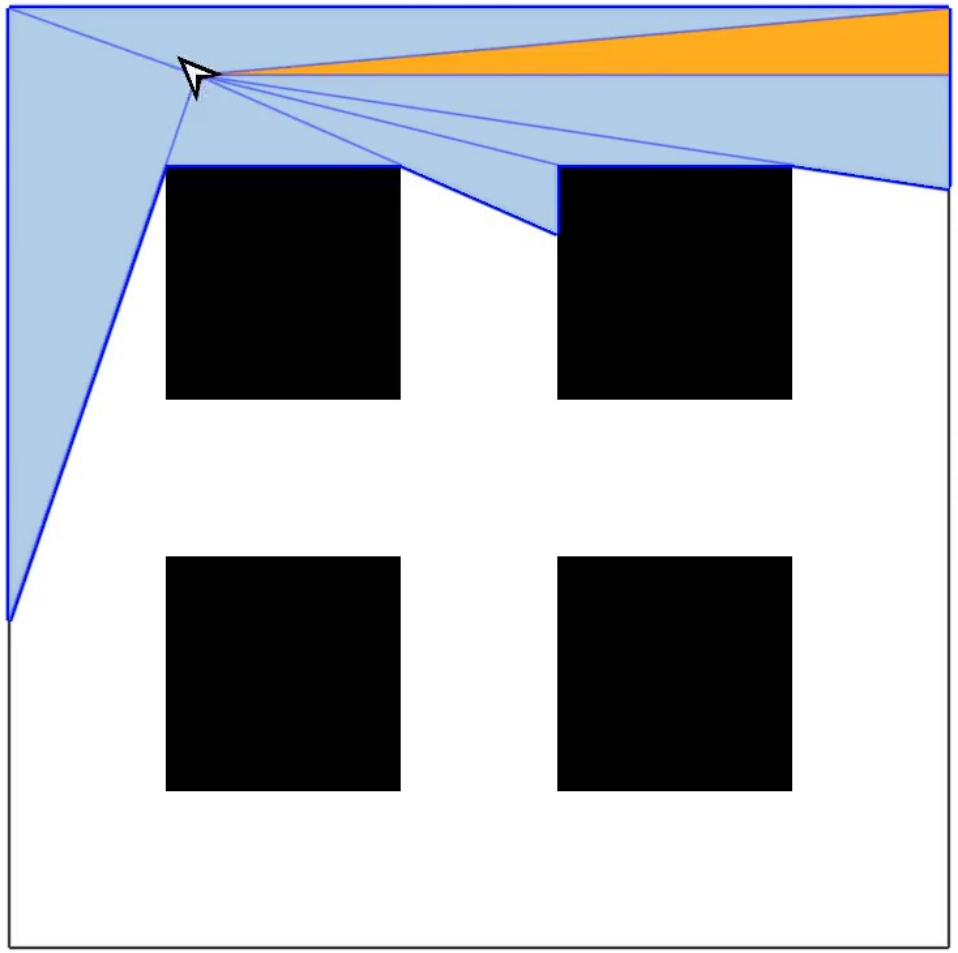


Motion planning for Redirected Walking

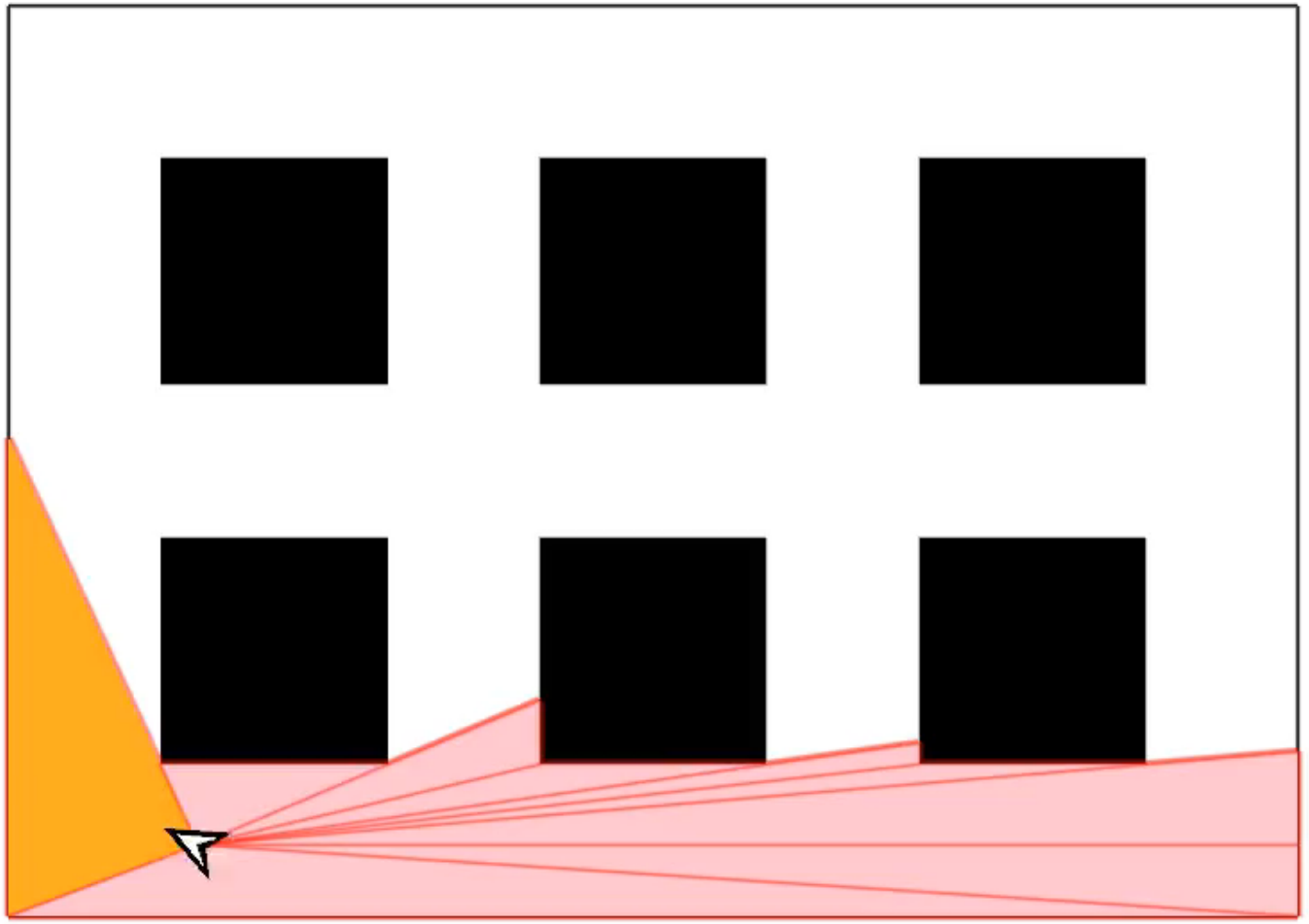


Motion planning for Redirected Walking

Physical Environment



Virtual Environment



Distractors for Redirected Walking

- Want to mask the injected rotations & translations
  - Give users something else to focus on
  - Force user to rotate their head

Distractors for Redirected Walking

- Distractor should feel realistic and compelling enough to grab the user's attention

https://www.youtube.com/watch?v=Z2ROu_FpJuU

https://youtu.be/96rxBzMK-2w?t=203

Distractors for Redirected Walking

- How to determine the distractor's behavior/movement?
  - Also motion planning!
  - Consider user's current position in the environments, and the current context

Haptics + Redirected Walking

- Can use haptics to improve the realism and strength of distractors
- Passive haptics is the opposite of redirected walking
  - Can we combine them? Sometimes…

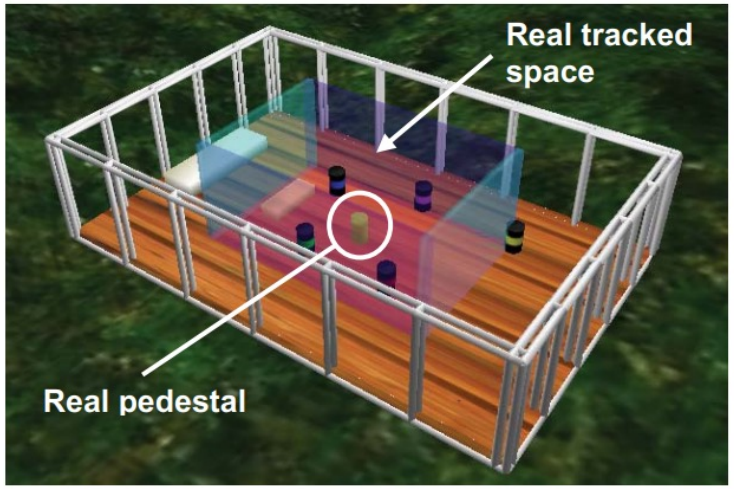
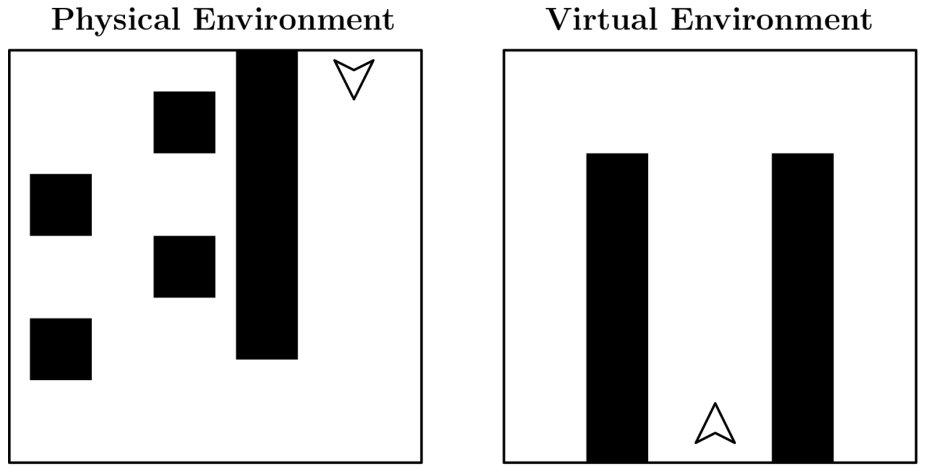


Fig. 1. A view of the virtual environment with the five striped virtual pedestals. A box indicating the size of the real tracked space is superimposed, along with the position of the real pedestal in the center.

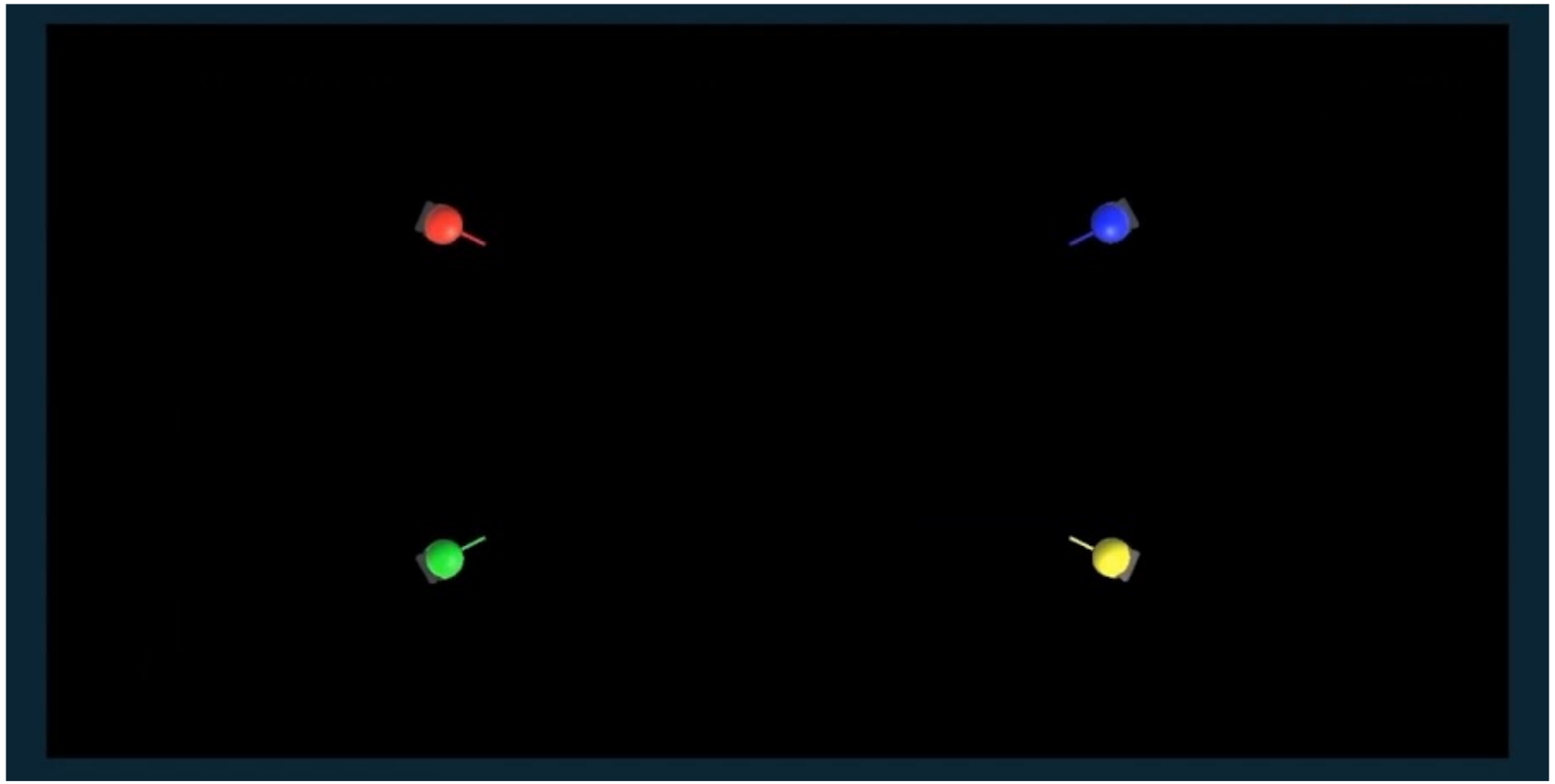
Fig. 2. A user touches the one cylindrical object intended to provide haptic feedback. The Styrofoam walls mark the limits of the tracked space.

Kohli, Luv, et al. "Combining passive haptics with redirected walking." *Proceedings of the 2005 international conference on Augmented tele-existence*. 2005.

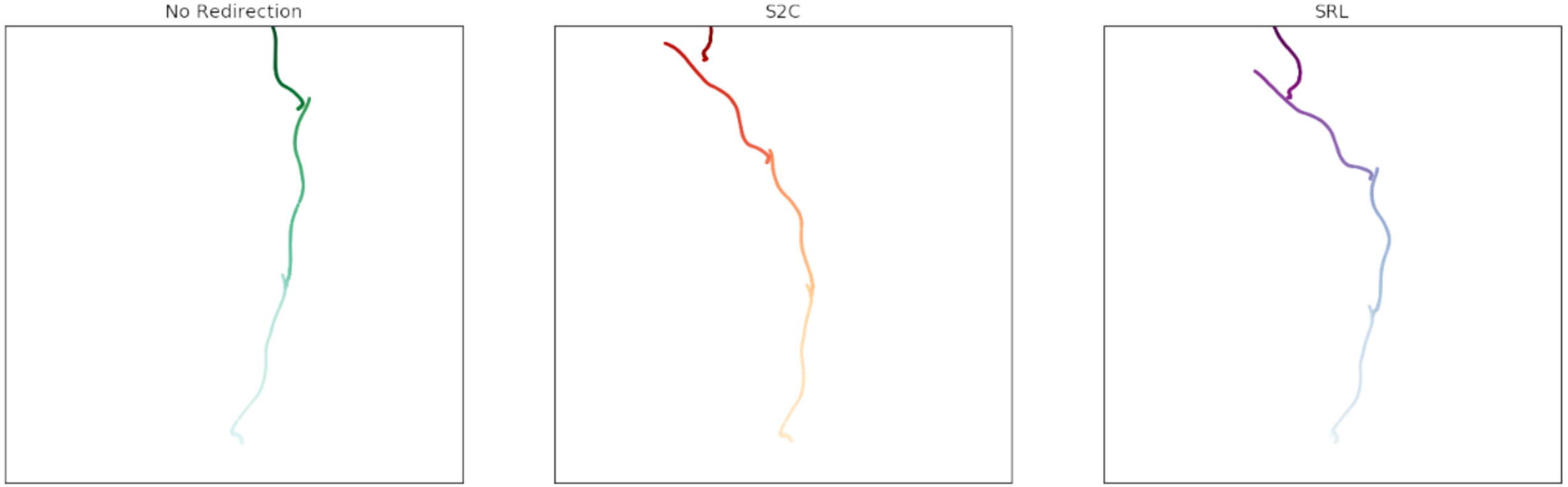


Williams, Niall L., Aniket Bera, and Dinesh Manocha. "Arc: Alignment-based redirection controller for redirected walking in complex environments." *IEEE Transactions on Visualization and Computer Graphics* 27.5 (2021): 2535-2544.

Multi-User Redirection

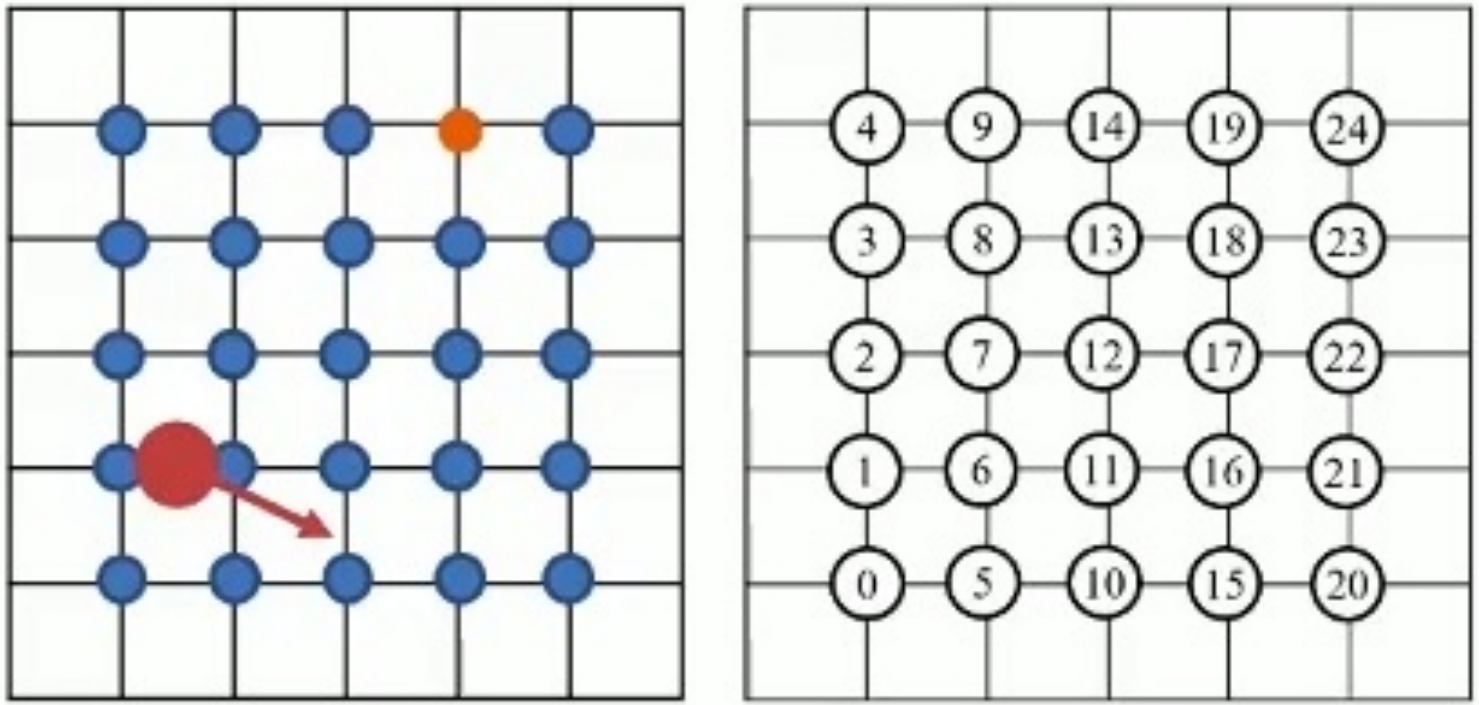


Deep Learning for Redirected Walking



Strauss, Ryan R., et al. "A steering algorithm for redirected walking using reinforcement learning." *IEEE transactions on visualization and computer graphics* 26.5 (2020): 1955-1963.

Deep Learning for Redirected Walking



https://www.youtube.com/watch?v=ZZfZ2AC2ec0

Lee, Dong-Yong, Yong-Hun Cho, and In-Kwon Lee. "Real-time optimal planning for redirected walking using deep q-learning." *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2019.