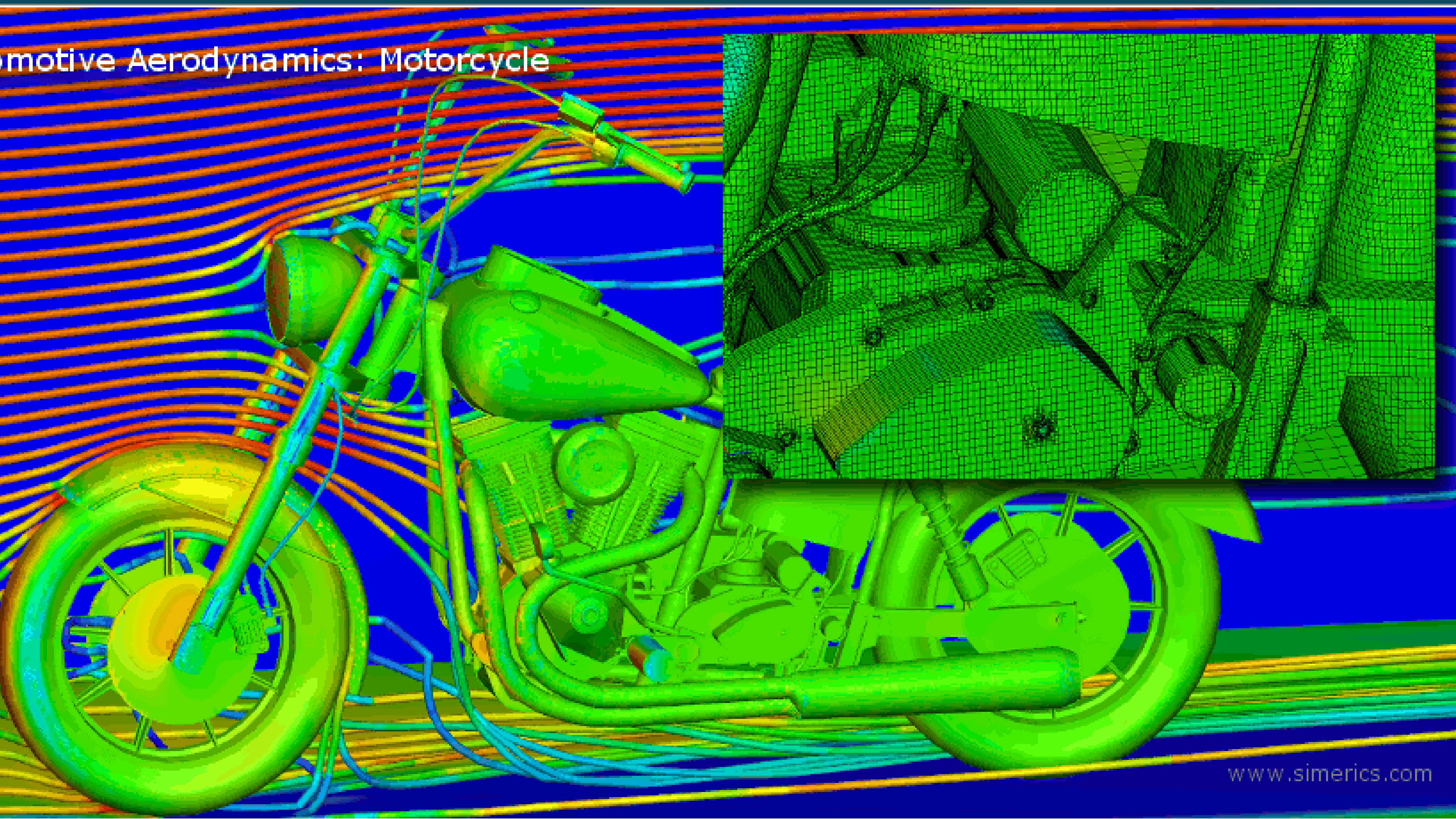
SAARBRÜCKEN
EUROGRAPHICS 2023

Effective User Studies in Computer Graphics

Sandra Malpica (1), Qi Sun (2), Petr Kellnhofer (3), Alejandro Beacco (4, 5), Gizem Senel (5), Rachel Mcdonnell (6) and Mauricio Flores Vargas (6)

(1) *Universidad de Zaragoza*, (2) *New York University*, (3) *TUDelft*, (4) *Universitat Politecnica de Catalunya*, (5) *Universitat de Barcelona*, (6) *Trinity College Dublin*


omotive Aerodynamics: Motorcycle
www.simerics.com

Introduction

We need to consider human perception and behavior

Introduction

Introduction

- Subjective by nature

Introduction

- Subjective by nature
- No direct measures

Introduction

- Subjective by nature
- No direct measures
- Confounding factors

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- Inter-user variability

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- Inter-user variability
- Metrics and models

Introduction

- Subjective by nature
- No direct measures
- Confounding factors
- High-dimensional space
- Bias
- Inter-user variability
- Metrics and models
- Generalization

How?

We study human perception and behavior through user studies

Why/When?

- Validation?

Why/When?

User studies are useful at every step of a project!

- Planning
- Early design
- Prototyping
- Feature exploration
- Applied proofs of concept
- Data collection for model training
- Validation
- Generalizability

What?

Different type of information obtained depending on the methodology

- Performance metrics
- Surveys
- Interviews
- Physiological data
- Ratings
- Behavioral data

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Overview

Good practices for user studies

Sandra Malpica (Universidad de Zaragoza)

- Now postdoctoral researcher at *Universidad Politecnica de Catalunya*
- Research: Visual and multimodal perception in immersive environments

Overview

Developing computational models with mathematical and neurological insights

Qi Sun (NYU)

- Assistant Professor at NYU
- Research: VR/AR, computational cognition and behavioral performance

Overview

Seeing in depth

Petr Kellnhofer (TU Delft)

- Assistant professor in the Computer Graphics and Visualization Group at TU Delft
- Research: Computational imaging and perceptual aspects of AR/VR/lightfield displays

Overview

Experiencing virtual reality through embodiment

Alejandro Beacco (Universitat Politecnica de Catalunya)

- Associate Professor in the VIRViG research group at Universitat Politecnica de Catalunya
- Research: Visualization, animation and simulation of virtual crowds

Overview

Experiencing virtual reality through embodiment

Gizem Senel (Universitat de Barcelona)

- Last-year PhD candidate at EVENT lab (University of Barcelona)
- Research: Body transformation and therapeutic applications of virtual reality

Overview

Virtual characters

Rachel McDonnell (Trinity College Dublin)

- Associate Professor in Creative Technologies at the School of Computer Science and Statistics at Trinity College Dublin
- Research: Character animation, virtual humans, VR and perception

Overview

Audio in virtual reality

Mauricio Flores Vargas (Trinity College Dublin)

- Creative arts professional and PhD student
- Research: Sound design and composition, AR and VR experiences

Overview

Good practices for user studies

Developing computational models with mathematical and neurological insights

Seeing in depth

Experiencing virtual reality through embodiment

Virtual characters

Audio in virtual reality

Good practices for user studies

Good practices for user studies

- Define your **research questions**
    - *How is depth perceived in a virtual environment?*
    - *Which of these compression methods has better perceived quality?*
    - *Is my model similar to human behavior?*
    - *What type of hardware is more comfortable for my users?*
    - *Do we perceive this physical phenomena accurately?*

Good practices for user studies

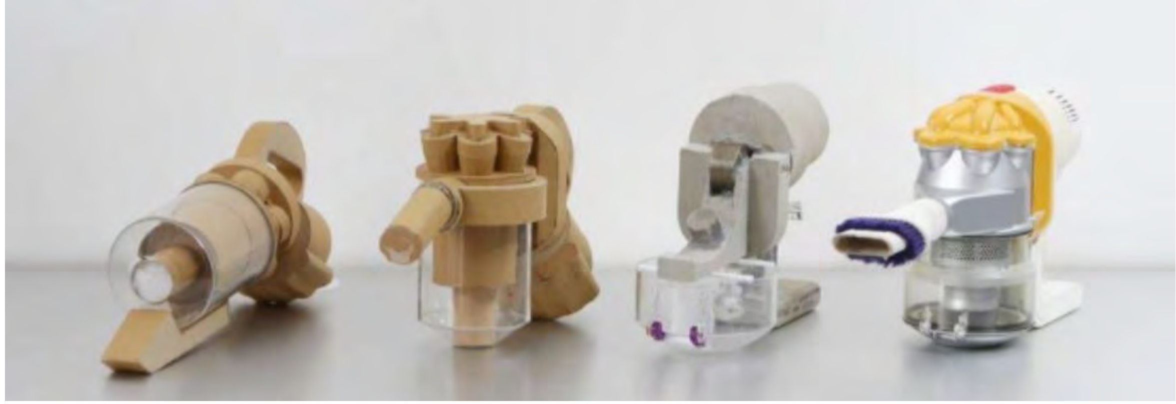
- Define your **experimental procedure**
  - Methodology
  - Stimuli
  - Metrics
  - Analysis
  - Duration
  - Ethics and compensation
  - Control
  - Randomization

Good practices for user studies

- Define your **target population**
    - Demographic characteristics: *age, gender, nationality, etc.*
    - Previous experience and knowledge
    - How many users do you need?
    - Can every user experience the same conditions?

Good practices for user studies

- **Prototyping** is good!
  - Use pilots to adjust the factors you study
  - Controlling confounding factors
  - Deciding between several alternatives
  - Optimizing time and resources!



Good practices for user studies

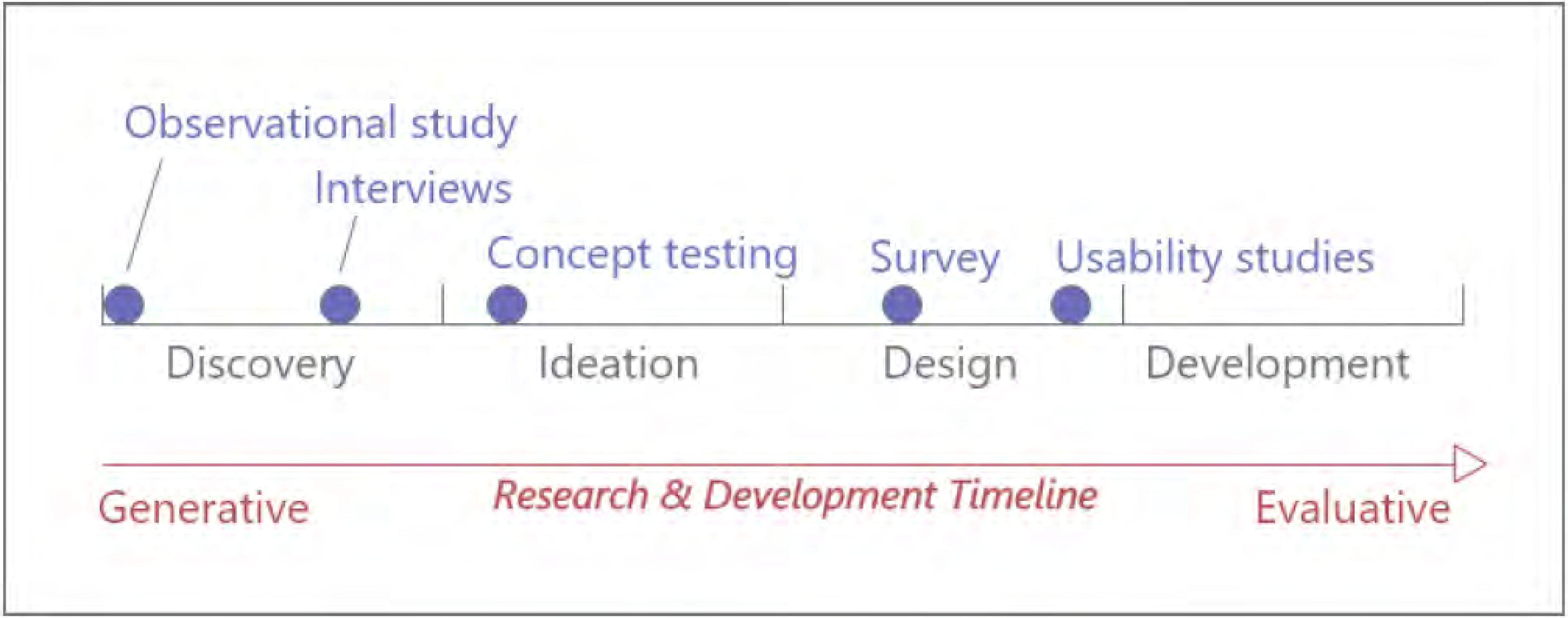
- What factors contribute to the experience?
- What methods can we use to measure an effect?

Not always a linear process!!

Methodology vs metrics

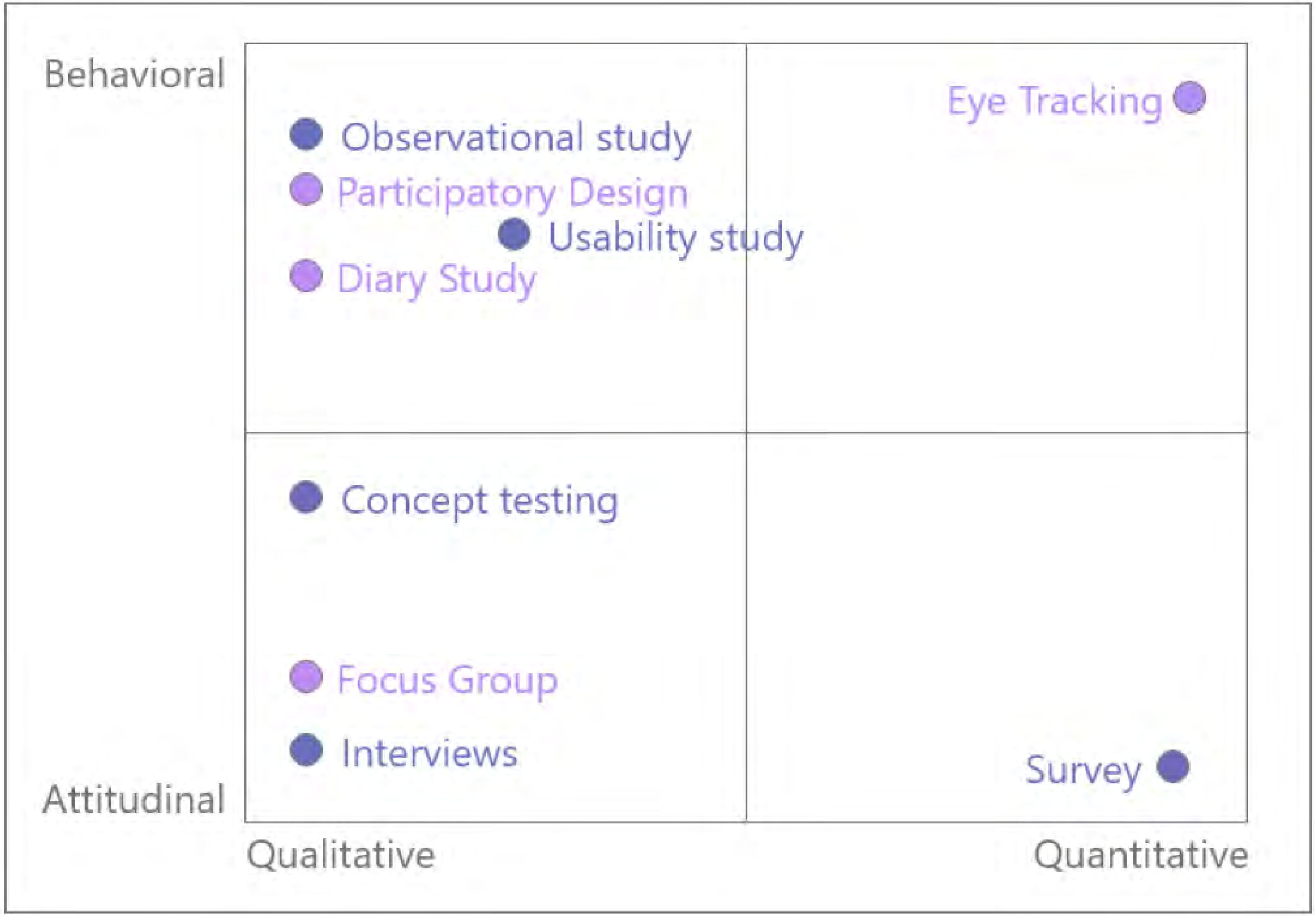
- Methodology: How to obtain information
- Metrics: The information you get

Generative to evaluative methods



Bylinskii, Z., Herman, L., Hertzmann, A., Hutka, S., & Zhang, Y. (2022). Towards Better User Studies in Computer Graphics and Vision. *arXiv preprint arXiv:2206.11461*.

Qualitative vs quantitative methods



Bylinskii, Z., Herman, L., Hertzmann, A., Hutka, S., & Zhang, Y. (2022). Towards Better User Studies in Computer Graphics and Vision. *arXiv preprint arXiv:2206.11461*.

Metrics

- Psychometrics: **objective** measurement of **latent constructs** that cannot be directly observed

Metrics

- Psychometrics: **objective** measurement of **latent constructs** that cannot be directly observed, inferred through **mathematical modelling** based on individuals’ **observable responses**

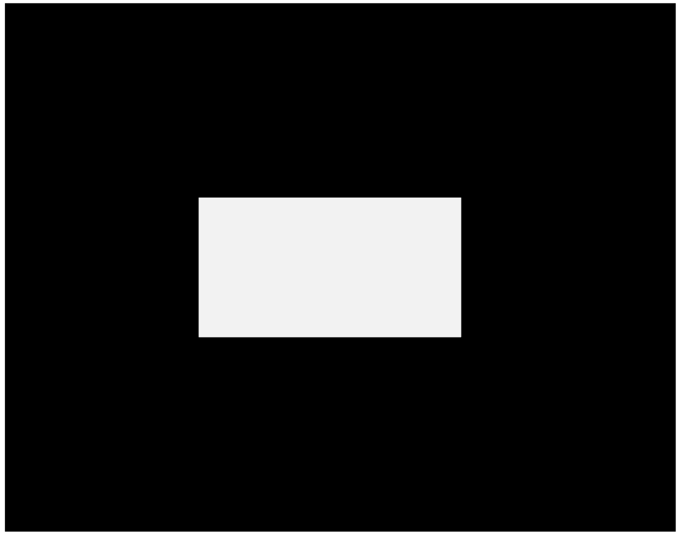
Metrics

- Psychometrics: **objective** measurement of **latent constructs** that cannot be directly observed, inferred through **mathematical modelling** based on individuals' **observable responses**

Common procedures

Detection

- Absolute value of a factor: *How bright?*



Discrimination

- Difference between levels: *Which is brighter?*

Scaling

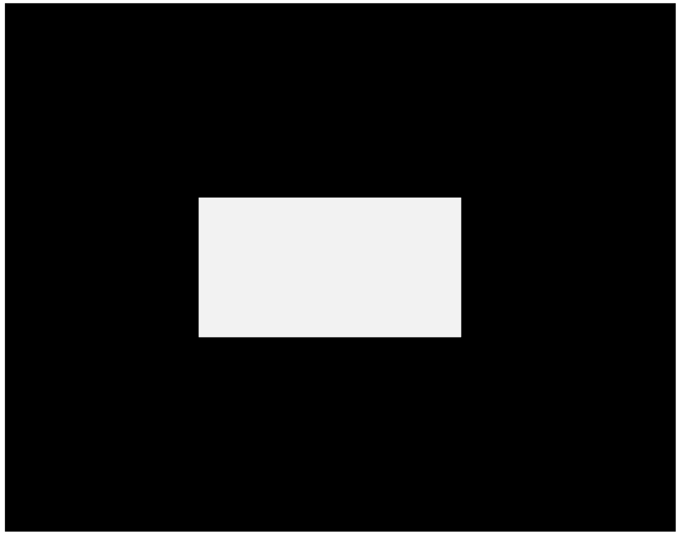
- Ordering levels: *Which is more similar? Which is twice as bright?*

Common procedures

Detection

- Absolute value of a factor: *How bright?*

Discerning between signal and noise



Signal detection theory (SDT)

	Respond "Absent"	Respond "Present"
Stimulus Present	**Miss**	**Hit**
Stimulus Absent	Correct Rejection	False Alarm

How far is the traffic light?

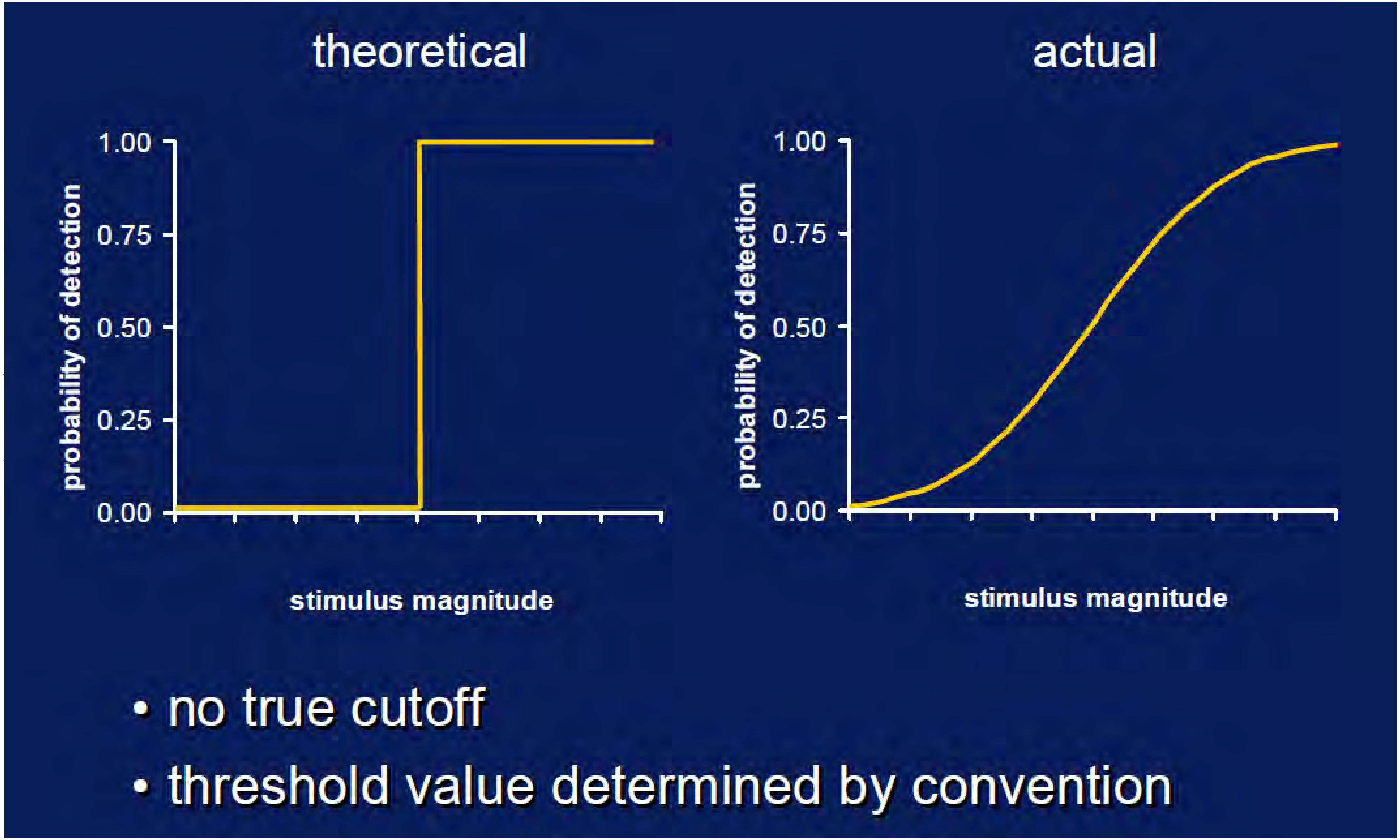
Common procedures

Discrimination

- Difference between levels: *Which is brighter?*

Difference threshold: Just noticeable differences (JND)

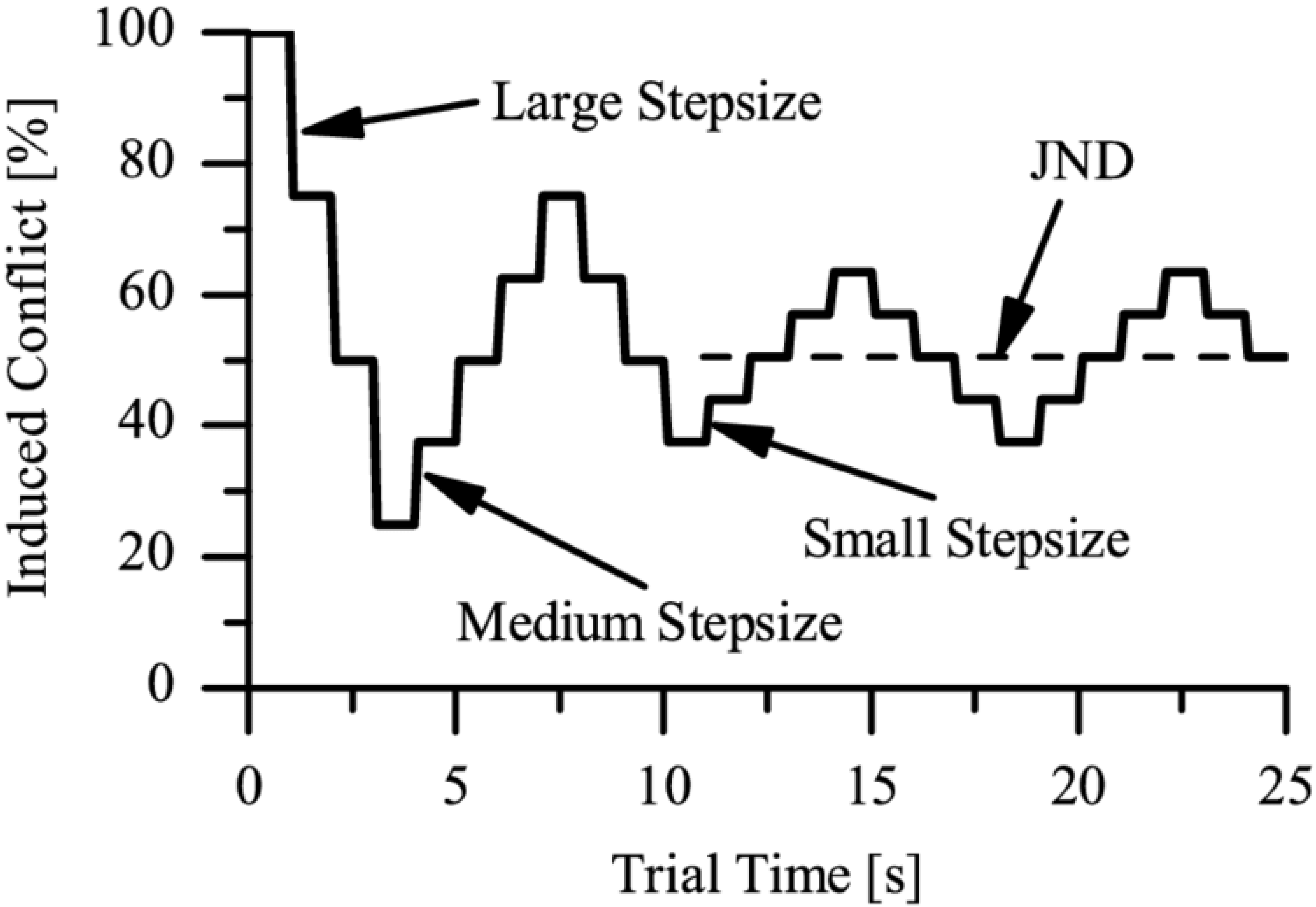
Measuring thresholds



- no true cutoff
- threshold value determined by convention

Ferwerda, J. A. (2008). Psychophysics 101: How to run perception experiments in computer graphics. In *ACM SIGGRAPH 2008 classes* (pp. 1-60).

Staircase method to measure JND



Kuschel, M. (2009). *Visual-Haptic Presence Systems: Utility Optimization, Compliance Perception, and Data Compression* (Doctoral dissertation, Technische Universität München).

Common procedures

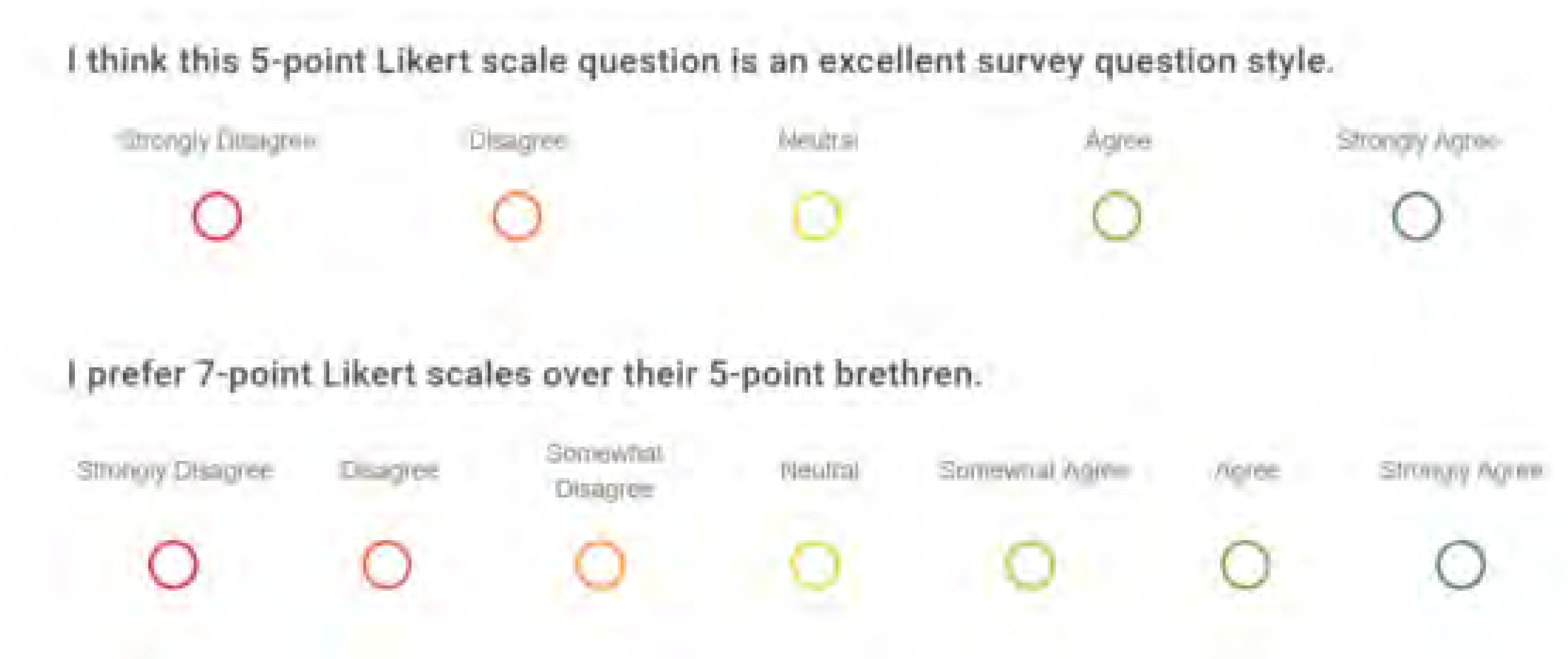
Scaling

- Ordering levels: *Which is more similar? Which is twice as bright?*

Direct and indirect scaling methods

Scaling methods

Indirect : Ranking



I think this 5-point Likert scale question is an excellent survey question style.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

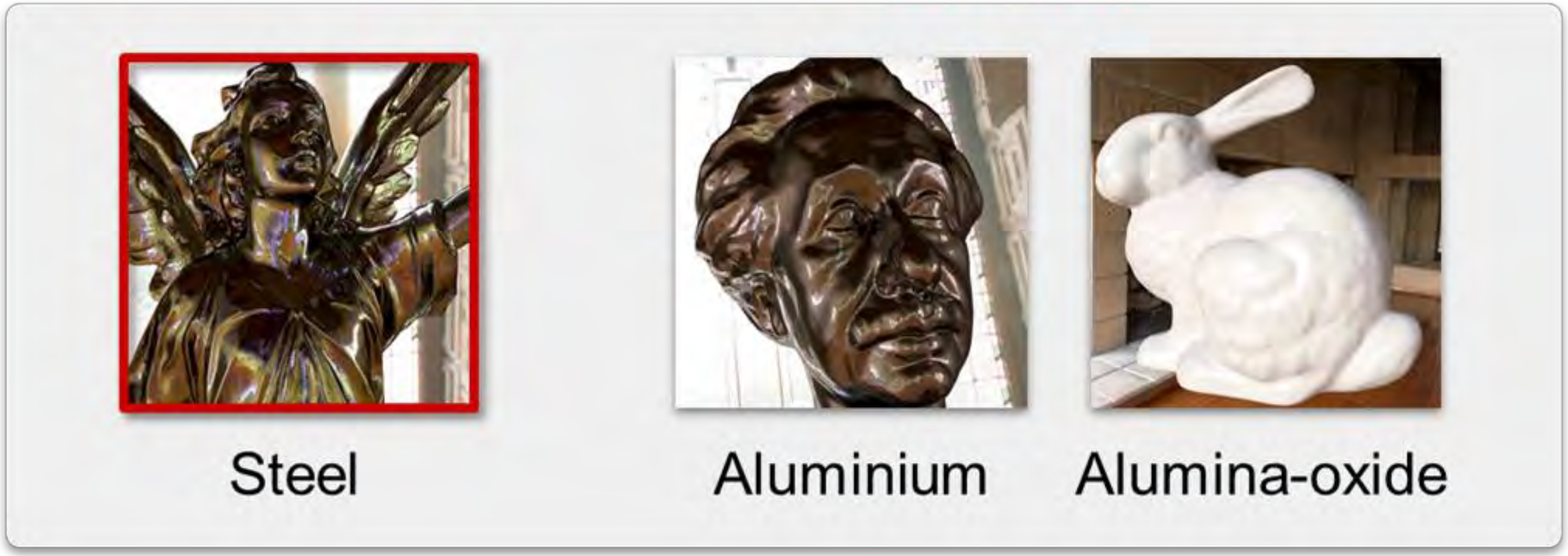
I prefer 7-point Likert scales over their 5-point brethren.

Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
○	○	○	○	○	○	○

Scaling methods

Indirect : Pair comparison

Which of these two candidates has a more similar appearance to the **reference**?



With or without reference!

Instructing users

- Explaining as objectively as possible the experimental procedure
- Obtaining written consent
- Recording demographic information
- Letting users stop/abandon the experiment if they need to

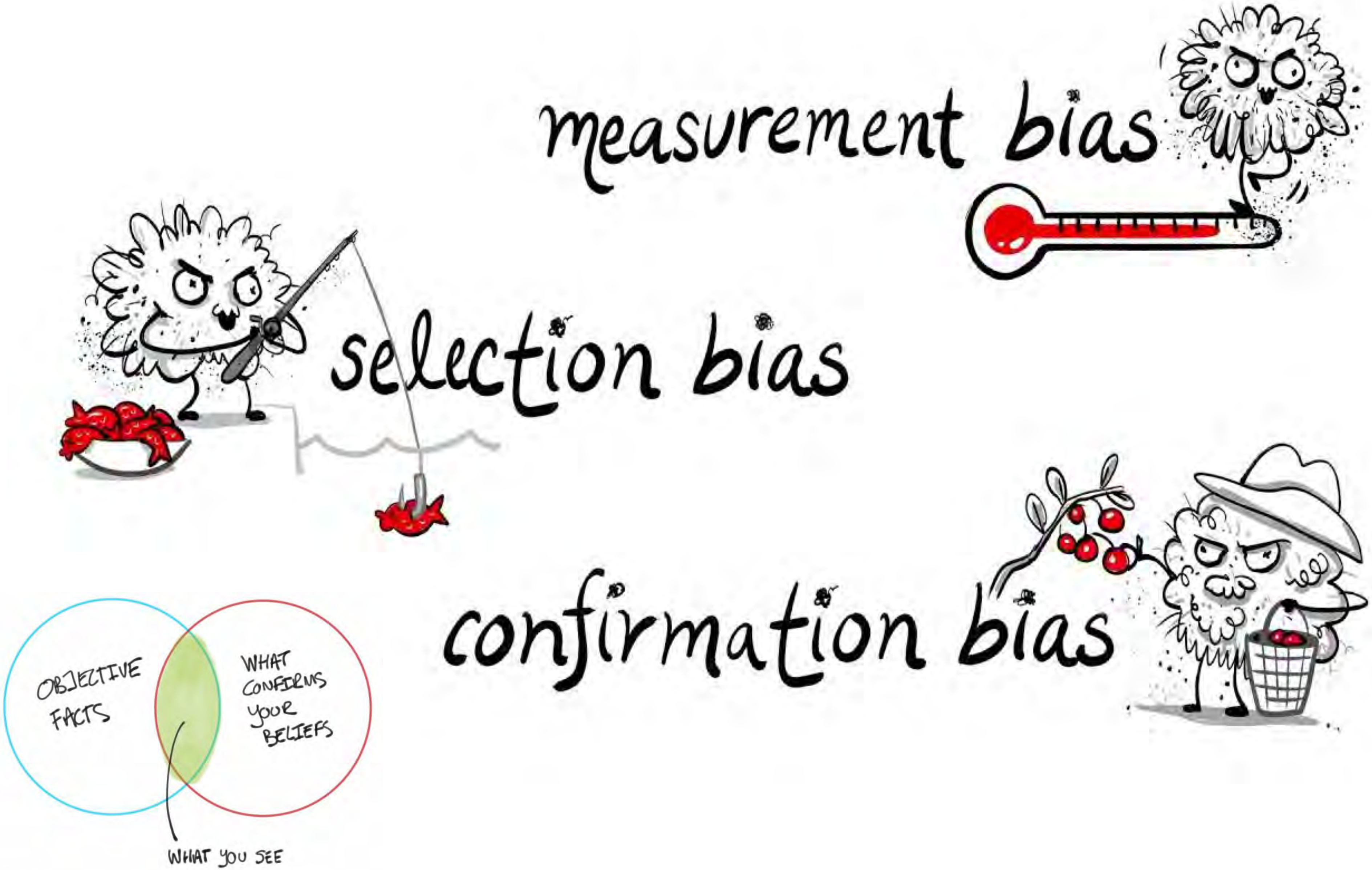
Avoid subject bias and be clear!

Bias

WAYS TO MINIMIZE OBSERVER BIAS

1. Assign random subjects
2. Blind studies
3. Assign multiple observers
4. Train observers
5. Standardize the procedures or protocols
6. Use double-blind studies
7. Be diligent while running an experiment

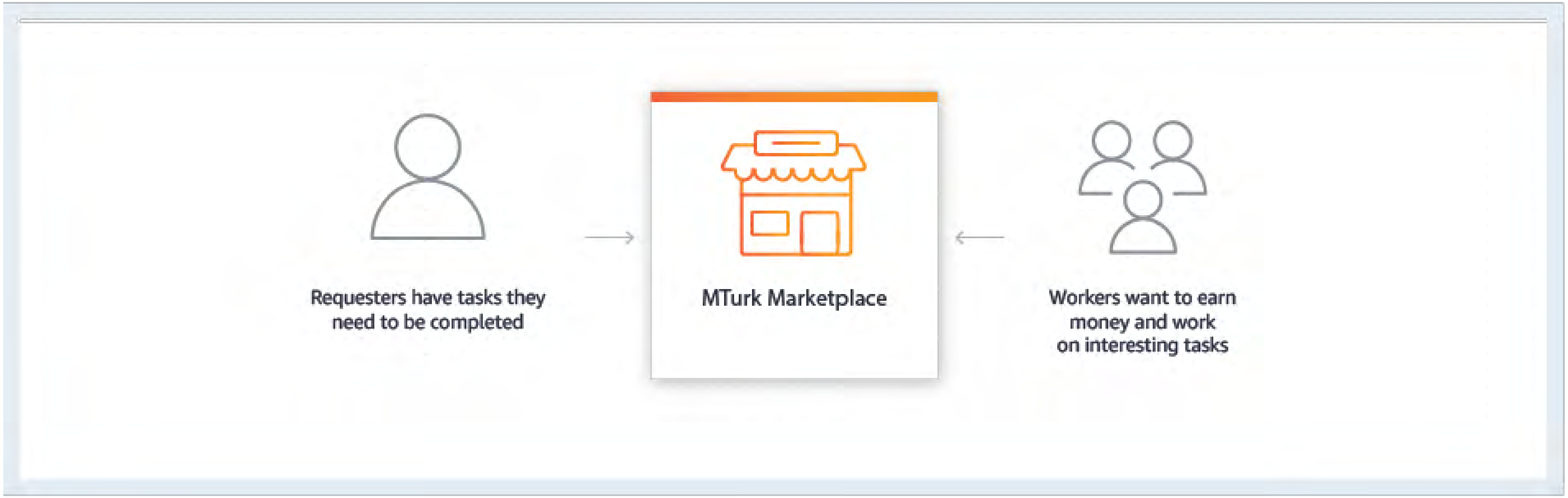
Bias


measurement bias
selection bias
confirmation bias
OBJECTIVE FACTS
WHAT CONFIRMS YOUR BELIEFS
WHAT YOU SEE

Good practices and ethics

- Guard human participants, their dignity, rights and welfare
- Protocol for recruitment and explanation of the study
- Informed consent
- Availability of data and code (data transparency)
- Ethics committee board approval
- Be sensitive towards the individuals that participate in your study
- Make clear that their personal information is safe

Crowdsourcing user studies



Requesters have tasks they need to be completed

MTurk Marketplace

Workers want to earn money and work on interesting tasks

Crowdsourcing user studies

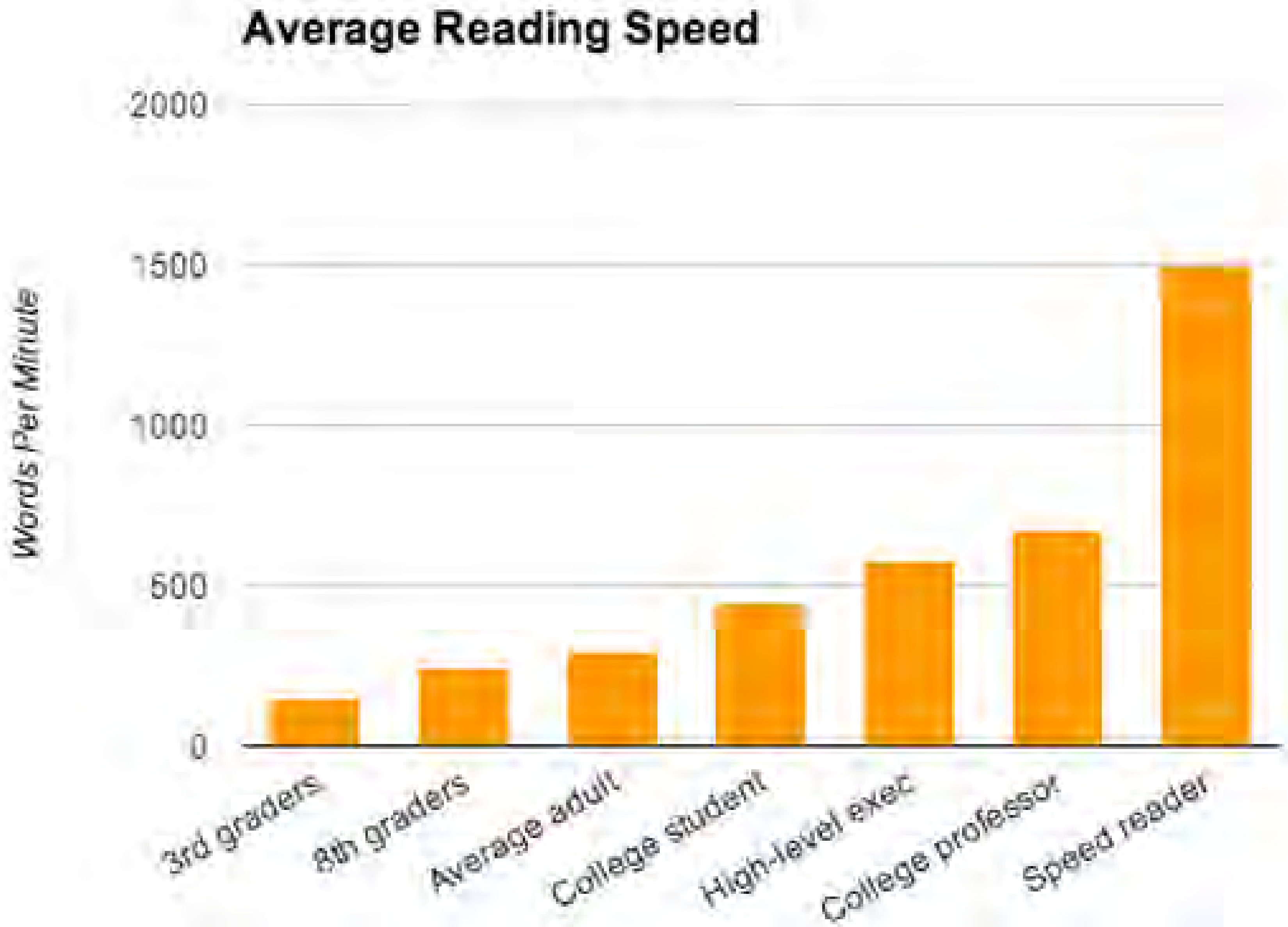
- Adapting your research plan
  - Choosing the right tools (hardware, connectivity, …)
  - Clear explanation and tasks
- Determining participant eligibility
- Rejections
- Consent forms

Use **sentinel** trials or control **thresholds**!

Sentinel question

How many dots can you see?

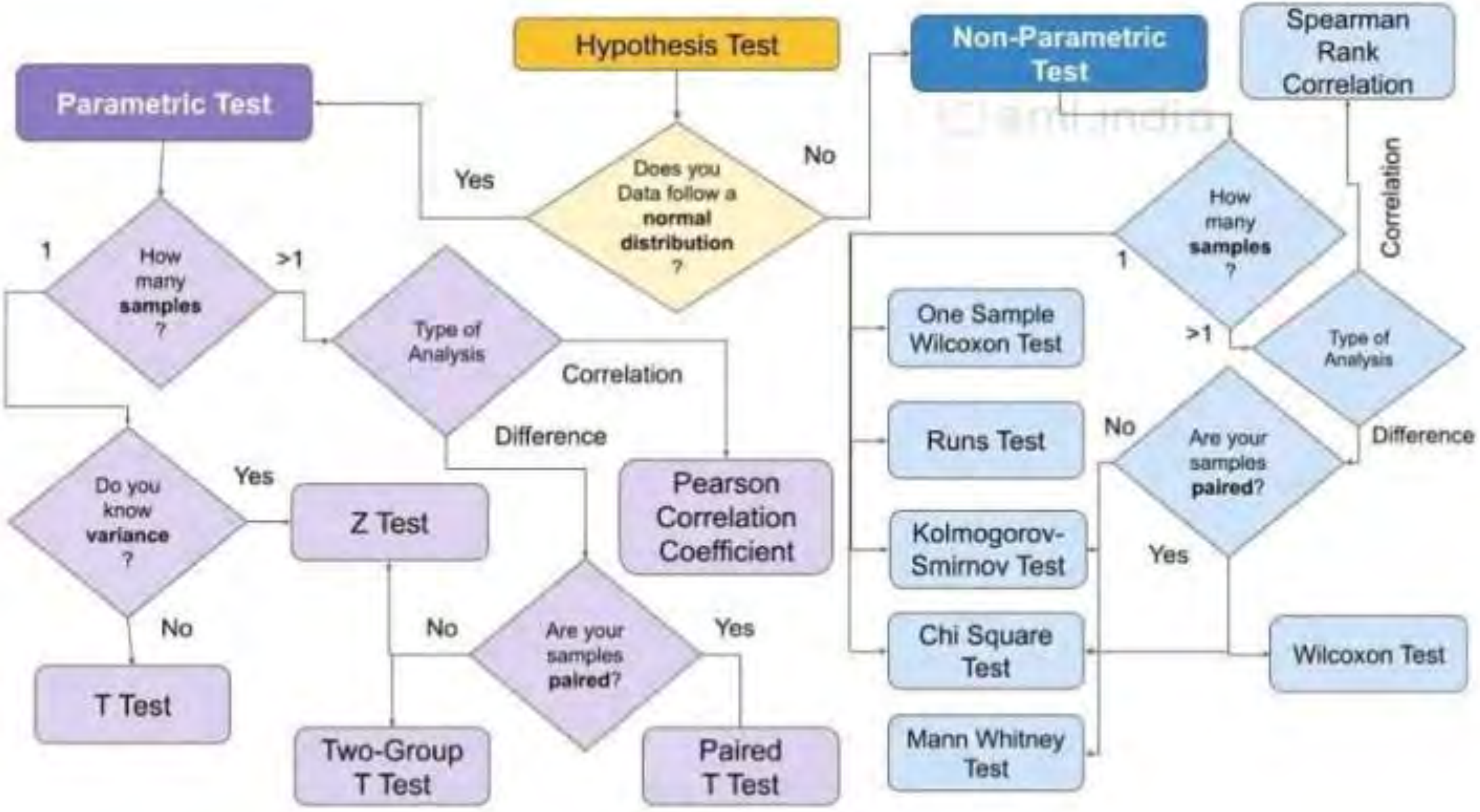
Control thresholds



Statistical analyses

- How many subjects?
    - A priori sample size and power calculation
- How to analyze my data?
    - Distribution check (Normality check)
    - Sample size consideration
    - Number of factors and type of metrics

Hypothesis testing cheatsheet:



Hypothesis Test

Does you Data follow a **normal distribution** ?

Yes

No

Parametric Test

How many **samples** ?

1

>1

Do you know **variance** ?

Yes

Z Test

No

T Test

Type of Analysis

Correlation

Pearson Correlation Coefficient

Difference

Are your samples **paired**?

No

Two-Group T Test

Yes

Paired T Test

Non-Parametric Test

How many **samples** ?

1

One Sample Wilcoxon Test

Runs Test

Kolmogorov-Smirnov Test

Chi Square Test

>1

Type of Analysis

Correlation

Spearman Rank Correlation

Difference

Are your samples **paired**?

No

Mann Whitney Test

Yes

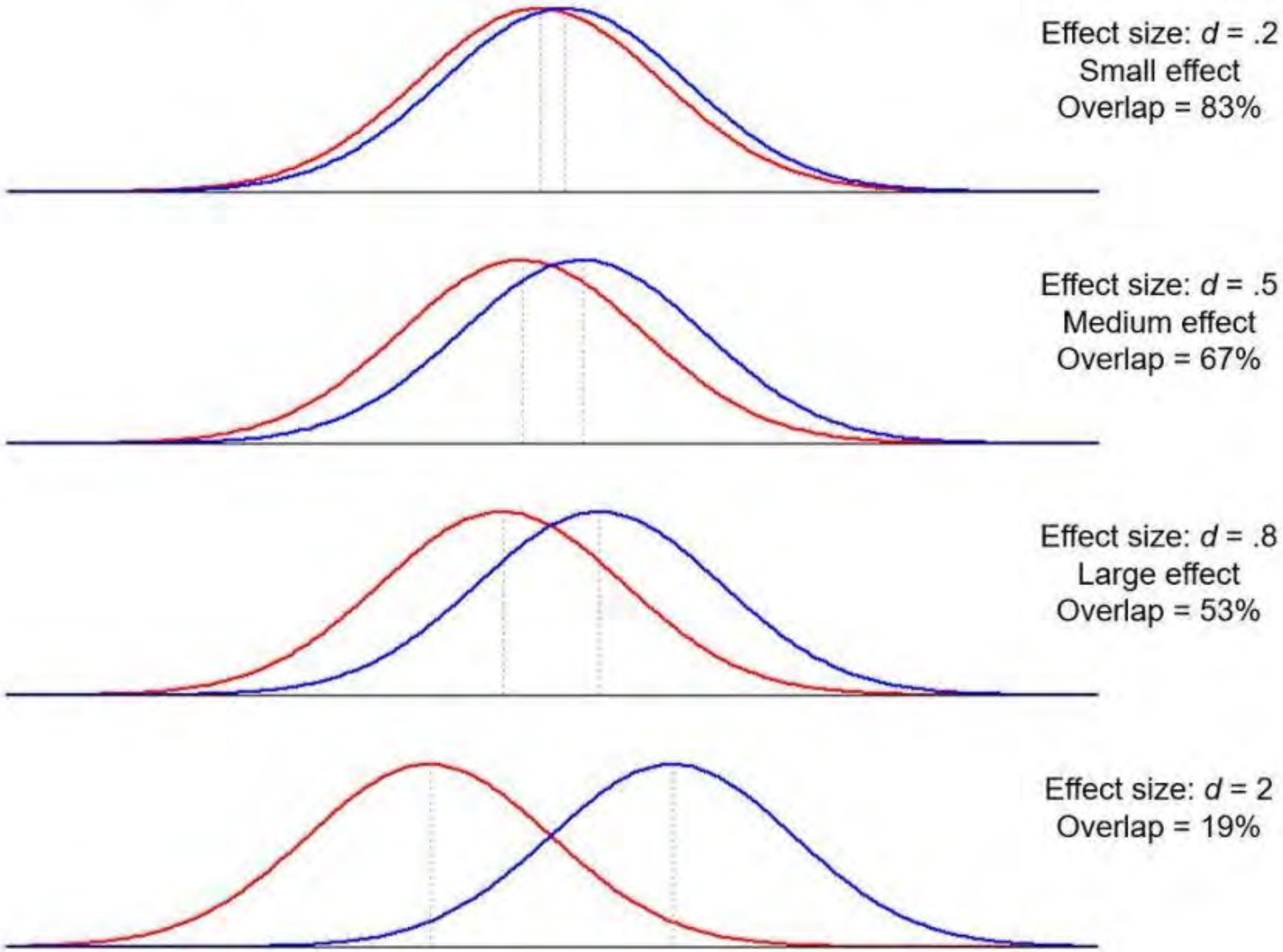
Wilcoxon Test

By Angelica Lo Duca, Researcher in Semantic Web, Data Integration, and Data Science, on KDNuggets.com

Statistical analyses

- How many subjects?
    - A priori sample size and power calculation
- How to analyze my data?
    - Distribution check (Normality check)
    - Sample size consideration
    - Number of factors and type of metrics
- Effect sizes
- Post-hoc analyses

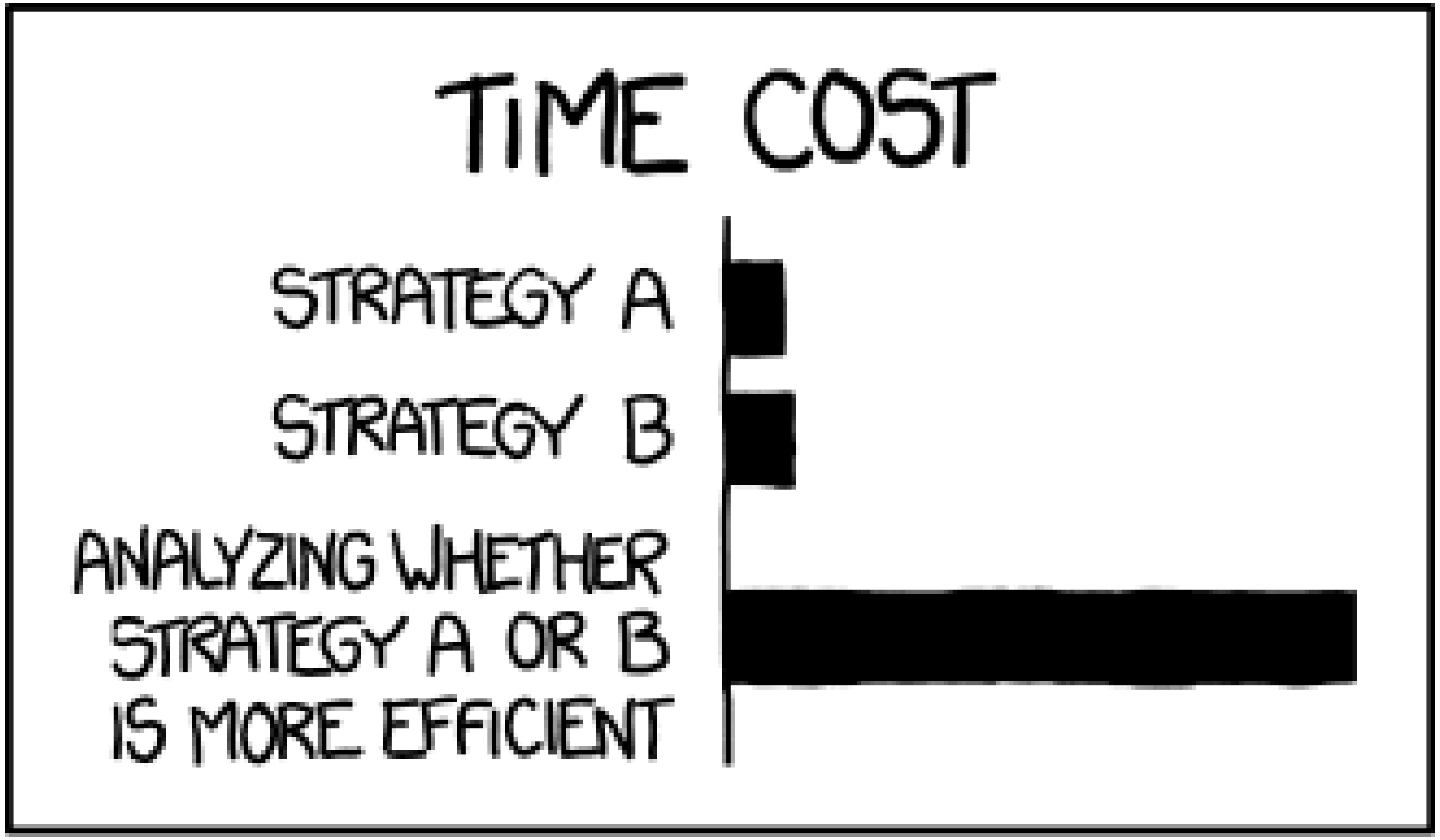
Understanding Effect Sizes



A smaller p-value is NOT more significant!

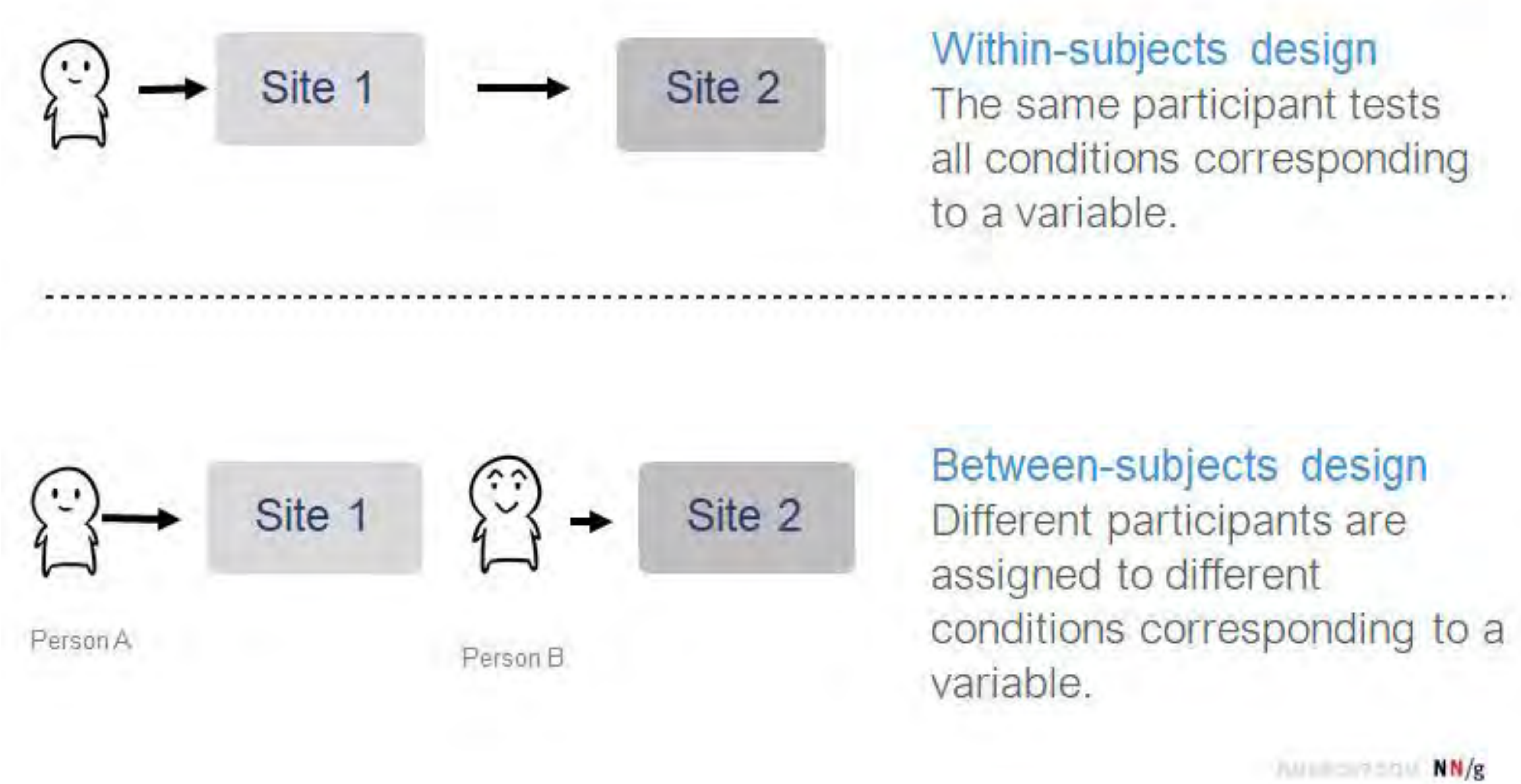
Tradeoffs

- What is the best configuration for my user study?



THE REASON I AM SO INEFFICIENT

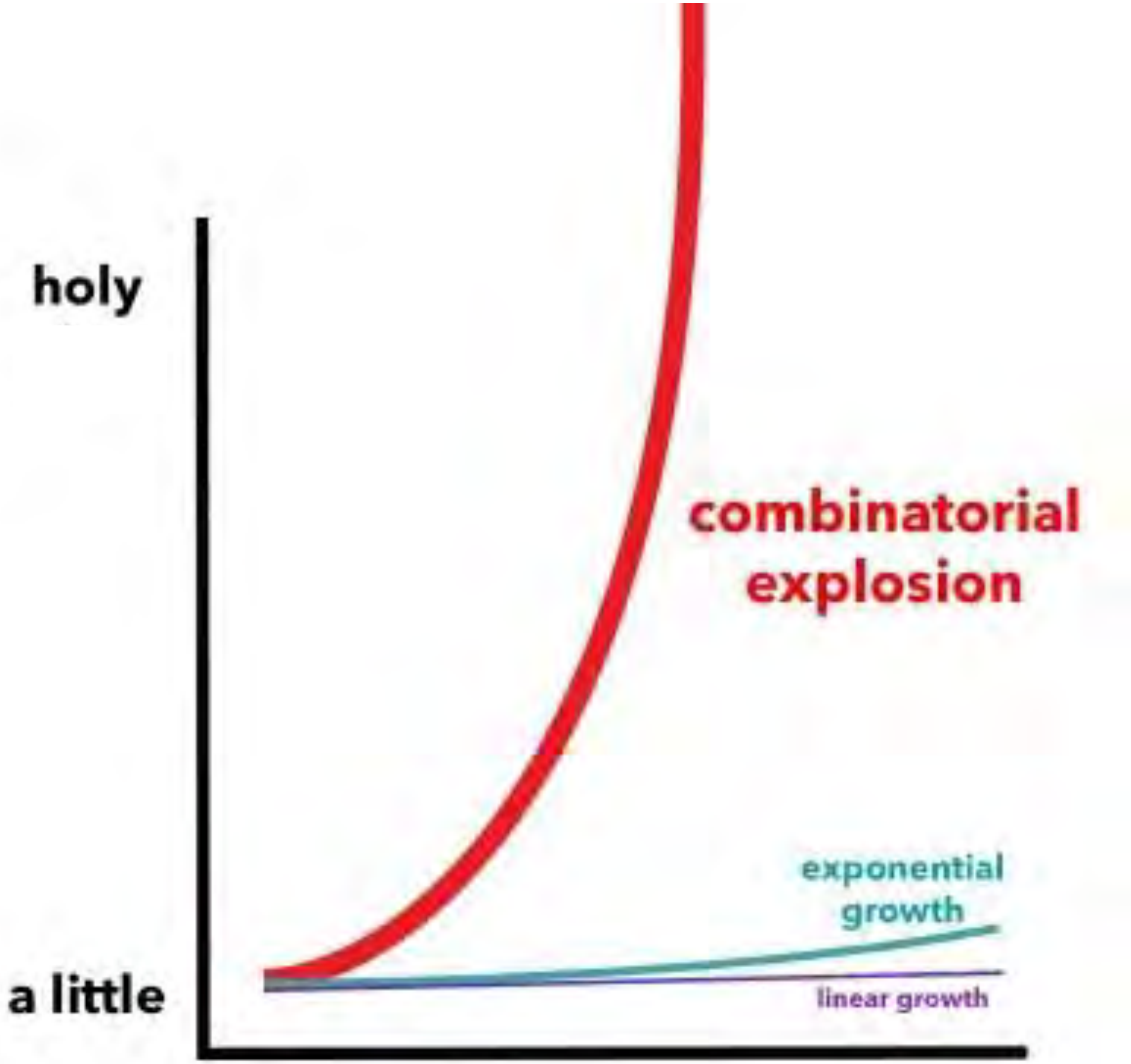
Between-users vs within-users study



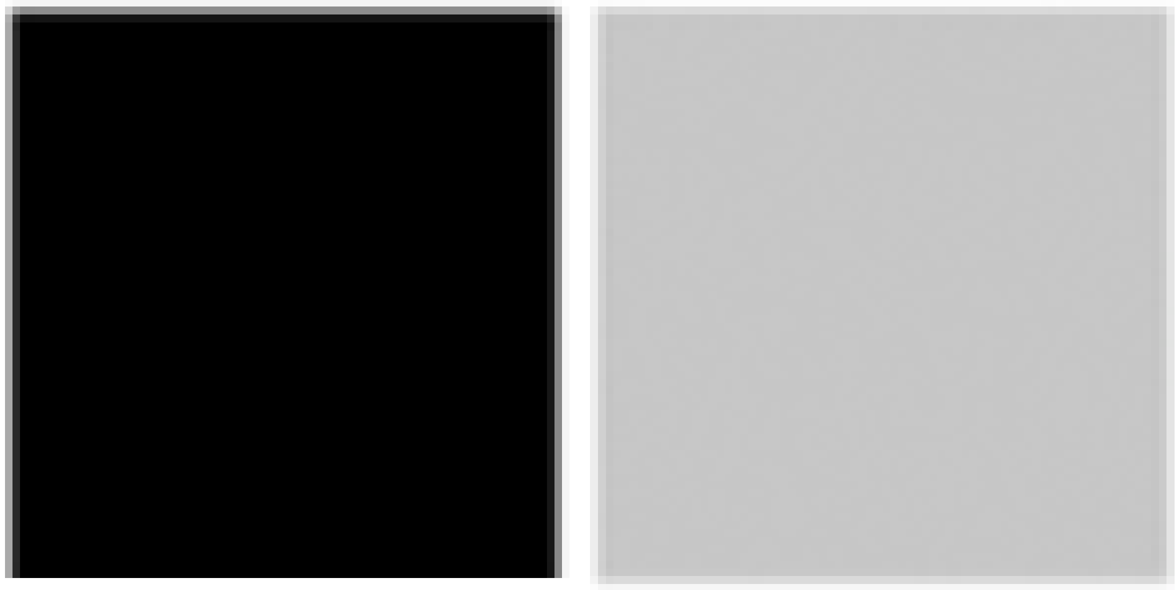
Within-subjects design
The same participant tests all conditions corresponding to a variable.

Between-subjects design
Different participants are assigned to different conditions corresponding to a variable.

Single vs several conditions

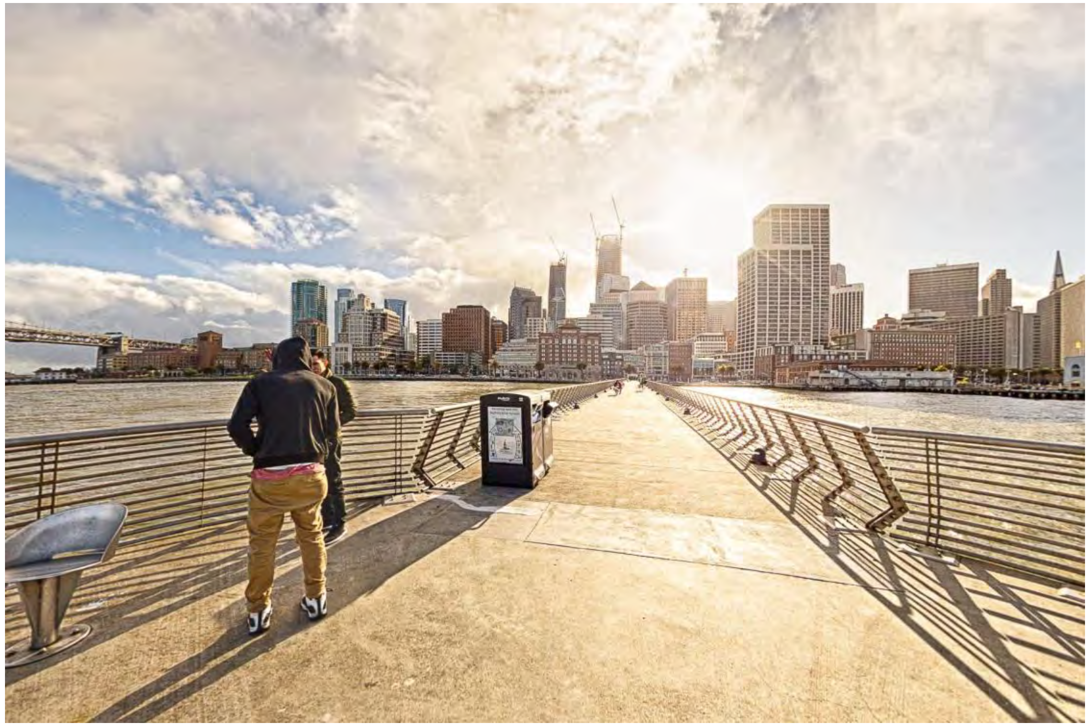


Control vs ecological validity



Luminance variation

Control vs ecological validity



Luminance variation?

In summary

- Plan before you experiment!
- User studies are useful at every stage of a research project
- Choose your metrics, methodology and analysis in advance
- Be open with your participants
- Small steps!

http://graphics.unizar.es/

https://smalpica.github.io/

Overview

Good practices for user studies

Experiencing virtual reality through embodiment

Developing computational models with mathematical and neurological insights

Virtual characters

Seeing in depth

Audio in virtual reality

Formulating Perception with Mathematical Models

Qi Sun

NYU

www.ImmersiveComputingLab.org

Probabilistic Models for Visual Behaviors

Can XR make us **faster?**

https://youtu.be/OR3pVrLWbpI

Behavioral Reactions

Critical to:

- Driving
- AR/VR Displays
- Athletics/E-Sports
- Defense
- Healthcare
- etc

Image Features Influence Reaction Time
Budmonde Duinkharjav et al, SIGGRAPH 2022
🏆 [Best Paper Award]

Behavioral Reactions

Critical to:

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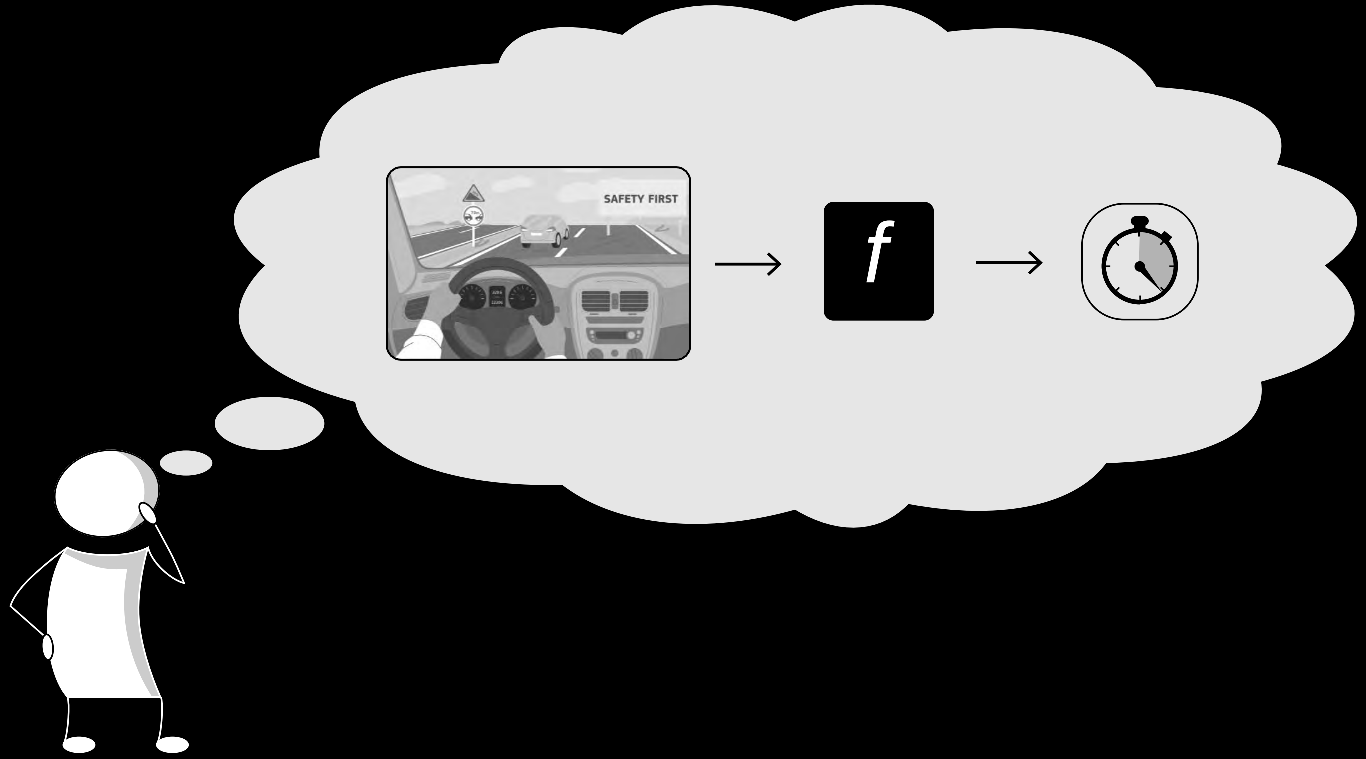
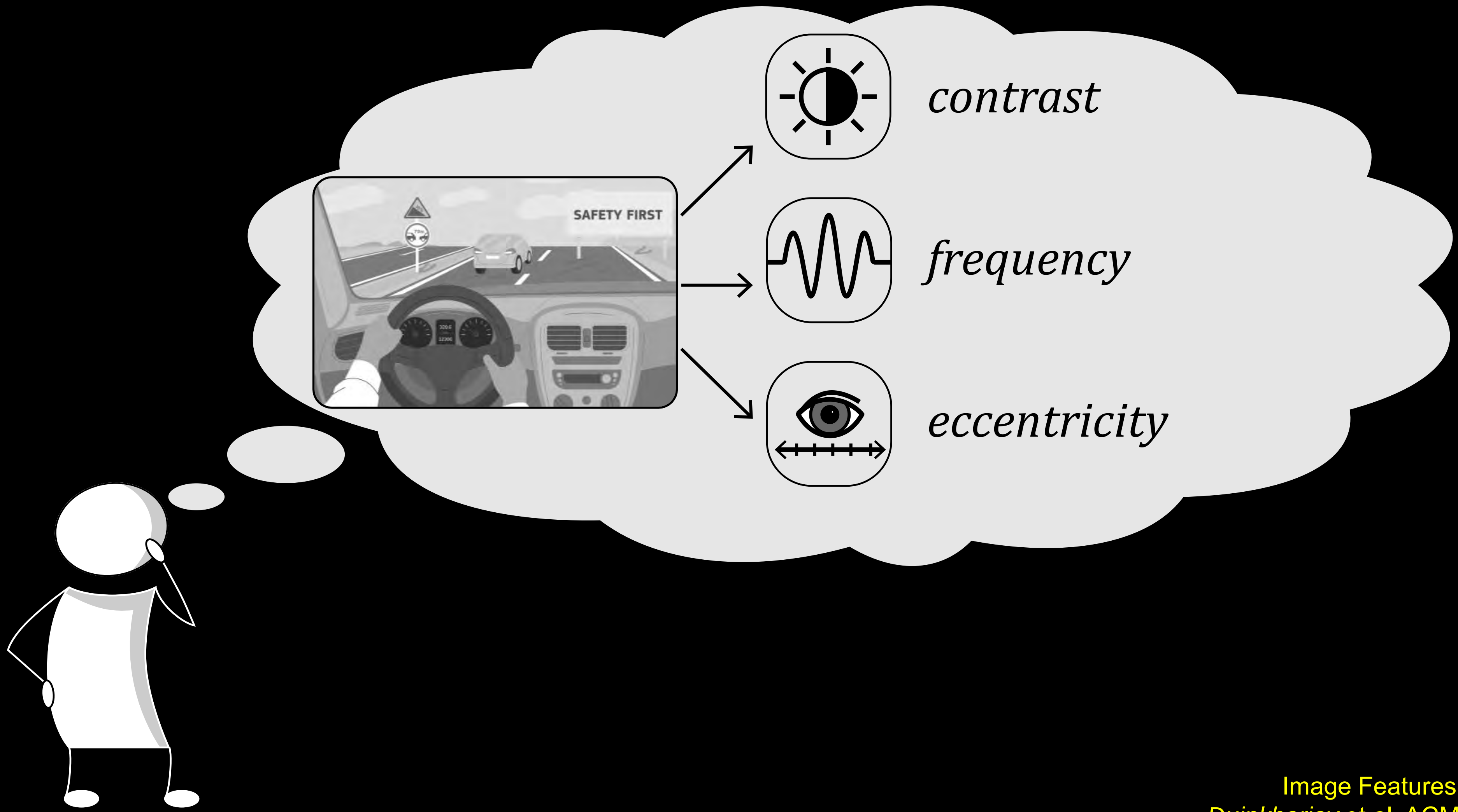


Image Features Influence Reaction Time
Budmonde Duinkharjav et al, SIGGRAPH 2022
🏆 [Best Paper Award]

Measure Reaction Time

Image Features Influence Reaction Time
Duinkharjav et al, ACM ToG (SIGGRAPH 2022)
🏆 [Best Paper Award]



contrast

frequency

eccentricity

Image Features Influence Reaction Time
Duinkharjav et al, ACM ToG (SIGGRAPH 2022)
[Best Paper Award]

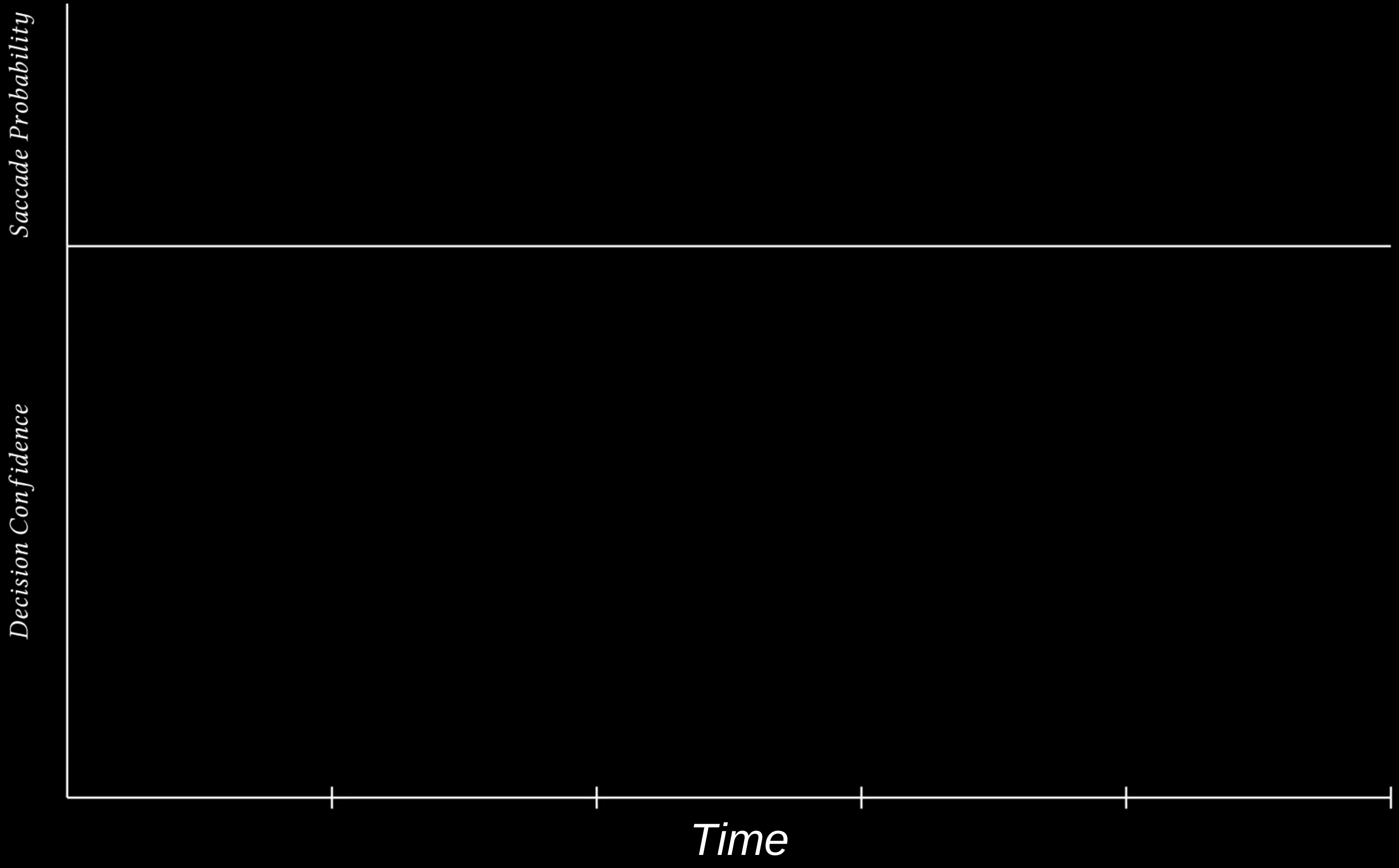
Drift-Diffusion Probabilistic Model

Neurologically decision-making with stochastic random walk

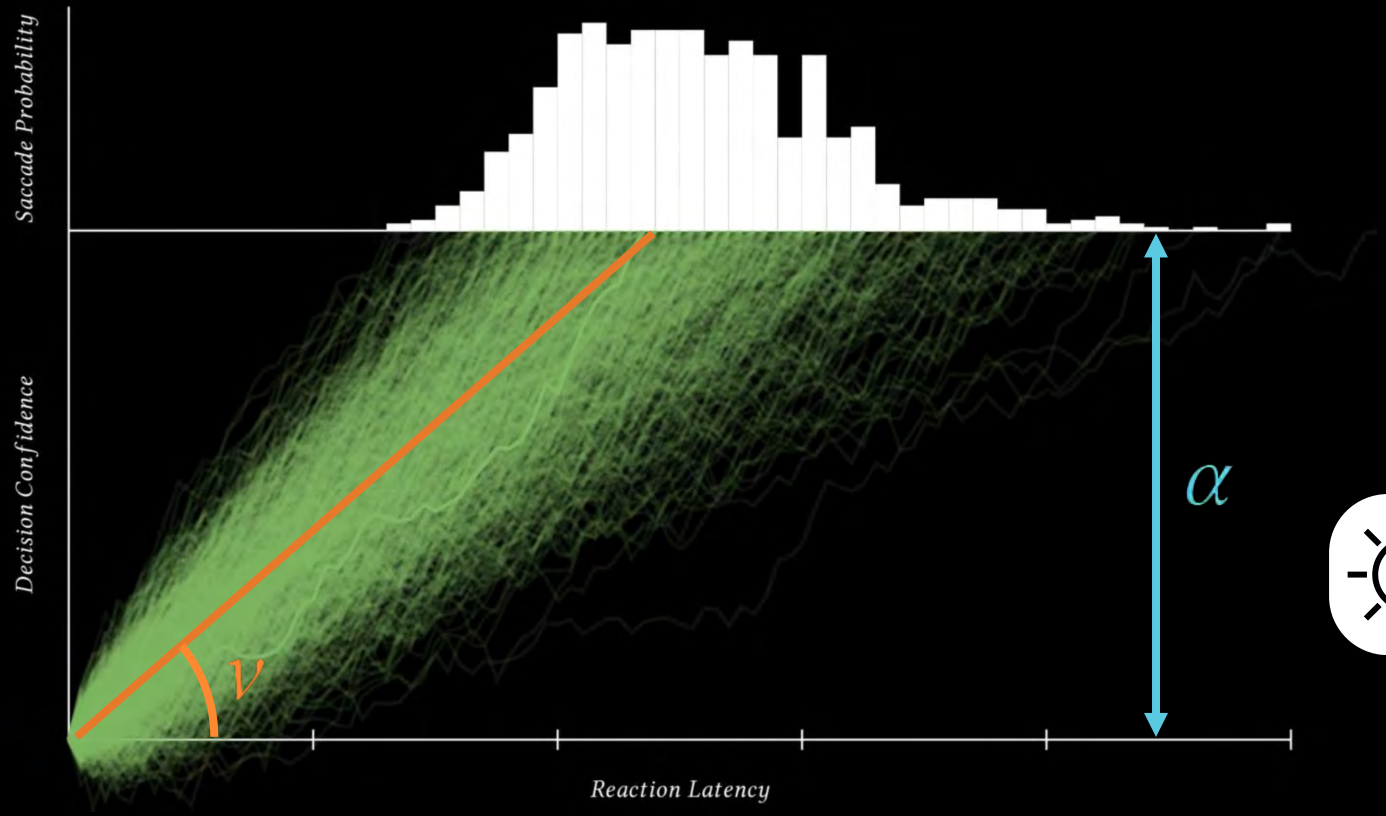
Image Features Influence Reaction Time
Duinkharjav et al, ACM ToG (SIGGRAPH 2022)
🏆 [Best Paper Award]

Drift-Diffusion Probabilistic Model

Neurologically decision-making with stochastic random walk



Reaction Time Probability Distribution



$$h(t;\alpha,\nu)=\frac{\alpha}{\sqrt{2\pi t^3}}\exp\frac{-(\alpha-\nu t)^2}{2t}$$

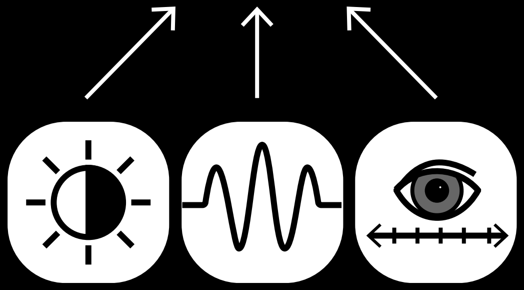


Image Features Influence Reaction Time
Duinkharjav et al, ACM ToG (SIGGRAPH 2022)
🏆 [Best Paper Award]

Enhancing VR/AR User Reaction Speed

Soccer

Esports

Photographic

Image Features Influence Reaction Time
Duinkharjav et al, ACM ToG (SIGGRAPH 2022)
🏆 [Best Paper Award]

Altered Reaction Speed

Configurations:

- Deferred
- Control
- Accelerated

User Study:

- 14 participants
- **~5.5k** saccades

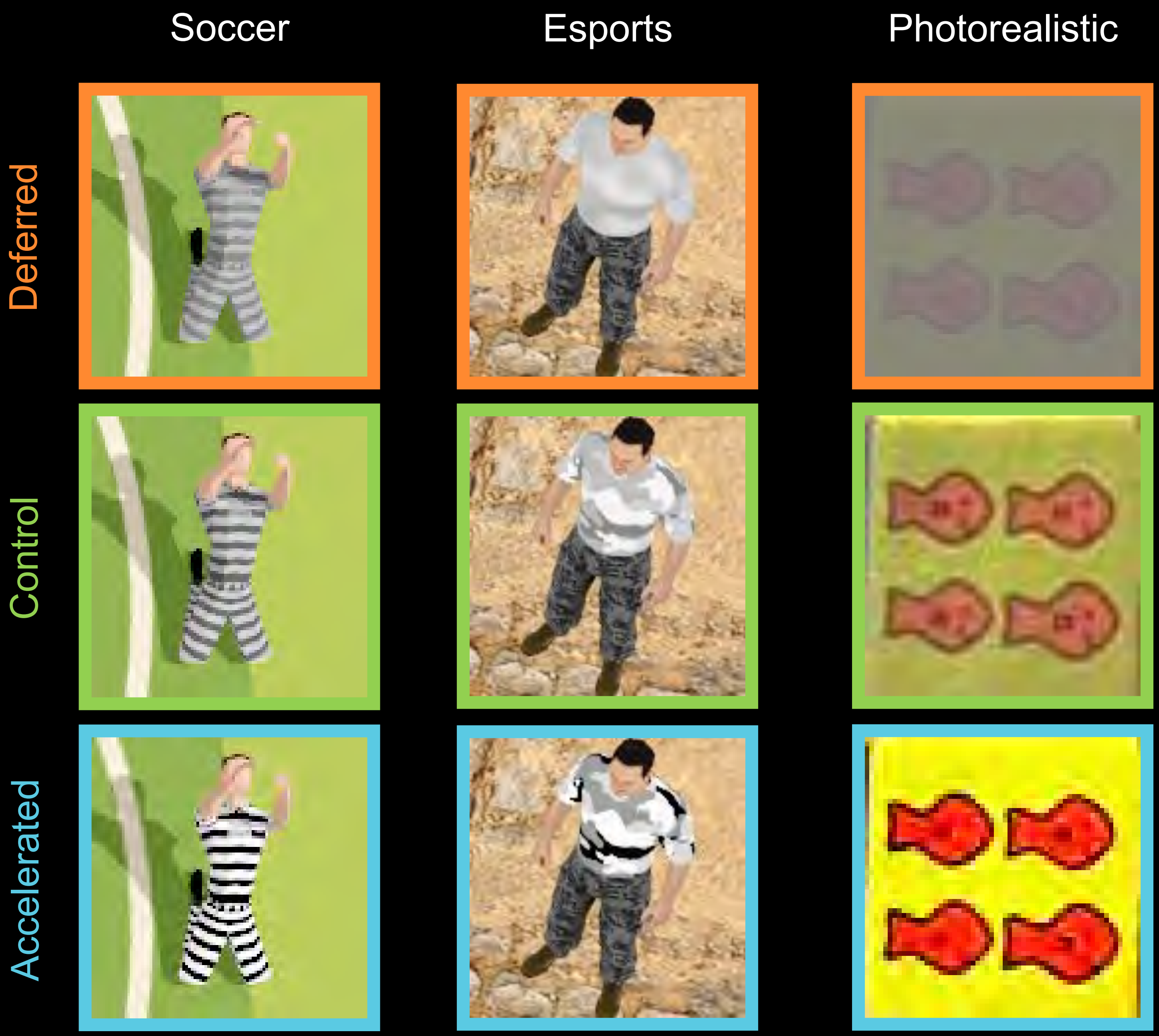
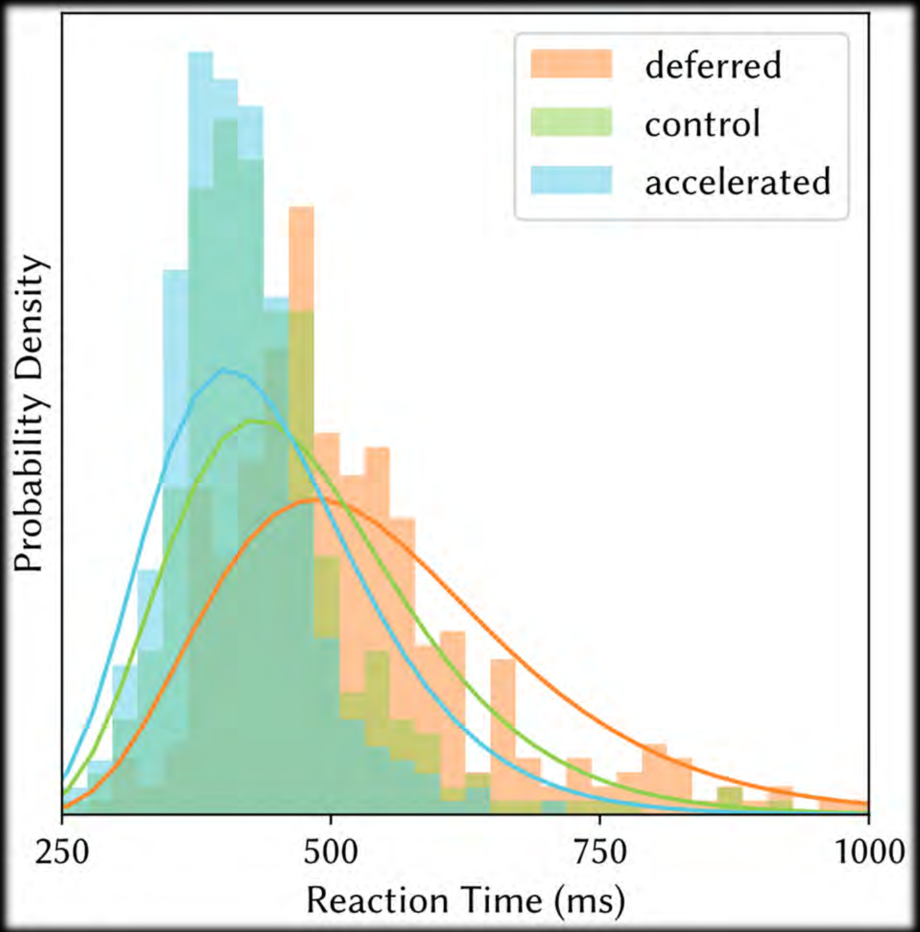
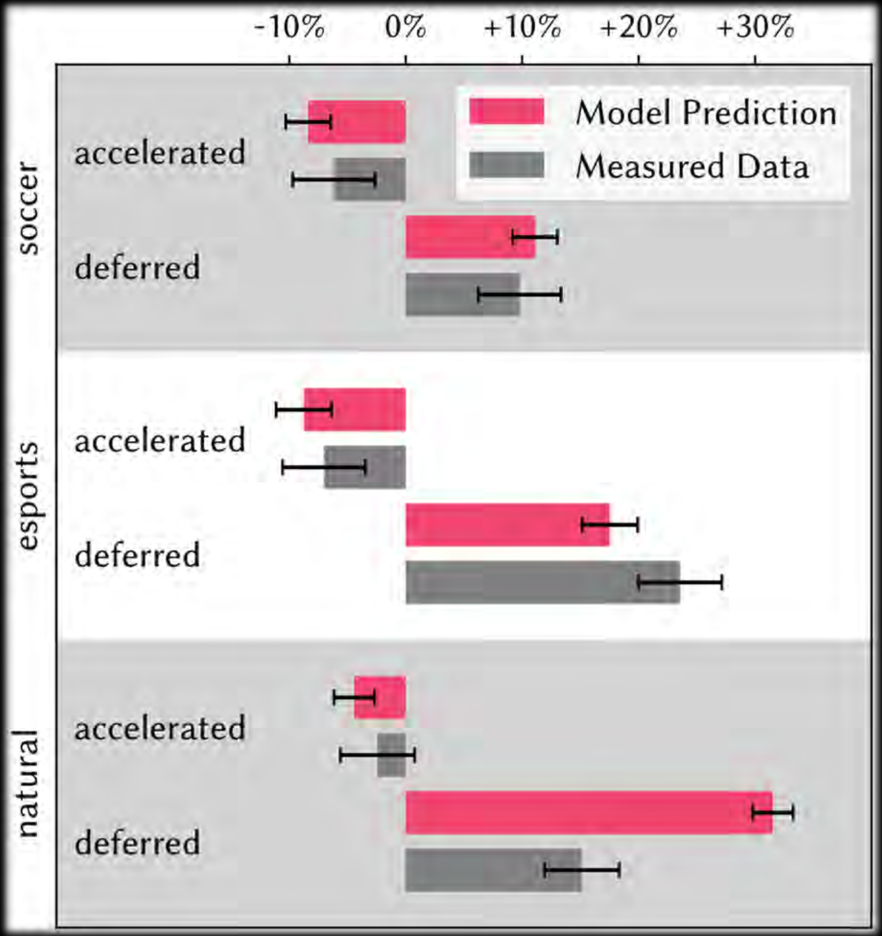


Image Features Influence Reaction Time
Duinkharjav et al, ACM ToG (SIGGRAPH 2022)
🏆 [Best Paper Award]

Model Prediction vs Measured Data



Esports scene reaction time histogram



Percentage change in mean reaction time

Measuring Competition Fairness

CT

1 frame

faster reaction

than

T

Learned Models for Visual Acuity

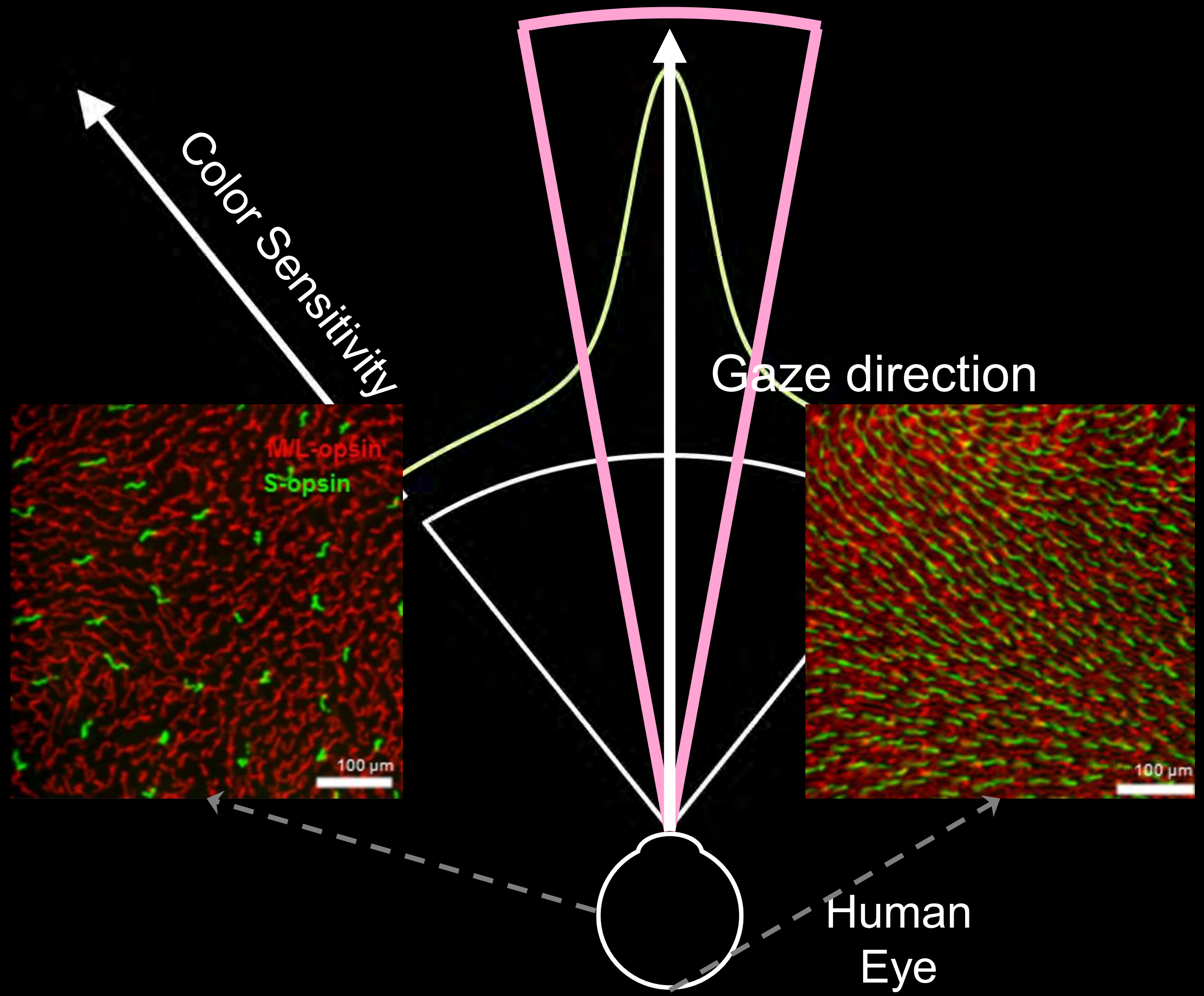
en.wikipedia.org/wiki/The_dress

https://youtu.be/Wa_5emYDD2I

Visually *Lossless* Display Energy Saving

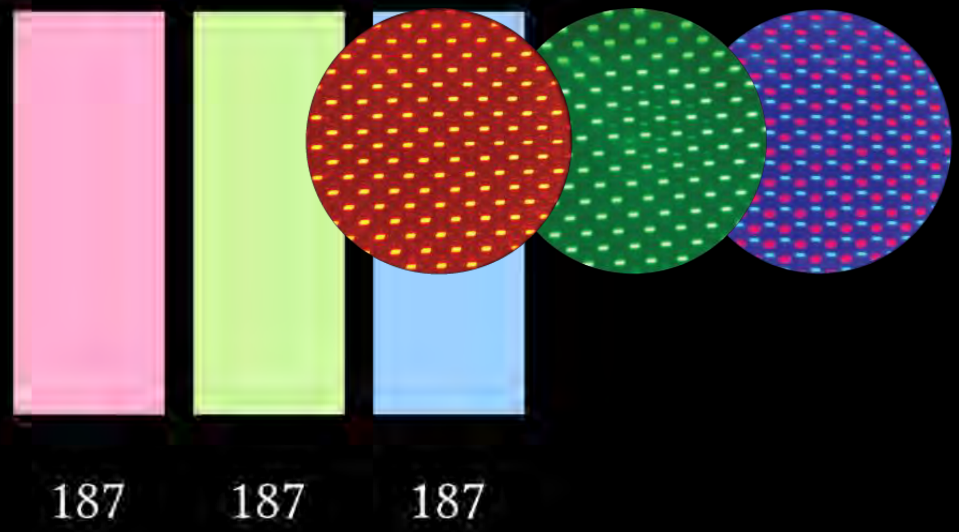
Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

1. Peripheral Color Perception



Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

2. Colored LED Power Consumption



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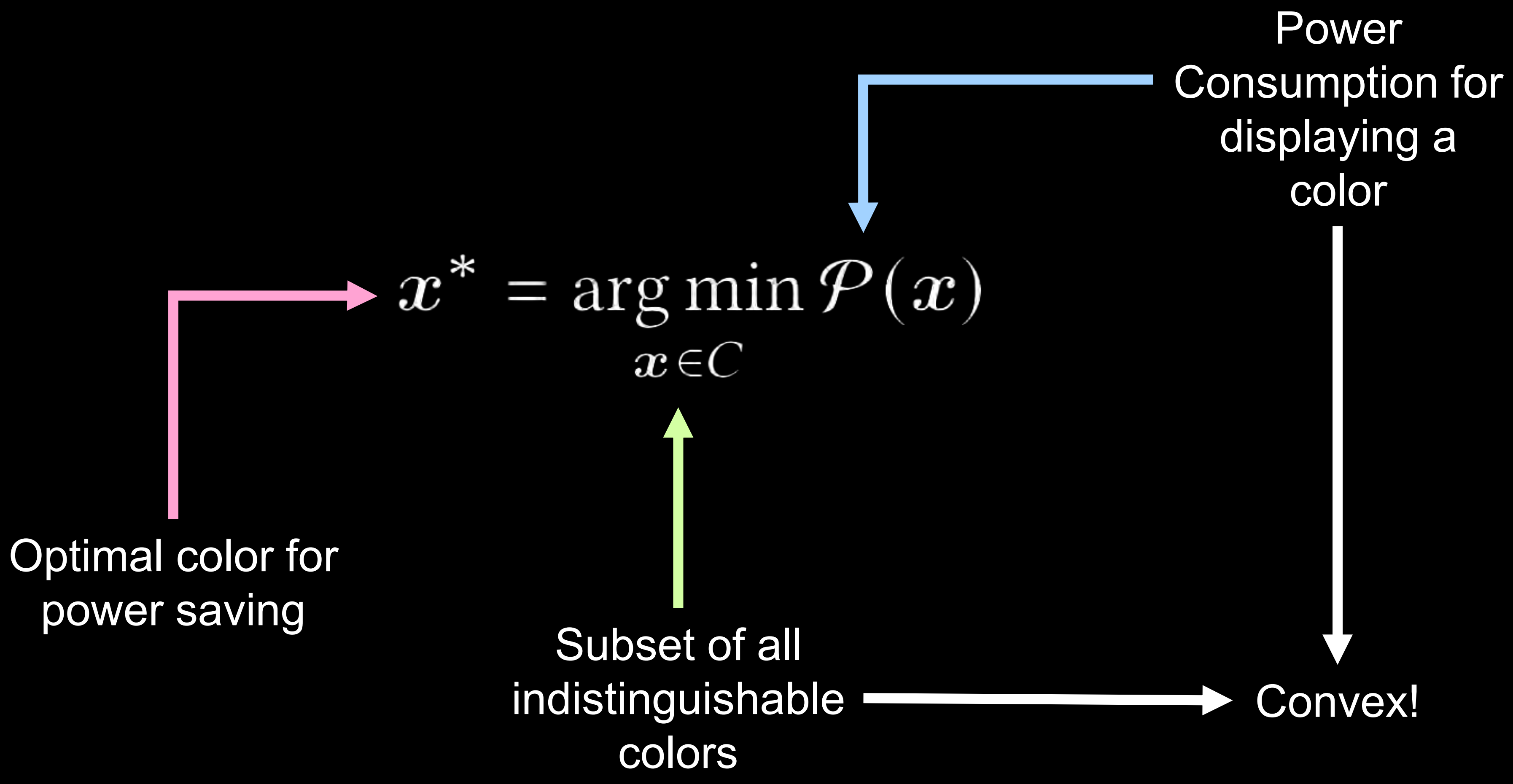
Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

original

https://www.youtube.com/watch?v=8t4VQ9gJHMk

27% energy saved

Problem Formulation



$$x^* = \arg\min_{x \in C} \mathcal{P}(x)$$

Power Consumption for displaying a color

Optimal color for power saving

Subset of all indistinguishable colors

Convex!

Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

Color Discrimination In Peripheral Vision

Subset *C*

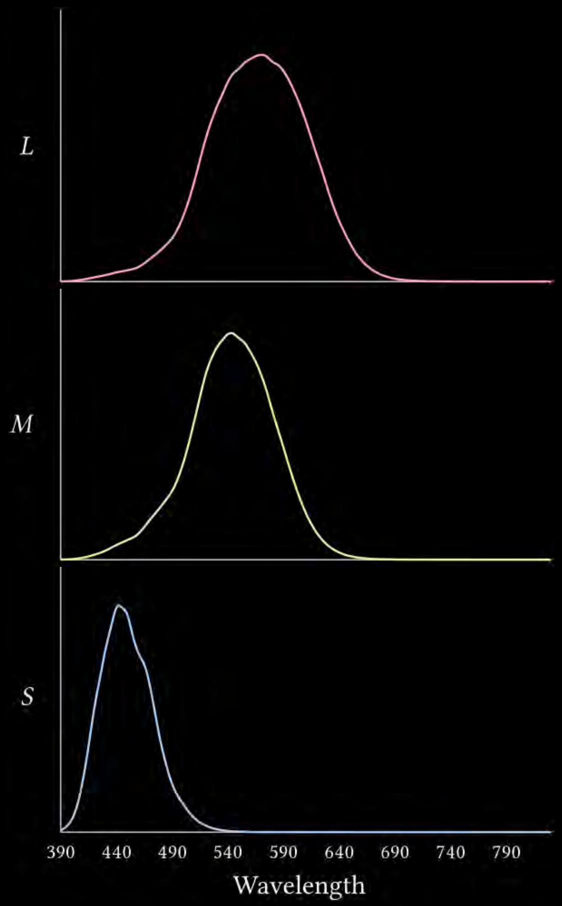
of indistinguishable colors

$$C = \{x \mid \mathcal{E}(x) \leq 0\}$$

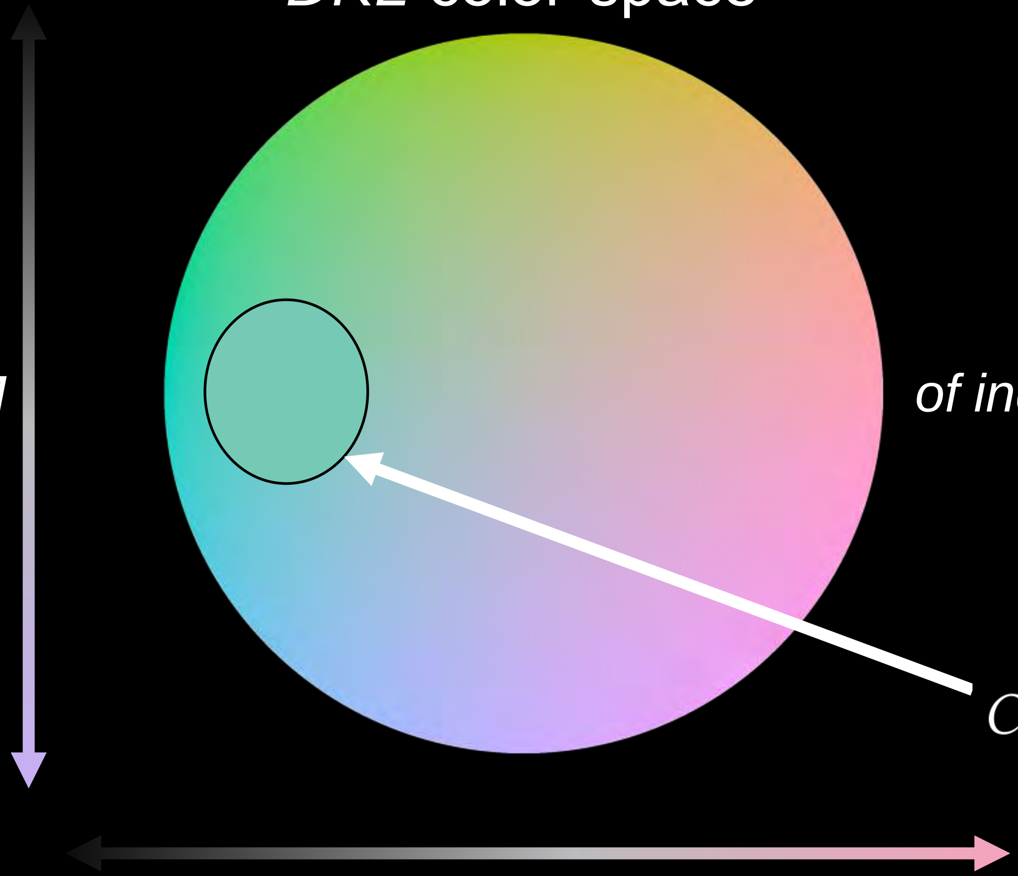
Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

Color Discrimination In Peripheral Vision

Cone Sensitivity



DKL color-space



S vs L + M

L vs M

Subset *C*
of indistinguishable colors

$C = \{x \mid \mathcal{E}(x) \leq 0\}$

Color-Perception-Guided Display Power Reduction for Virtual Reality
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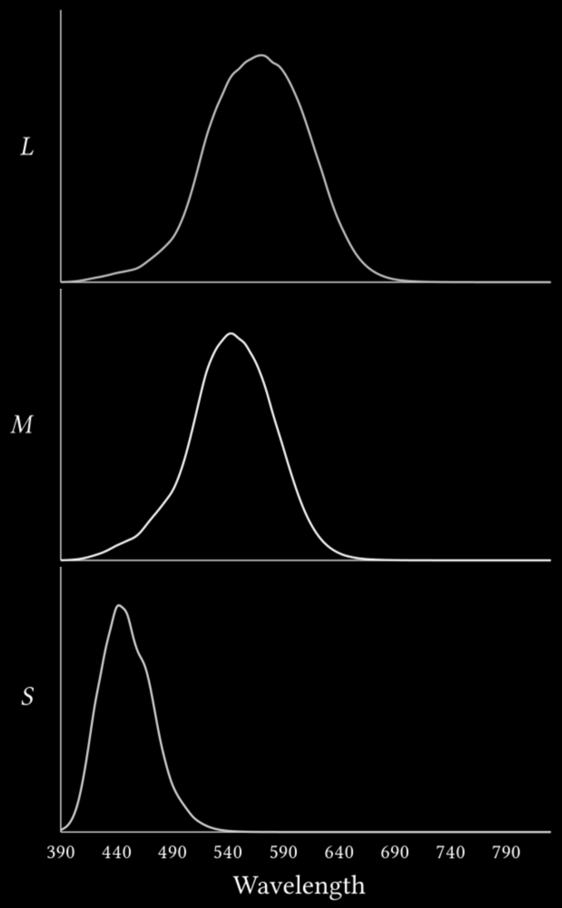
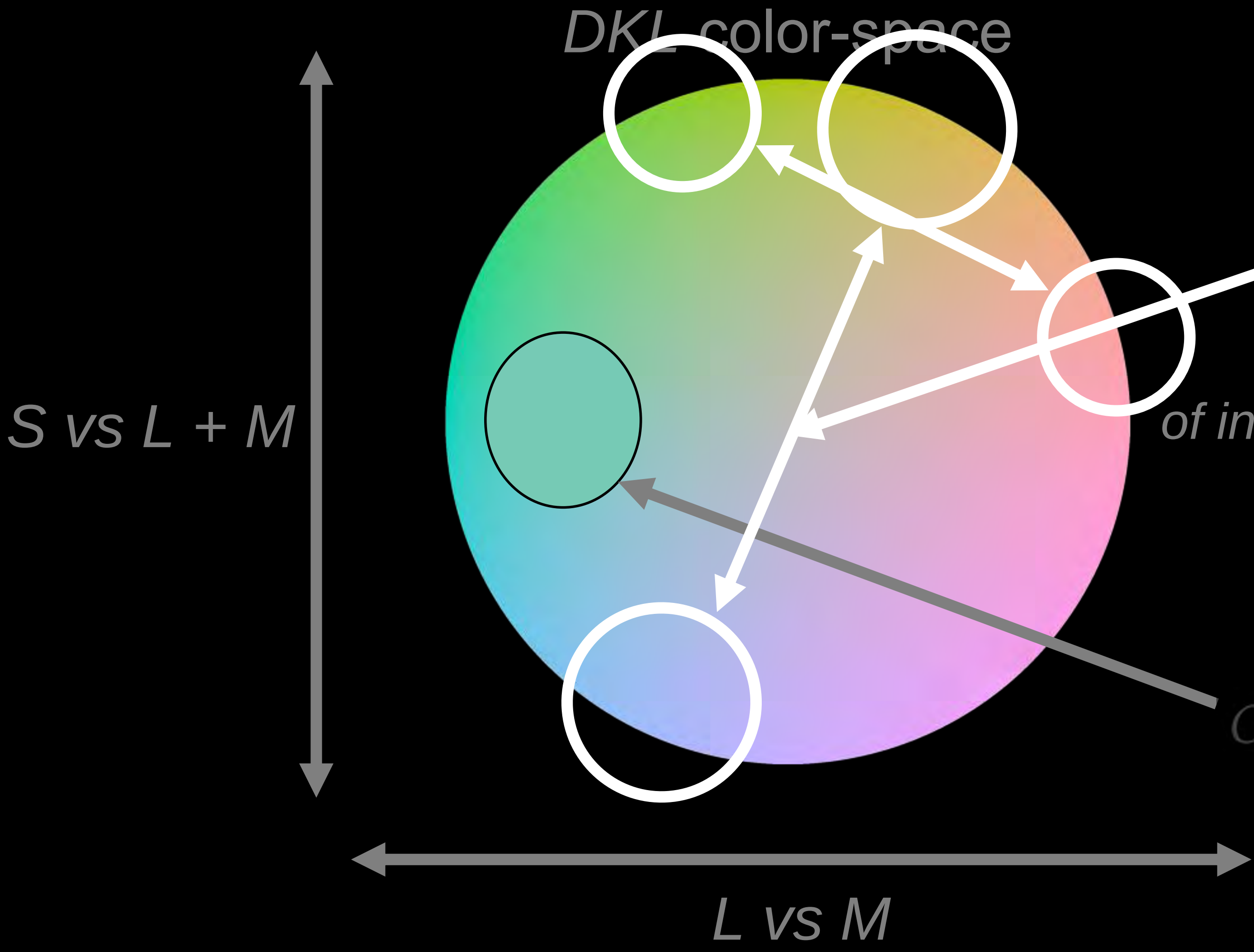
Cone Sensitivity





Neutral Gray

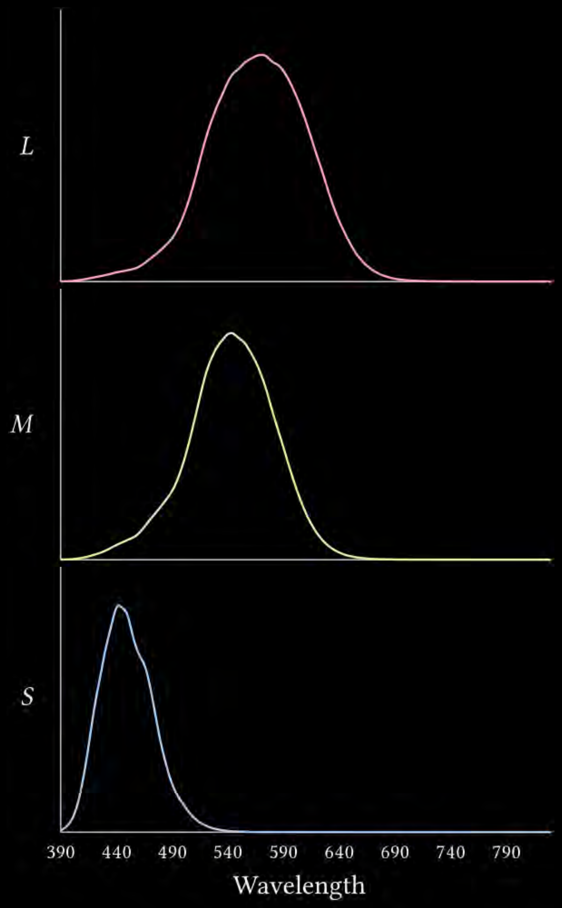
Subset *C*
of indistinguishable colors

$C = \{x \mid \mathcal{E}(x) \leq 0\}$

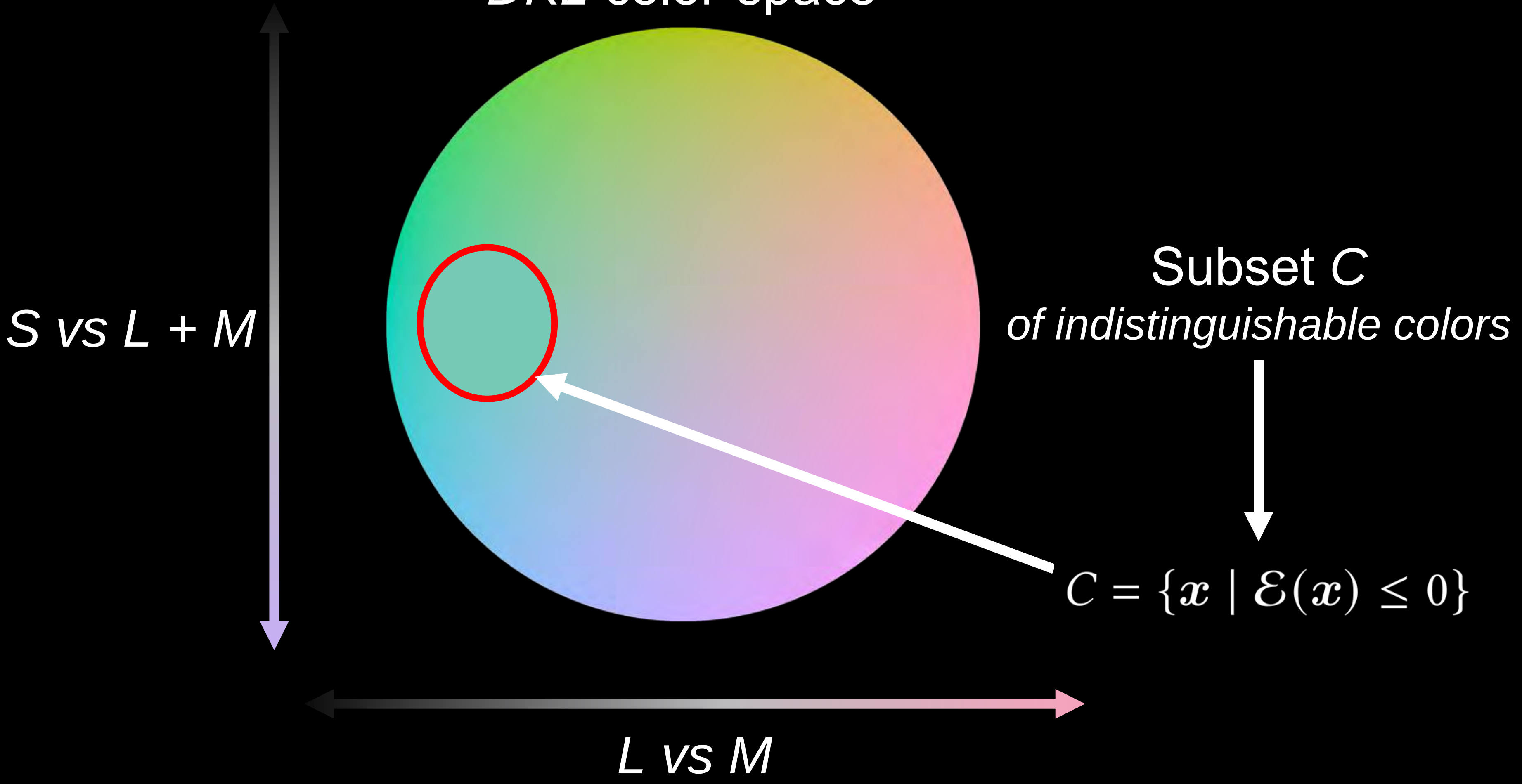
Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

Color Discrimination In Peripheral Vision

Cone Sensitivity



DKL color-space



S vs L + M

L vs M

Subset *C*

of indistinguishable colors

$C = \{\boldsymbol{x} \mid \mathcal{E}(\boldsymbol{x}) \leq 0\}$

Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

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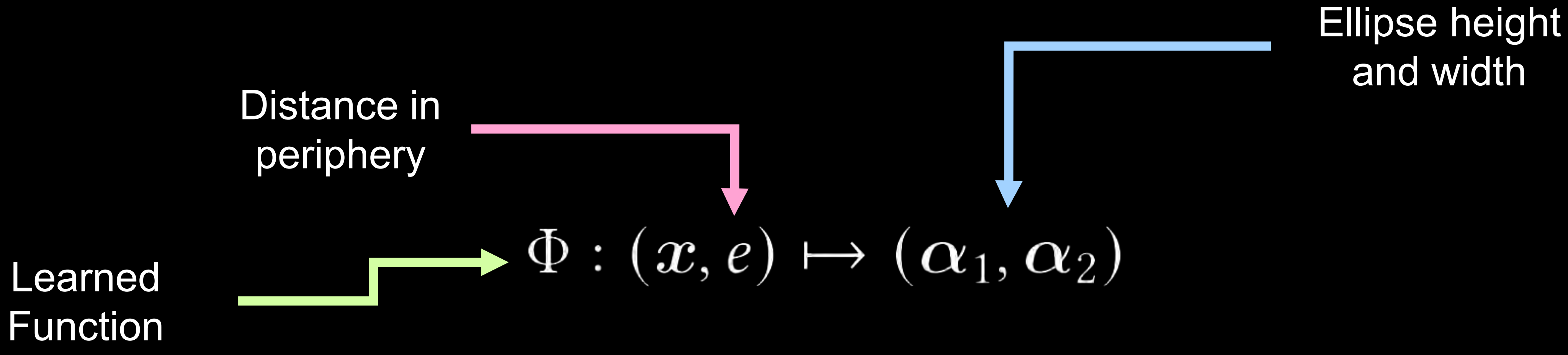


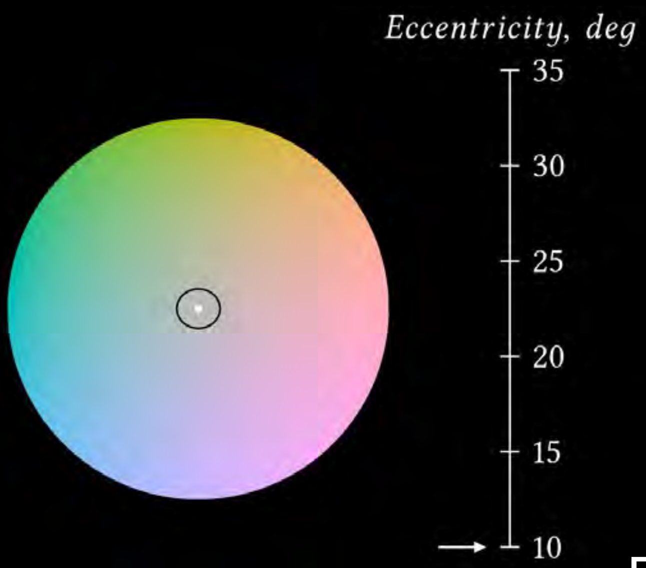
Ellipse height and width

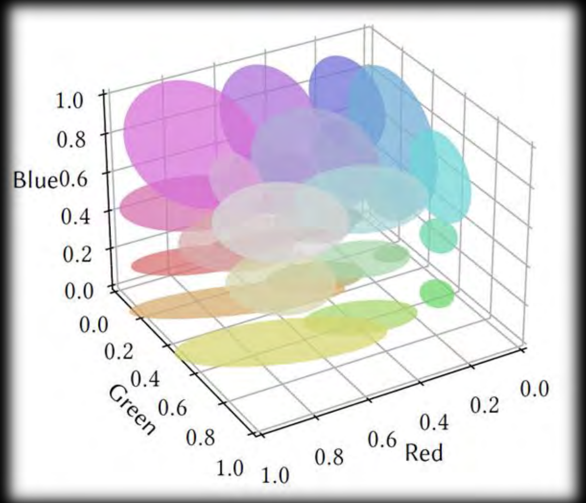
Distance in periphery

Learned Function

$$\Phi : (x, e) \mapsto (\alpha_1, \alpha_2)$$

which color appears different?

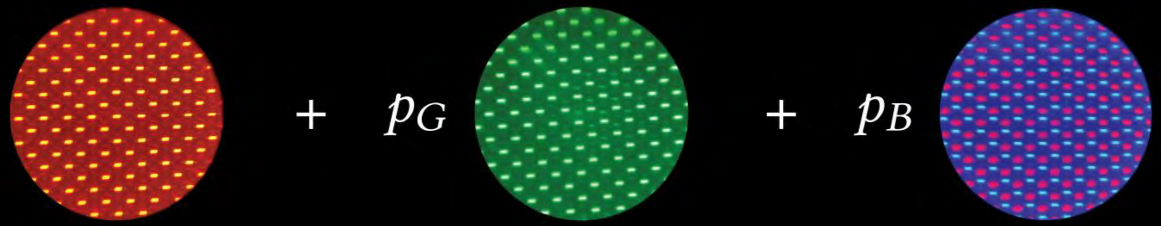




Ellipse Regions in (linear) *sRGB*

LED Power Consumption

LED Power Consumption



$$\mathcal{P}(x) = p_R \, R + p_G \, G + p_B \, B$$

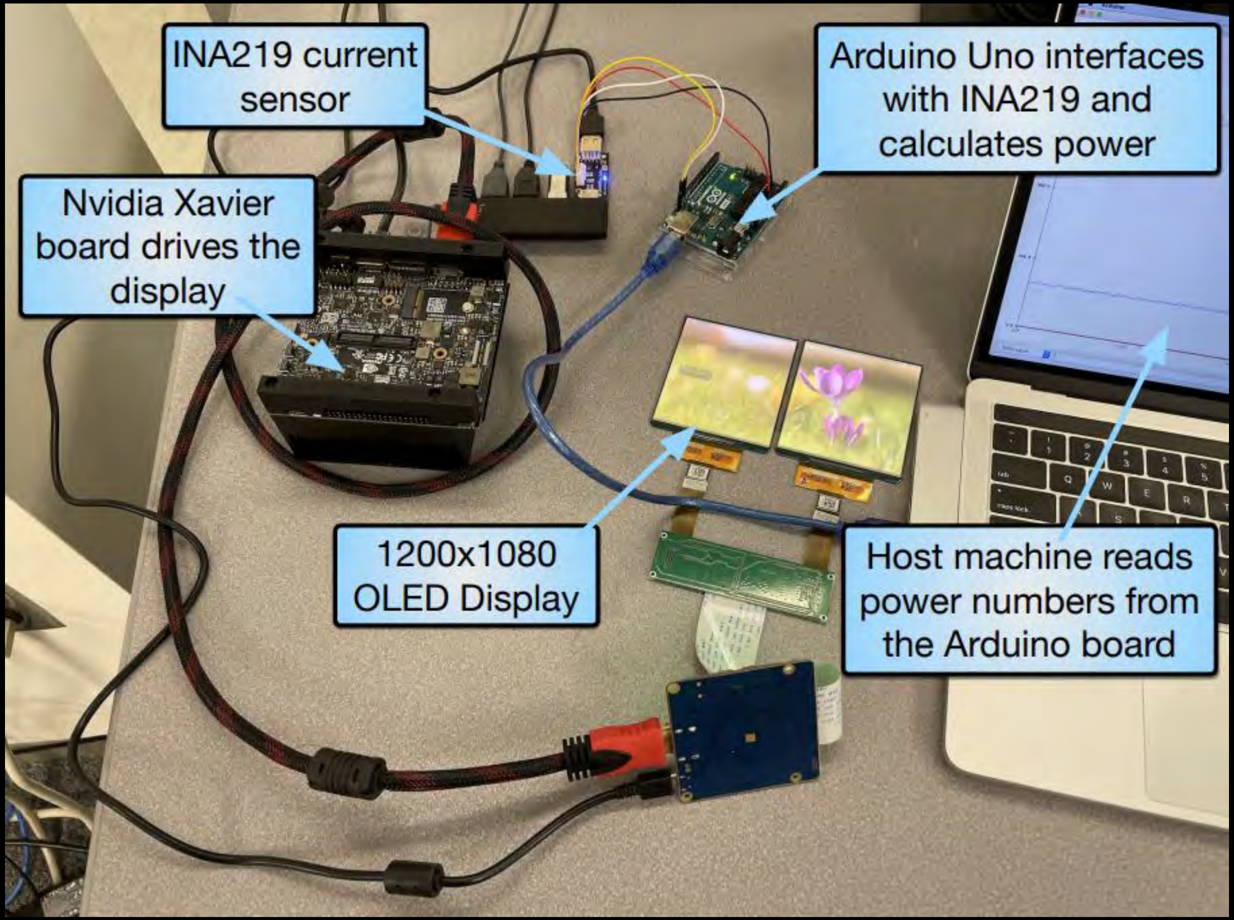
$$p_R = 231 \text{ mW}$$

$$p_G = 246 \text{ mW}$$

$$p_B = 531 \text{ mW}$$

Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

LED Power Model



Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

LED Power Model

Color-Perception-Guided Display Power Reduction for Virtual Reality
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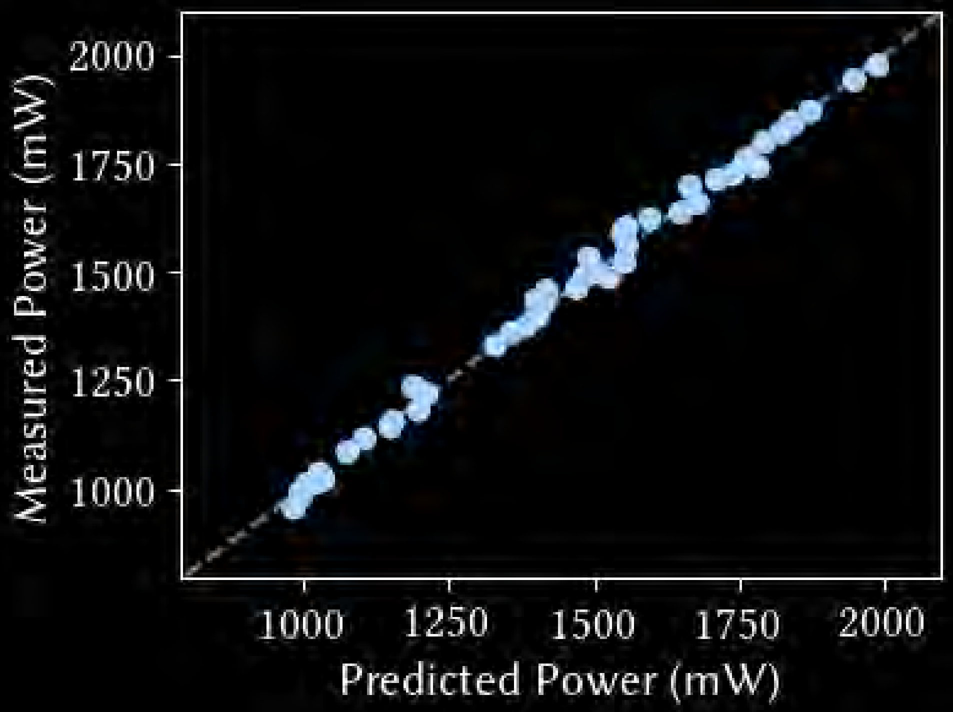
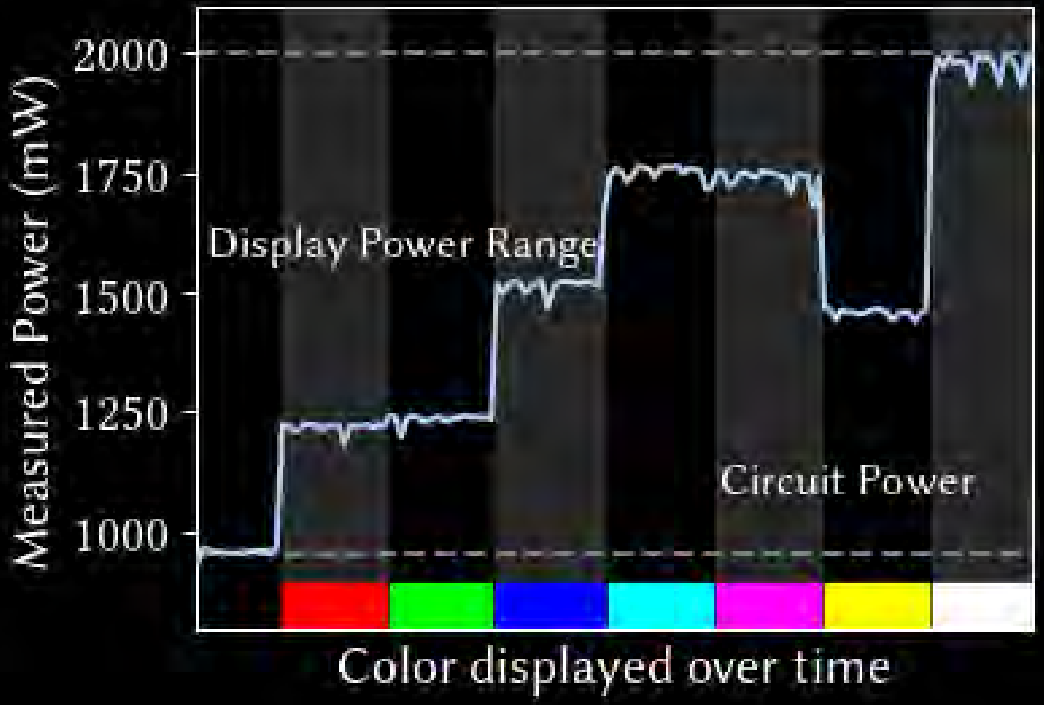
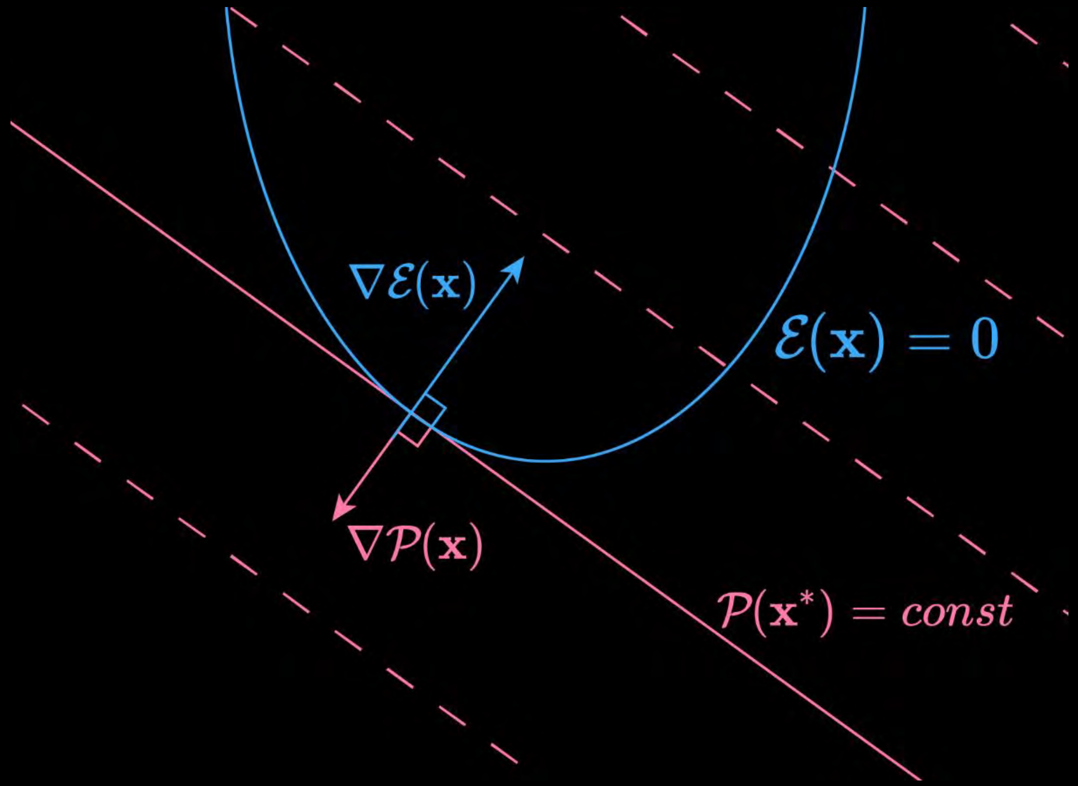




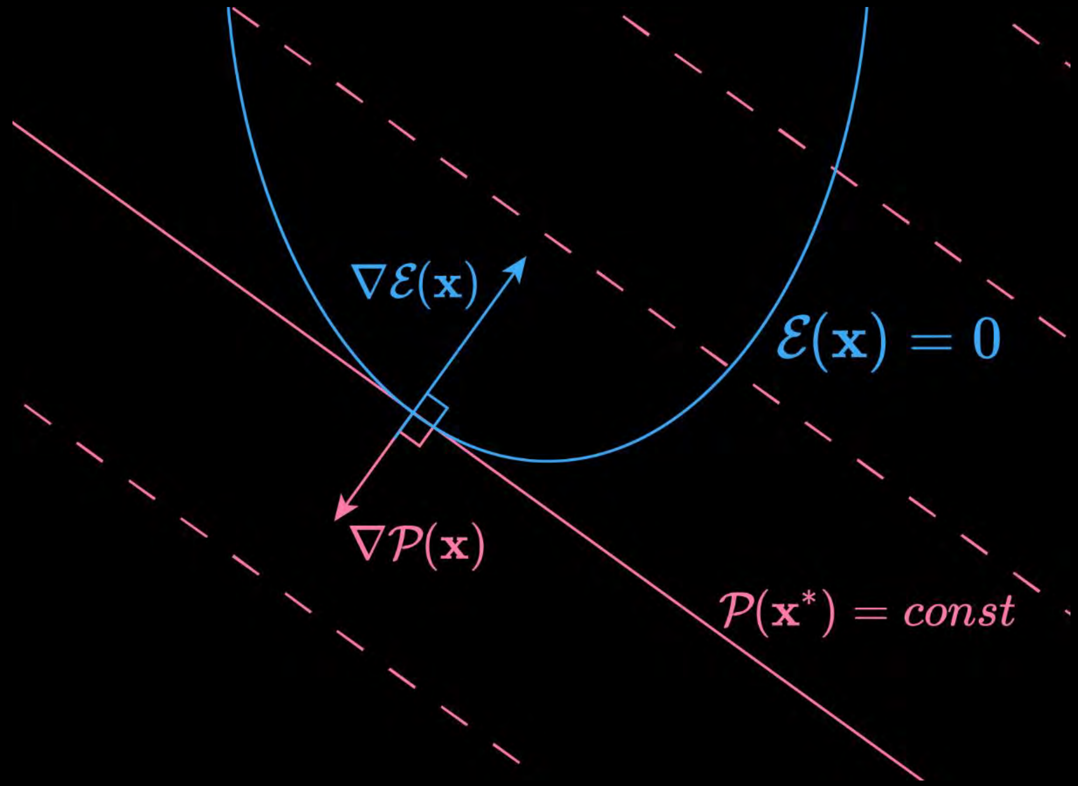
Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

Constraint Optimization for Power Saving



Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

Constraint Optimization for Power Saving



$$x^* = \arg\min_{x \in C} \mathcal{P}(x)$$

$$C = \{x \mid \mathcal{E}(x) \leq 0\}$$

Color-Perception-Guided Display Power Reduction for Virtual Reality
Budmonde Duinkharjav et al., ACM ToG (SIGGRAPH Asia 2022)

Save screen energy in the wild

Percentile of power savings

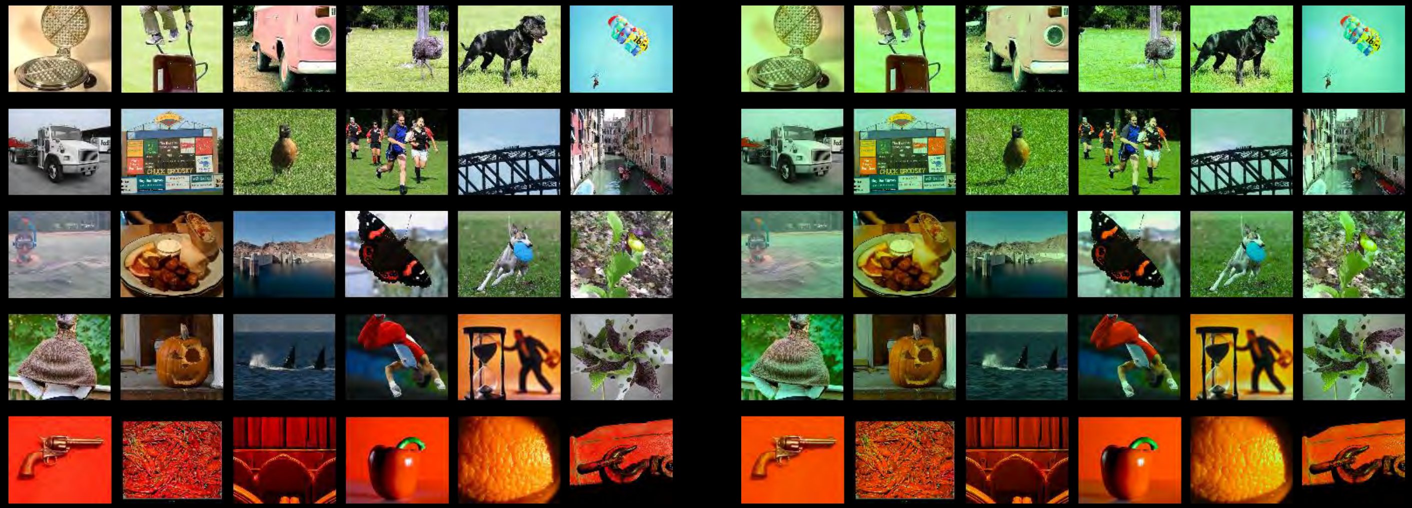
>99.9%

>55%

>45%

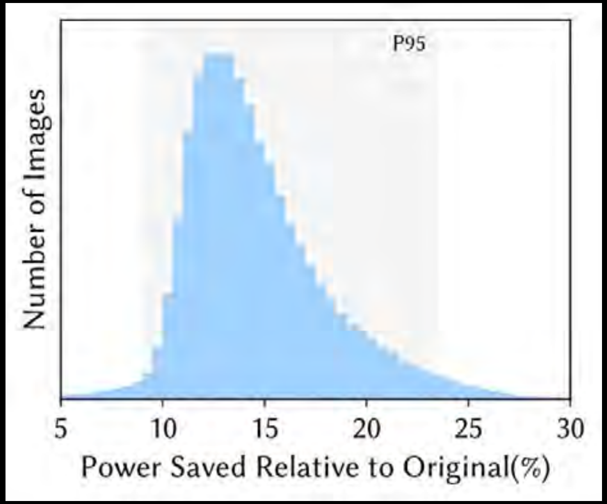
>0.1%

<0.1%



Original

Ours



From Screen to Computation

Low-Cost and Real-Time Neural Radiance Field (NeRF) for VR

NeRF in VR

~90s/frame

FoV-NeRF: Foveated Neural Radiance Fields for Virtual Reality
Nianchen Deng et al., TVCG (ISMAR) 2022
🏆 [Best Paper Award]

From Screen to Computation

Low-Cost and Real-Time Neural Radiance Field (NeRF) for VR

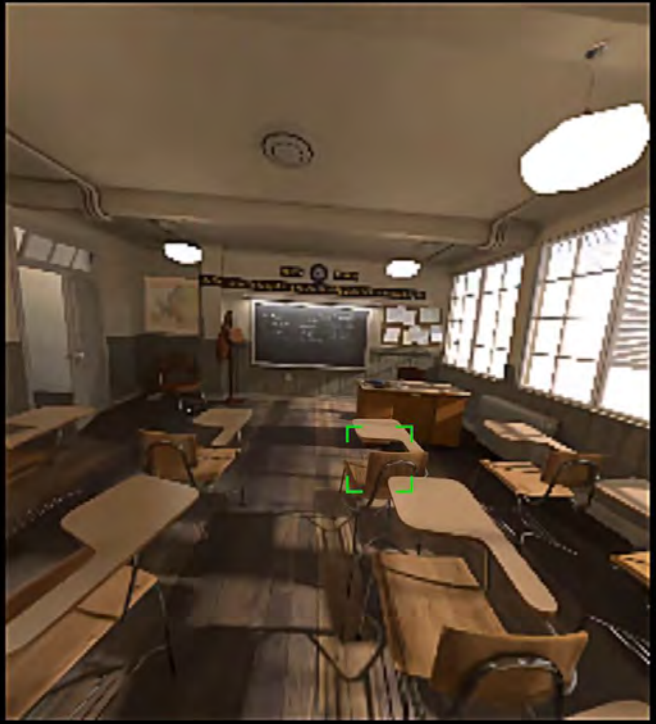
NeRF in VR

~**90s**/frame

Gaze-Contingent NeRF

98% Less Computation

~20ms/frame

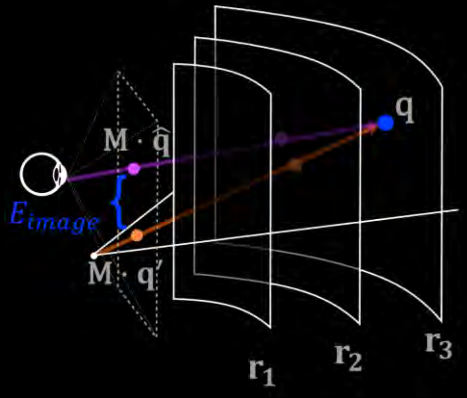


FoV-NeRF: Foveated Neural Radiance Fields for Virtual Reality

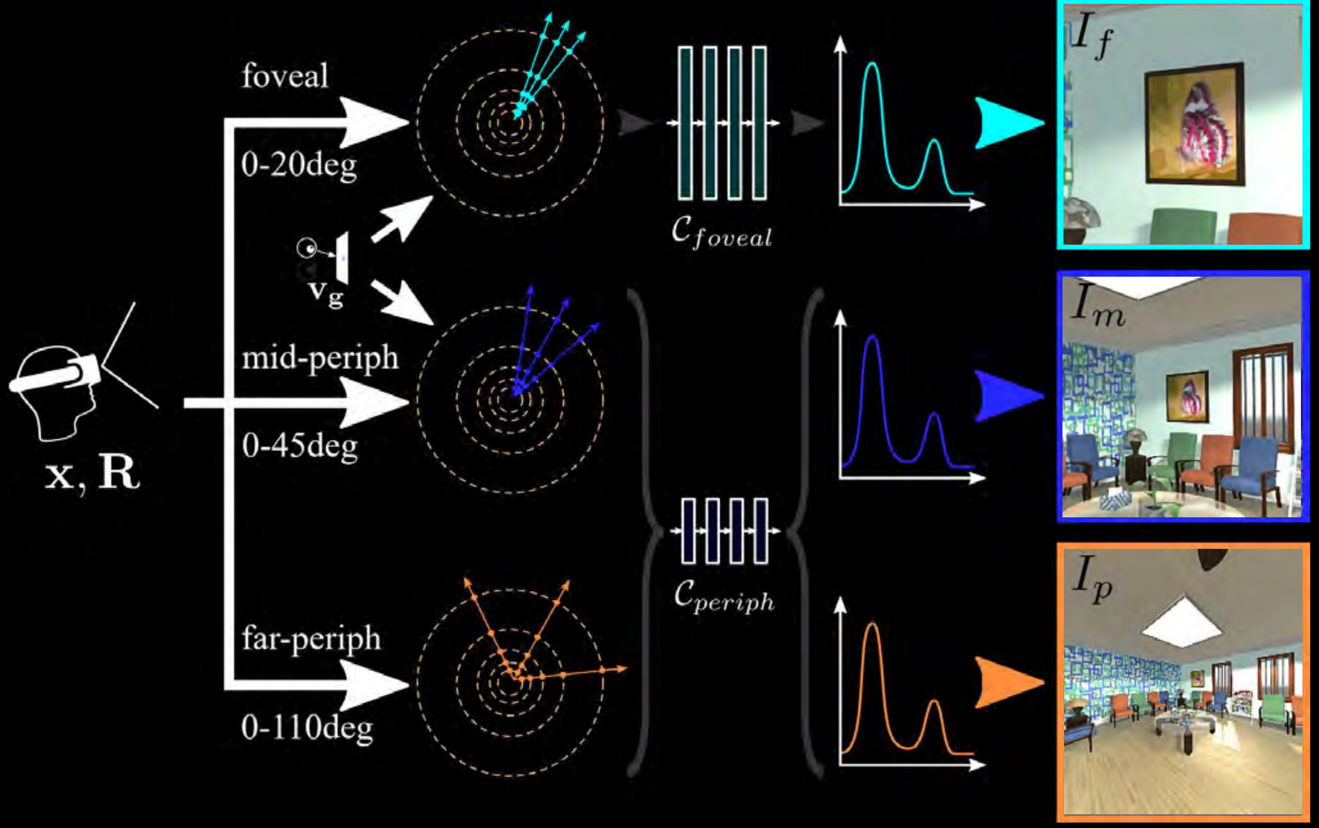
Nianchen Deng et al., TVCG (ISMAR) 2022

🏆 [Best Paper Award]

Gaze-Contingent Neural Radiance Field



egocentric coordinate



foveated inference

foveated stereopsis

FoV-NeRF: Foveated Neural Radiance Fields for Virtual Reality
Nianchen Deng et al., TVCG (ISMAR) 2022
🏆 [Best Paper Award]

From Screen to Computation

Low-Cost and Real-Time Neural Radiance Field (NeRF) for VR

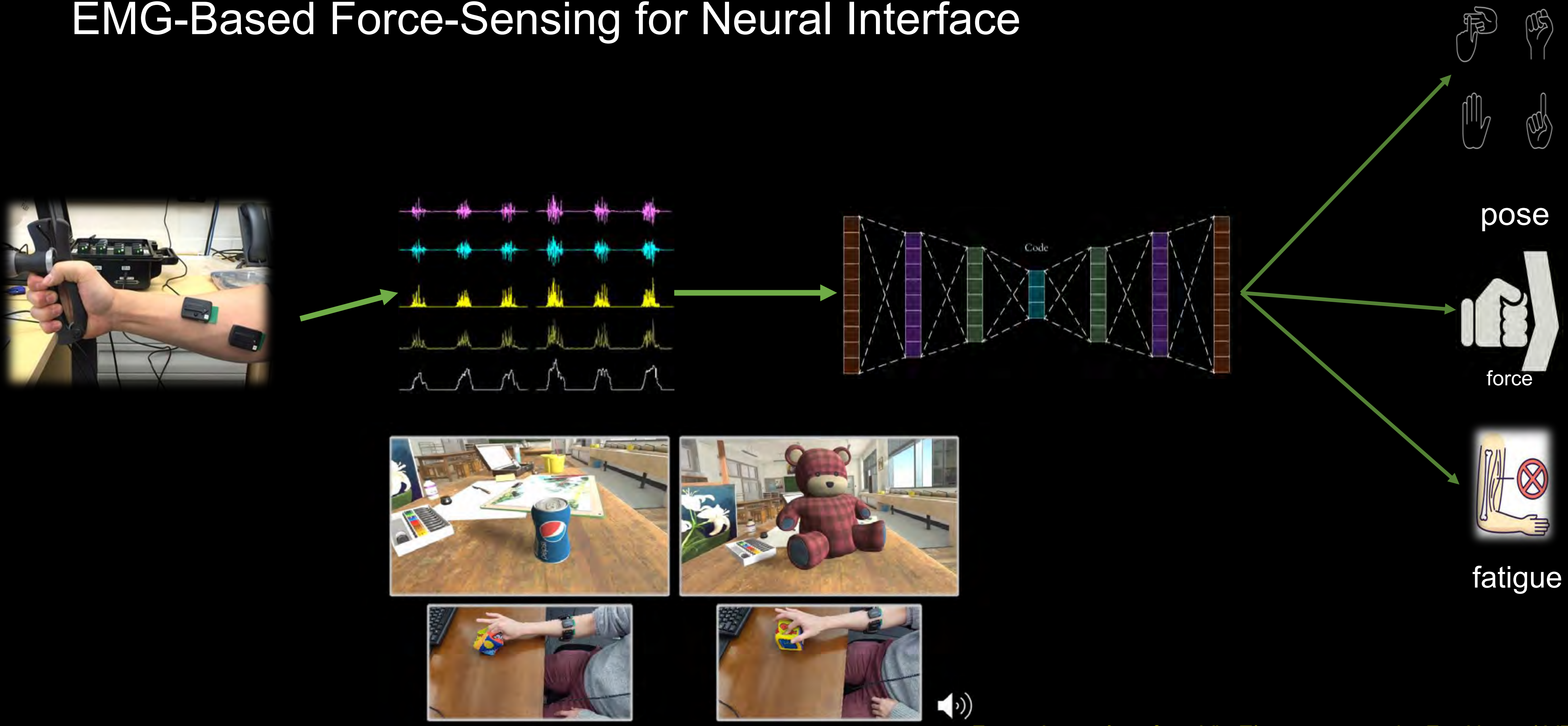
Physical Scenes

FoV-NeRF: Foveated Neural Radiance Fields for Virtual Reality
Nianchen Deng et al., TVCG (ISMAR) 2022
🏆 [Best Paper Award]

Deep Learning Models for Bio-Metrics

From the Eyes to the Muscle

EMG-Based Force-Sensing for Neural Interface



Force-Aware Interface Via Electromyography For Natural VR/AR Interaction
Zhang et al. ACM ToG (SIGGRAPH Asia 2022)

Overview

Good practices for user studies

Experiencing virtual reality through embodiment

Developing computational models with mathematical and neurological insights

Virtual characters

Seeing in depth

Audio in virtual reality

Seeing in Depth

Effective User Studies in Computer Graphic

Eurographics 2023 Tutorial

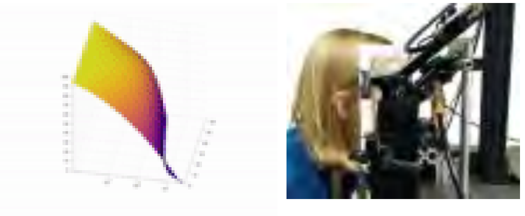
Petr Kellnhofer

About me…

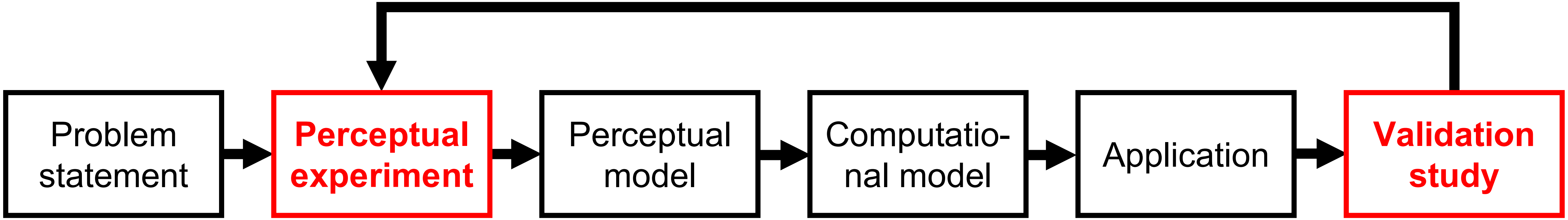
- Assistant Professor at TU Delft.
- Computer **Graphics** and Computer **Vision**.

  - **Generating** images
    - Neural rendering

  - **Understanding** images
    - **Perceptual modeling**



Perception in Computer Graphics



Problem statement

Perceptual experiment

Perceptual model

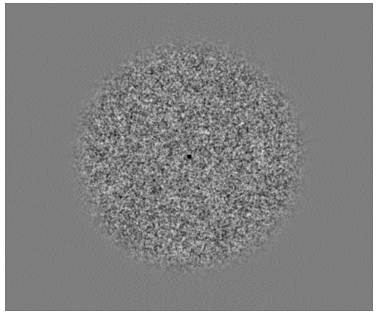
Computational model

Application

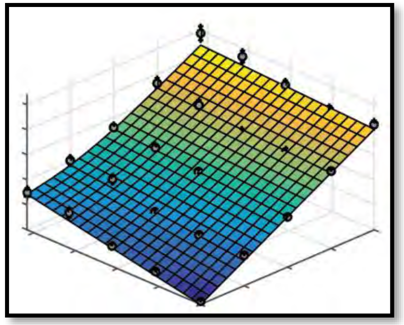
Validation study

"Objects look flat."

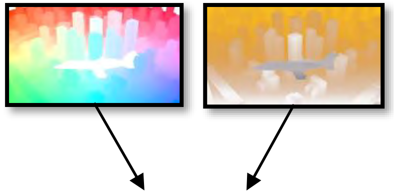
"How much depth do we get by using adding depth cue XY?"



Perceived depth for each variable combination.

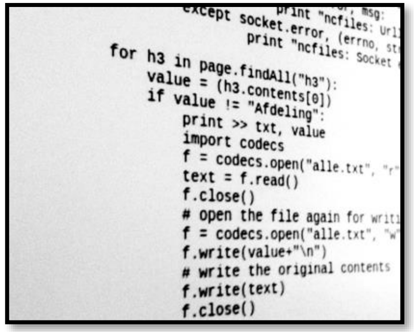


Map computed properties to model variables.



$f(x_0, x_1, \ldots)$

Design and implement a practical algorithm.



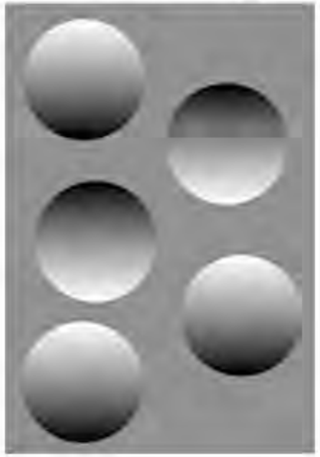
```
except socket.error, (errno, st
                print "ncfiles: Socket
for h3 in page.findAll("h3"):
    value = (h3.contents[0])
    if value != "Afdeling":
        print >> txt, value
        import codecs
        f = codecs.open("alle.txt", "r"
        text = f.read()
        f.close()
        # open the file again for writi
        f = codecs.open("alle.txt", "w"
        f.write(value+"\n")
        # write the original contents
        f.write(text)
        f.close()
```

Conduct a user study.

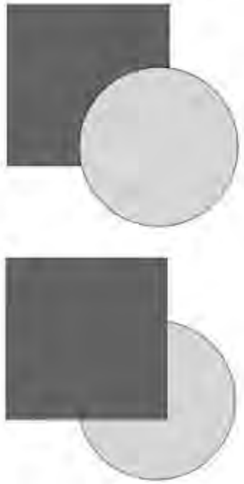
Chauvet-Pont-d’Arc Cave (~ 30,000 BCE). Credit: Claude Valette @ Wikipedia.org

Pictorial Depth Cues

Shading

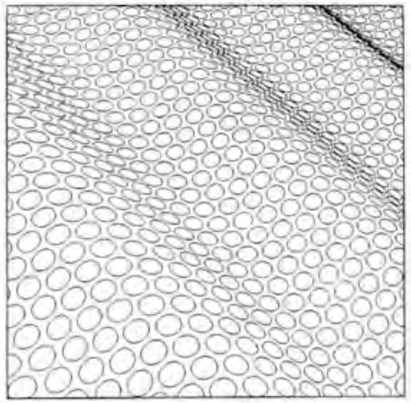


Occlusion



Perspective

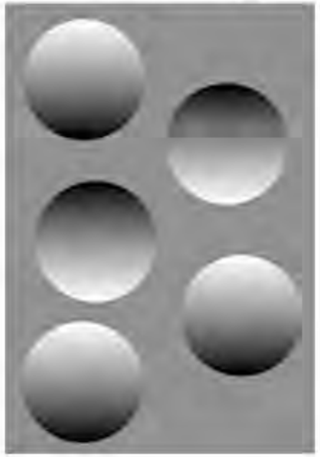
Texturing



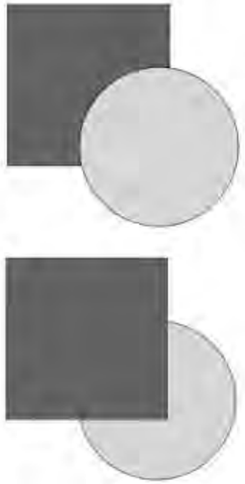
Krajancich, Brooke, Petr Kellnhofer, and Gordon Wetzstein. "Optimizing depth perception in virtual and augmented reality through gaze-contingent stereo rendering." ACM Transactions on Graphics (TOG) 39.6 (2020): 1-10.

Pictorial Depth Cues

Shading

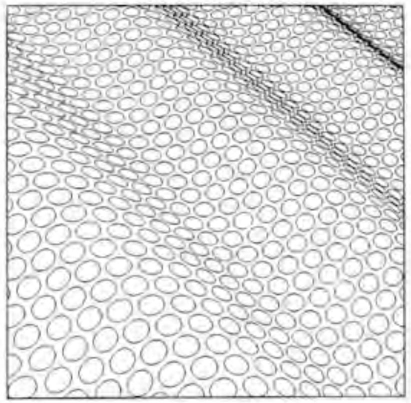


Occlusion



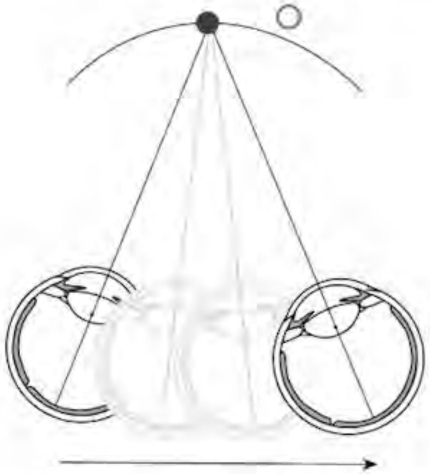
Perspective

Texturing

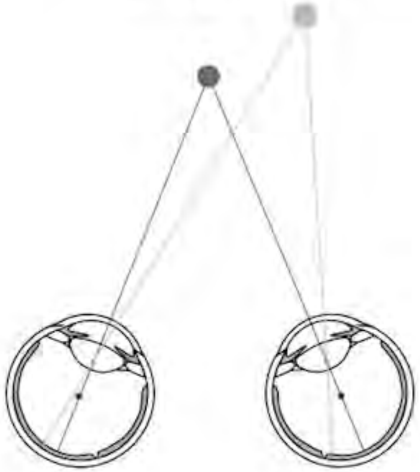


Non-Pictorial Depth Cues

Motion Parallax



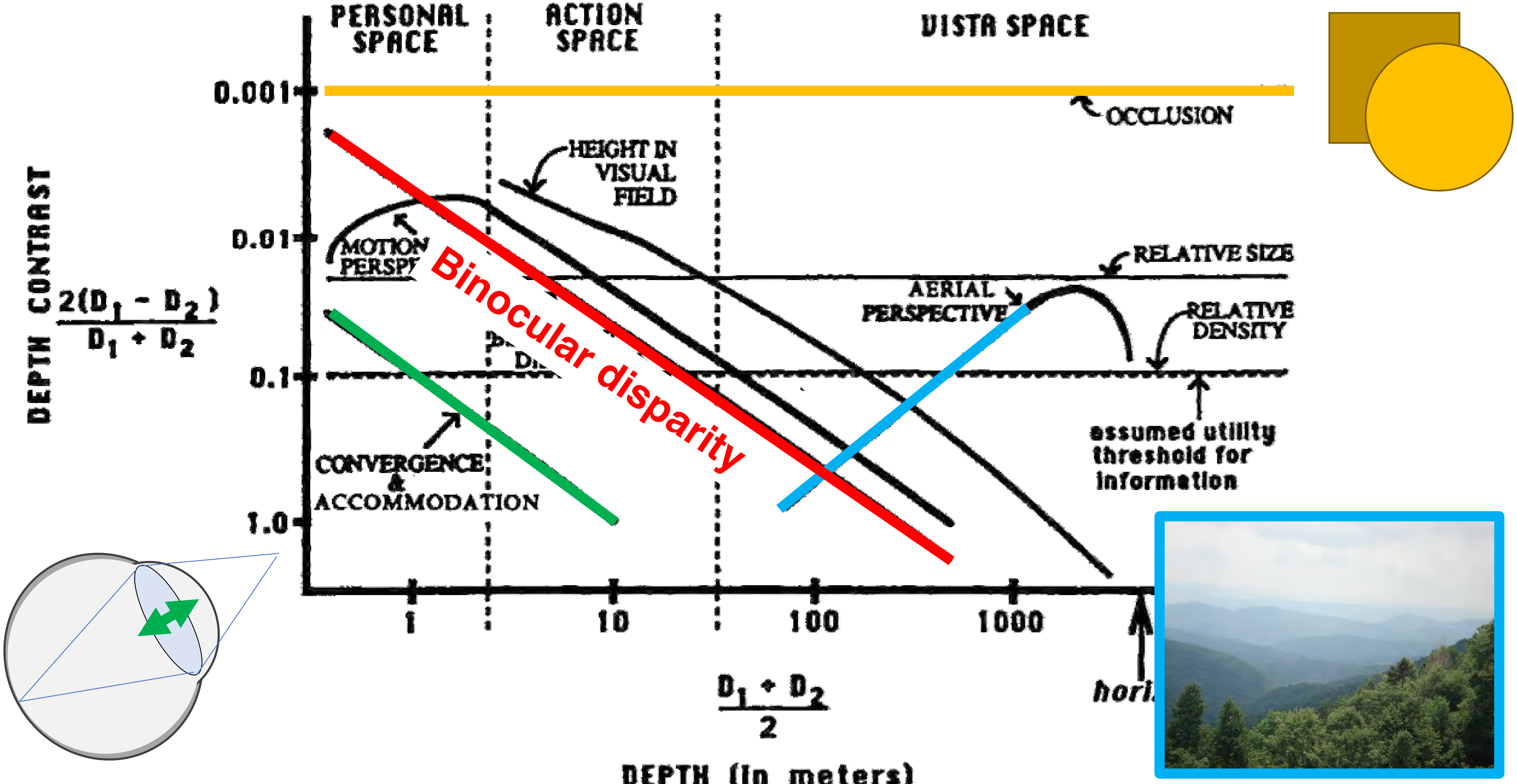
Disparity



Retinal Blur

Ocular Parallax

Krajancich, Brooke, Petr Kellnhofer, and Gordon Wetzstein. "Optimizing depth perception in virtual and augmented reality through gaze-contingent stereo rendering." ACM Transactions on Graphics (TOG) 39.6 (2020): 1-10.



Credit: Valerius Tygart

James E. Cutting, and Peter M. Vishton. "Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth." Perception of space and motion. Academic Press, 1995.

Depth reproduction

- **Pictorial depth cues**
  - Occlusion, size, shadows,…

Easily reproducible on **any display**

Our focus

- **Stereoscopic depth cues**
  - Binocular disparity
  - Vergence

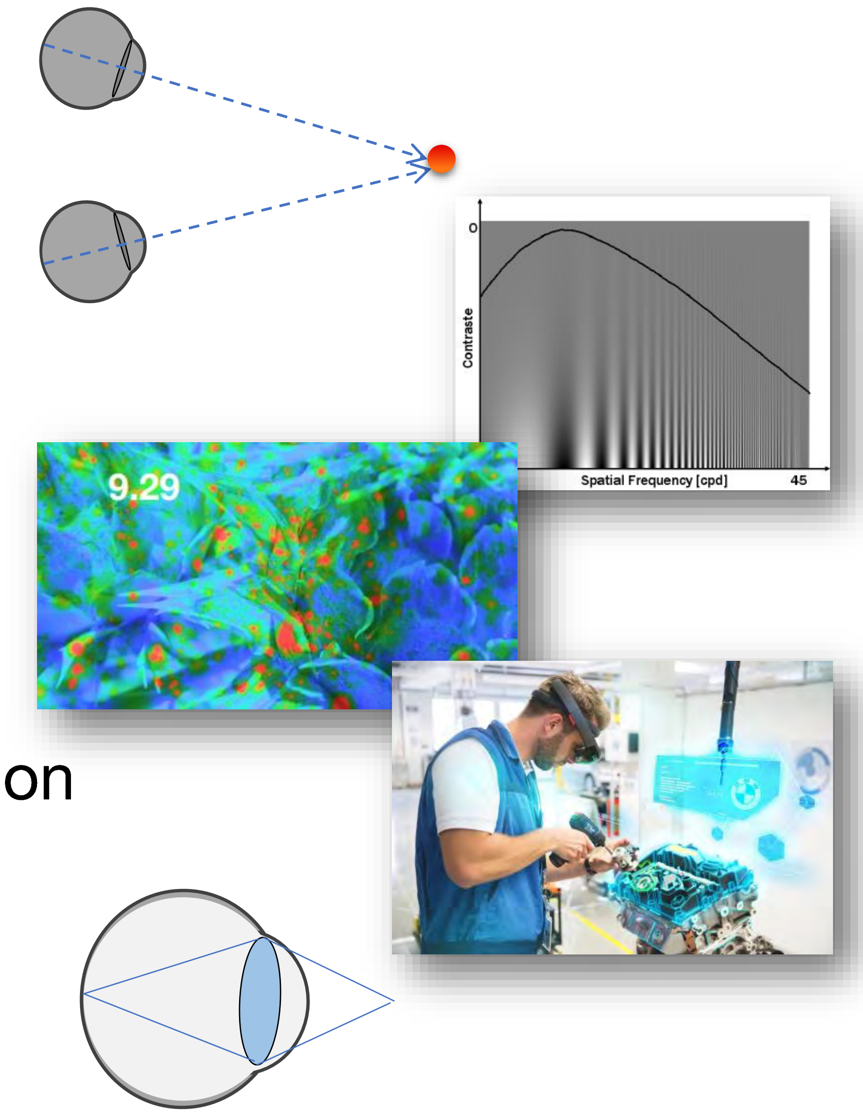
Requires **a stereoscopic display**

- **Ocular depth cues**
  - Accommodation

A bit more difficult (Varifocal, multifocal, light field, holographic display)

Outline

1. **Binocular vision**
   - How does it work?
2. **Depth sensitivity**
   - What is it? How can we measure it?
3. **Subjective qualities**
   - Visual preference, perceptual realism
4. **Task performance**
   - Absolute depth, time-to-collision, shape estimation
5. **Accommodation**
   - VAC conflict, depth of field
6. **Conclusion**
   - Interaction between cues



Outline

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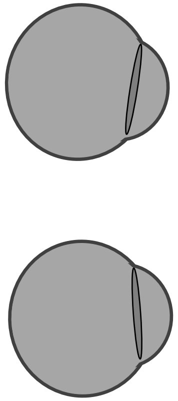
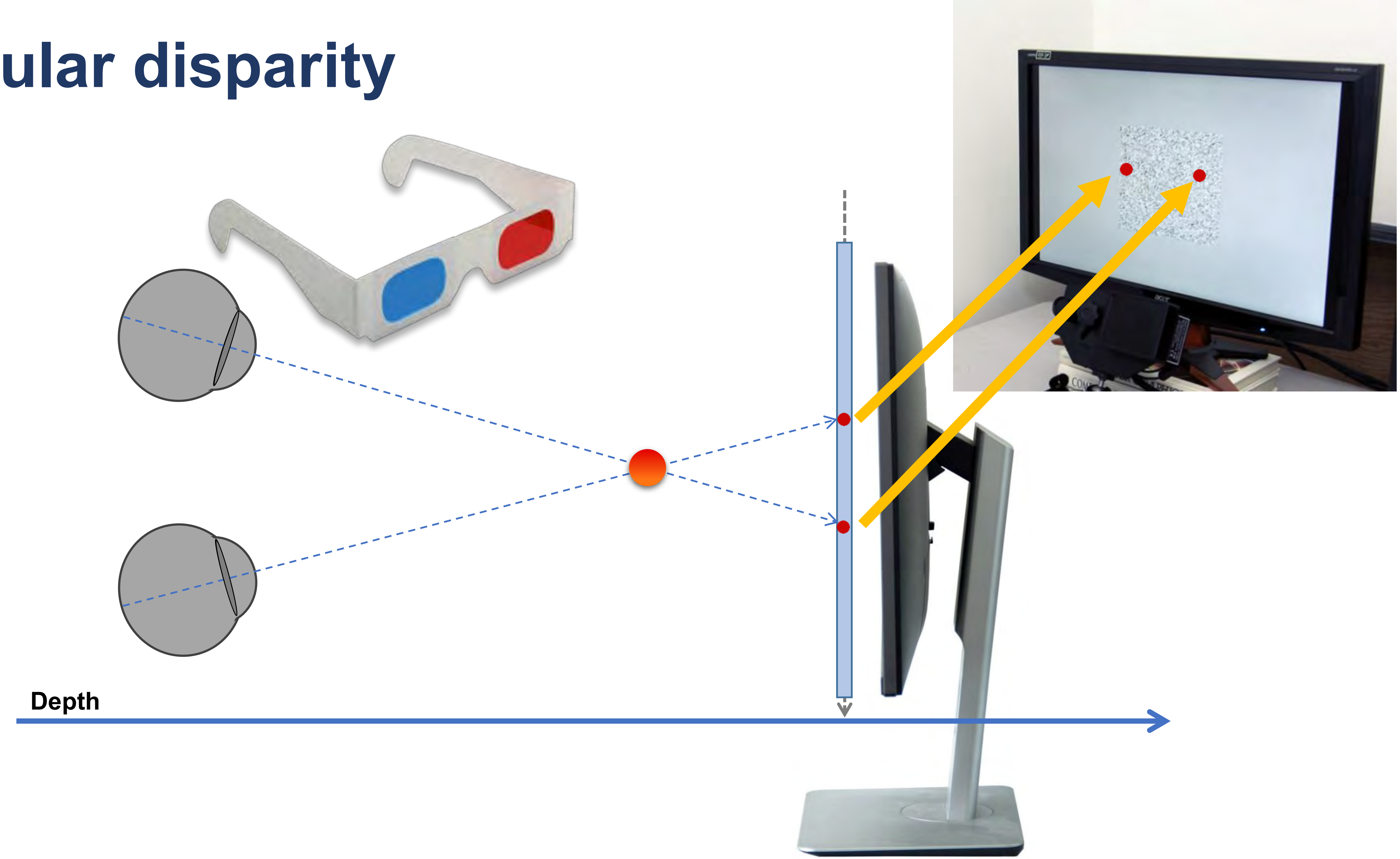
   - Absolute depth, time-to-collision, shape estimation
5. **Accommodation**
   - VAC conflict, depth of field
6. **Conclusion**
   - Interaction between cues

Classical stereoscopic 3D



Binocular disparity



Stereoscopy nowadays

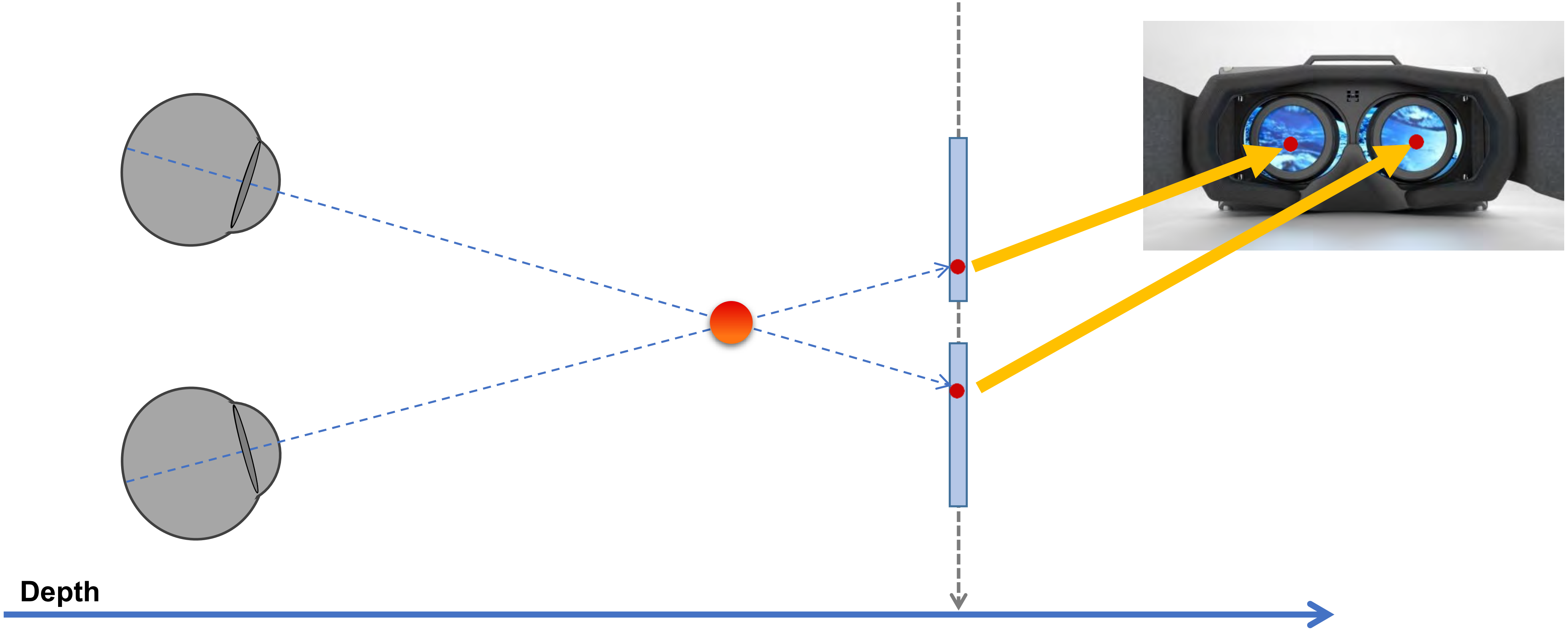

Hololens 2


Playstation VR2

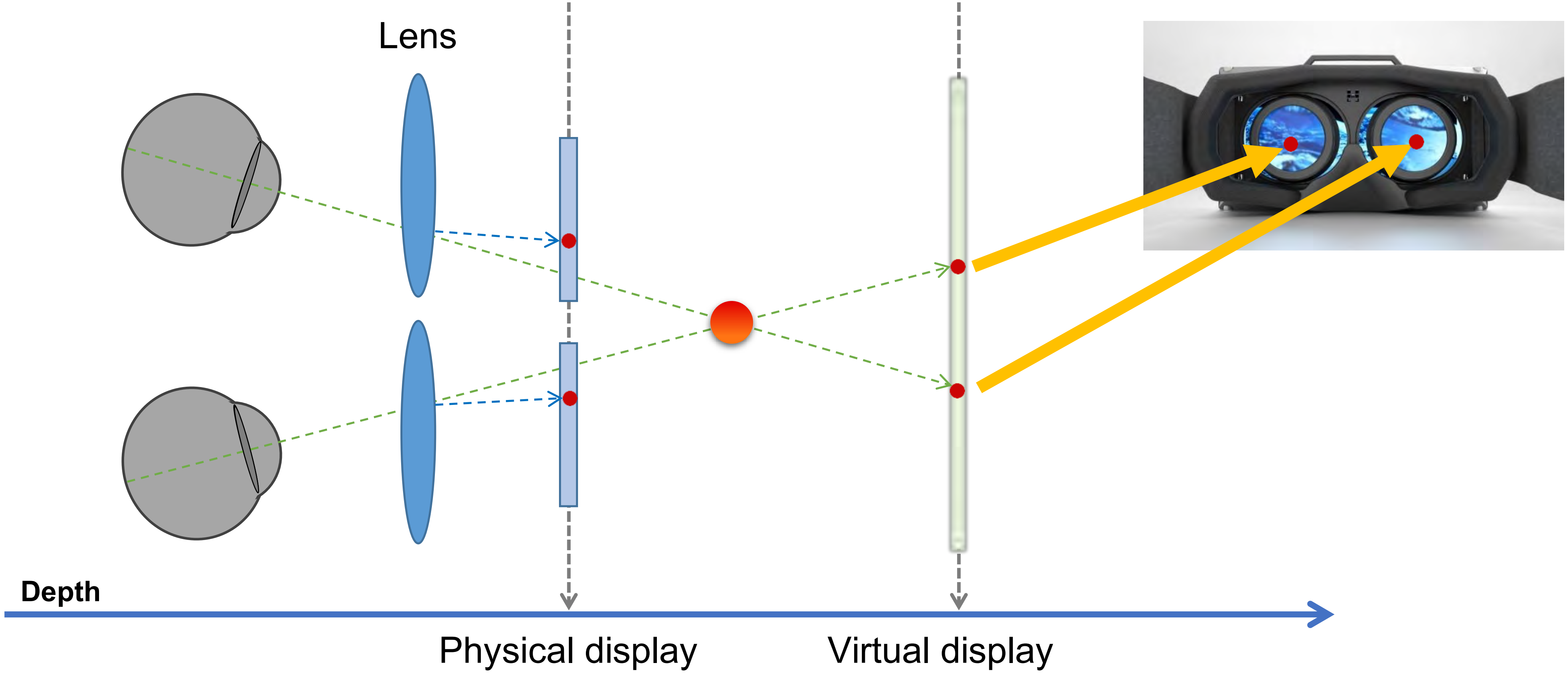
AR

VR

Binocular disparity



Binocular disparity



Lens

Depth

Physical display

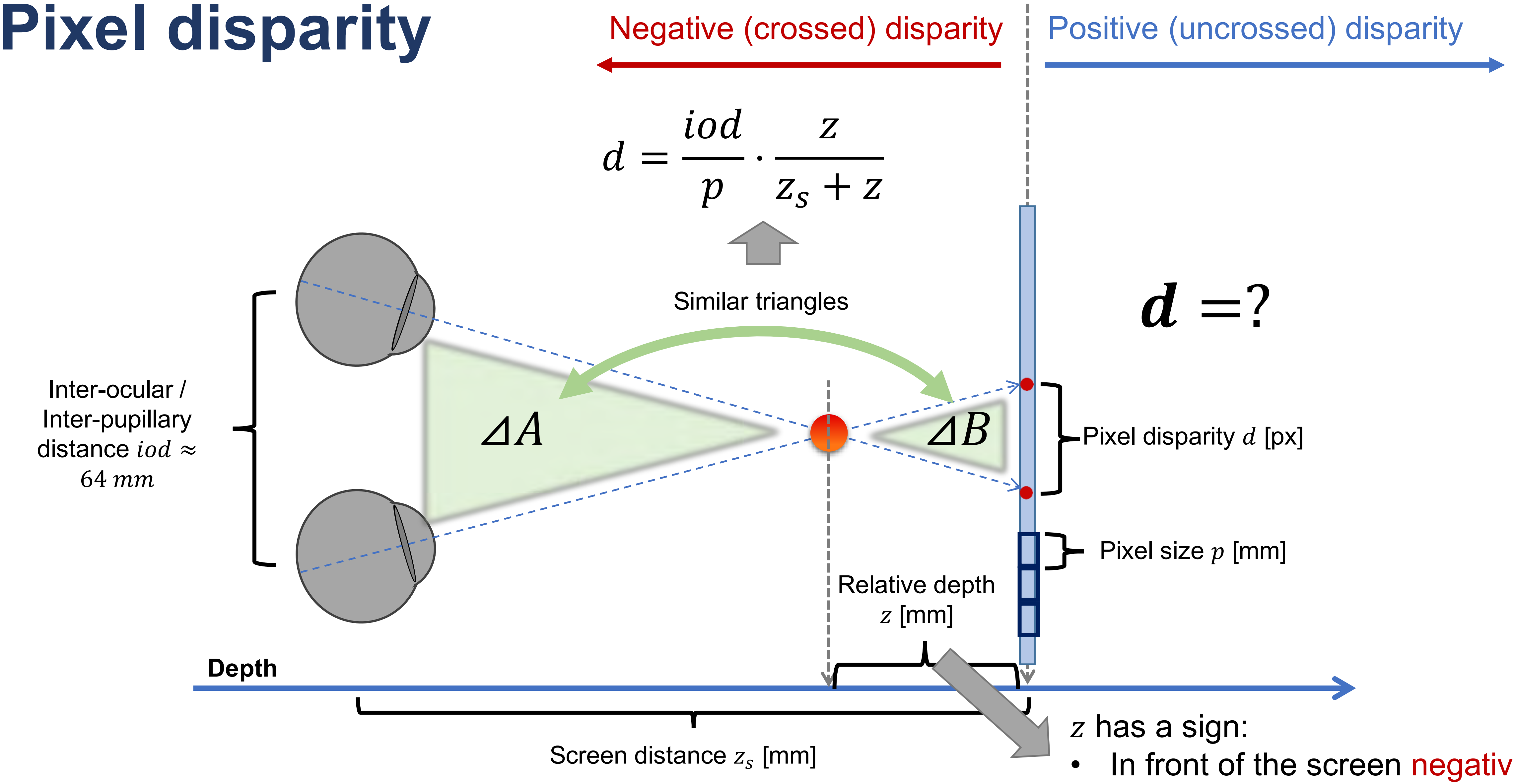
Virtual display

Pixel disparity

Negative (crossed) disparity

Positive (uncrossed) disparity

$$d = \frac{iod}{p} \cdot \frac{z}{z_s + z}$$



Similar triangles

$$\boldsymbol{d} = ?$$

Inter-ocular / Inter-pupillary distance $iod \approx 64\ mm$

Pixel disparity d [px]

Pixel size p [mm]

Relative depth z [mm]

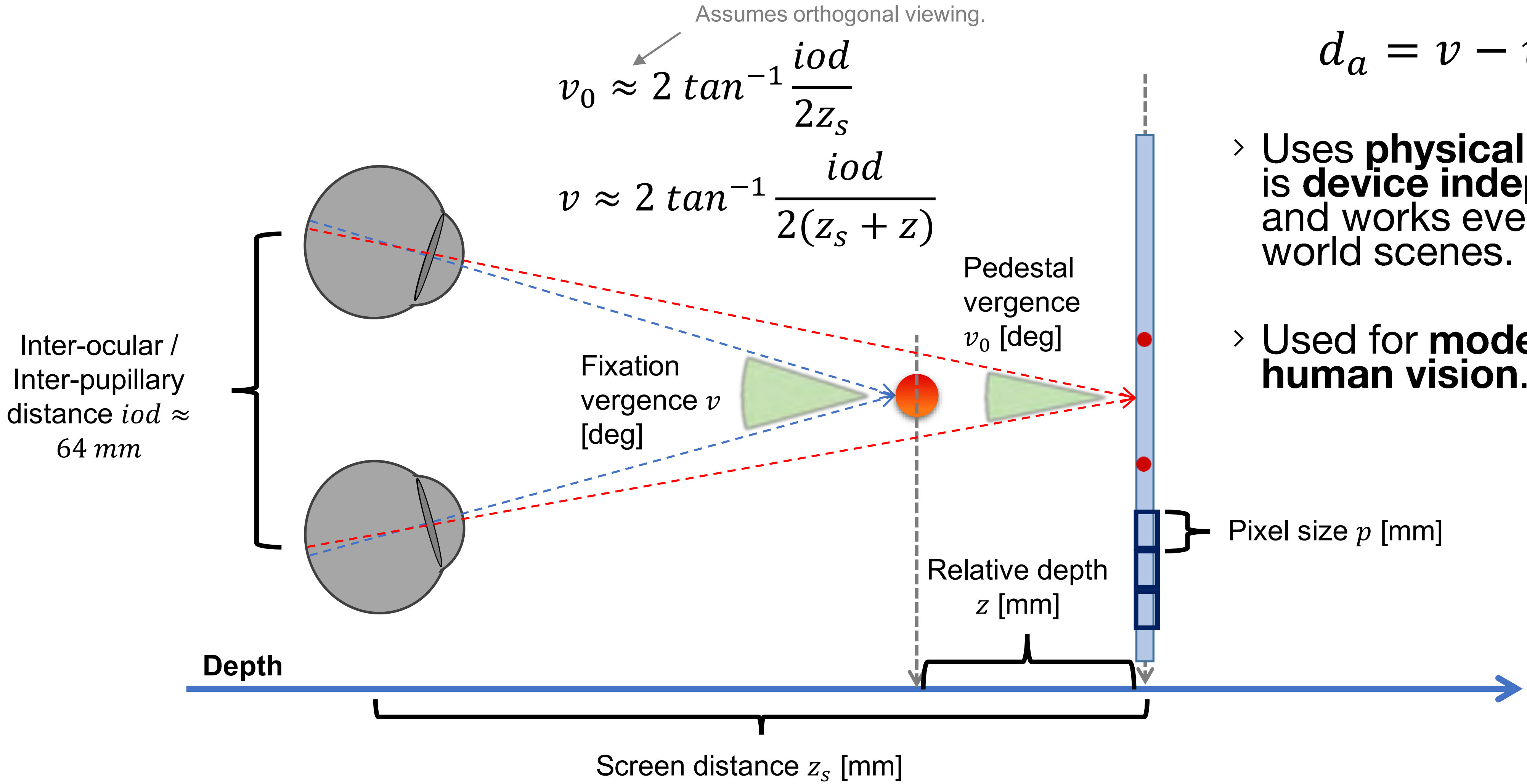
Depth

Screen distance z_s [mm]

z has a sign:

- In front of the screen negative.
- Behind the screen positive.

Angular disparity



$$v_0 \approx 2\, tan^{-1} \frac{iod}{2z_s}$$

$$v \approx 2\, tan^{-1} \frac{iod}{2(z_s + z)}$$

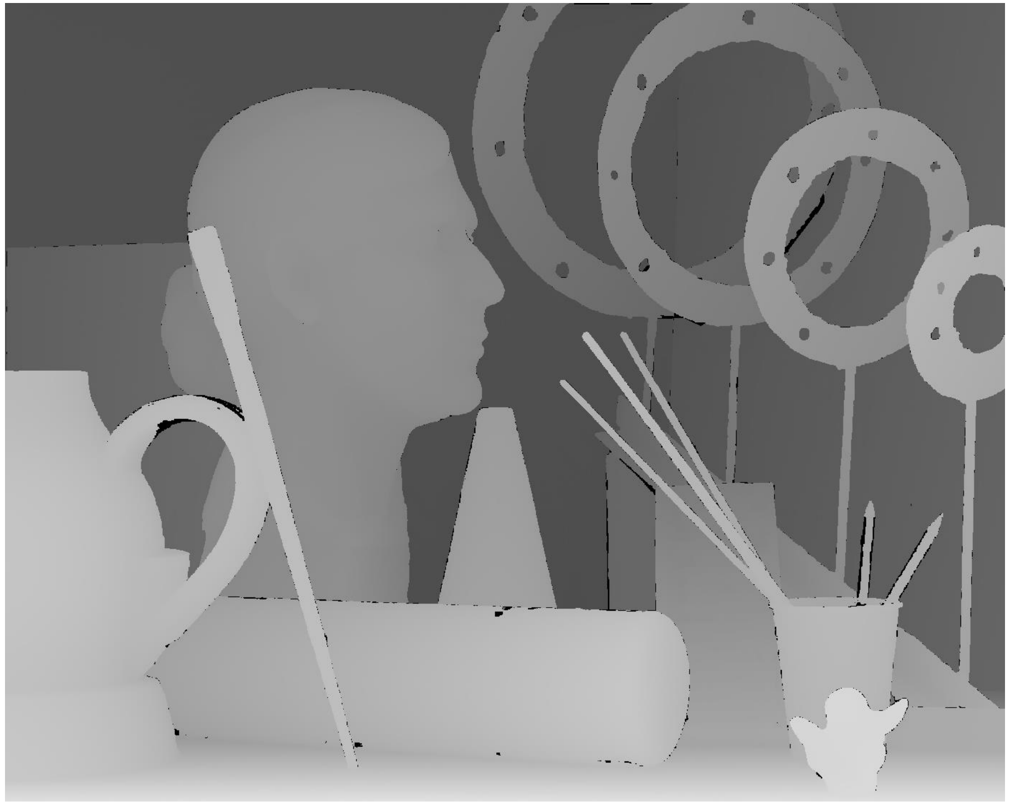
Angular disparity [deg]

$$d_a = v - v_0$$

- Uses **physical units** => is **device independent** and works even in real world scenes.
- Used for **modeling of human vision.**

Disparity signal

Image



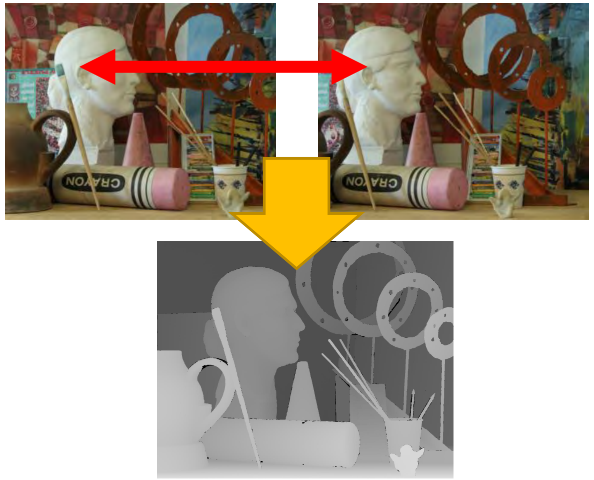
Disparity ~ 1/Depth

Device specific units (pixels,…)

D. Scharstein and C. Pal. Learning conditional random fields for stereo.
In IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2007), Minneapolis, MN, June 2007.

Disparity signal

(Multiview) Stereo Matching



Credit: Middlebury Stereo Dataset

Depth sensor

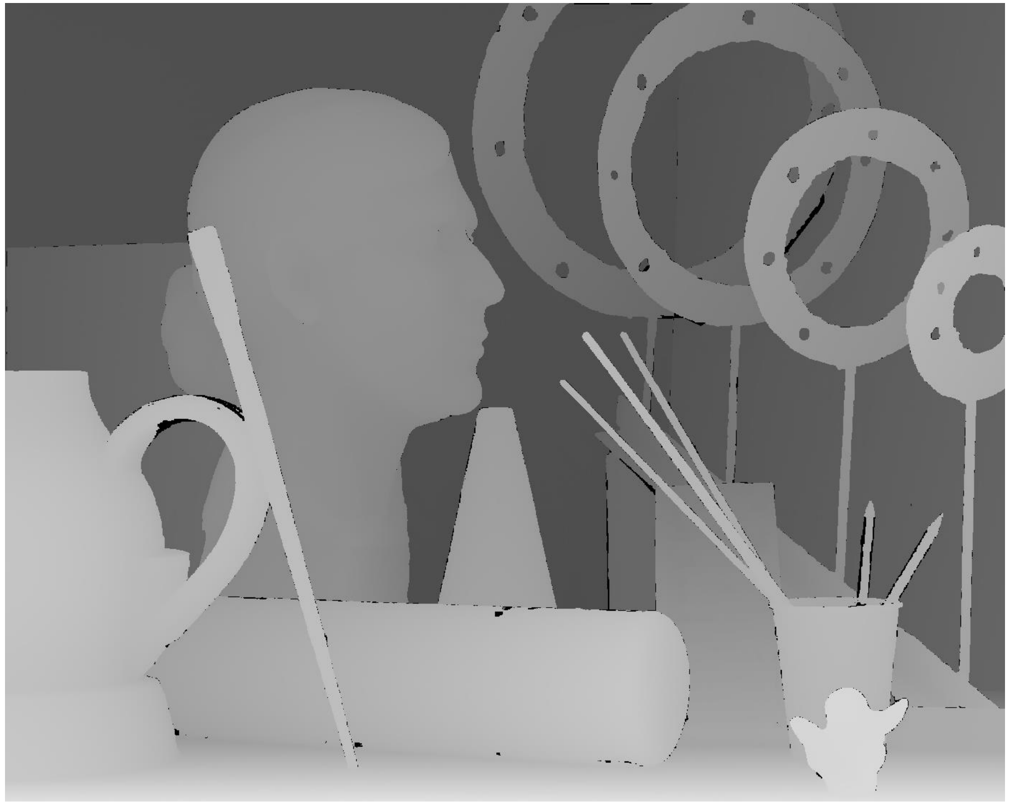
Credit: Microsoft Kinect & 3-byte

Synthetic data (CG)

Credit: MPI Sintel Dataset

Disparity signal

Image



Disparity ~ 1/Depth

Device specific units (pixels,…)

D. Scharstein and C. Pal. Learning conditional random fields for stereo.
In IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2007), Minneapolis, MN, June 2007.

Disparity signal

Image

Disparity ∝ 1/Depth

Physical units (arcmin,…)

D. Scharstein and C. Pal. Learning conditional random fields for stereo.
In IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2007), Minneapolis, MN, June 2007.

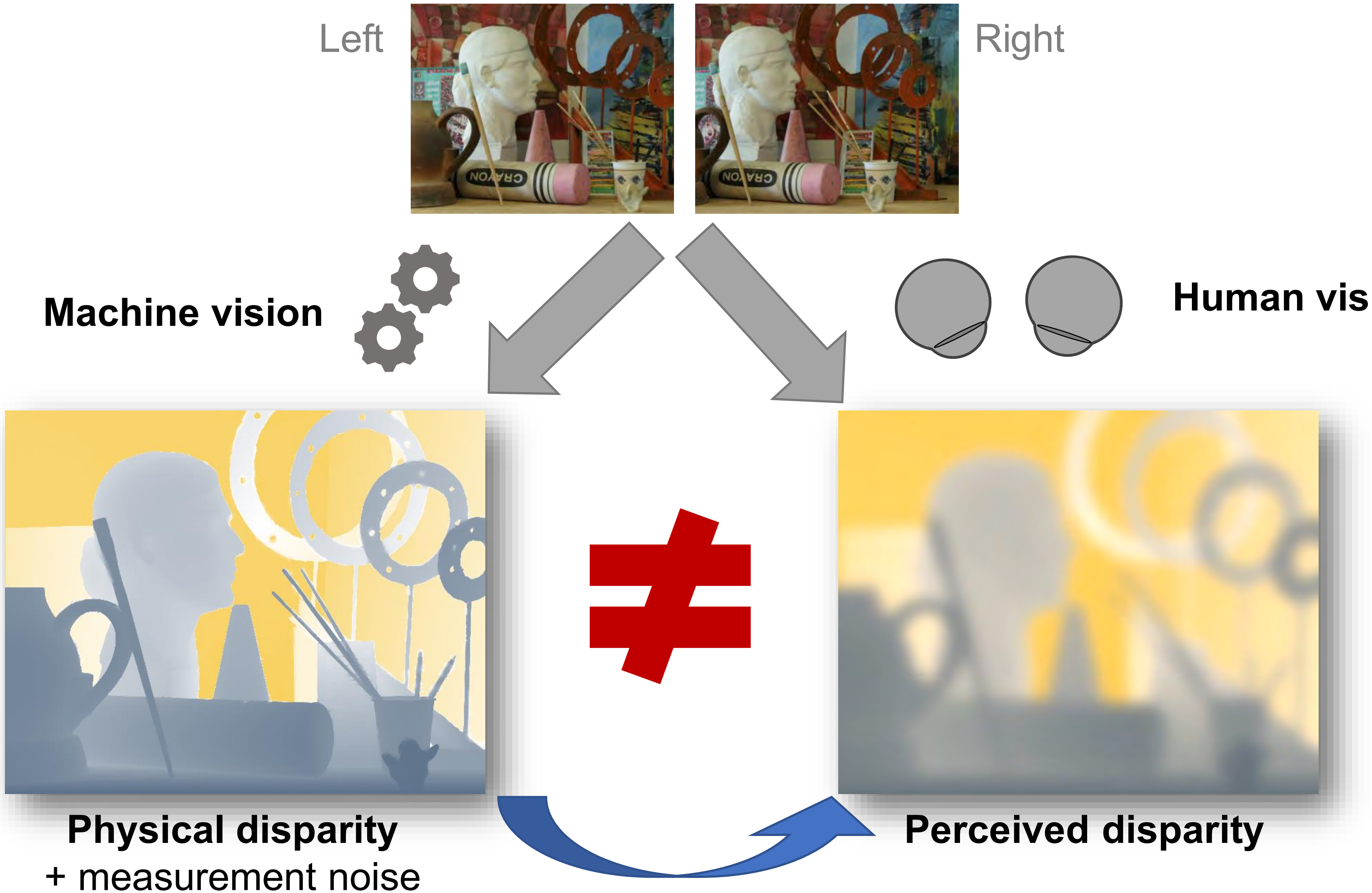
Disparity signal

Stereoscopic pair

Disparity ∝ 1/Depth

Physical units (arcmin,…)

D. Scharstein and C. Pal. Learning conditional random fields for stereo.
In IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2007), Minneapolis, MN, June 2007.



Left

Right

Machine vision

Human vision

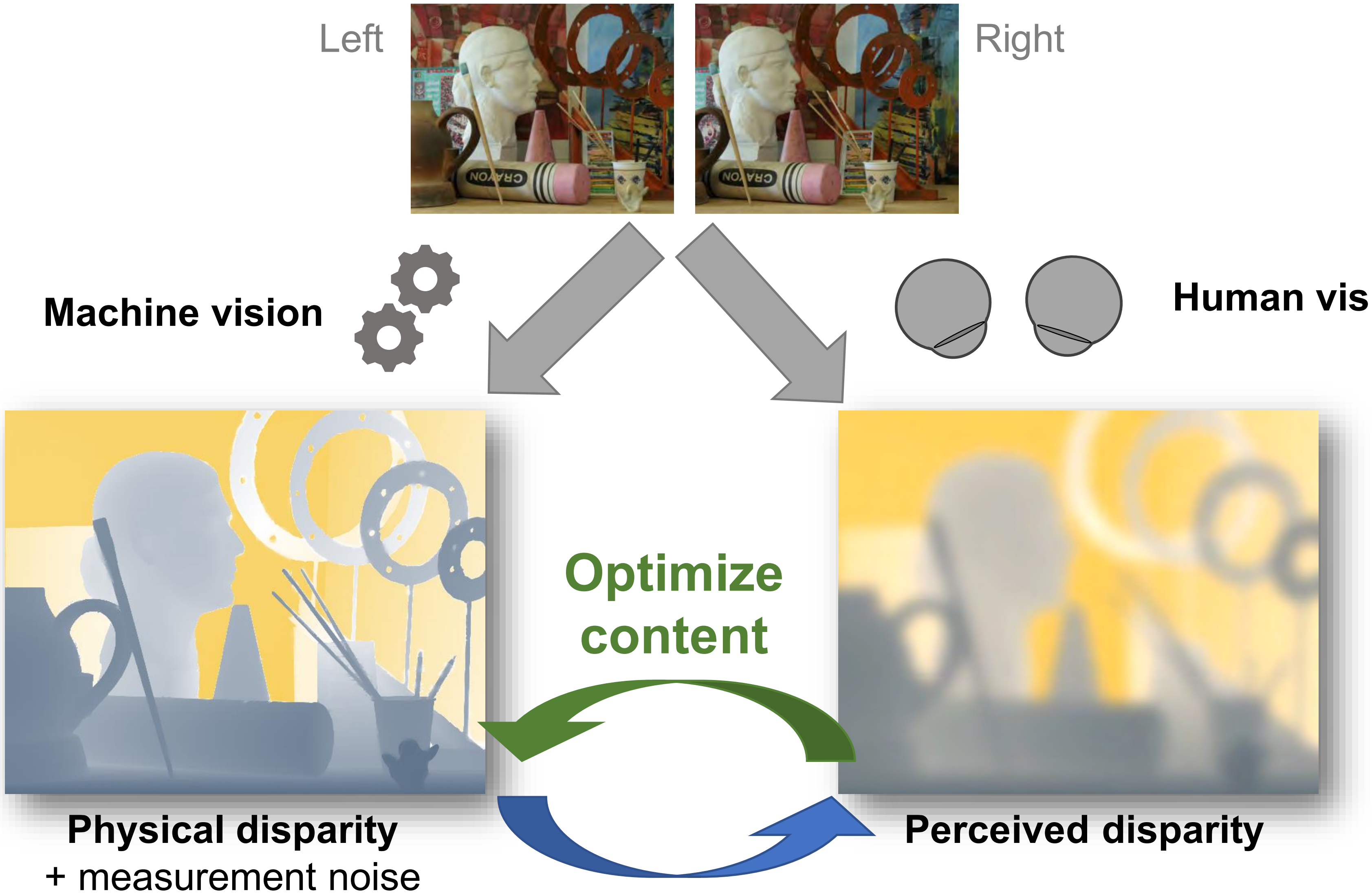
Physical disparity
+ measurement noise

Perceived disparity

Product of:
- Physical disparity.
- Ambiguity of depth.
- Cue fusion.
- **HVS limits**.
- …

Perceptual model

Calibrated using perceptual **experiments**.



Left

Right

Machine vision

Human vision

Optimize content

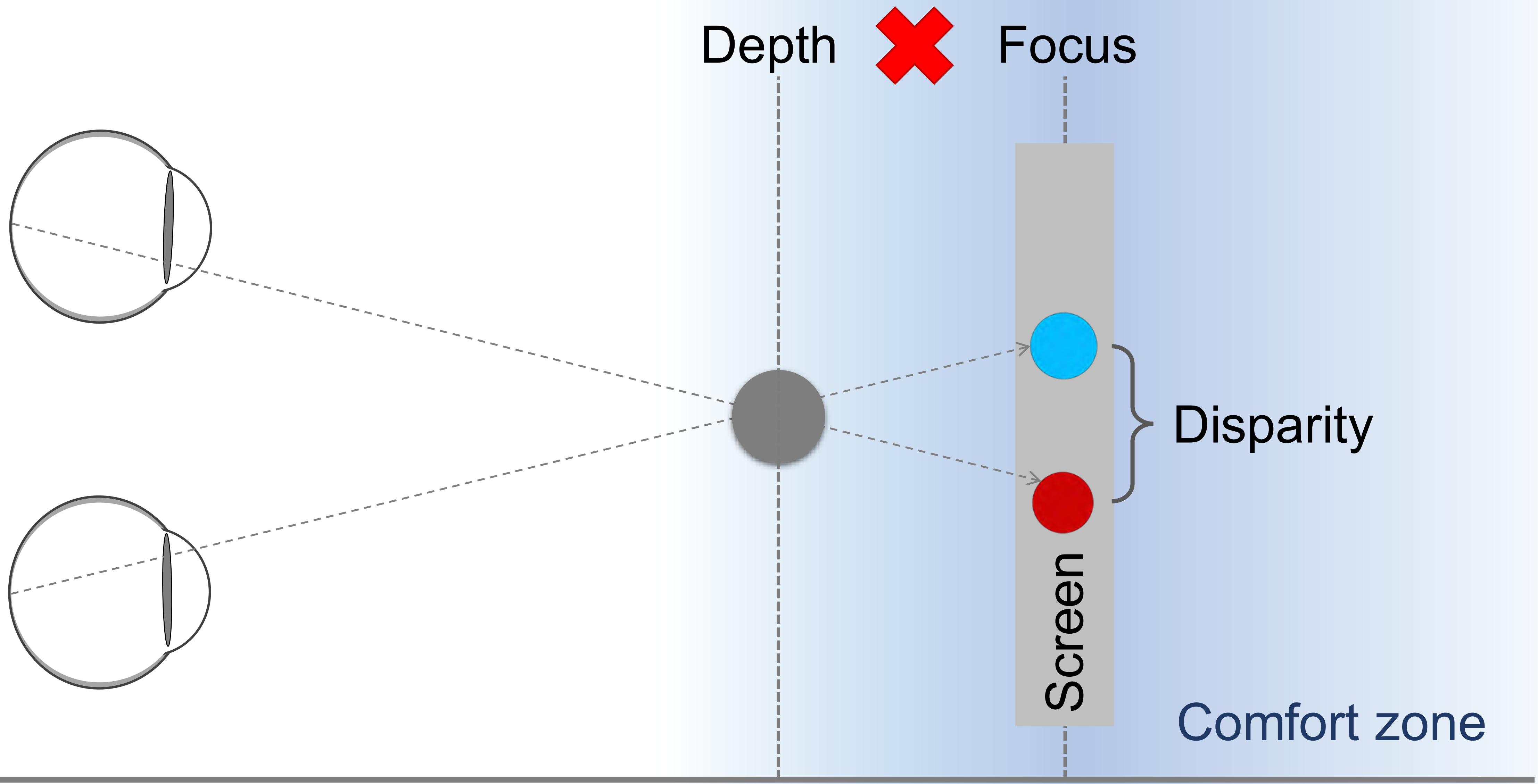
Physical disparity
+ measurement noise

Perceived disparity

Perceptual model

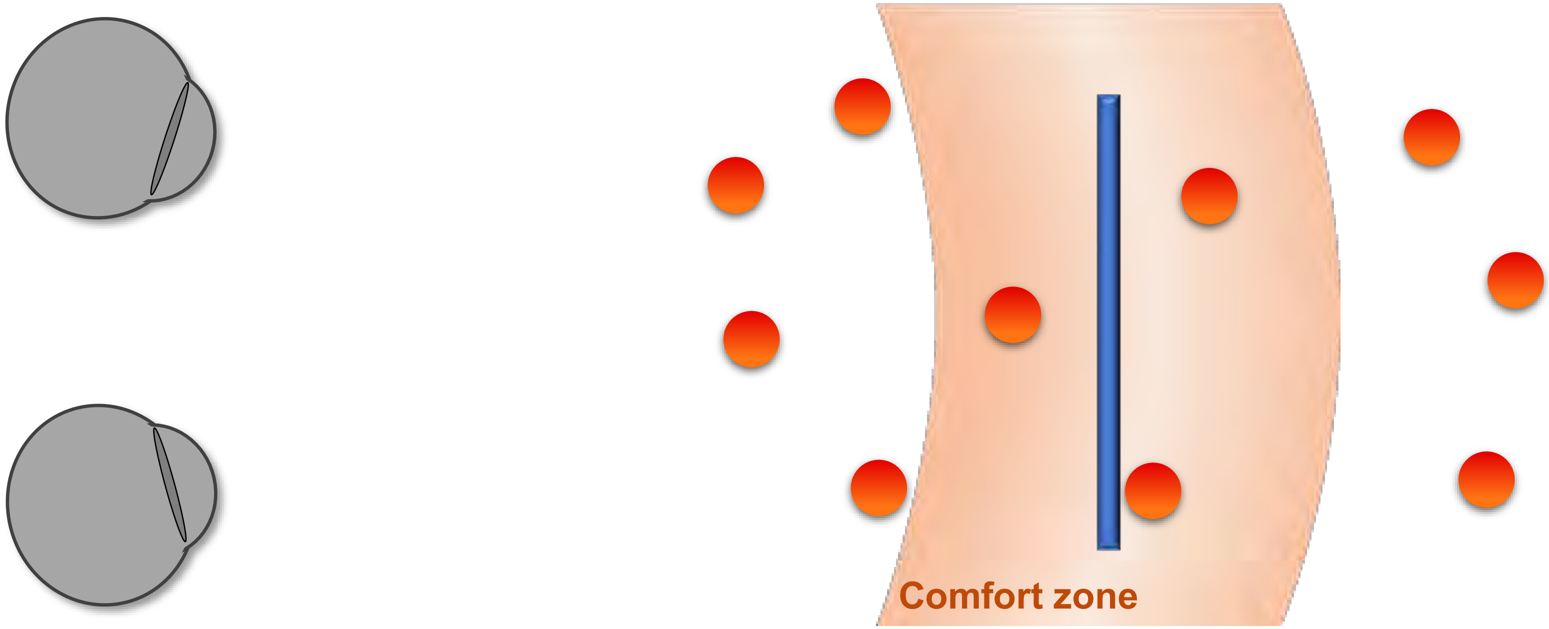
Calibrated using perceptual **experiments**.

Product of:
- Physical disparity.
- Ambiguity of depth.
- Cue fusion.
- **HVS limits**.
- …


Depth
Focus
Disparity
Screen
Comfort zone

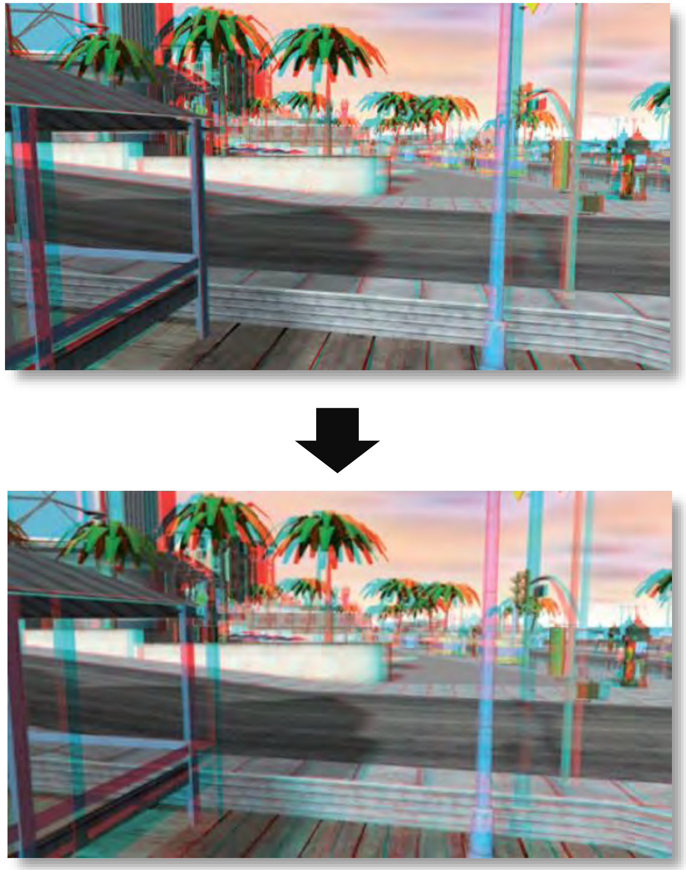
Vergence-Accommodation Conflict

Depth compression

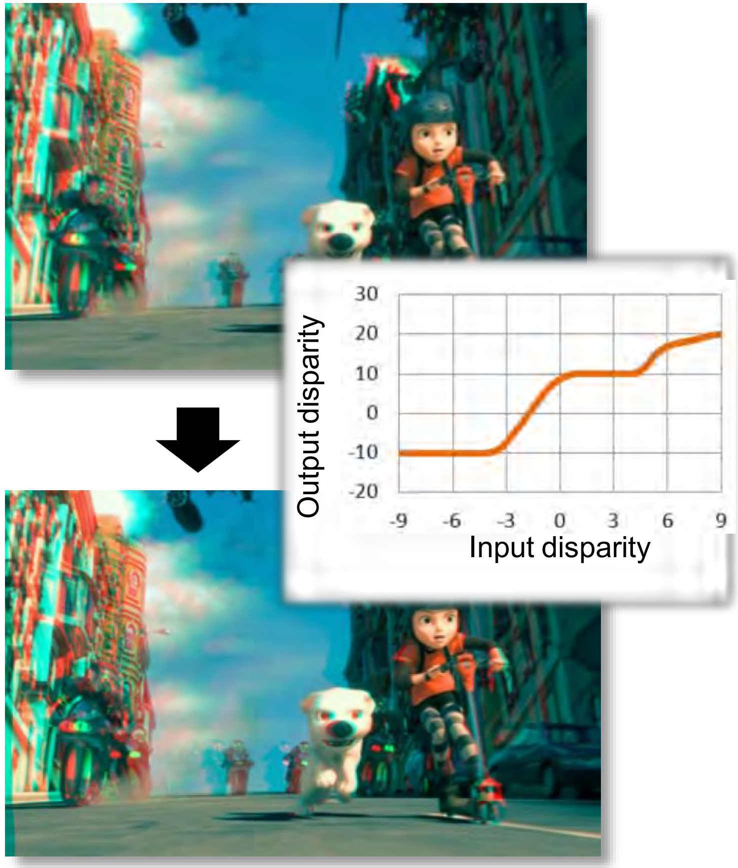


Viewing discomfort

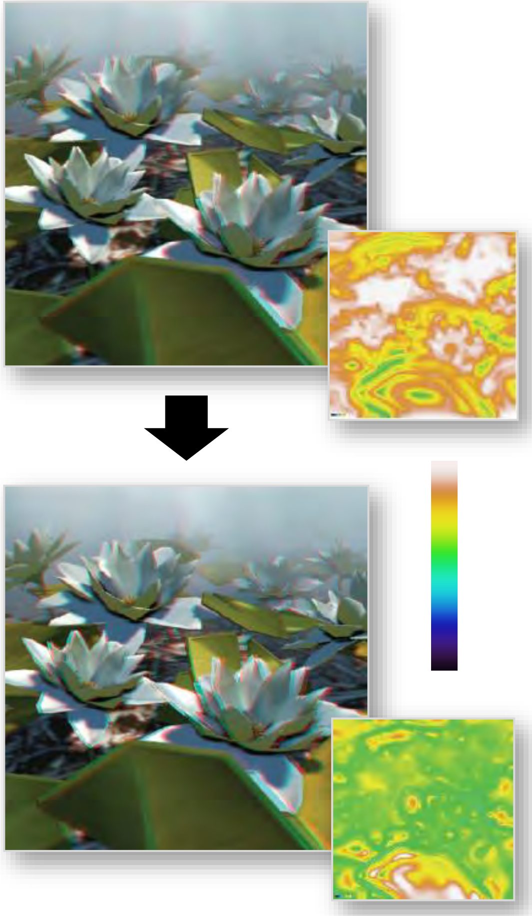
Viewing comfort



Oskam et al.
OSCAM - Optimized Stereoscopic Camera Control for Interactive 3D.
SIGGRAPH Asia 2011



Lang et al.
Nonlinear Disparity Mapping for Stereoscopic 3D.
SIGGRAPH 2010

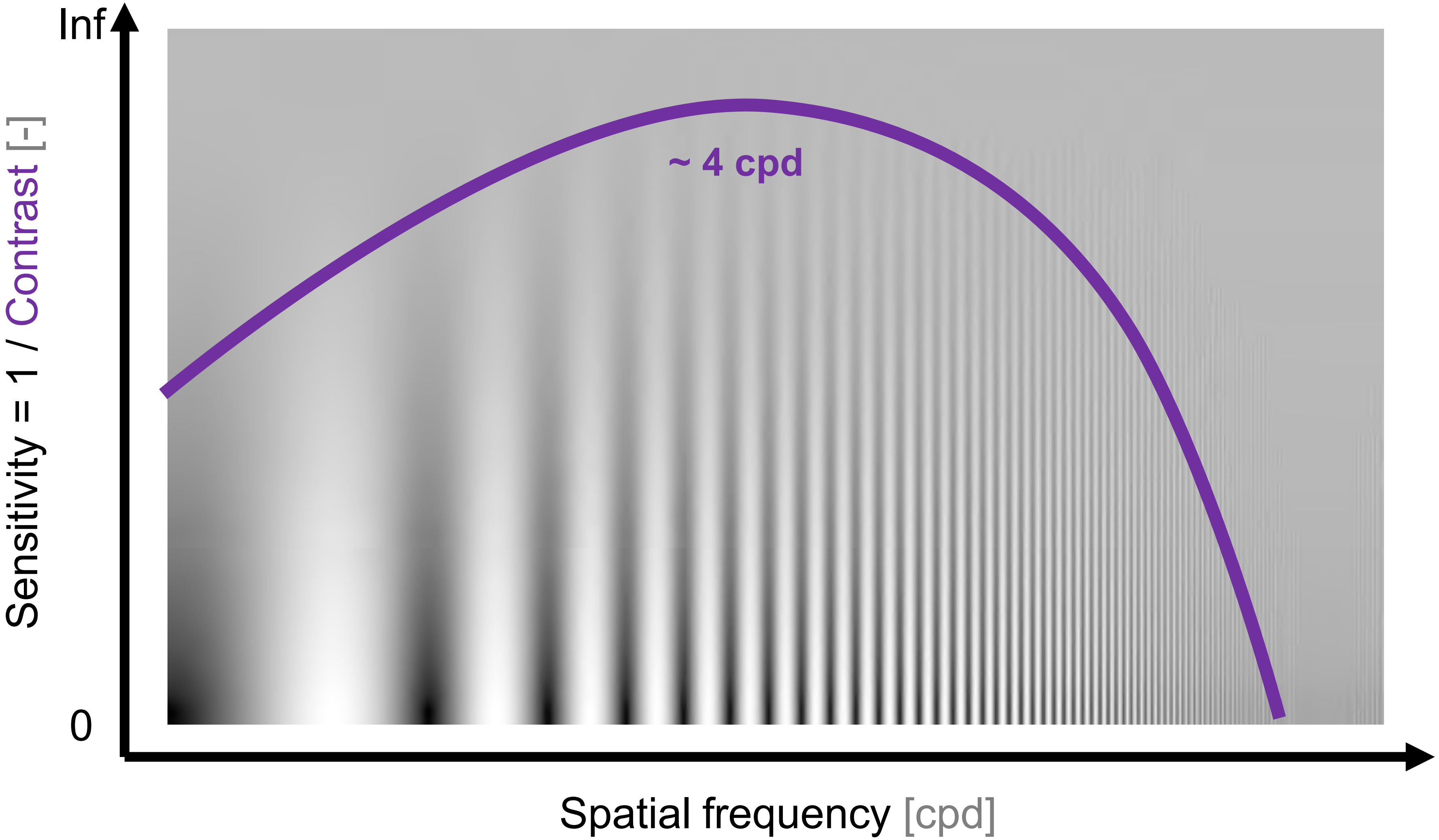


Didyk et al.
A perceptual model for disparity.
SIGGRAPH 2011

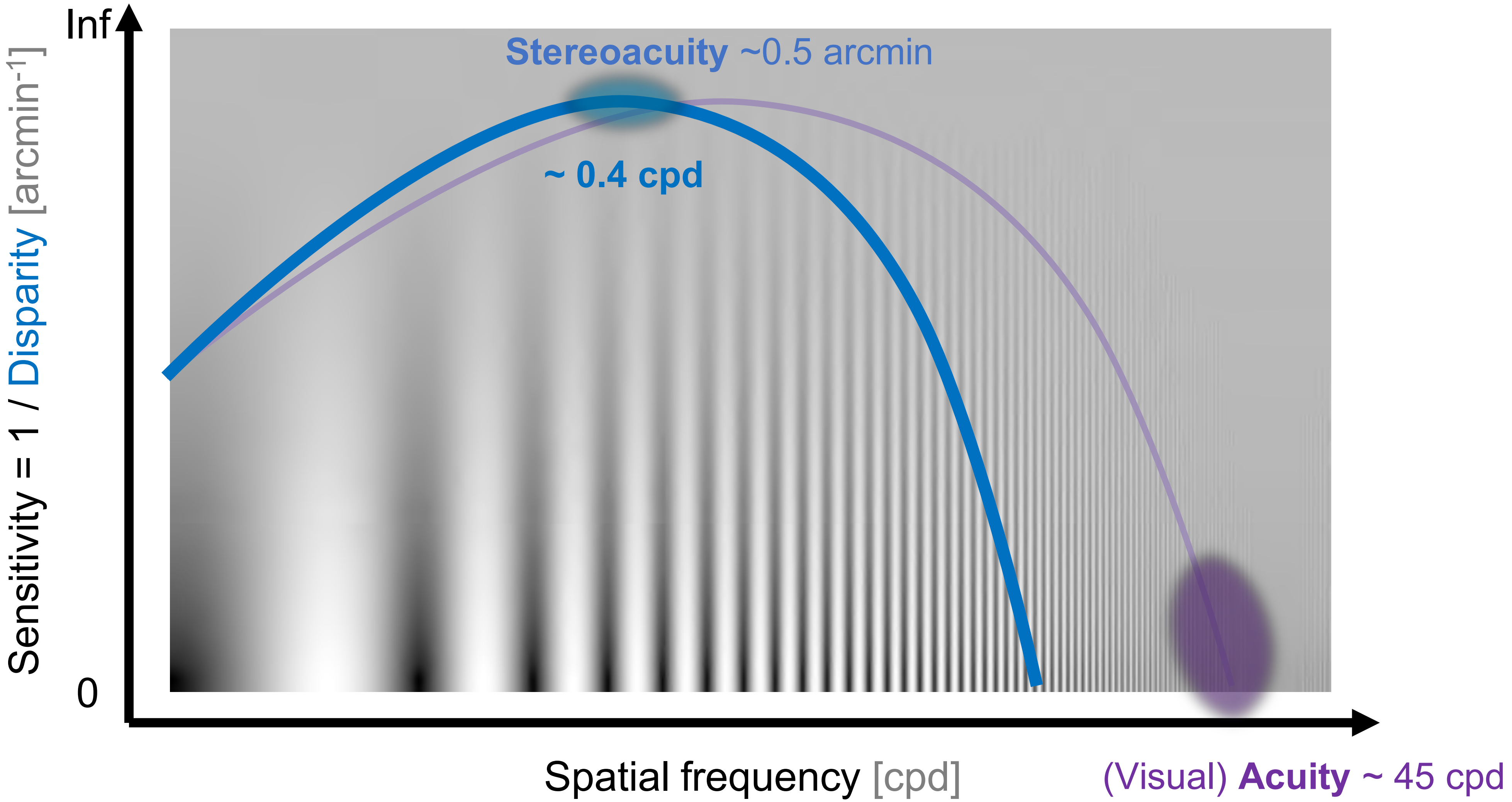
Outline

1. **Binocular vision**
   - How does it work?
2. **Depth sensitivity**
   - What is it? How can we measure it?
3. **Subjective qualities**
   - Visual preference, perceptual realism
4. **Task performance**
   - Absolute depth, time-to-collision, shape estimation
5. **Accommodation**
   - VAC conflict, depth of field
6. **Conclusion**
   - Interaction between cues

Contrast Sensitivity Function

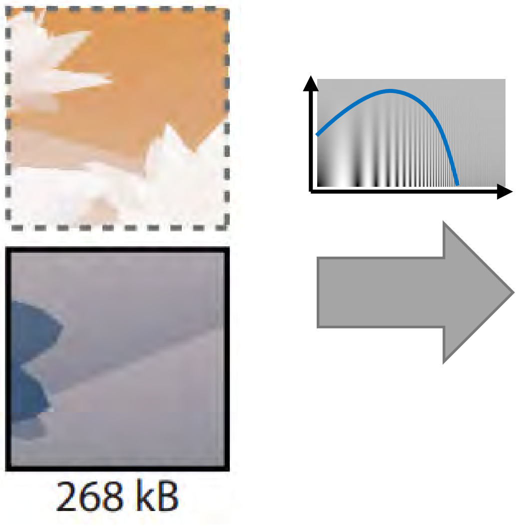


Disparity Sensitivity Function



Kane, David, Phillip Guan, and Martin S. Banks. "The limits of human stereopsis in space and time." *Journal of Neuroscience* 34.4 (2014).

Disparity Compression



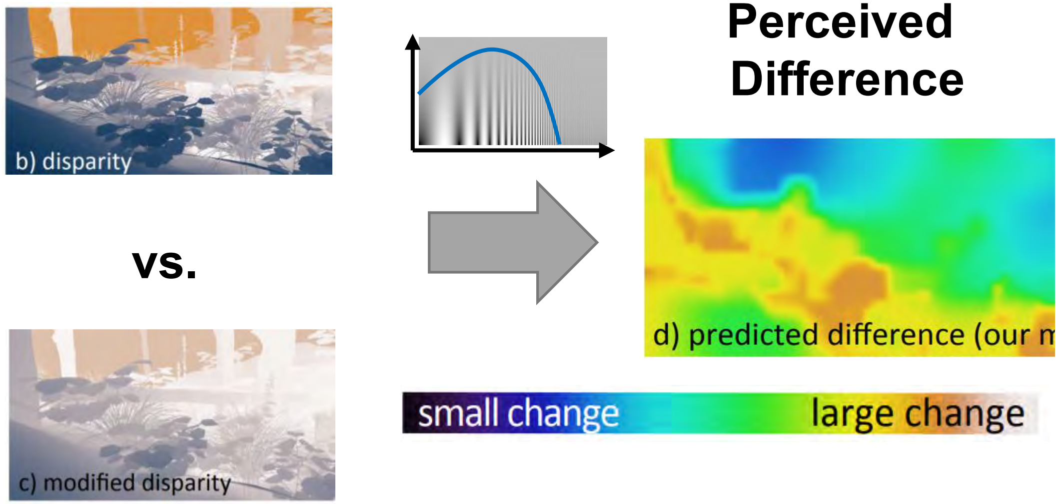
Original Disparity

Compressed

Compare to DSF
-> remove if not perceivable.

Disparity Metric

Disparity **A**



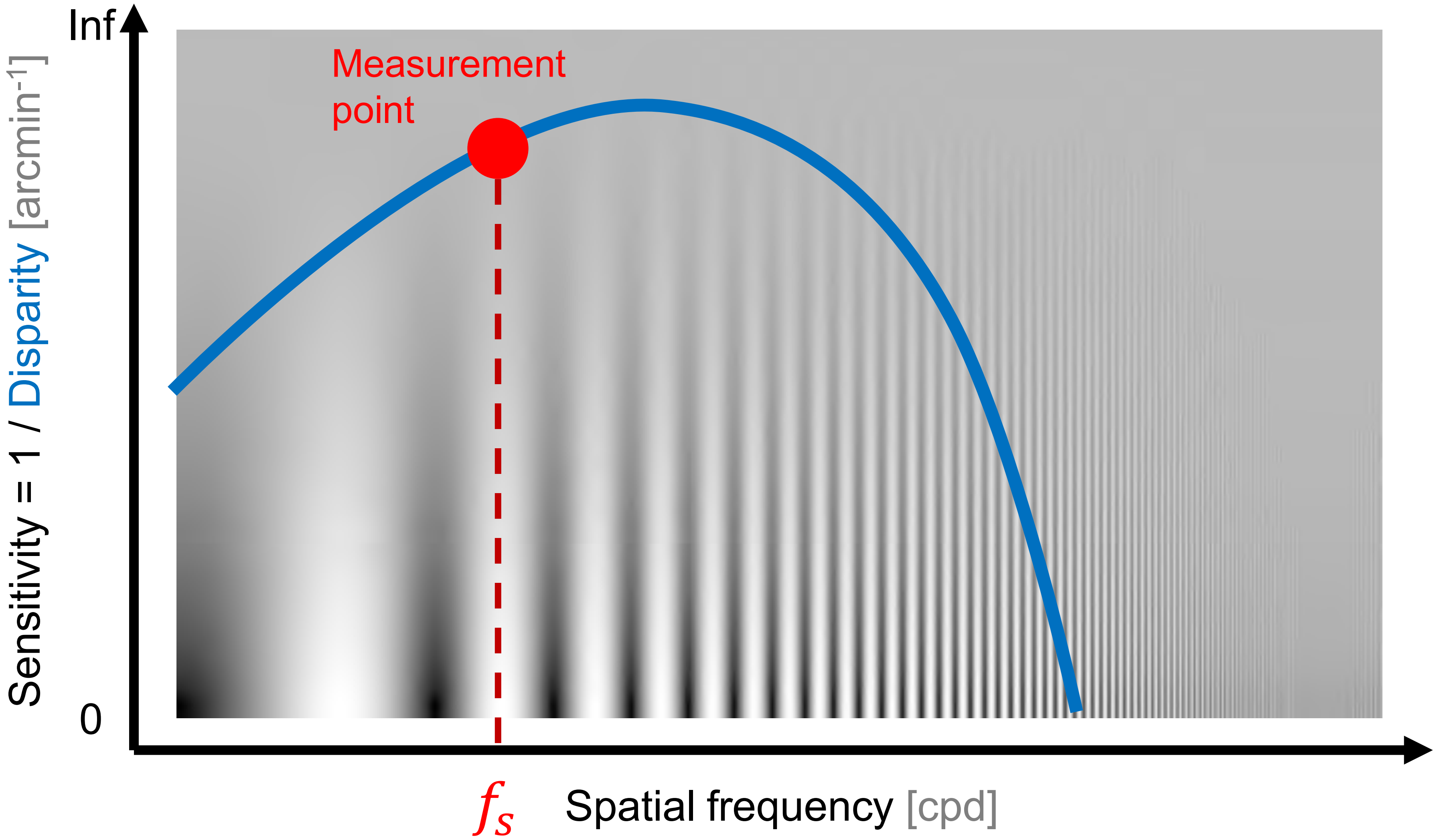
Disparity **B**

Perceived Difference

Measure difference
in a perceptually linear space.

Didyk, Piotr, et al. "A luminance-contrast-aware disparity model and applications." *ACM Transactions on Graphics (TOG)* 31.6 (2012): 1-10.

Disparity Sensitivity Function



Measurement

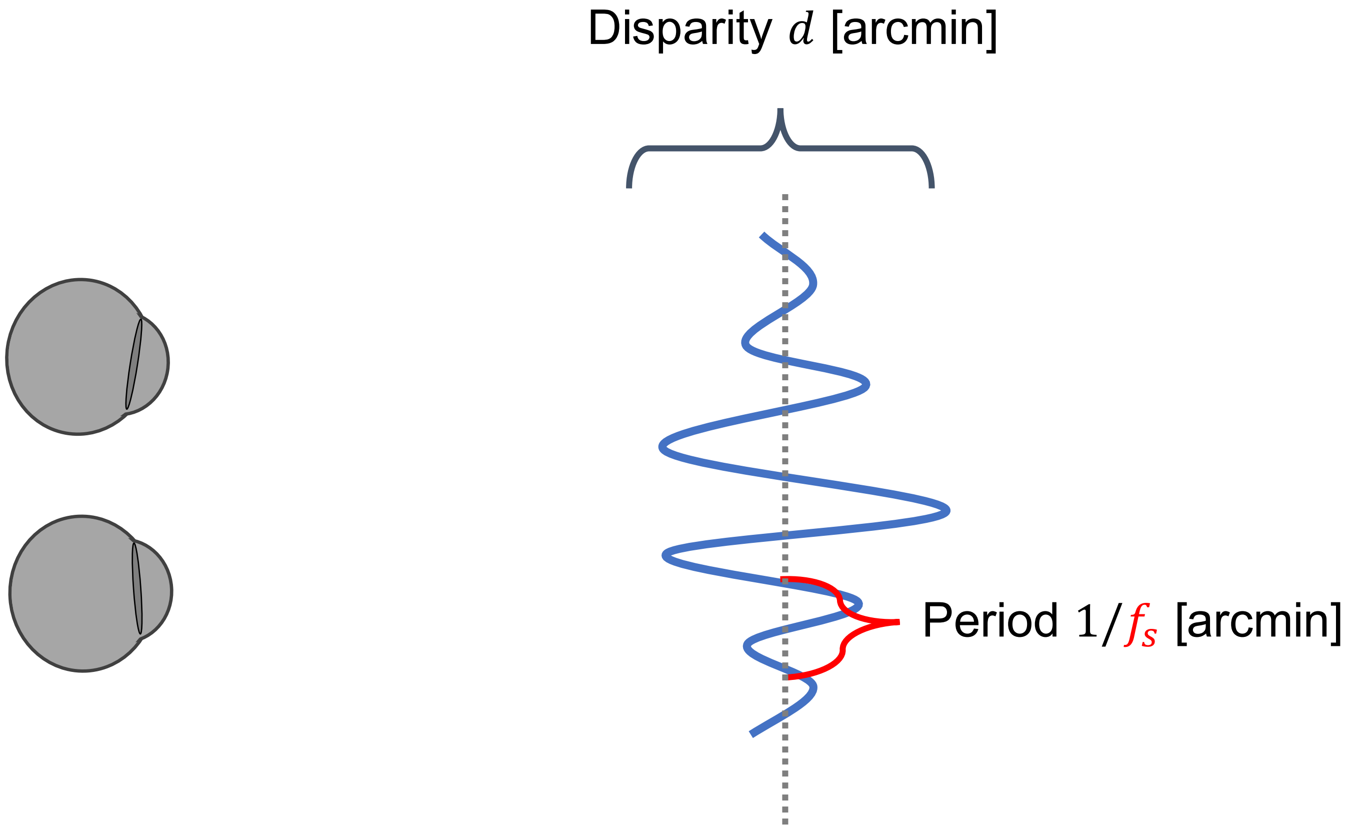
$$DSF(f_s) = ?$$

$$DSF(f_s) = \frac{1}{\boxed{d(f_s\ )}}$$

Threshold disparity

$$P\big(d(f_s\ )\big) = threshold$$

e.g., 0.75



Stimulus

- We want **maximum control**:

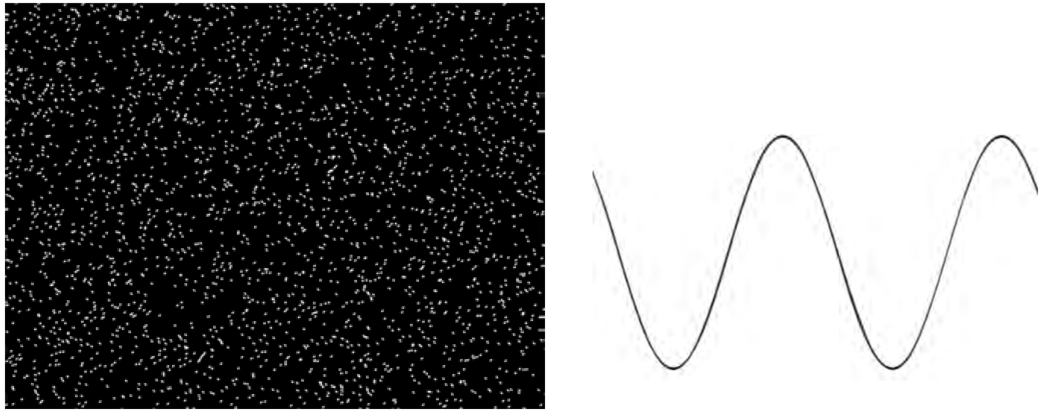
    => Simple pattern with few control parameters.

- We want to **isolate the effect**:

    => Remove other (depth) cues.

Disparity patterns

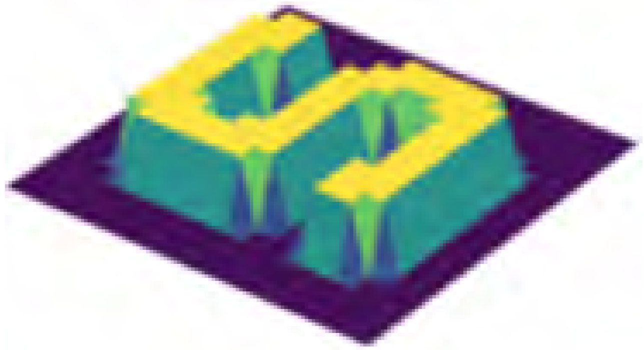
Waves and corrugations



Kane, David, Phillip Guan, and Martin S. Banks. "The limits of human stereopsis in space and time." *Journal of Neuroscience* 34.4 (2014): 1397-1408.

=> For measuring **frequency-dependency**

Symbols and letters

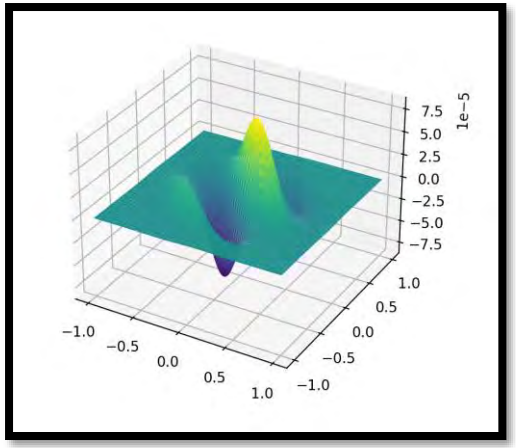


Lew, Wei Hau, and Daniel R. Coates. "Assessment of depth perception with a comprehensive disparity defined letter test: A pilot study." *Plos one* 17.8 (2022): e0271881.

=> For measuring **peak sensitivity**

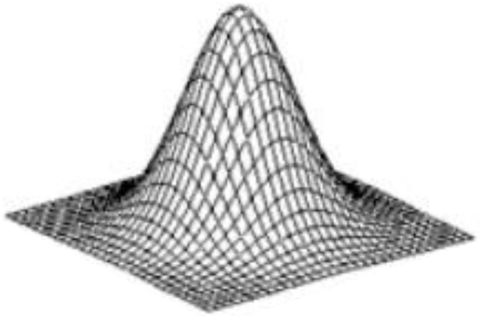
Gabor wavelet

(Disparity pattern)



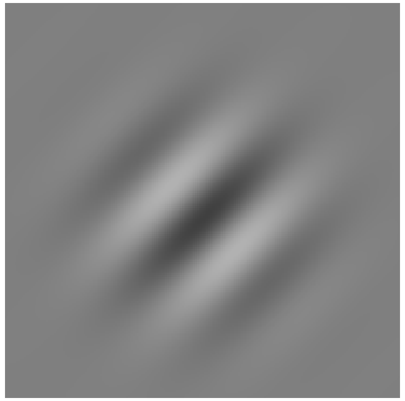
Sinusoid

×



Gaussian

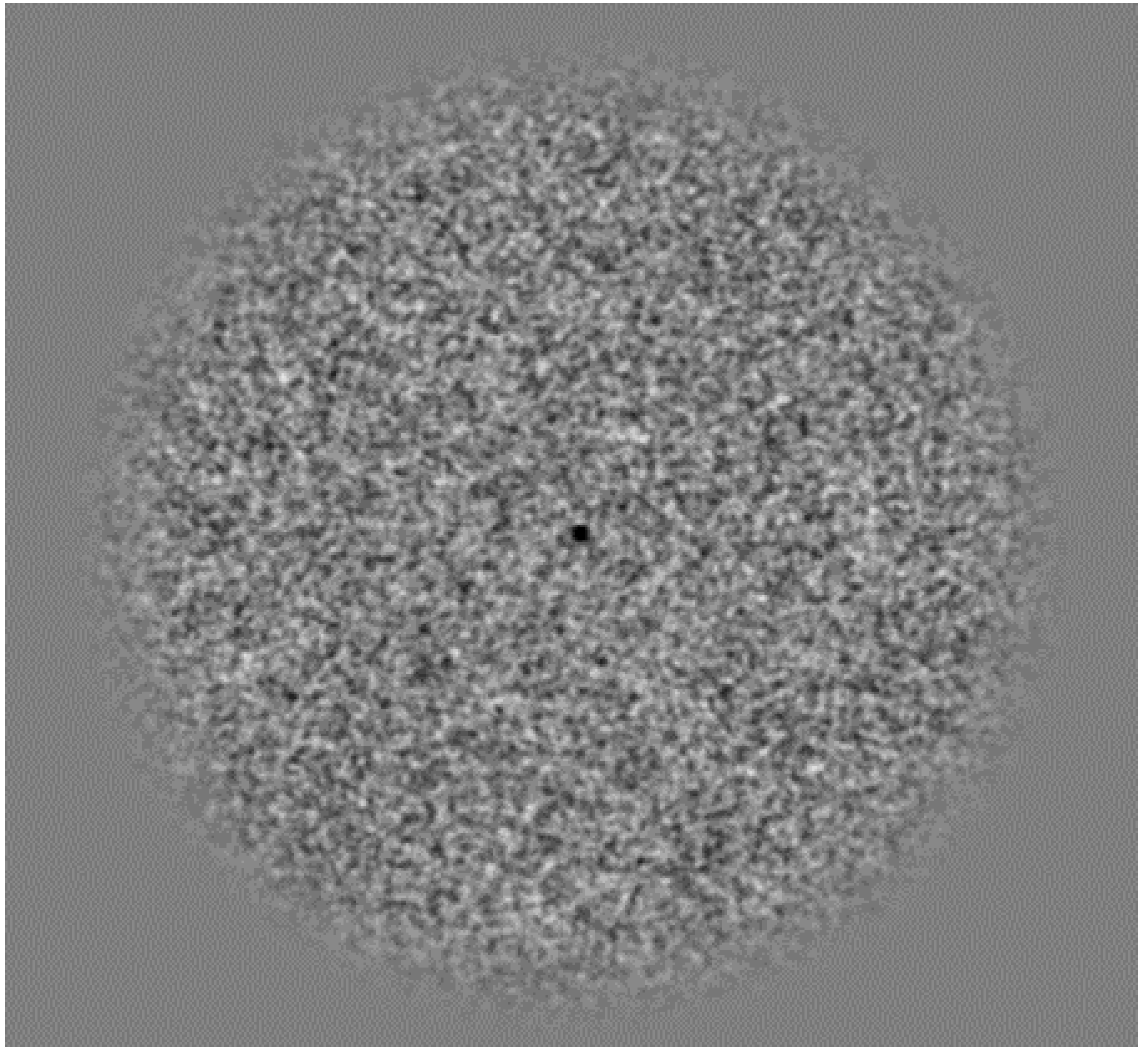
=

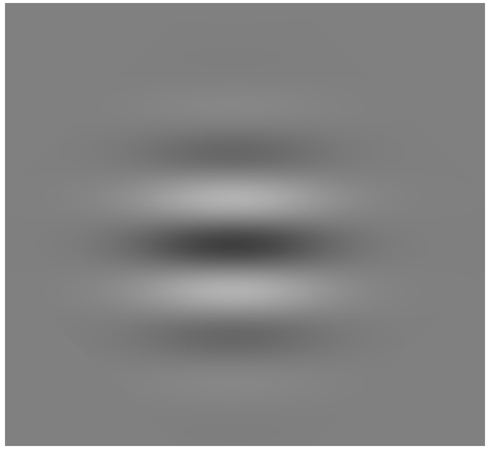


Gabor

Offers control over **Frequency, Orientation** and **Location**.

Random Dot Stereogram (RDS)



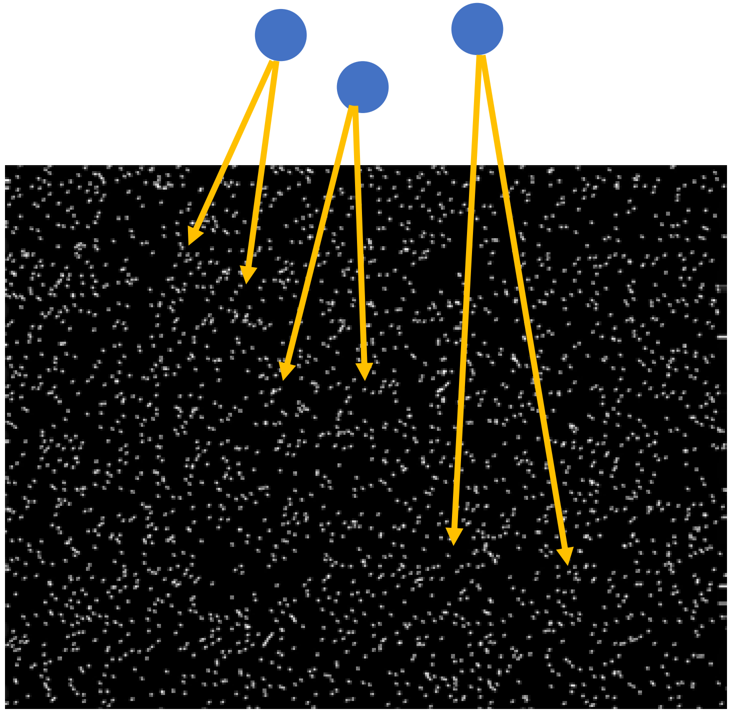


Disparity pattern

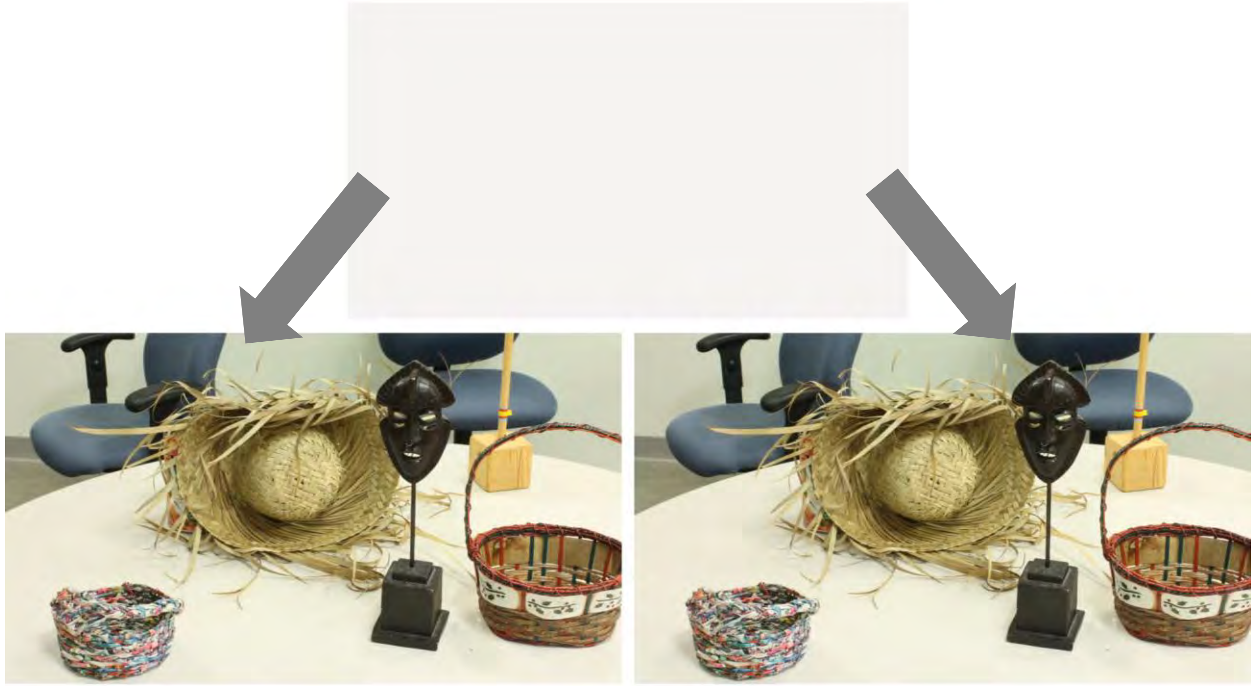
=> No monocular cues.

Stereoscopic rendering

Warping



=> Render each point **twice**.



=> Render **once** and warp **twice**.

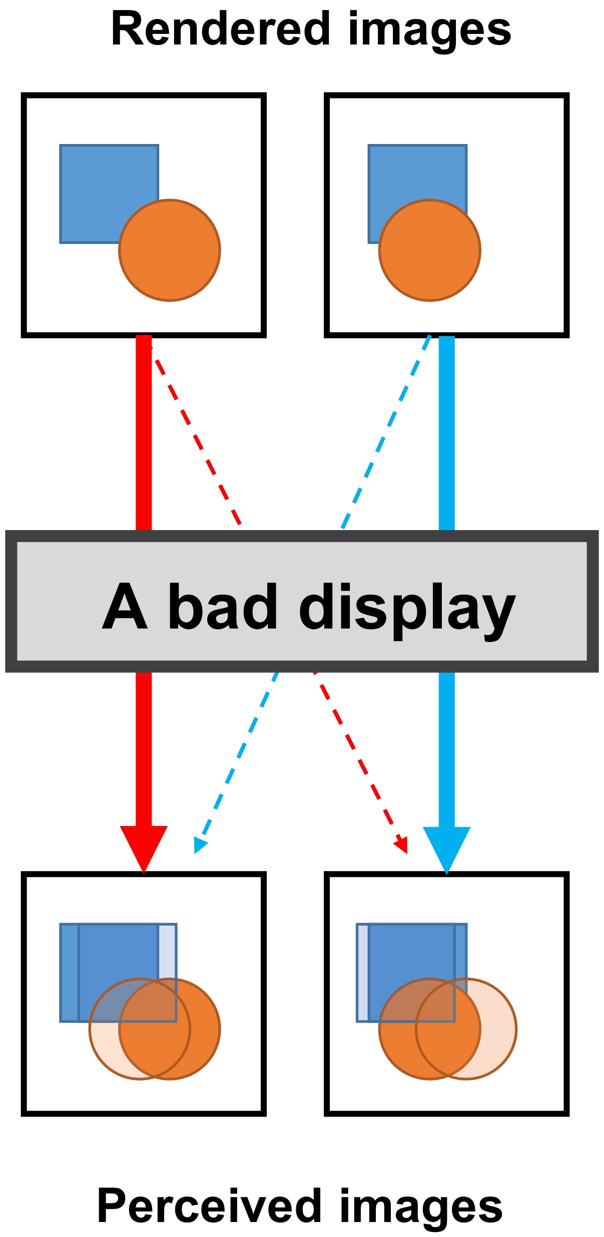
Fine control of disparity vs. **disocclusions**.

How to display?

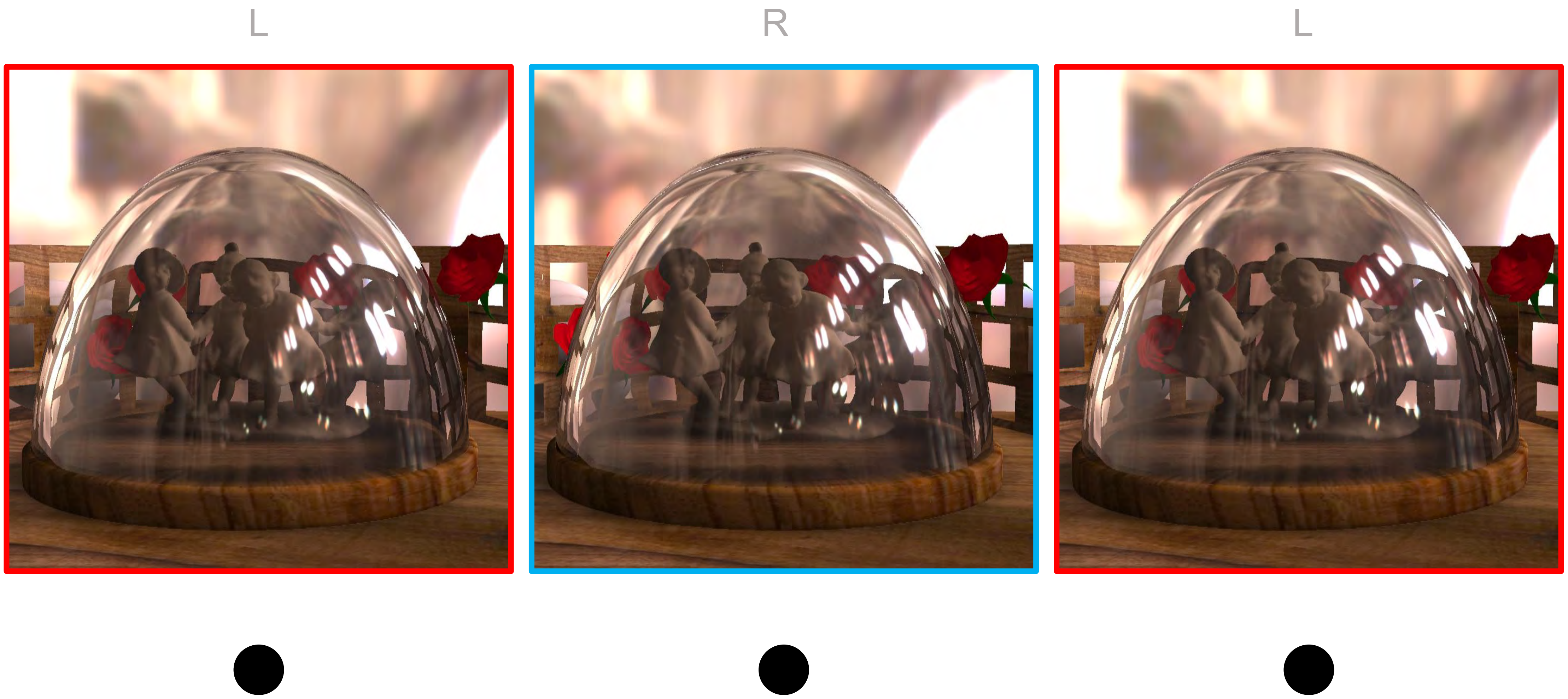
- Depends on the experiment:
  - Do we need large FOV?
  - Do we need HDR?
  - Do we need retinal acuity?

- What we **do not** want is

Cross-talk

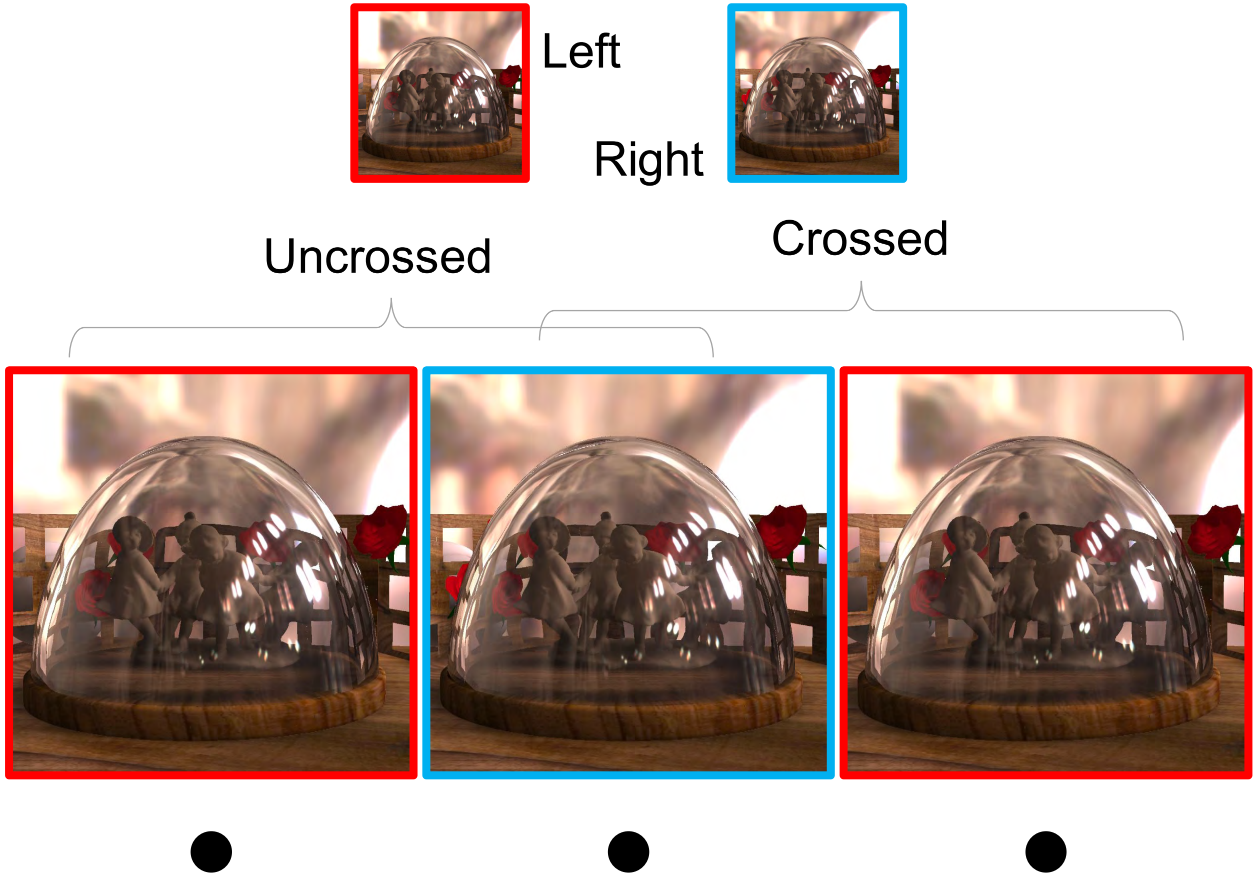


Uncrossed Crossed



Display

- **Free viewing**



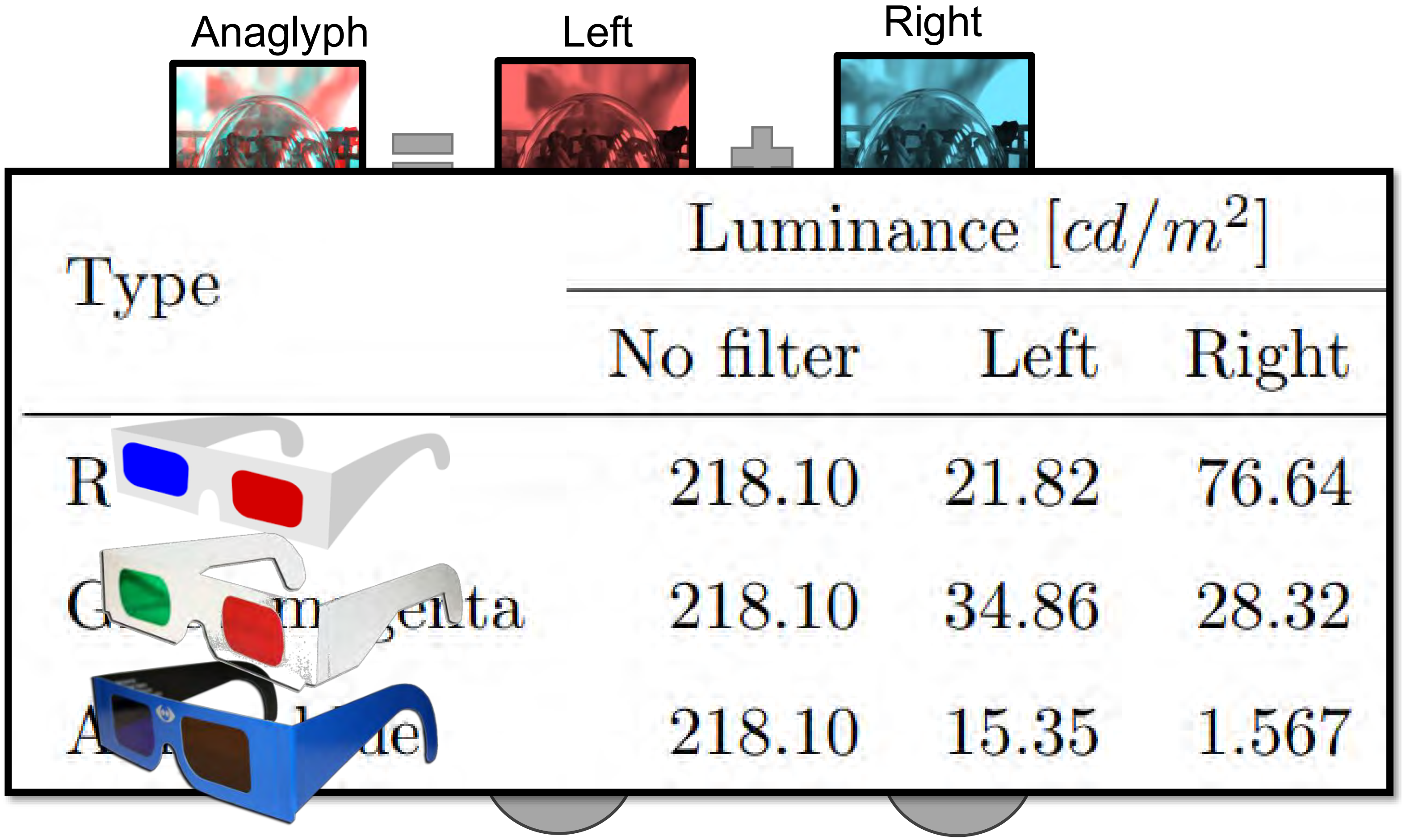
+ **No cross-talk.**
+ **Can be printed.**
+ Cheap.
+ High image quality (resolution, contrast,…).

- **Most people fail see it.**
- Takes time to see.
- Uncomfortable.

Dąbała, Łukasz, et al. "Manipulating refractive and reflective binocular disparity." Computer Graphics Forum. Vol. 33. No. 2. 2014.

Display

- Free viewing
- Glasses
  - **Anaglyph**



Type	Luminance $[cd/m^2]$		
	No filter	Left	Right
R	218.10	21.82	76.64
G m enta	218.10	34.86	28.32
A le	218.10	15.35	1.567

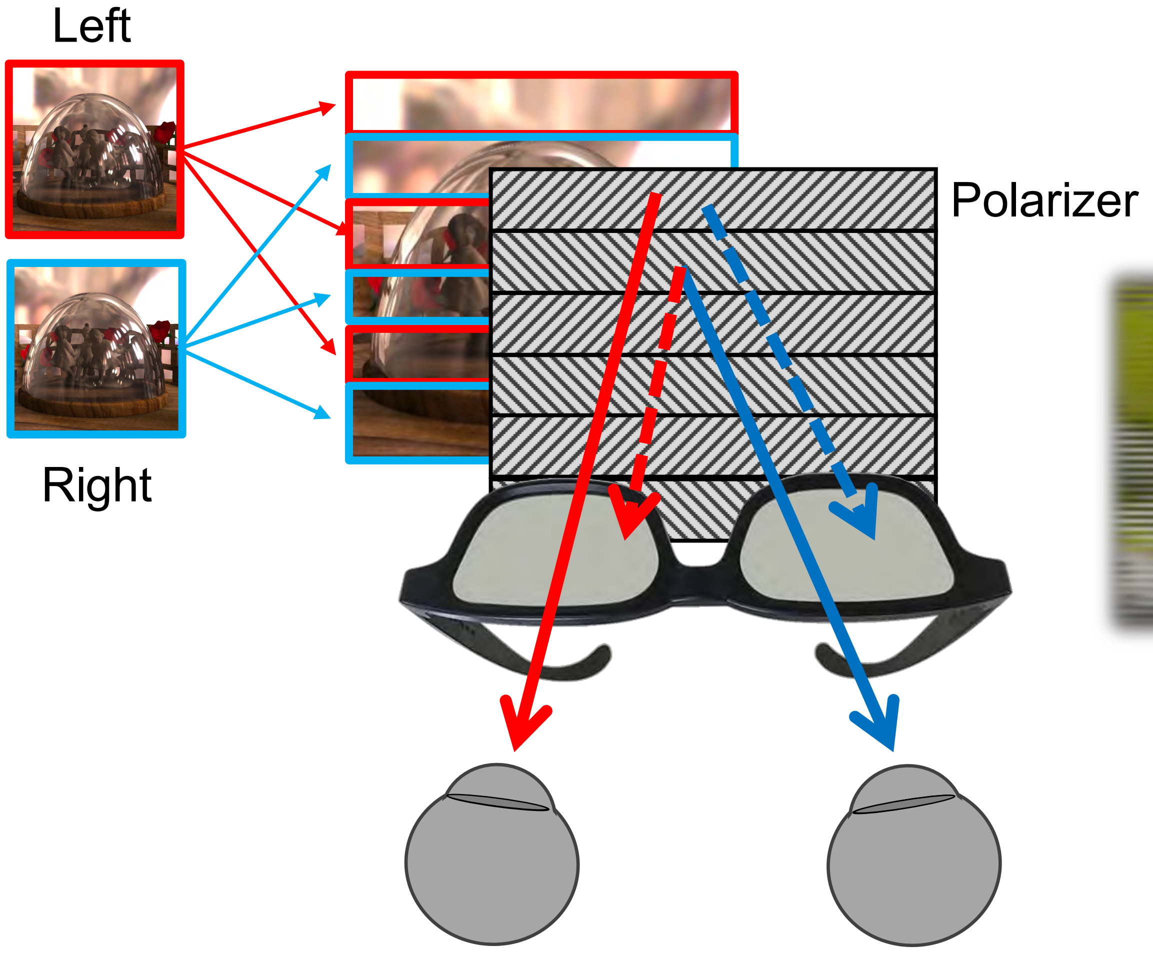
+ **Cheap.**
+ High quality 2D display.
~ Can sometimes be printed.

- **Bad cross-talk.**
- Bad or no colors.
- Pulfrich effect.

Kellnhofer, Petr, et al. "Improving perception of binocular stereo motion on 3D display devices." Stereoscopic Displays and Applications XXV. Vol. 9011. SPIE, 2014.

Display

- Free viewing
- Glasses
  - Anaglyph
  - **Polarized**

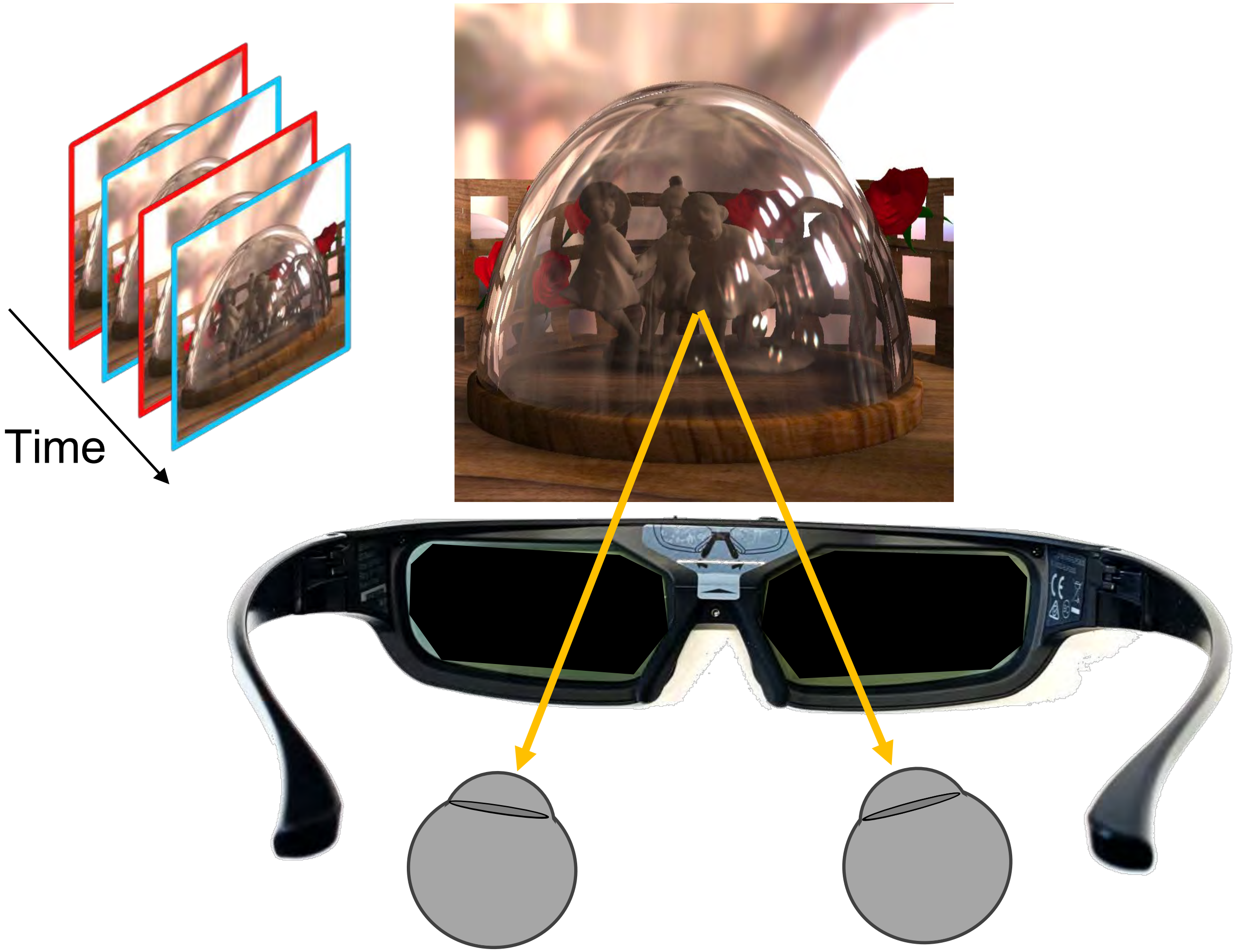


+ No temporal distortions.
+ Good colors.
~ Cross-talk may vary.

- Sensitive to position.
- Reduced vertical resolution.
- Reduced brightness.

Display

- Free viewing
- Glasses
  - Anaglyph
  - Polarized
  - **Shutter**



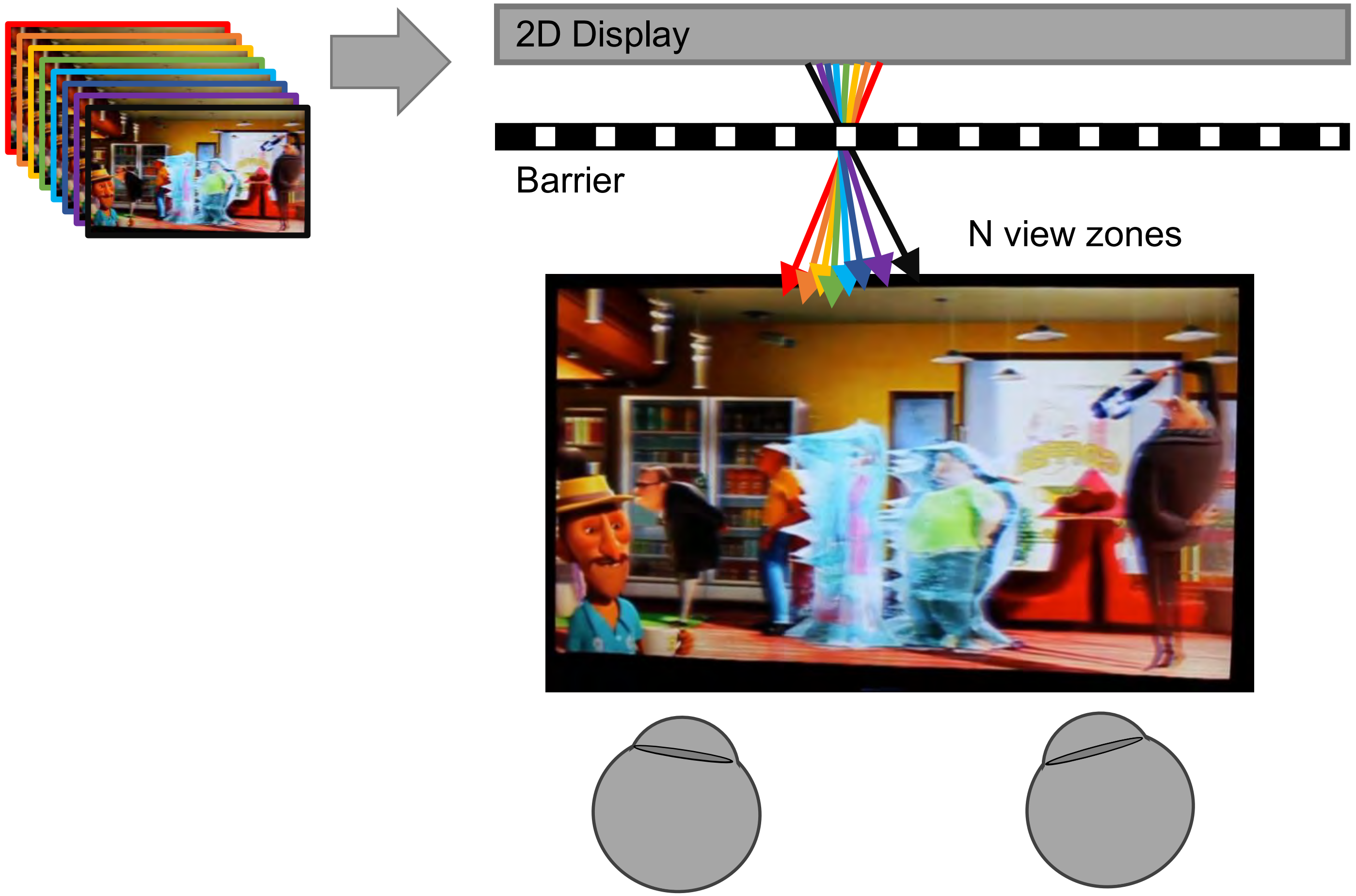
+ Good colors.
+ Good resolution.
~ Acceptable cross-talk
with a fast screen.

- Limited support.
- Reduced brightness.
- Can flicker.
- Motion artifacts.

Kellnhofer, Petr, et al. "Improving perception of binocular stereo motion on 3D display devices." Stereoscopic Displays and Applications XXV. Vol. 9011. SPIE, 2014.

Display

- Free viewing
- Glasses
  - Anaglyph
  - Polarized
  - Shutter
- Auto stereo/multiscopic
  - **Parallax barrier**



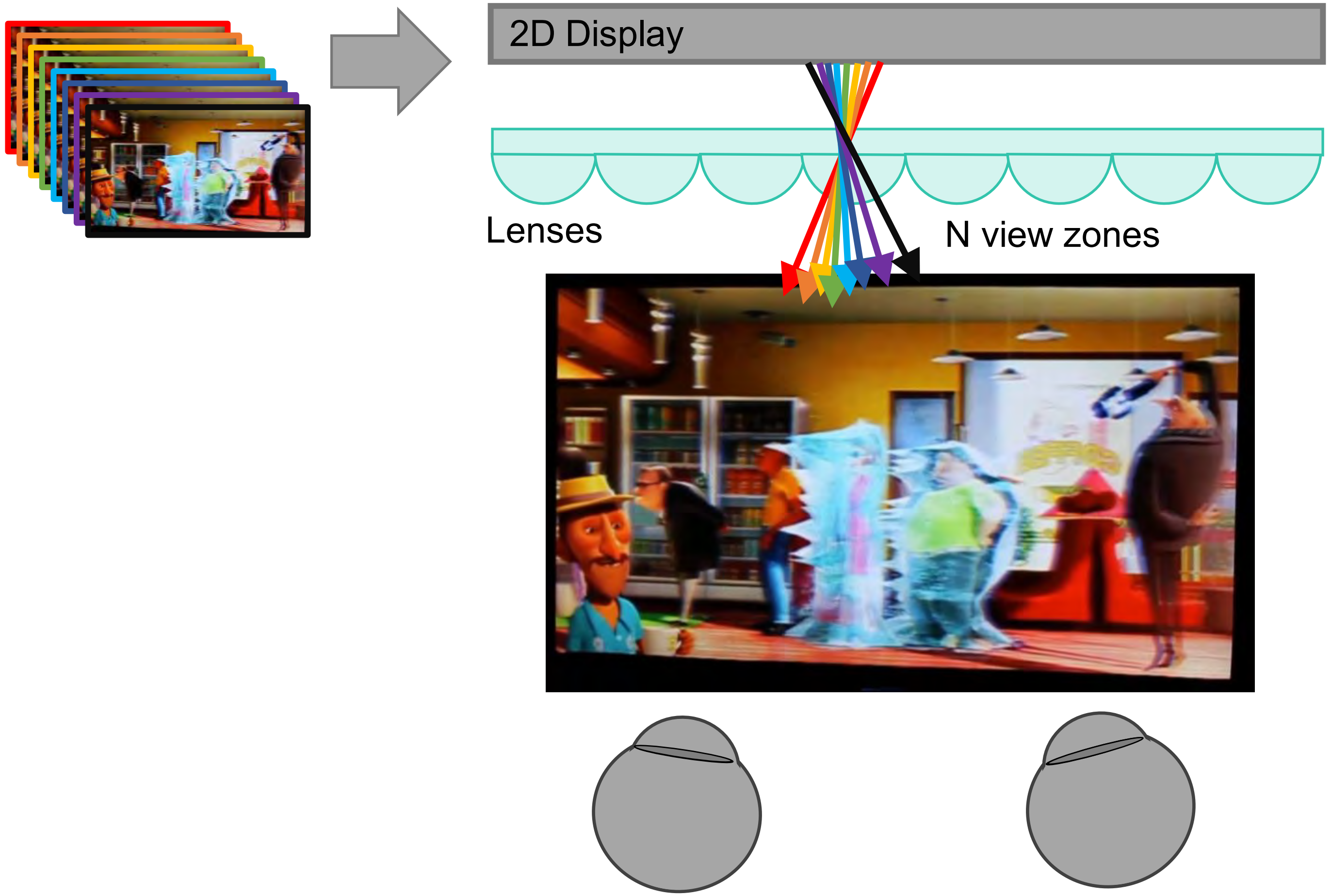
+ No glasses.
+ Provides real parallax.

- Sensitive to position.
- Reduced resolution.
- Cross-talk.
- Reduced brightness.

Kellnhofer, Petr, et al. "3DTV at home: Eulerian-Lagrangian stereo-to-multiview conversion." ACM Transactions on Graphics (TOG) 36.4 (2017): 1-13.

Display

- Free viewing
- Glasses
  - Anaglyph
  - Polarized
  - Shutter
- Auto stereo/multiscopic
  - Parallax barrier
  - **Lenticular**



+ No glasses.
+ Provides real parallax.

- Sensitive to position.
- Reduced resolution.
- Cross-talk.

Kellnhofer, Petr, et al. "3DTV at home: Eulerian-Lagrangian stereo-to-multiview conversion." ACM Transactions on Graphics (TOG) 36.4 (2017): 1-13.

Display

- Free viewing
- Glasses
  - Anaglyph
  - Polarized
  - Shutter
- Auto stereo/multiscopic
  - Parallax barrier
  - Lenticular
- Head-Mounted
  - **Virtual Reality**

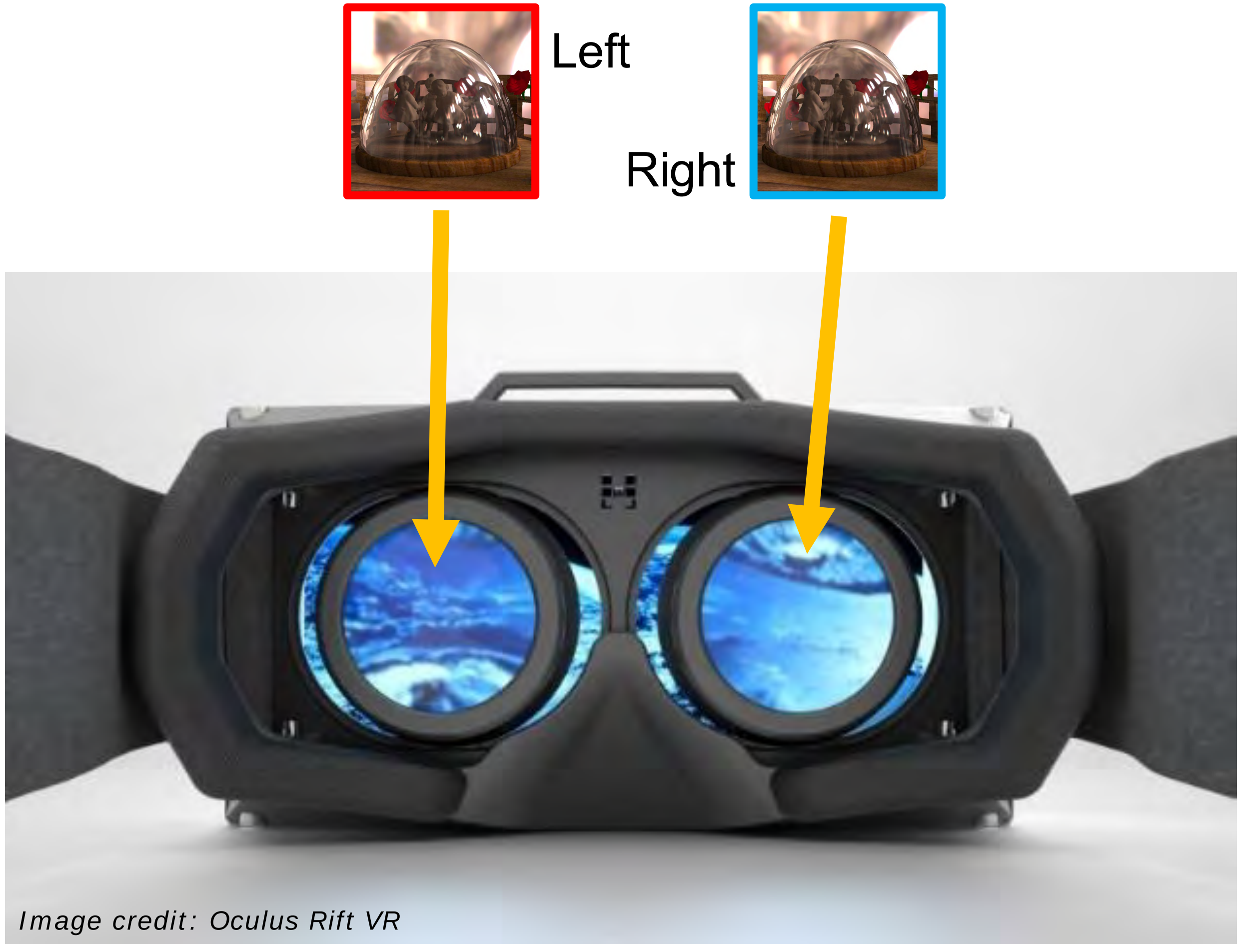


Image credit: Oculus Rift VR

+ No ghosting.
+ Large field of view.
+ Simulated parallax.

- Lens distortion.
- Limited resolution.

Display

- Free viewing
- Glasses
  - Anaglyph
  - Polarized
  - Shutter
- Auto stereo/multiscopic
  - Parallax barrier
  - Lenticular
- Head-Mounted
  - Virtual Reality
  - **Augmented Reality**

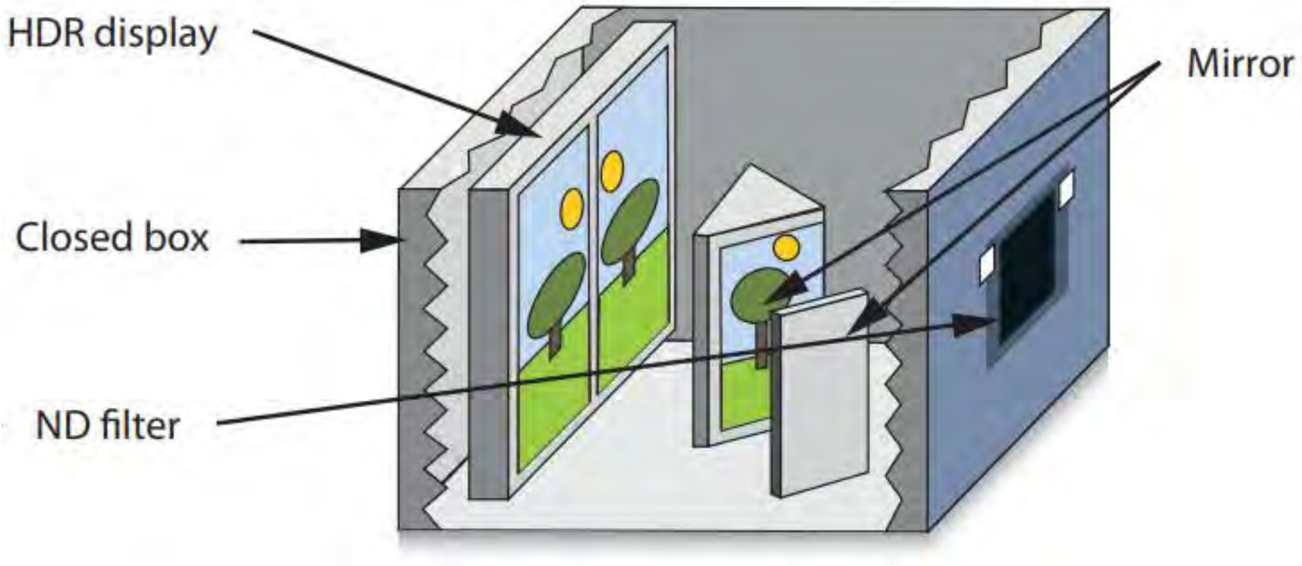
Image credit: Microsoft Hololens

\+ **See-through**.
\+ Simulated parallax.

- Poor contrast.
- Small field of view.

Display

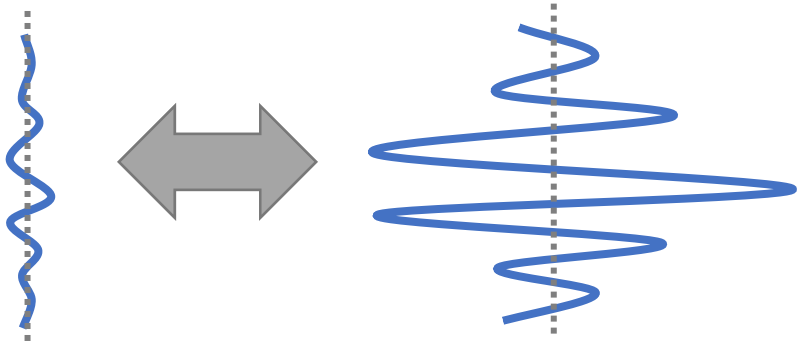
- Free viewing
- Glasses
  - Anaglyph
  - Polarized
  - Shutter
- Auto stereo/multiscopic
  - Parallax barrier
  - Lenticular
- Head-Mounted
  - Virtual Reality
  - Augmented Reality
- **Stereoscope**



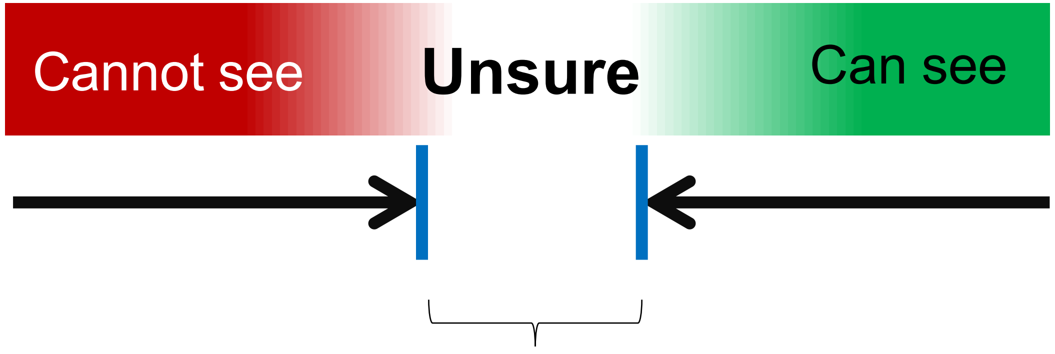
+ **No cross-talk**.
+ **Very flexible** (resolution, color gamut, framerate,…).
+ Easy to use.

- **Bulky.**
- **Not off-the-shelve.**

Direct adjustment



https://www.pexels.com/photo/person-holding-volume-knob-1345630/



Cannot see **Unsure** Can see

Hysteresis

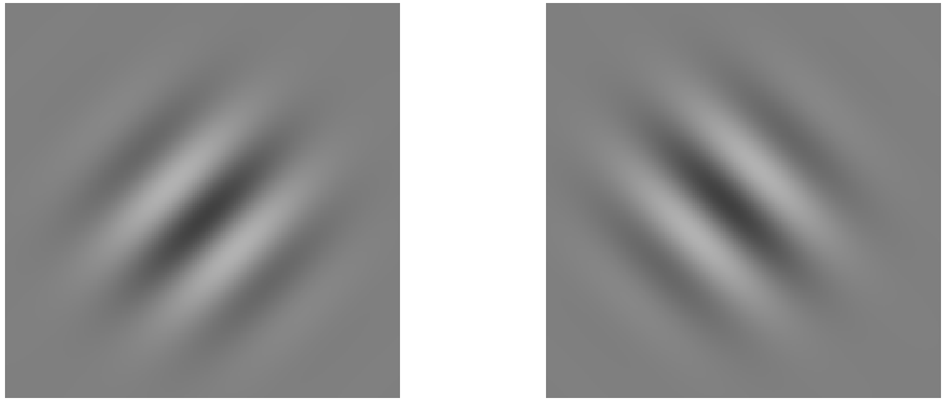
Two Alternative Forced Choice (2AFC)

Detection

Where is the pattern?

LEFT **RIGHT**

Discrimination



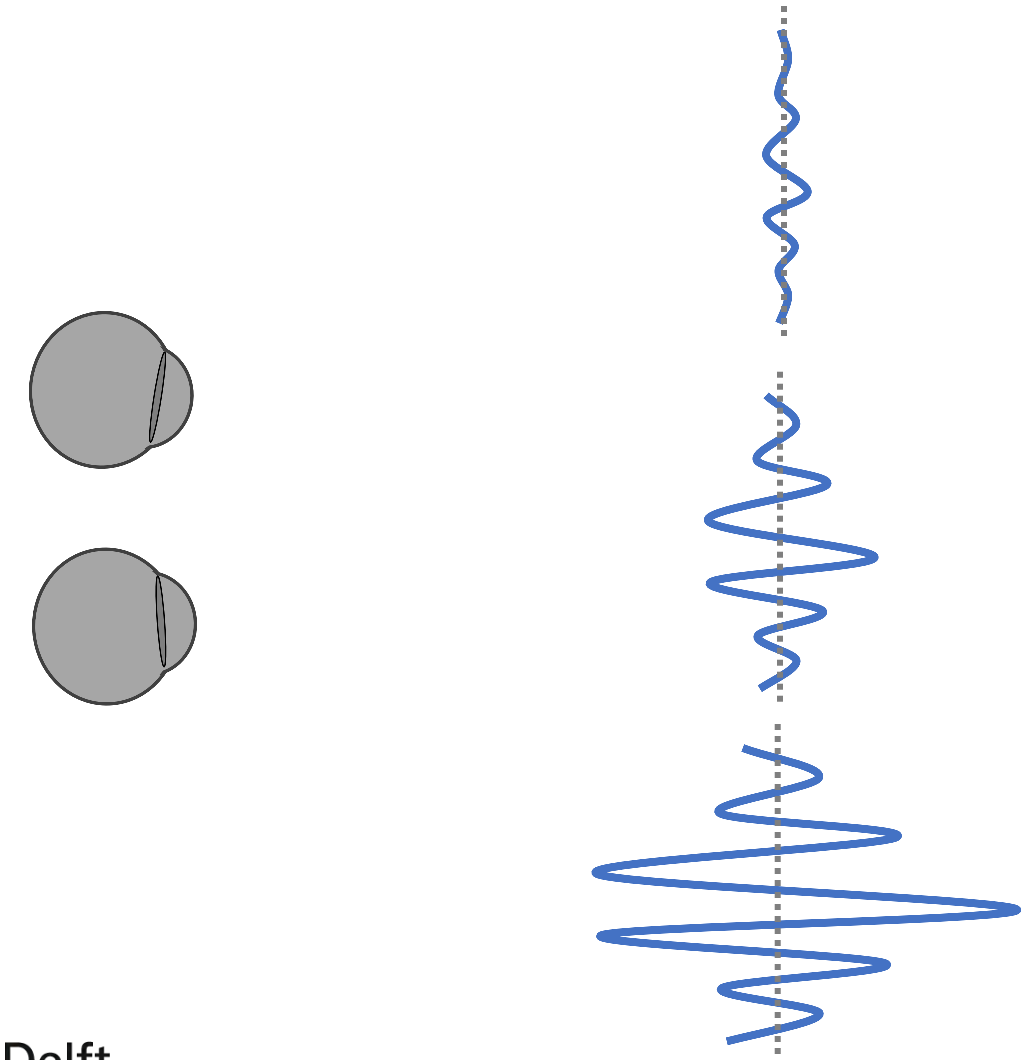
The same orientation?

YES **NO**

- No “I do not know” option.

Measurement

$$DSF(f_s) = ?$$



d_0 = Low

“Not visible”

$$P(d_0) = 0.5$$

d_1 = Medium

Just XY disparity

$$P(d_1) = 0.75$$

Noticeable/Detectable

- or -

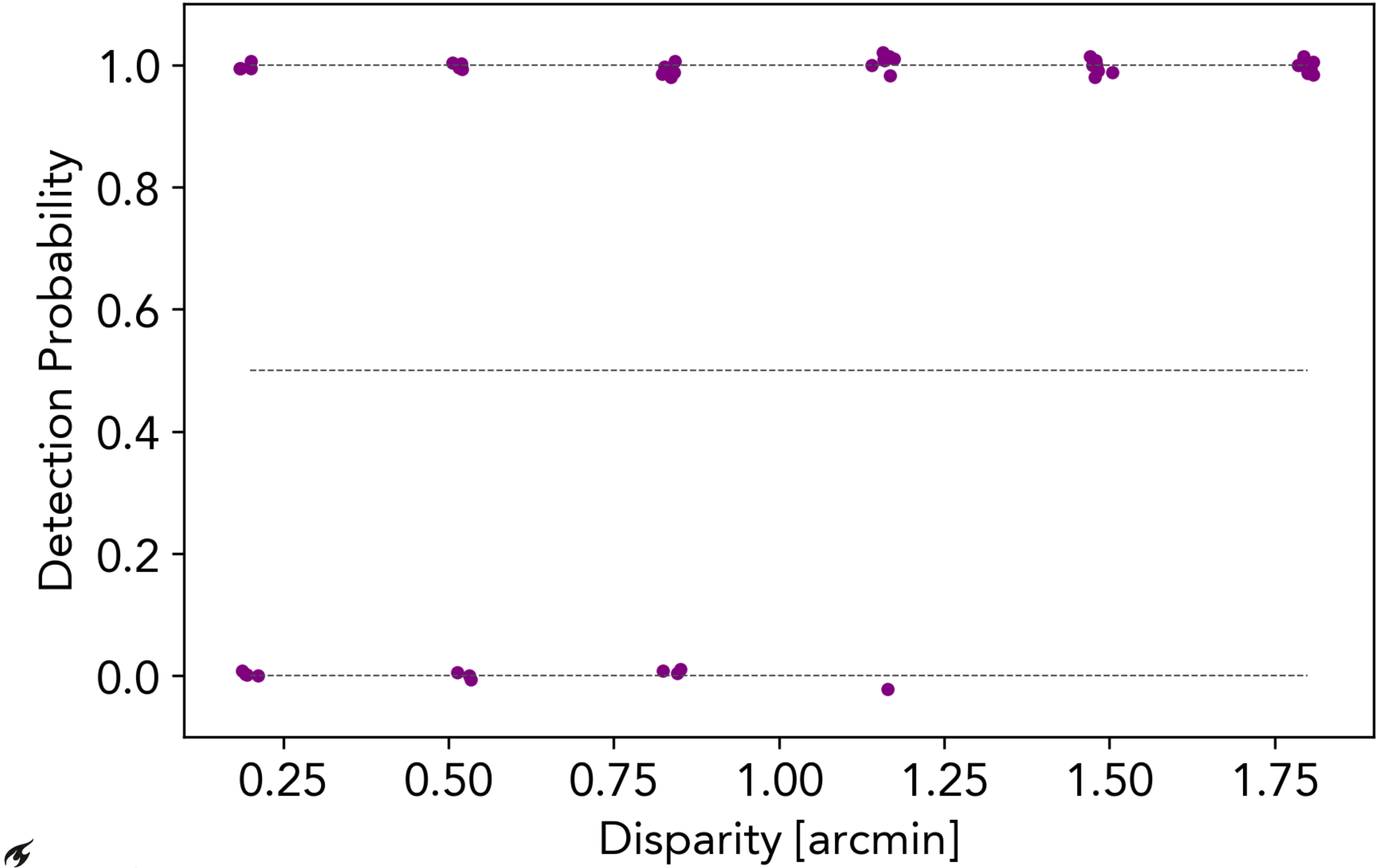
Discriminable

d_2 = High

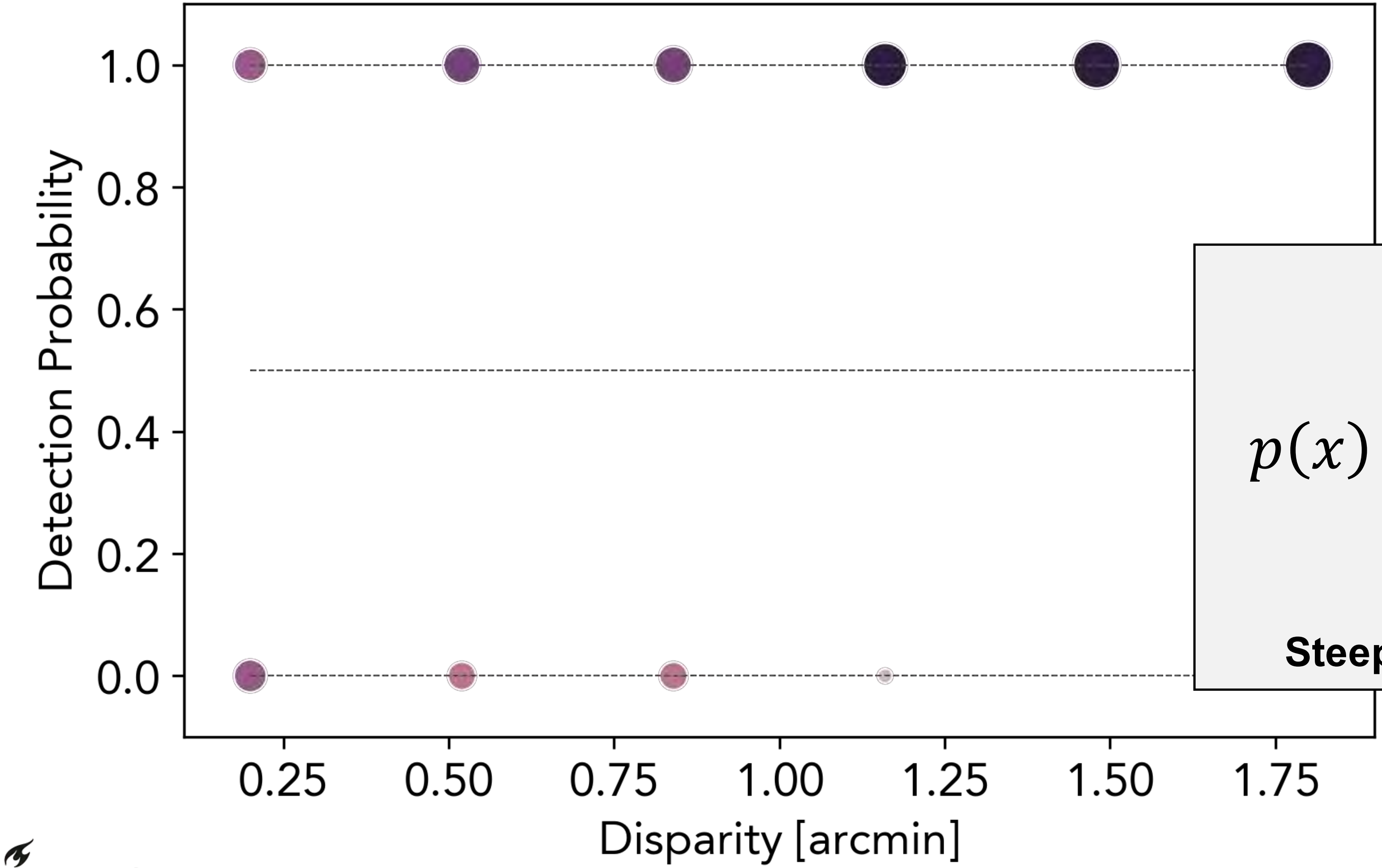
“Easily visible”

$$P(d_2) = 1$$

Psychometric function fit



Psychometric function fit



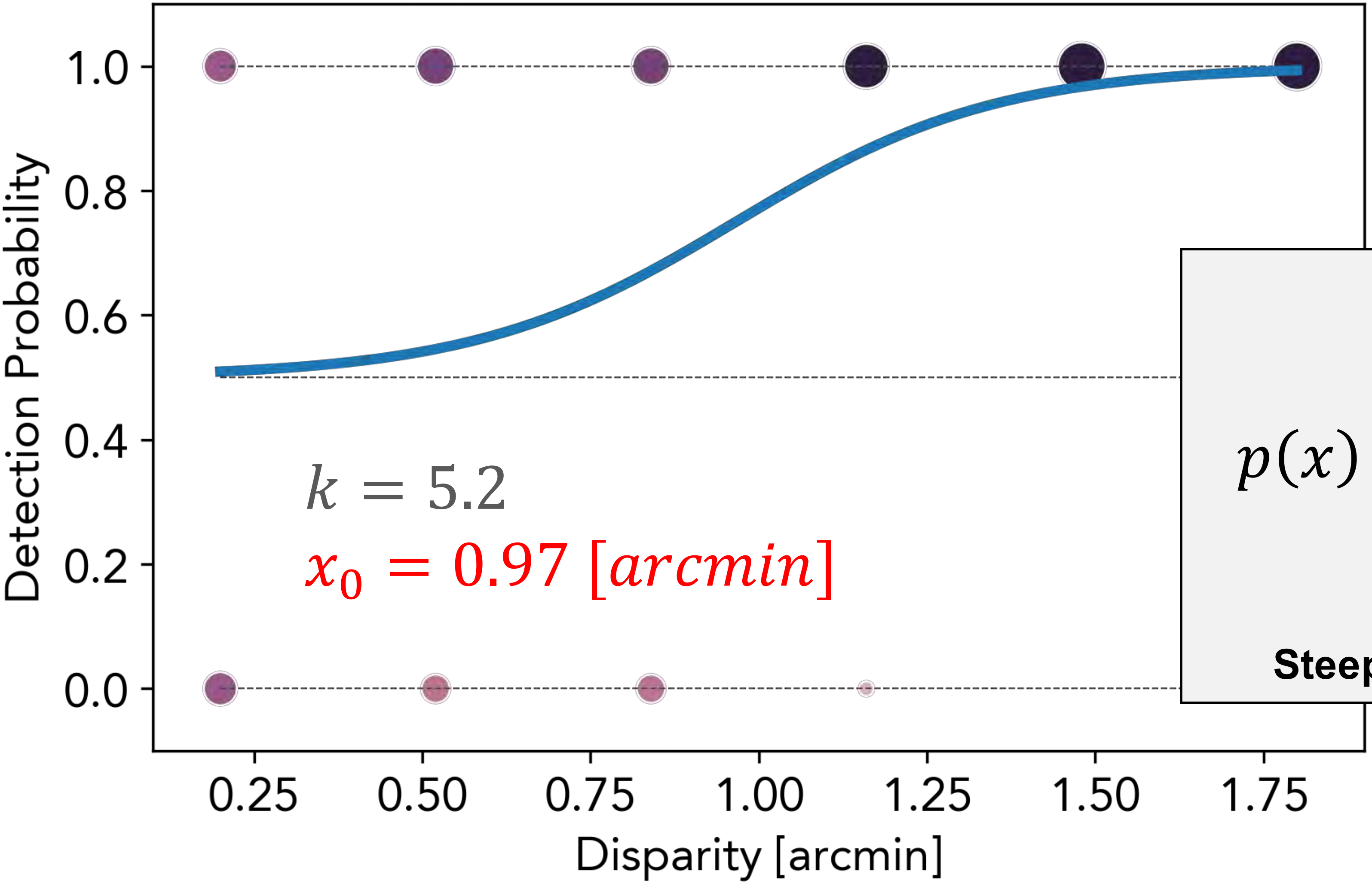
Logistic function

$$p(x) = \frac{0.5}{1 + e^{-k \cdot (x - x_0)}} + 0.5$$

Steepness

Threshold value

Psychometric function fit



$k = 5.2$

$x_0 = 0.97\ [arcmin]$

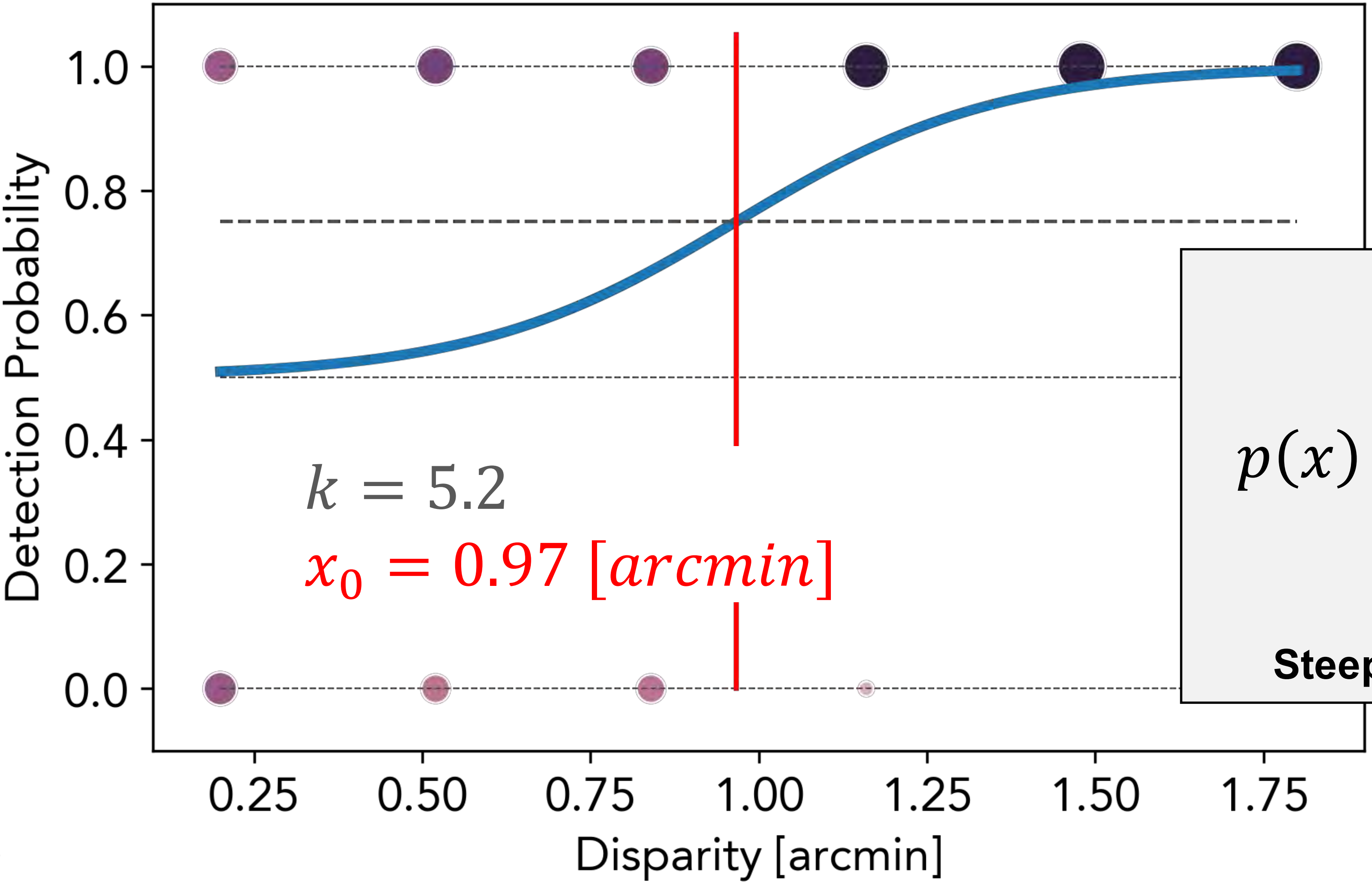
Logistic function

$$p(x) = \frac{0.5}{1 + e^{-k \cdot (x - x_0)}} + 0.5$$

Steepness

Threshold value

Psychometric function fit



$k = 5.2$

$x_0 = 0.97\ [arcmin]$

Logistic function

$$p(x) = \frac{0.5}{1 + e^{-k\cdot(x-x_0)}} + 0.5$$

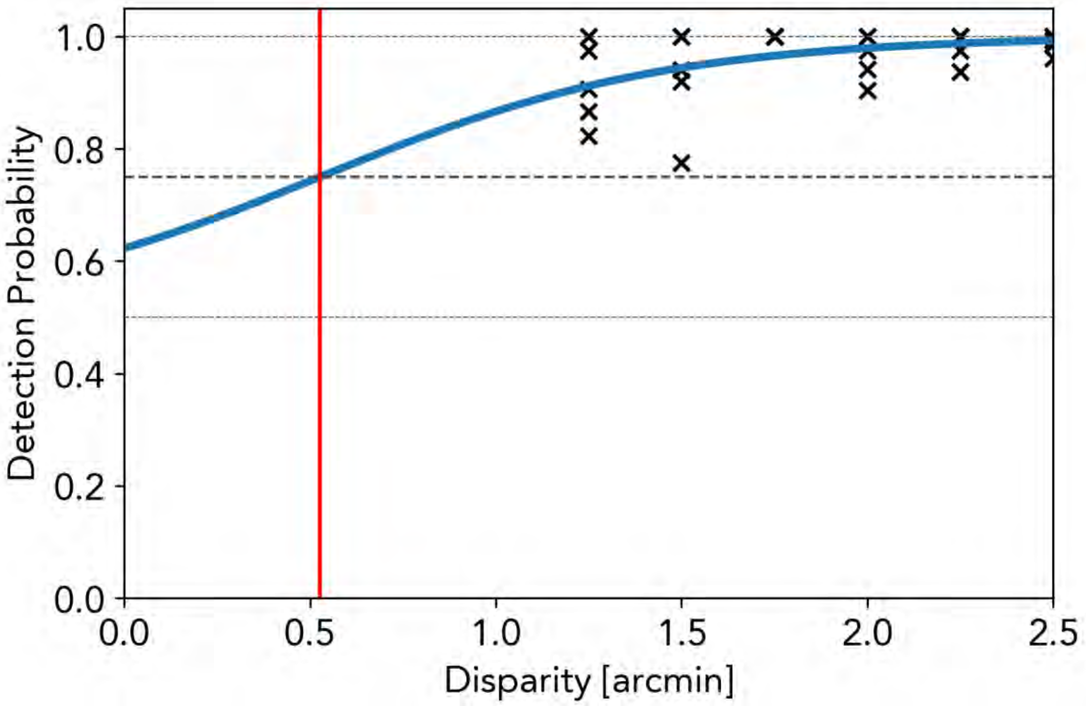
Steepness

Threshold value

Constant stimuli

Staircase [1]

(QUEST [2], PEST [3],…)



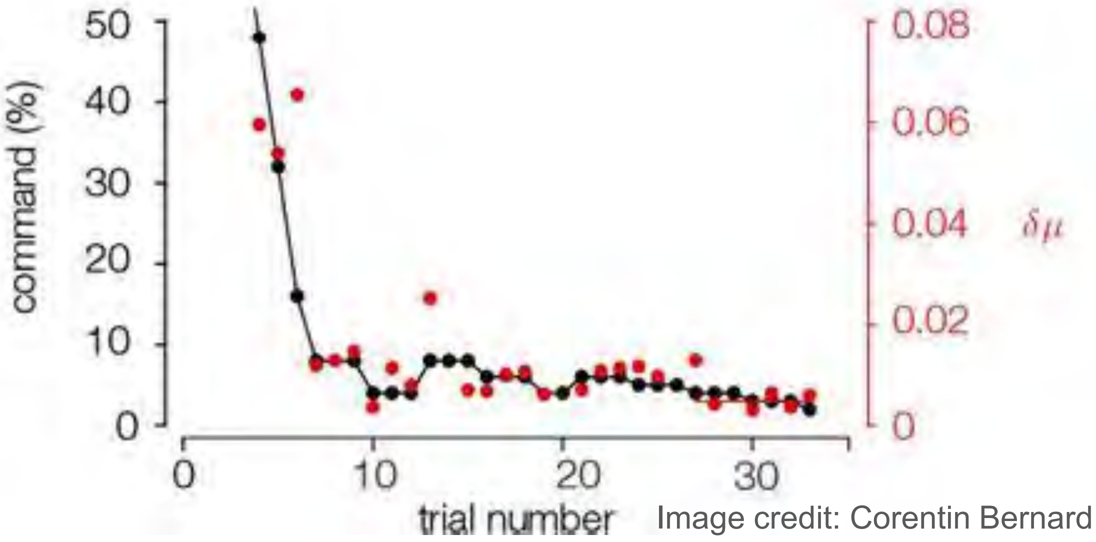


Image credit: Corentin Bernard

Good sample selection is critical!

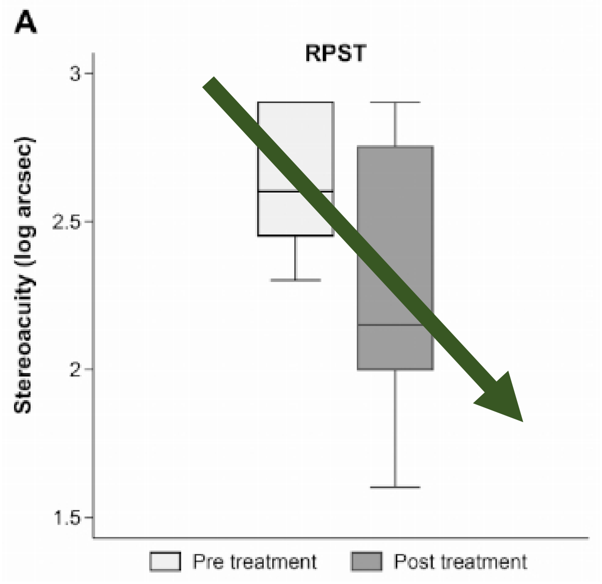
Good initialization is critical!

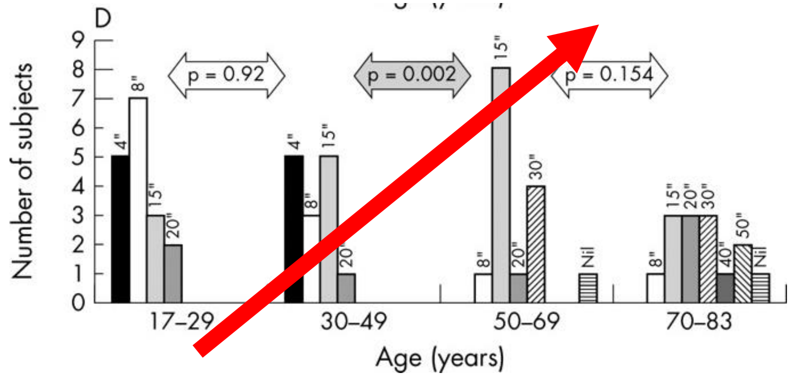
[1] Cornsweet, Tom N. "The staircase-method in psychophysics." *The American journal of psychology* 75.3 (1962).
[2] Watson, Andrew B., and Denis G. Pelli. "QUEST: A Bayesian adaptive psychometric method." *Perception & psychophysics* 33.2 (1983).
[3] Pentland, A. P. "The Best PEST, a maximum-likelihood parameter estimation procedure." *Perception and Psychophysics* 28 (1980).

Procedure

```
Get “Institutional Review Board approval”
Foreach participant in Participants:
  Screening()
  Instructions()
  Foreach condition in Conditions:
    Foreach level in Levels:
      ShowStimulus(condition, level)
      Responses += 2AFC()
    Thresholds += FitPsychometric(Responses)
DSF = FitCurve(Conditions, Thresholds)
```

Population variation

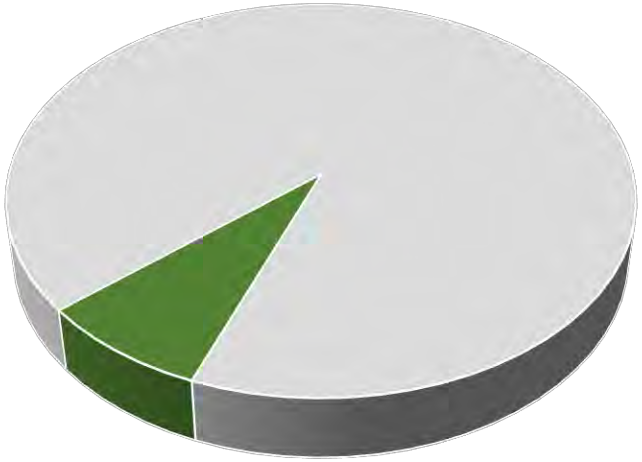


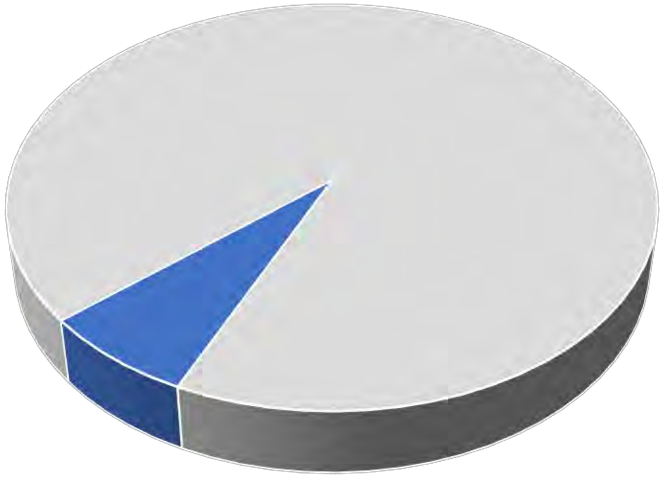


Stereoacuity… …improves with **experience** [1] …degrades with **age** [2]

[1] Martín-González, Santiago, et al. "Stereoacuity improvement using random-dot video games." JoVE (Journal of Visualized Experiments) 155 (2020): e60236.

[2] Garnham, L., and J. J. Sloper. "Effect of age on adult stereoacuity as measured by different types of stereotest." British journal of ophthalmology 90.1 (2006).





~8% men / ~0.5% women are **color-blind** [1]

~ 7% of population is **stereo-blind** [2]

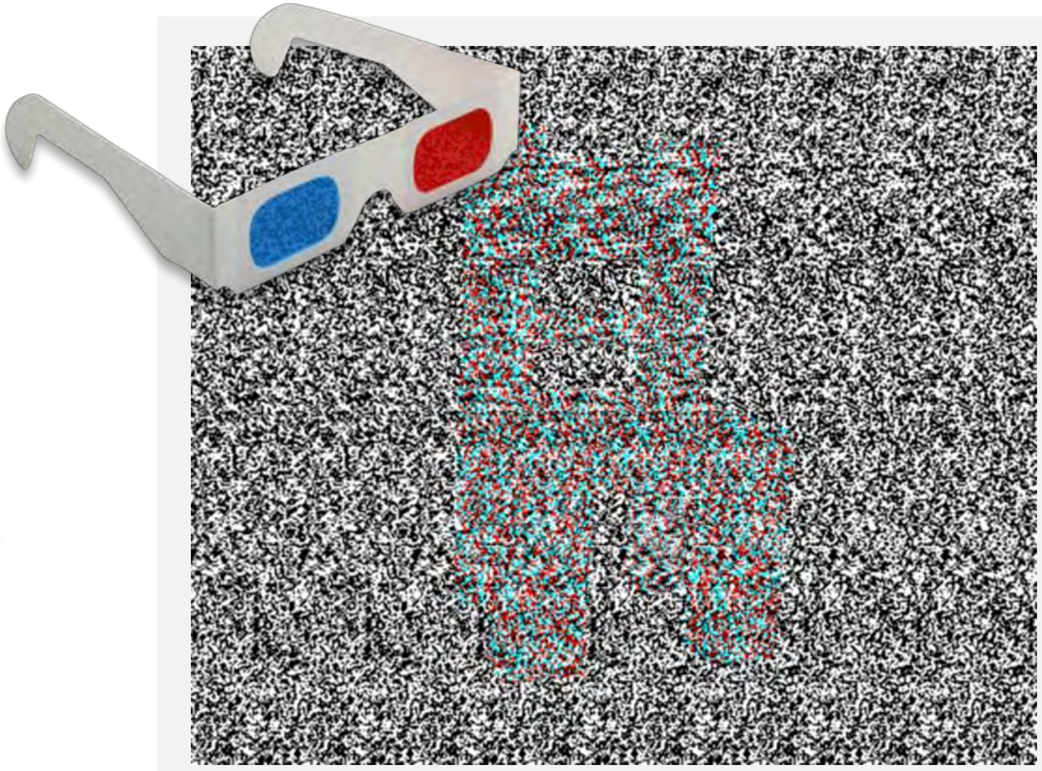
[1] Deeb, S. S. "The molecular basis of variation in human color vision." Clinical genetics 67.5 (2005): 369-377.

[2] Chopin, Adrien, Daphne Bavelier, and Dennis Michael Levi. "The prevalence and diagnosis of 'stereoblindness' in adults less than 60 years of age: a best evidence synthesis." *Ophthalmic and Physiological Optics* 39.2 (2019): 66-85.

Subject screening

- Test for **stereo blindness**!

Image Credit: Stereo Optical



Backup solution: Anaglyph RDS

IPD measurement

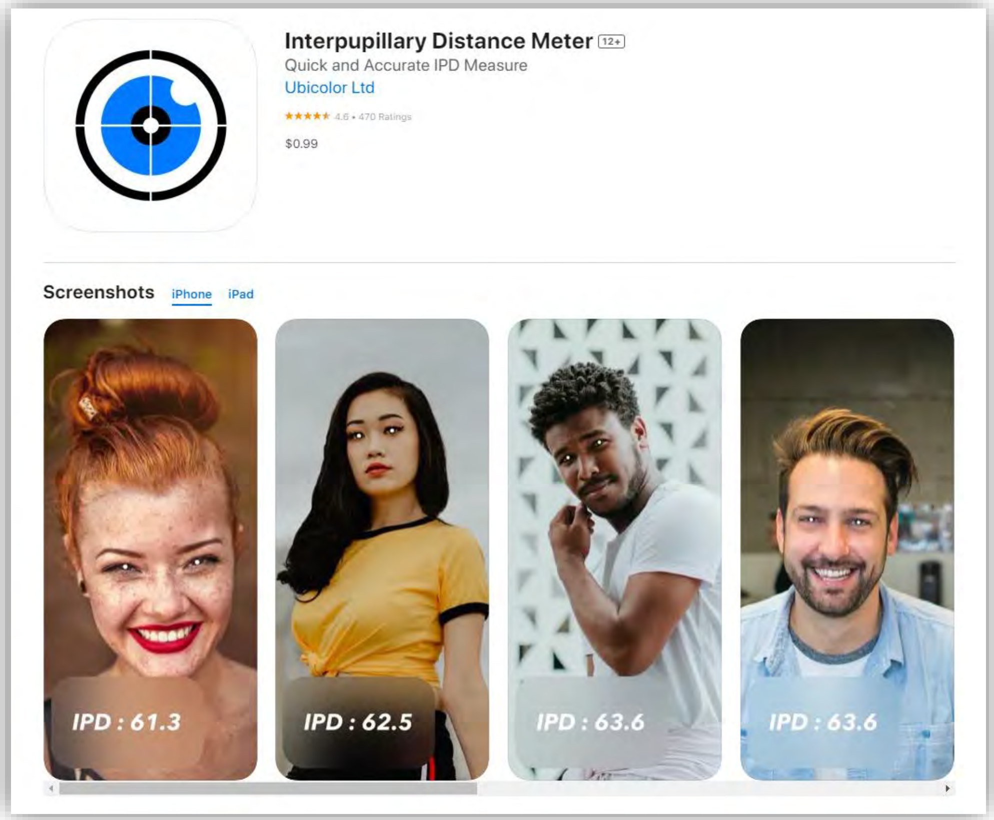
= Inter-Pupillary or Inter-Ocular Distance

Image credit: Viswanathan Sivaraman

Digital Pupilometer

Image credit: dibbleoptical.co.uk

Image credit: Ubicolor Ltd



Interpupillary Distance Meter 12+

Quick and Accurate IPD Measure

Ubicolor Ltd

★★★★★ 4.6 • 470 Ratings

$0.99

Screenshots iPhone iPad

IPD measurement with iPhone

IPD measurement

- Warning: IPD changes with vergence distance!

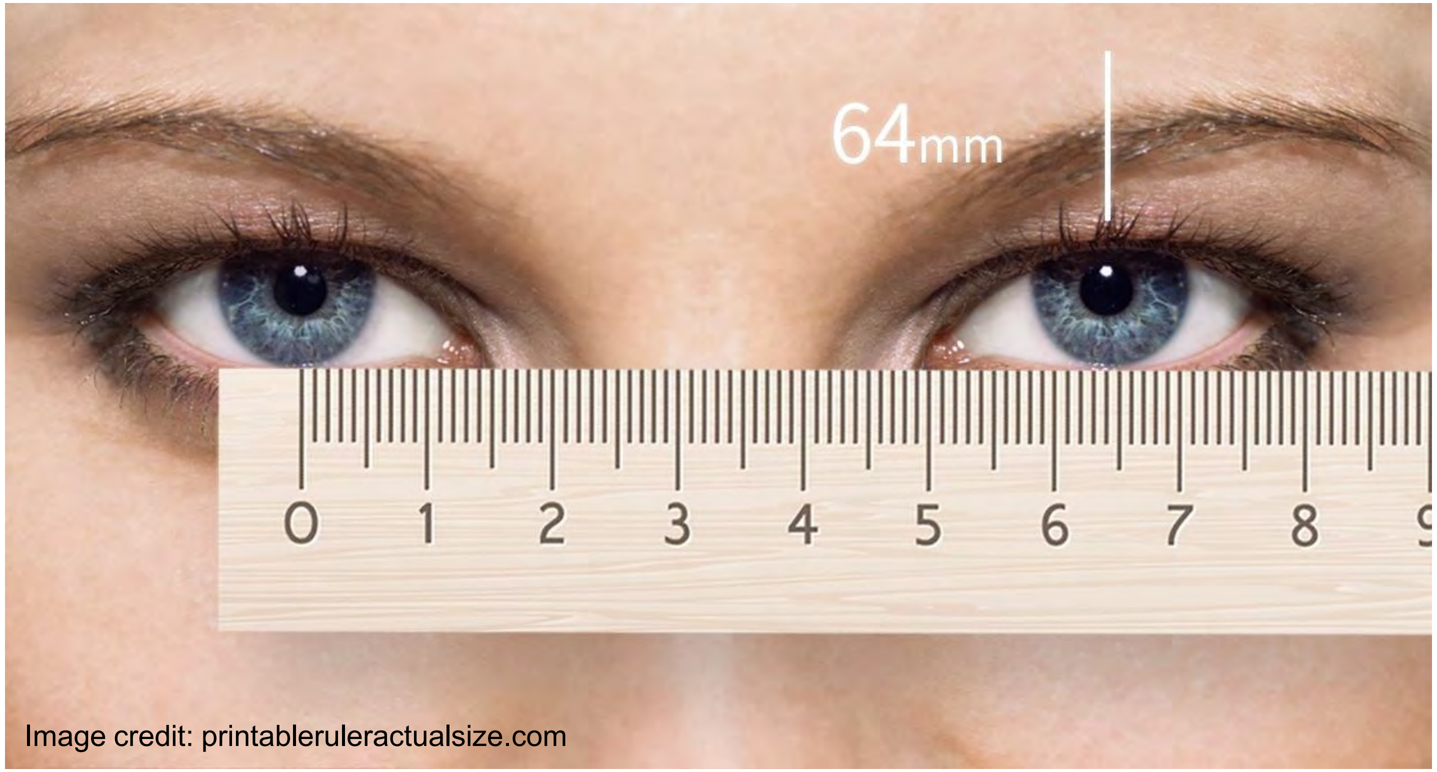


Image credit: printableruleractualsize.com

Self-measurement using a ruler and a mirror

Other considerations

Luminance adaptation

Display calibration

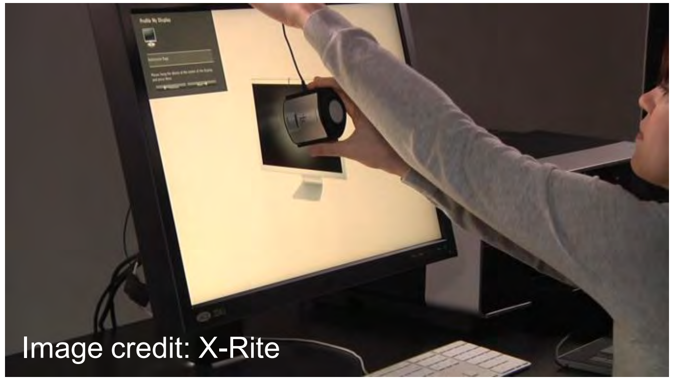


Image credit: X-Rite

Ambient light control

Image credit: wallpaperflare.com

Comfort & Fatigue

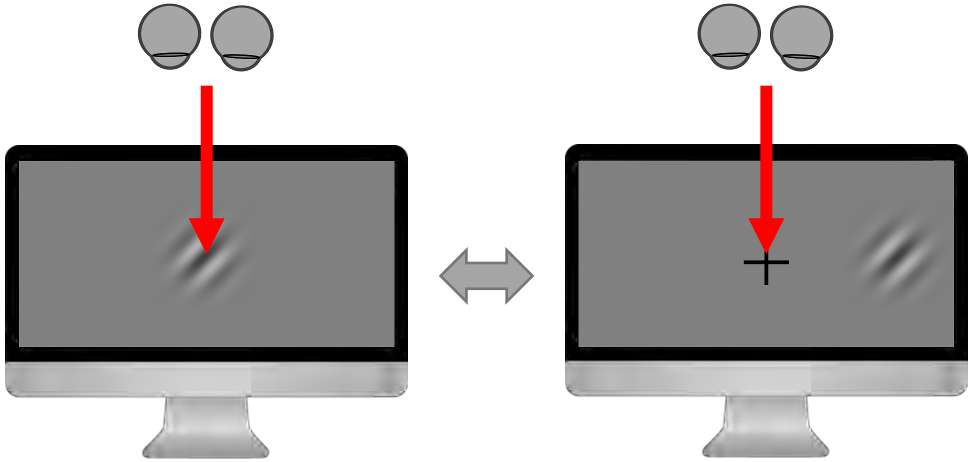
Image credit: Tobii

Comfortable viewing position, chin rest

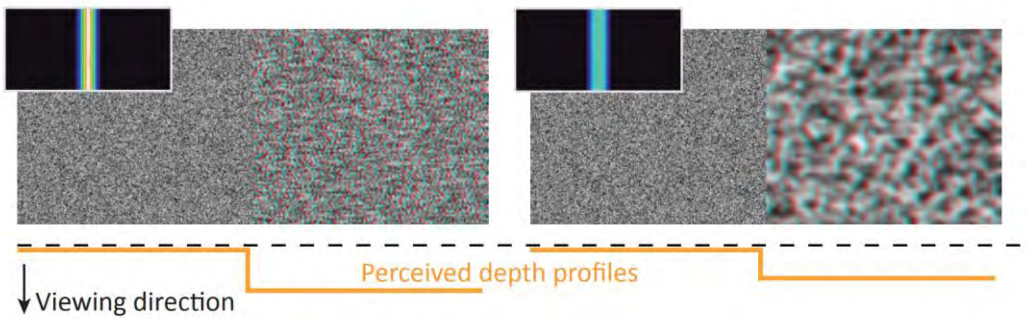
Time management, breaks

Sensitivity depends on many factors…

- Personal characteristic
- Adaptation luminance
- Retinal eccentricity
- Luminance contrast
- …

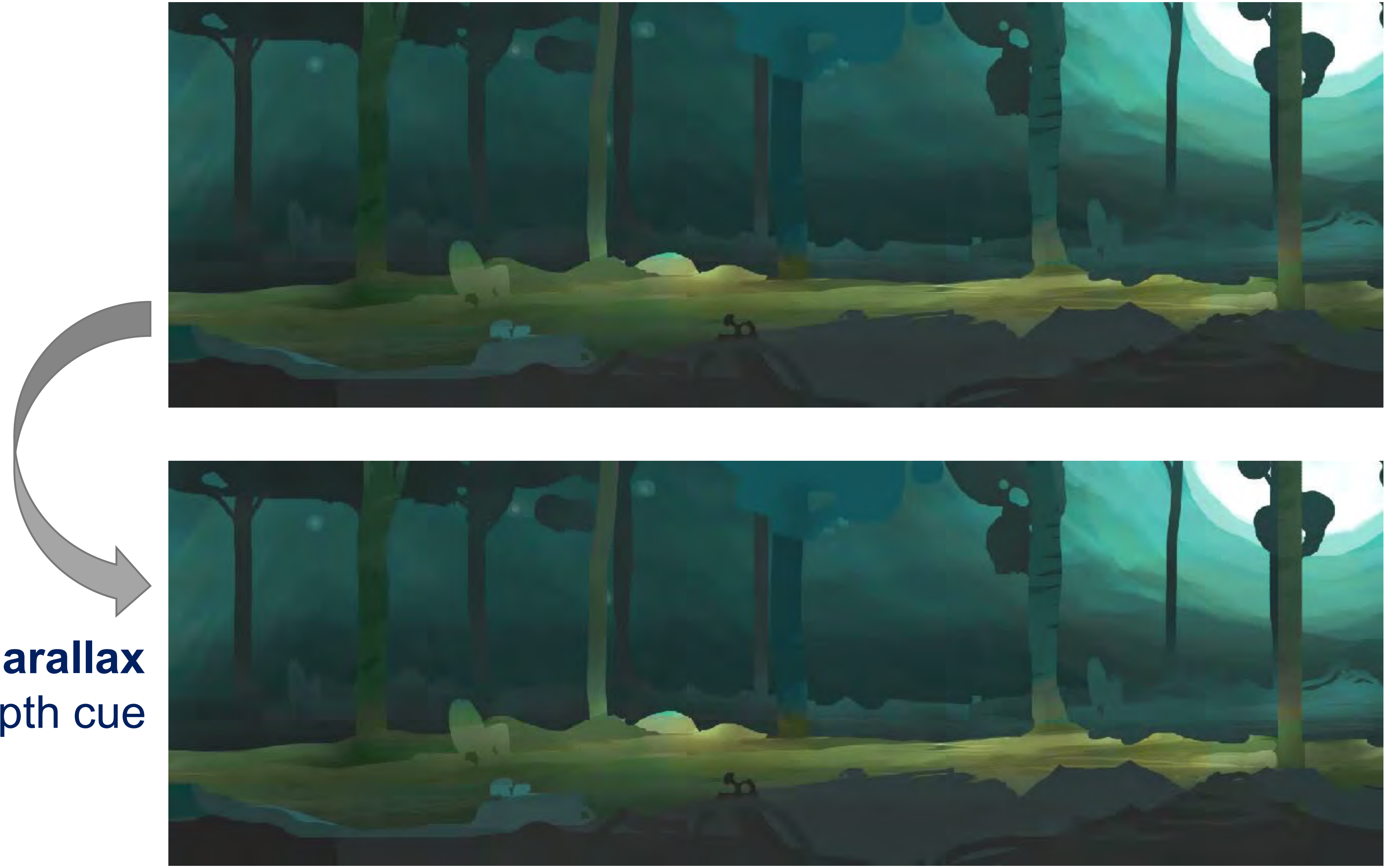


More eccentricity -> **Less** sensitivity



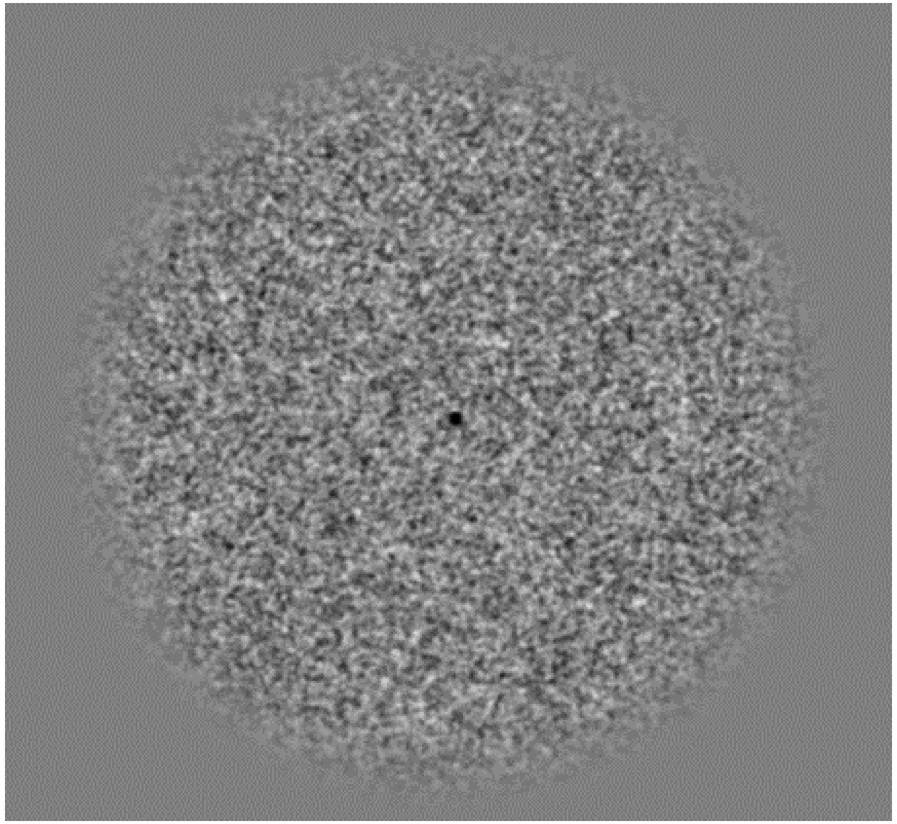
Less contrast -> **Less** sensitivity

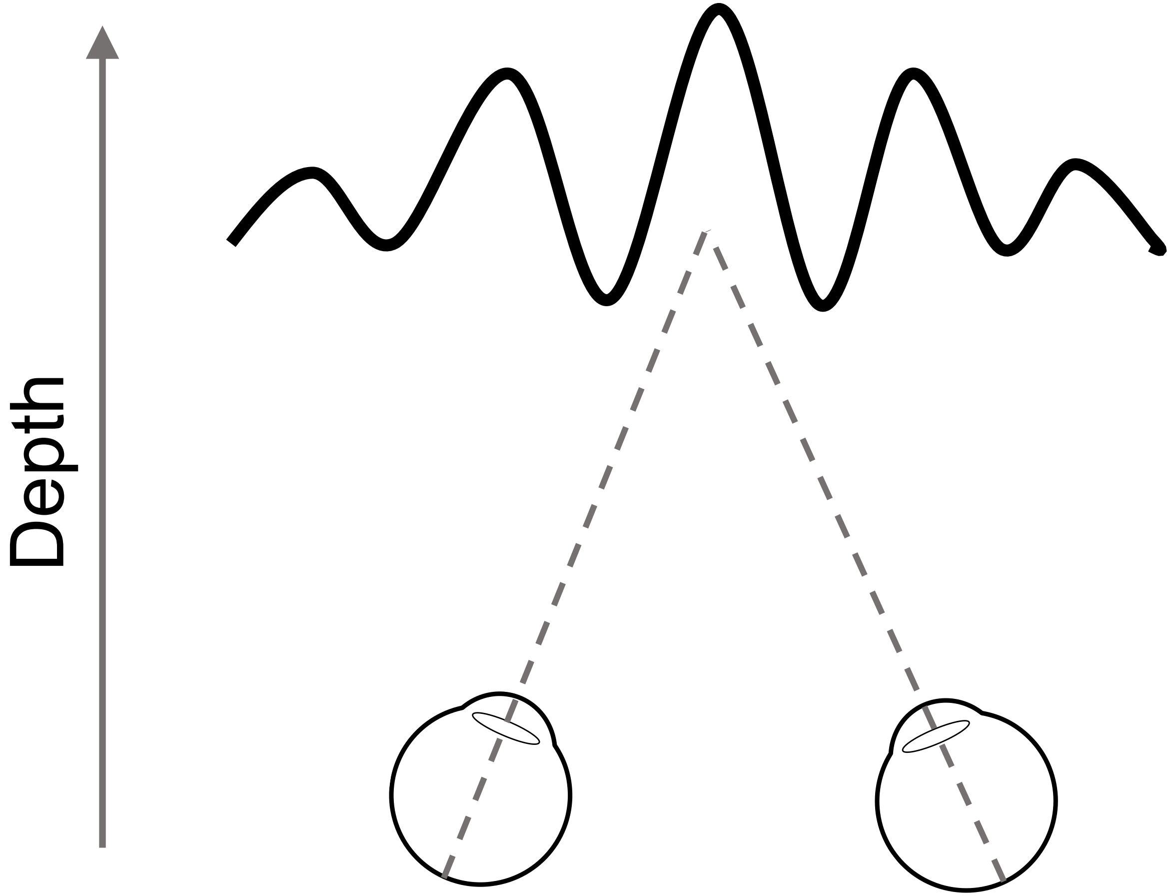
Didyk, Piotr, et al. "A luminance-contrast-aware disparity model and applications." *ACM Transactions on Graphics (TOG)* 31.6 (2012): 1-10.

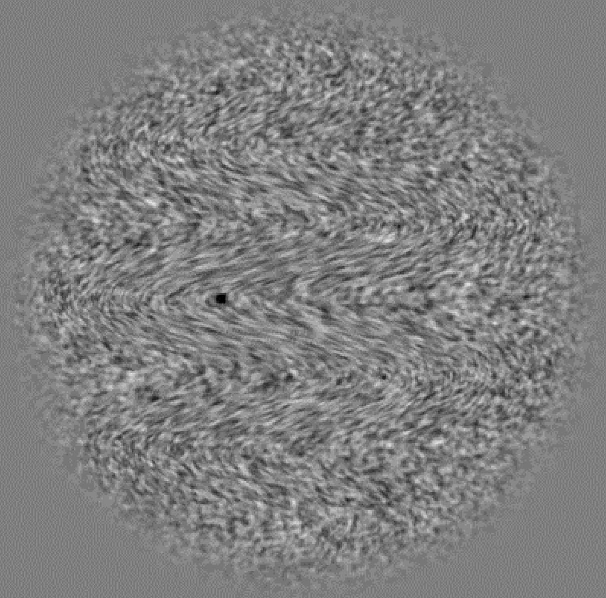


+ Motion Parallax
depth cue

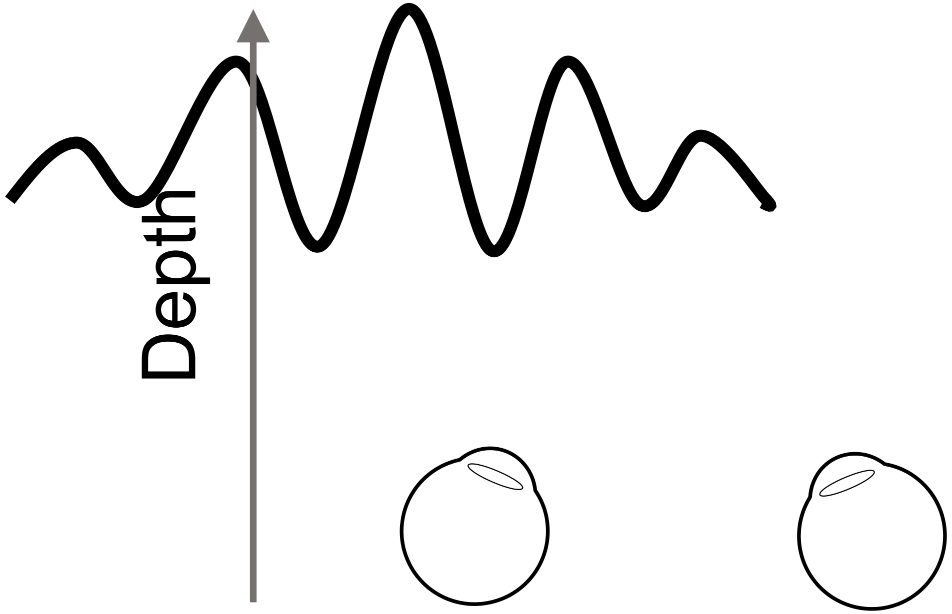
Binocular disparity only

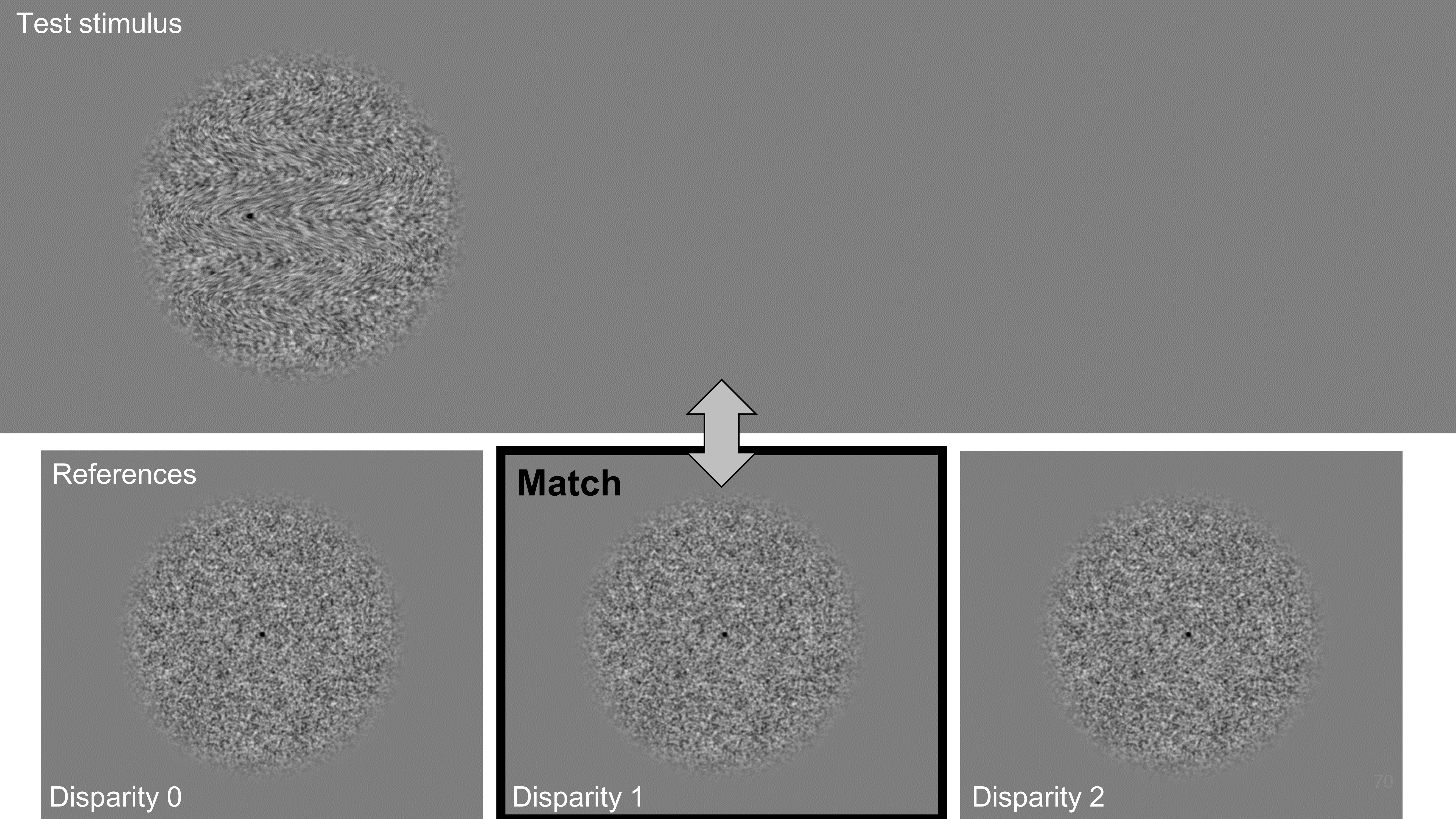






Binocular disparity + motion parallax





Test stimulus

References

Match

Disparity 0

Disparity 1

Disparity 2

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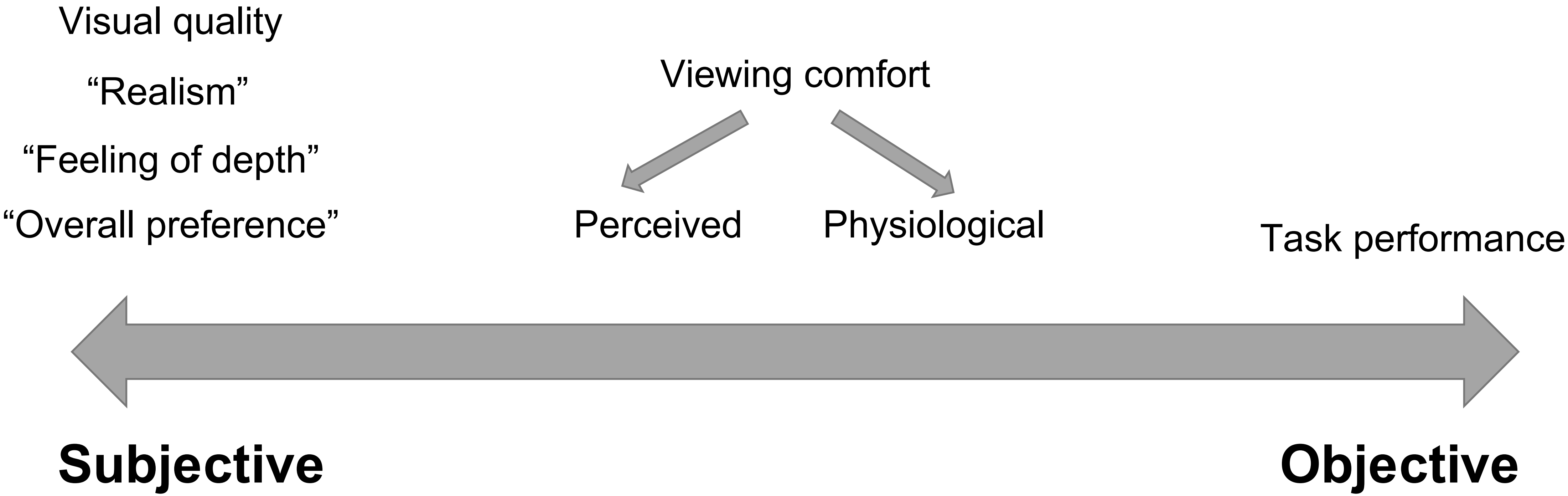
Spectrum of questions



Visual quality

“Realism”

“Feeling of depth”

“Overall preference”

Viewing comfort

Perceived

Physiological

Task performance

Subjective

Objective

Visual quality

- Stereo view synthesis -> **specific artifacts**.

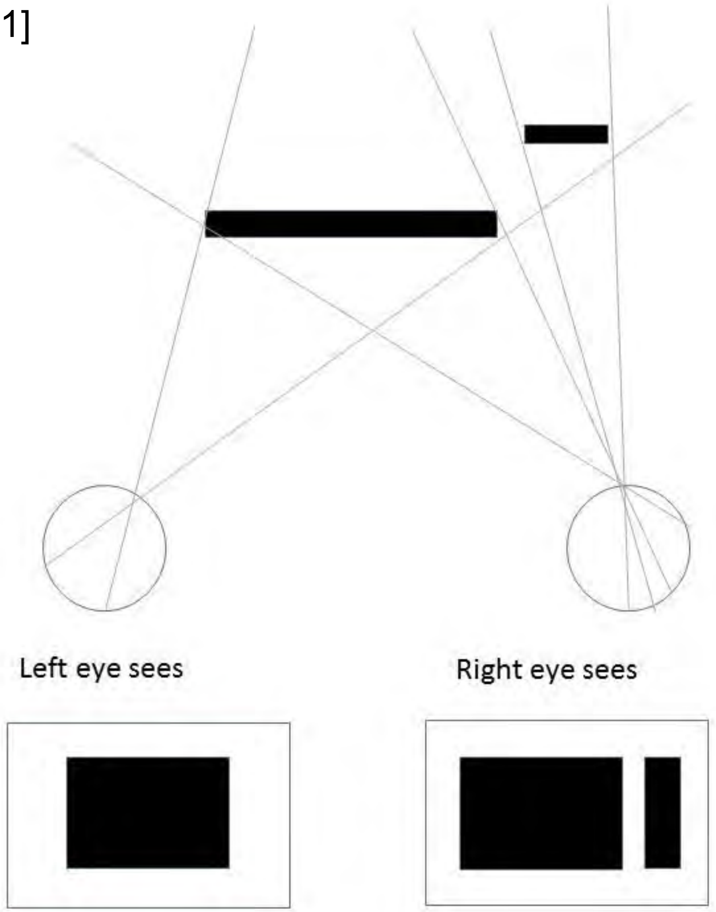
- Most image metrics only process monocular images.

- What if artifact only in one eye?

Image-Based Rendering artifacts

Kellnhofer, Petr, et al. "Optimizing disparity for motion in depth." *EGSR 2013*.

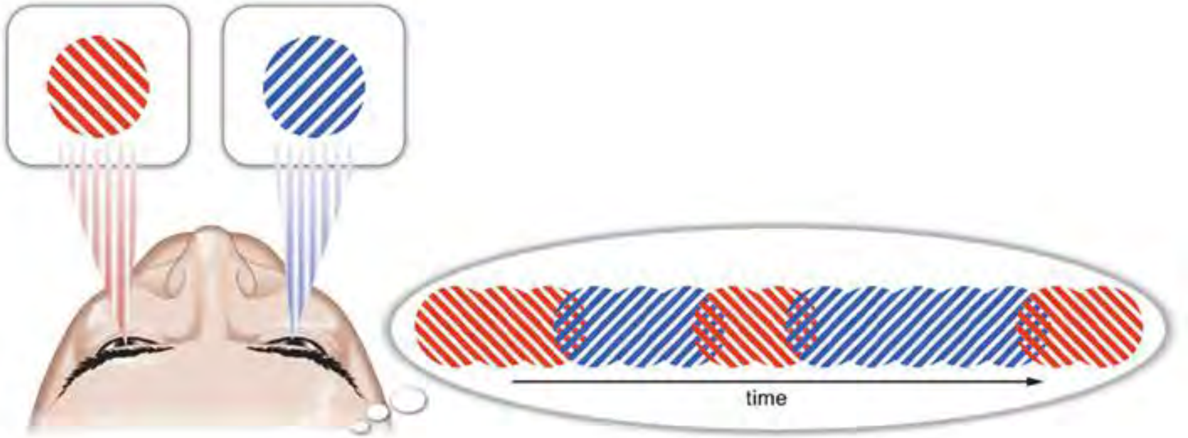
[1]



Da Vinci stereopsis ✓

vs.

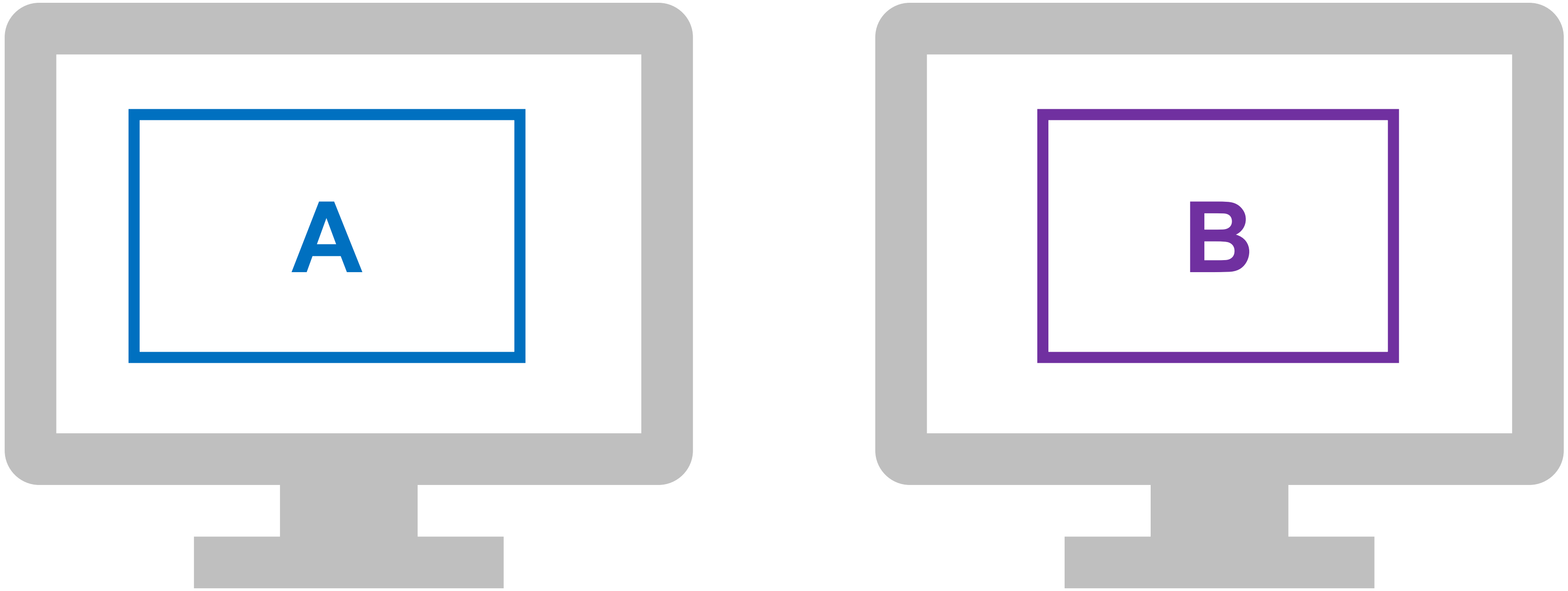
[2]



Binocular rivalry ✗

[1] Jenny Read, 2018, https://www.jennyreadresearch.com/2018/da-vinci-stereopsis/
[2] Dieter, Kevin Conrad, and Duje Tadin. "Understanding attentional modulation of binocular rivalry: a framework based on biased competition." *Frontiers in Human Neuroscience* 5 (2011): 155.

Mean Opinion Scores

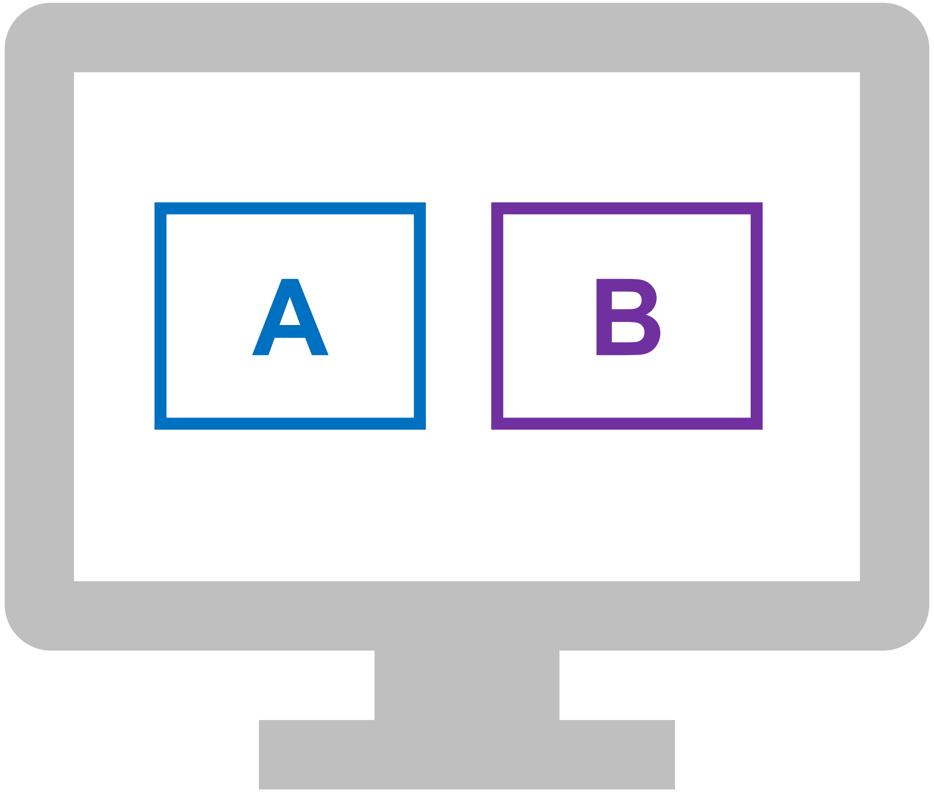


Outcome: **A** has rating X. **B** has rating Y.

Many different scales: [1-100], ITU-T J.247, Lickert scale,…

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
○	○	○	○	○

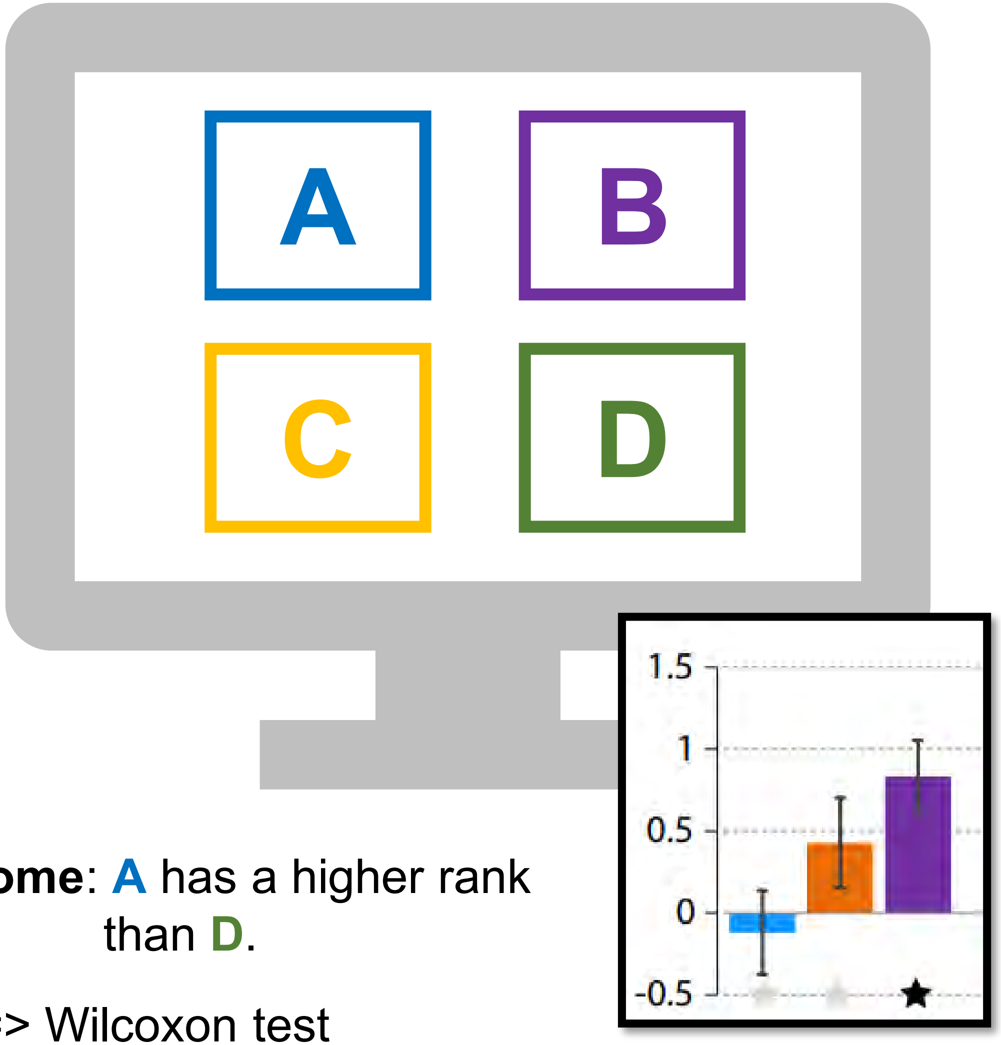
Side-by-side comparison (2AFC)



Outcome: A is better than B.

=> Binomial test

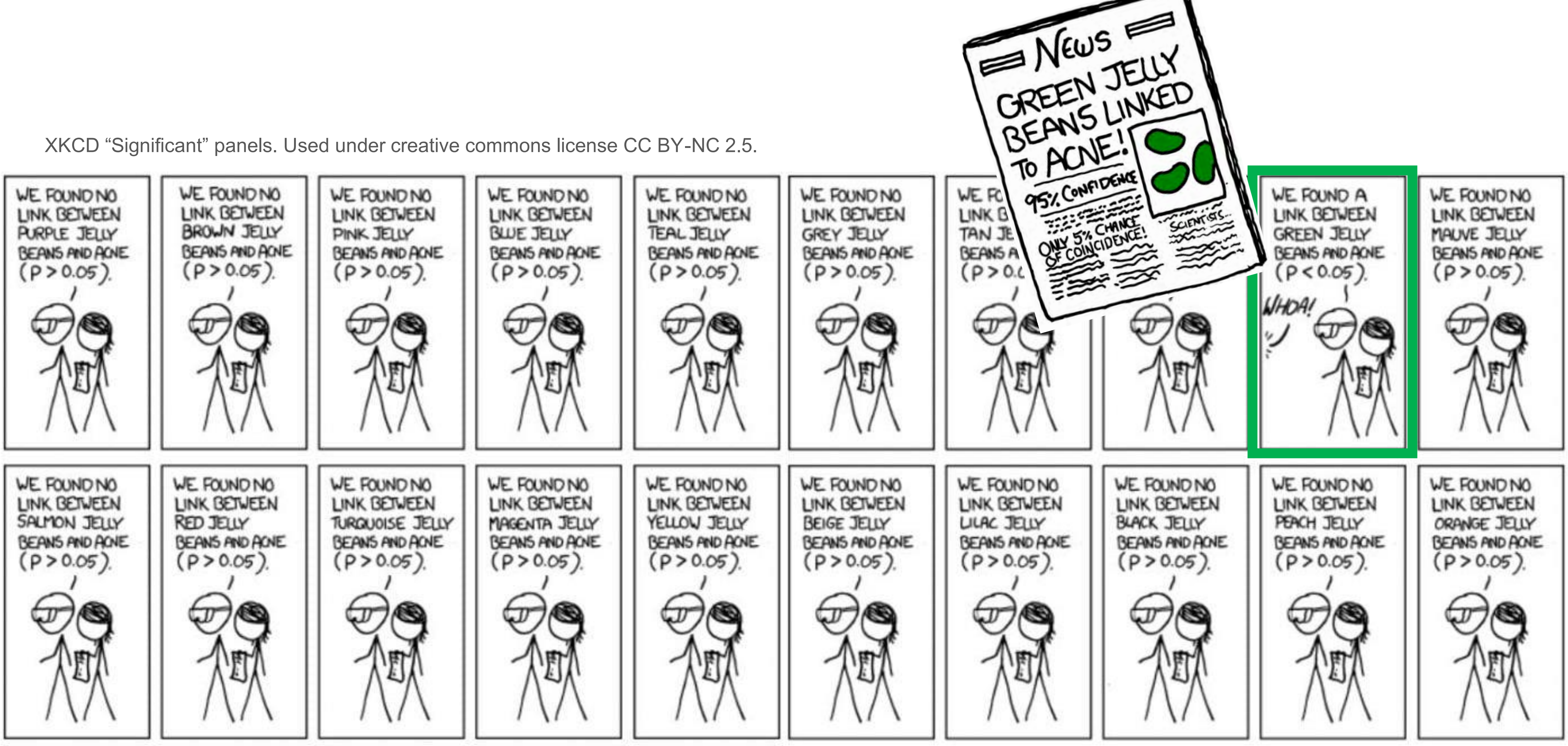
Ranking (Ranking)



Outcome: A has a higher rank than D.

=> Wilcoxon test

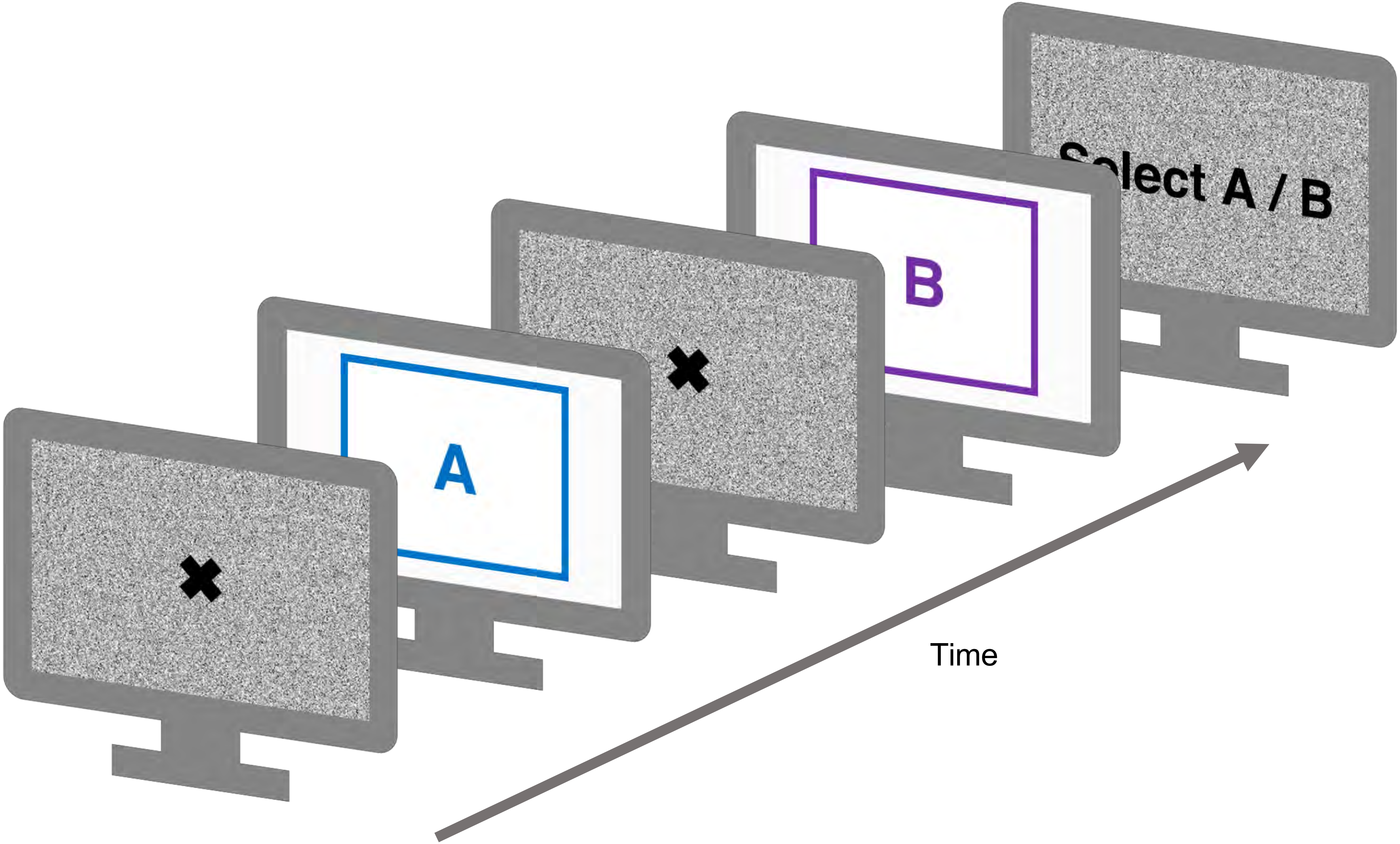
XKCD “Significant” panels. Used under creative commons license CC BY-NC 2.5.



=> Correct for multiple comparisons (e.g., Bonferroni correction)

Which image do you prefer?

Which image do you prefer?


A
B
Select A / B
Time

Which image do you prefer?

Order by:

Realism	Accurate depth? Accurate illumination? …. ?
Viewing comfort	Less 3D? Fewer artifacts?
Visual quality	Fewer artifacts? Sharper?
Overall preference	???

A

B

D

C

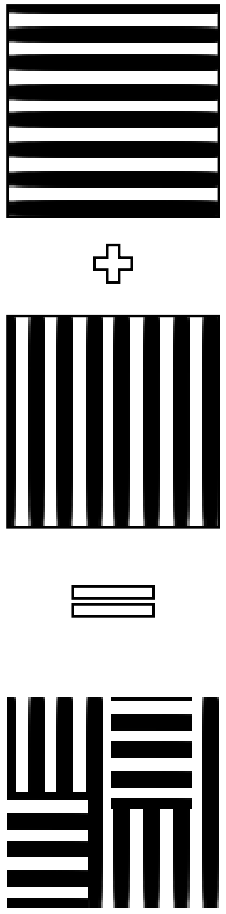
Dąbała, Łukasz, et al. "Manipulating refractive and reflective binocular disparity." *Computer Graphics Forum*. Vol. 33. No. 2. 2014.

Final notes

- Questions should be **clear**.

- Examples can be helpful but avoid **bias**.
  - Ideally completely unrelated to the study.
  - *Example: Rivalry demonstrated with an abstract example.*

- “I do not see a difference” choice is not useful.
  - Makes statistics harder.
  - Same output can be produced by random guessing.



Viewing comfort and fatigue

- Viewing **discomfort** + time -> **fatigue**.

- **Subjective** – Questionnaire
  - Sparse samples (e.g., before and after a session)

- **Objective** – Physiological indicators
  - *Examples: eye blinking rate, saccade speed [1]*
  - Continuous measurements
  - Many confounding factors (fatigue, distraction…)

- **Theoretical**
  - ⬇ Rivalry -> ⬇ Conflict -> ⬆ Comfort

Image credit: Tima Miroshnichenko @ pexels.com

[1] Zhang, Li, et al. "Visual comfort and fatigue when watching three-dimensional displays as measured by eye movement analysis." *British Journal of Ophthalmology* 97.7 (2013): 941-942.

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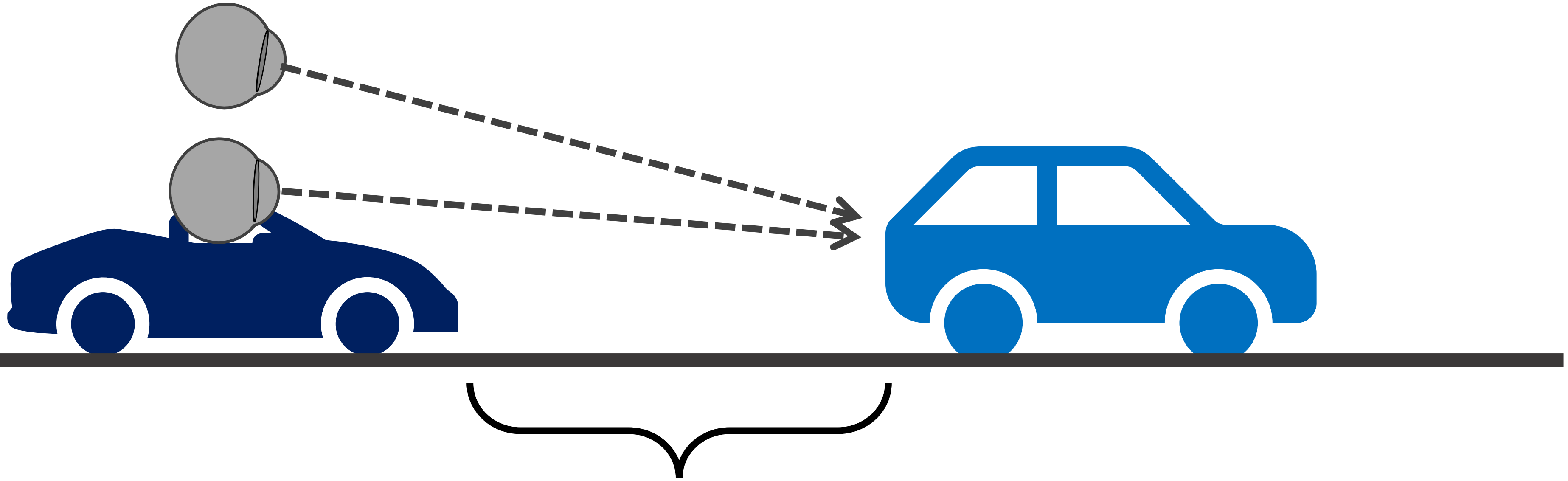
Binocular vision is important

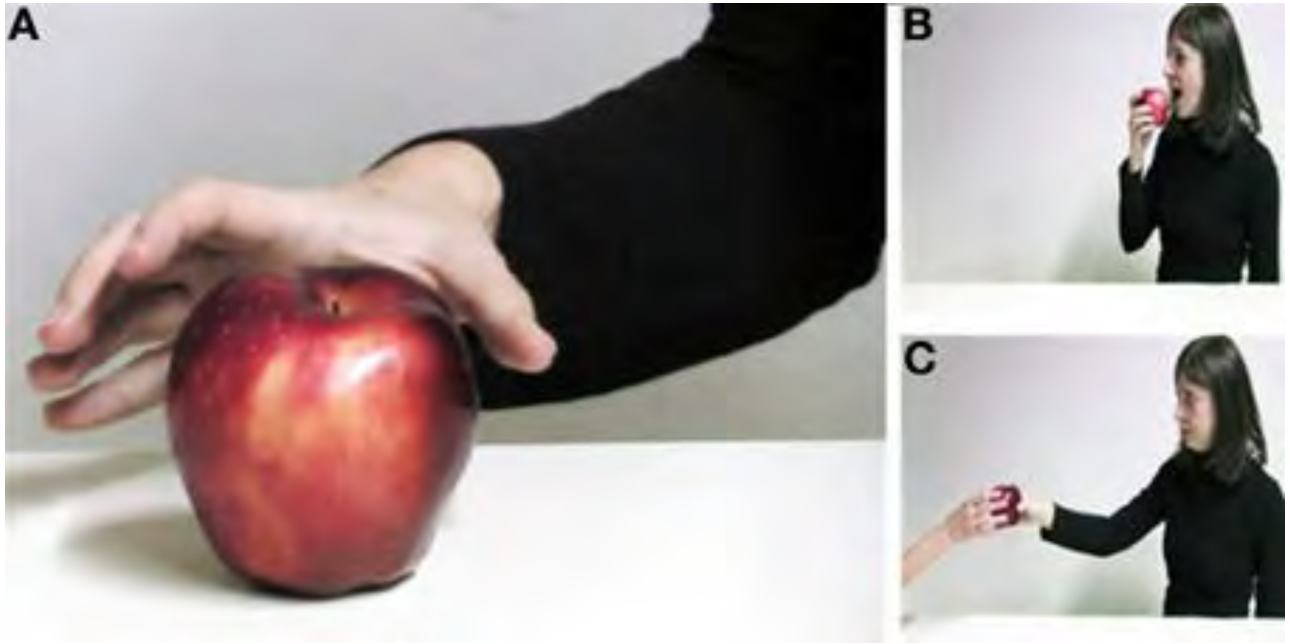
- Driving performance impaired without proper binocular vision



Absolute distance, relative distance, velocity, time-to-collision…

Absolute distance

- Important for interactions in **personal space** (grasping,…).
- Requires coordination of **multiple depth cues.**
- Often **underestimated** in VR.

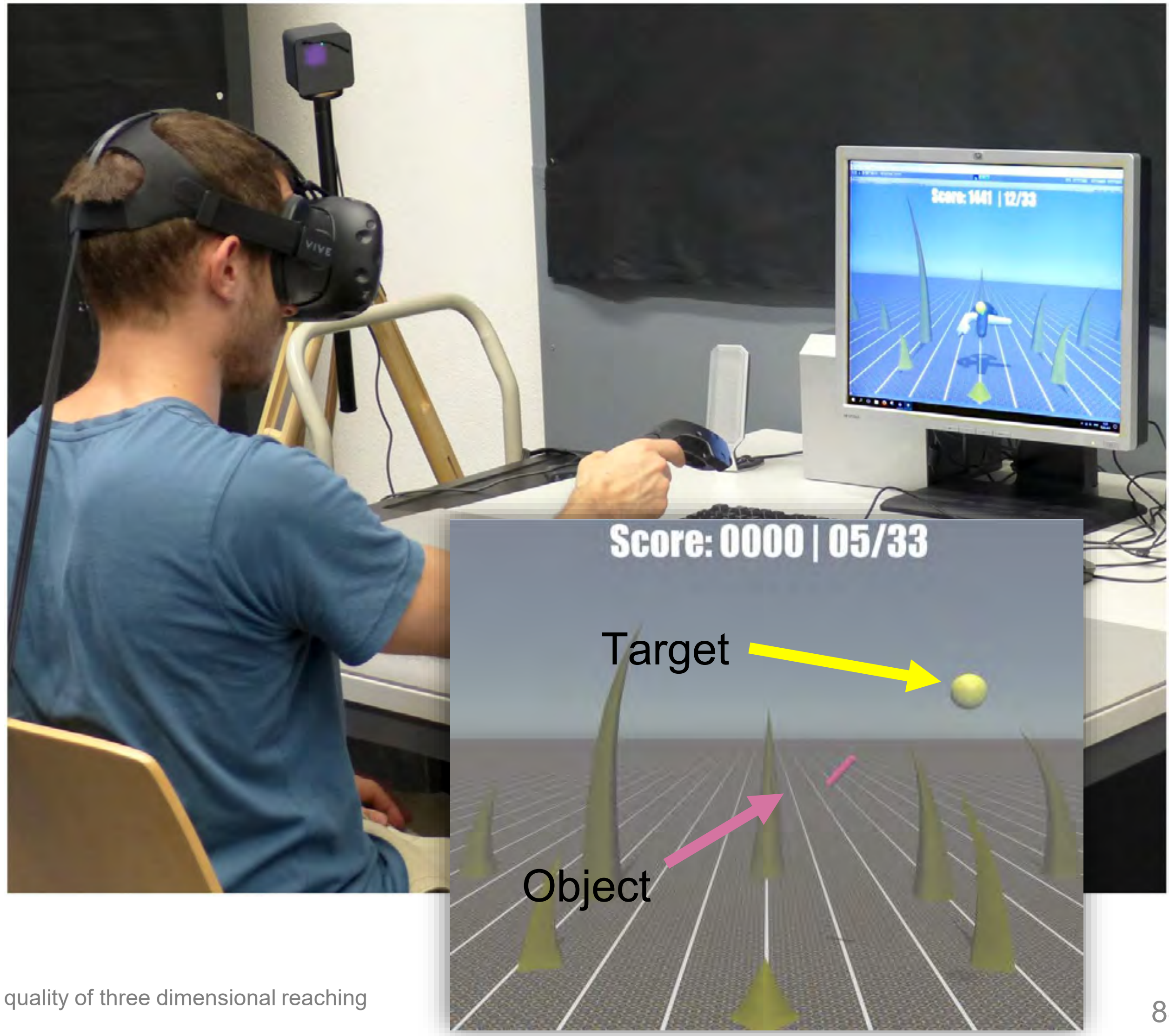


Becchio, Cristina, et al. "Grasping intentions: from thought experiments to empirical evidence." *Frontiers in human neuroscience* 6 (2012): 117.

Reaching experiments

- **Ask** subject to:
  - **Reach** a target.
    - or -
  - **Move** an object to a target.

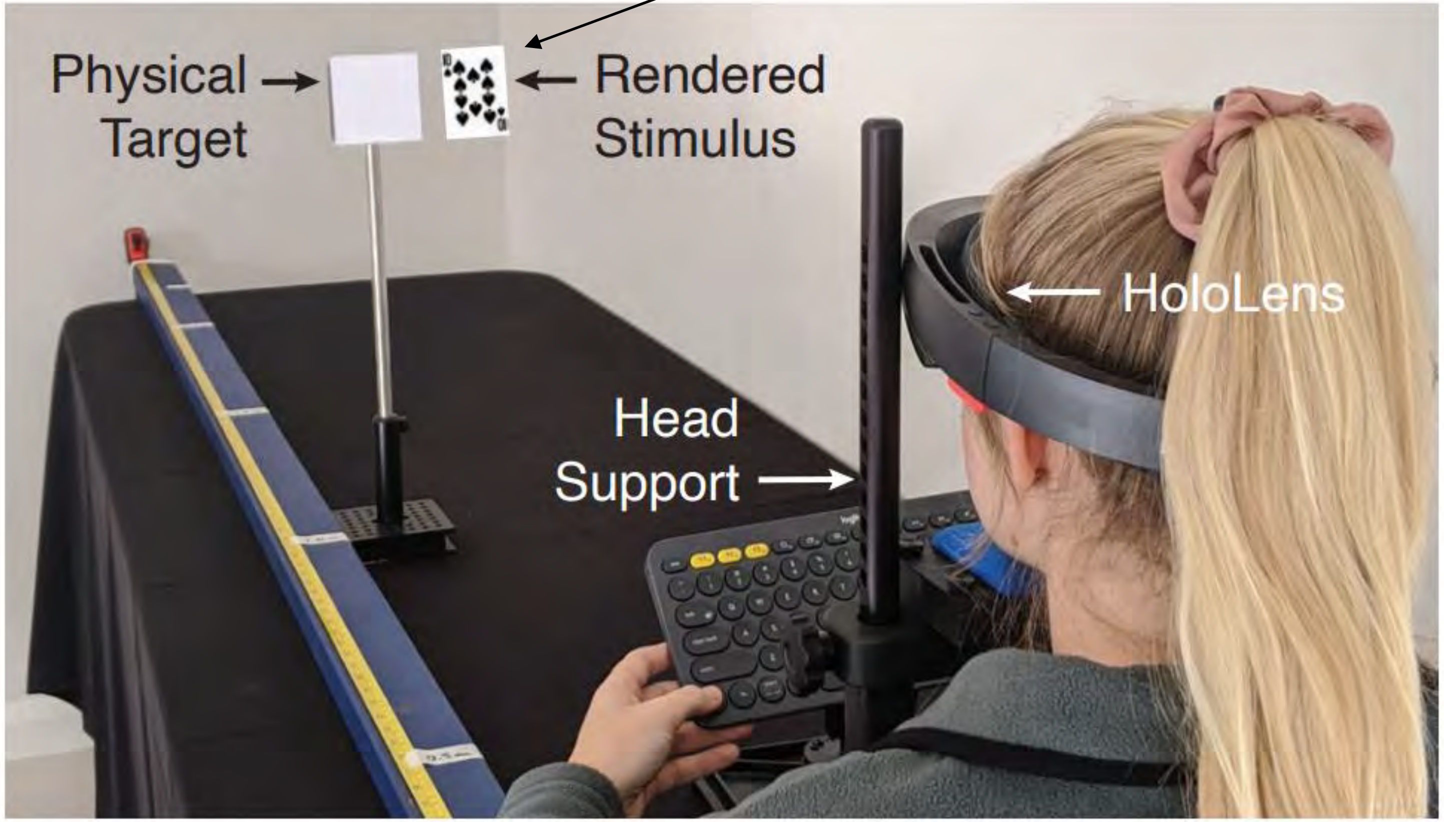
- **Measure:**
  - Position **error**.
    - or -
  - Completion **speed**.



Gerig, Nicolas, et al. "Missing depth cues in virtual reality limit performance and quality of three dimensional reaching movements." *PLoS one* 13.1 (2018): e0189275.

Comparison experiments

- Compare **physical** reference vs. a **virtual**.

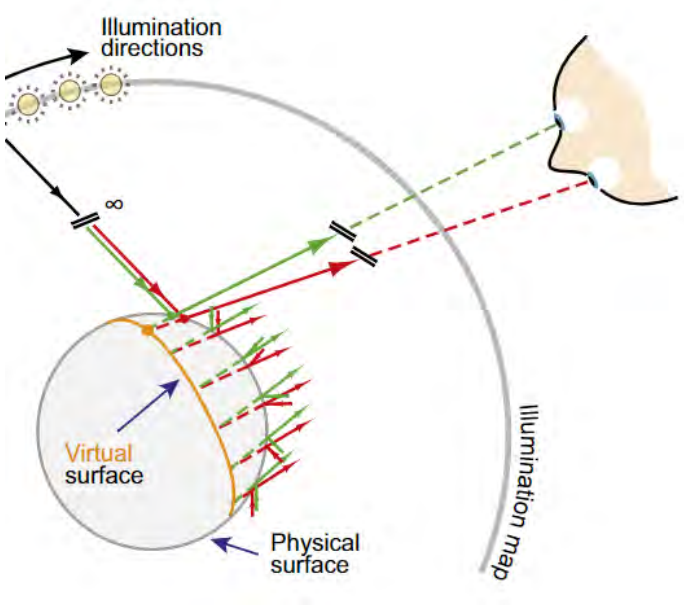


Adjust depth until matched.

Krajancich, Brooke, Petr Kellnhofer, and Gordon Wetzstein. "Optimizing depth perception in virtual and augmented reality through gaze-contingent stereo rendering." *ACM Transactions on Graphics (TOG)* 39.6 (2020): 1-10.

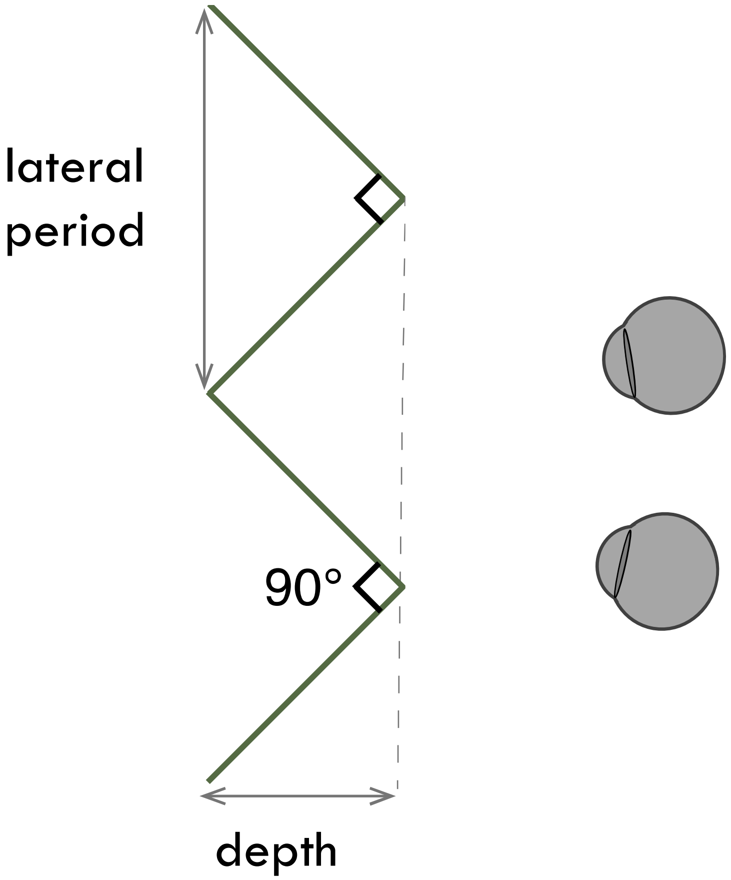
Shape understanding

- Function of both **relative** and **absolute** depth.

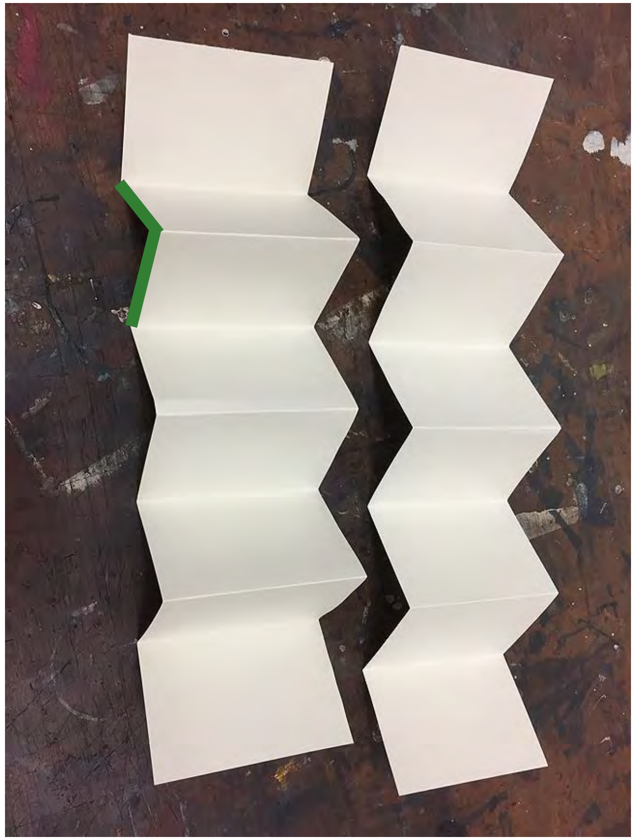


Muryy, Alexander A., et al. "Specular reflections and the estimation of shape from binocular disparity." Proceedings of the National Academy of Sciences 110.6 (2013): 2413-2418.

Familiar reference

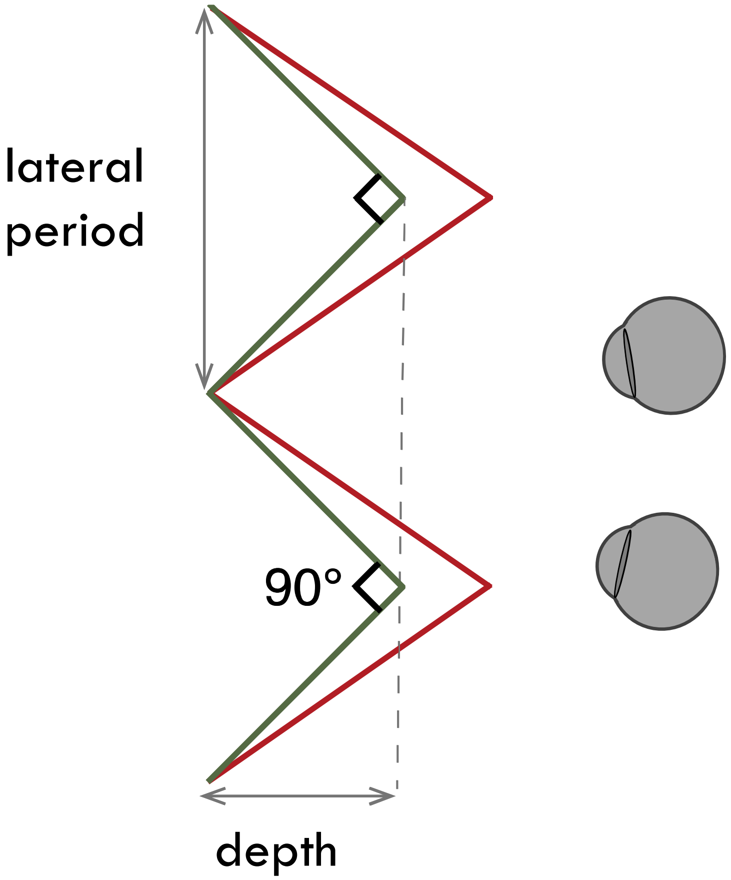


Triangle Wave

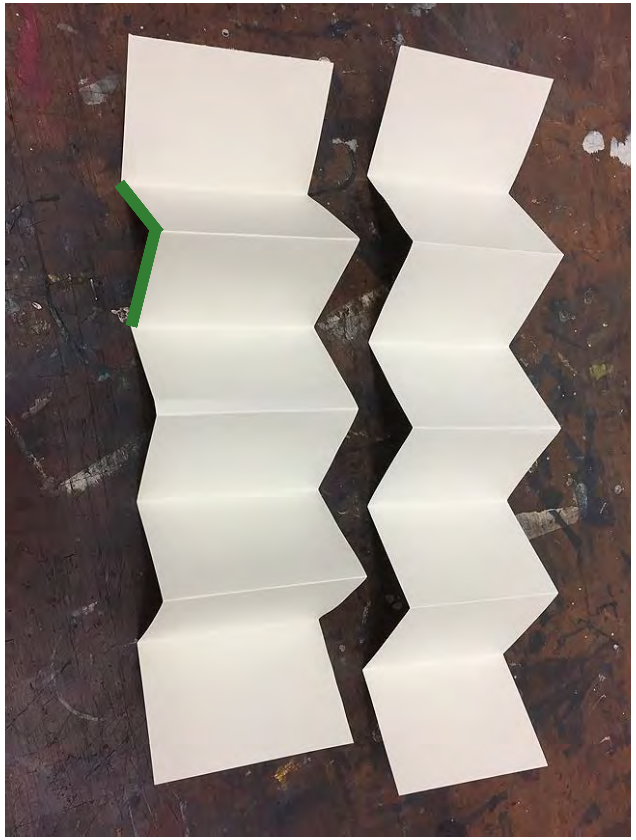


Krajancich, Brooke, Petr Kellnhofer, and Gordon Wetzstein. "Optimizing depth perception in virtual and augmented reality through gaze-contingent stereo rendering." *ACM Transactions on Graphics (TOG)* 39.6 (2020): 1-10.

Familiar reference

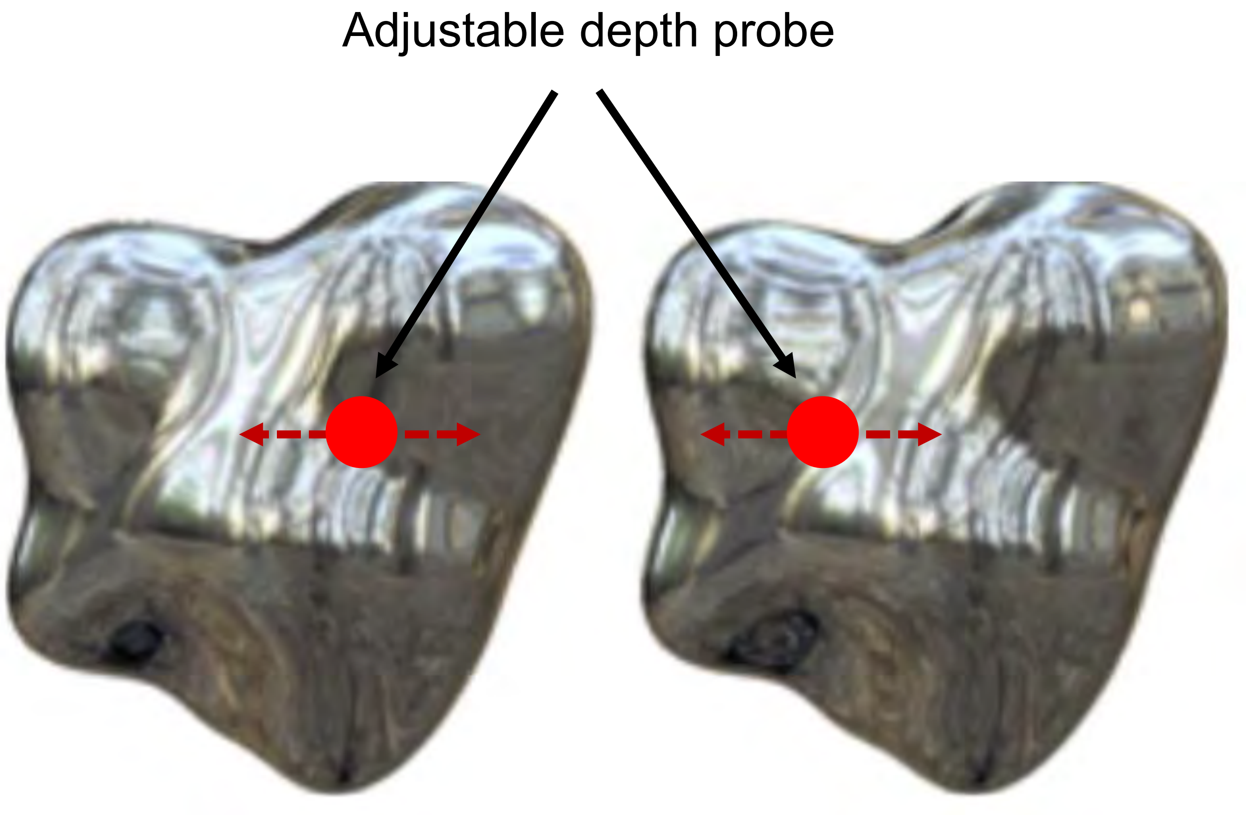


Triangle Wave

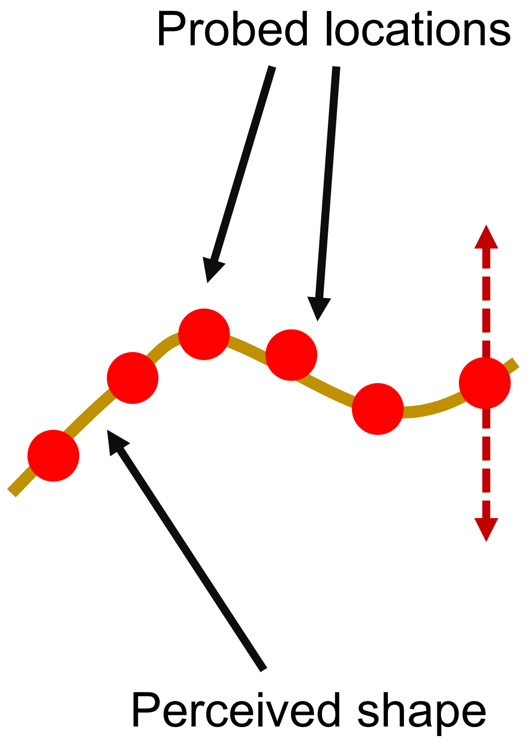


Krajancich, Brooke, Petr Kellnhofer, and Gordon Wetzstein. "Optimizing depth perception in virtual and augmented reality through gaze-contingent stereo rendering." *ACM Transactions on Graphics (TOG)* 39.6 (2020): 1-10.

Direct shape measurement

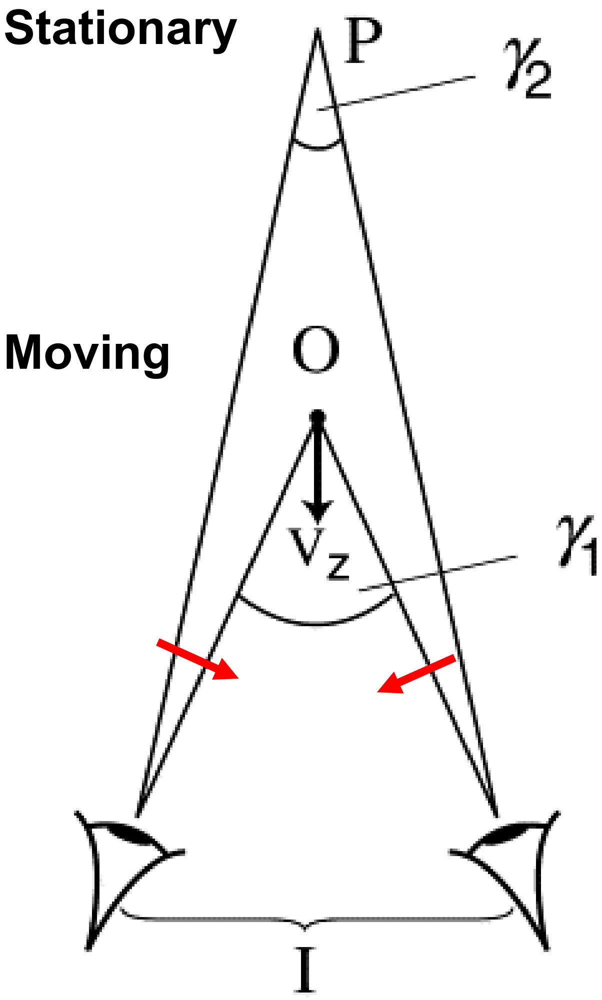


Stereoscopic image



Muryy, Alexander A., et al. "Specular reflections and the estimation of shape from binocular disparity." Proceedings of the National Academy of Sciences 110.6 (2013): 2413-2418.

Time-to-collision

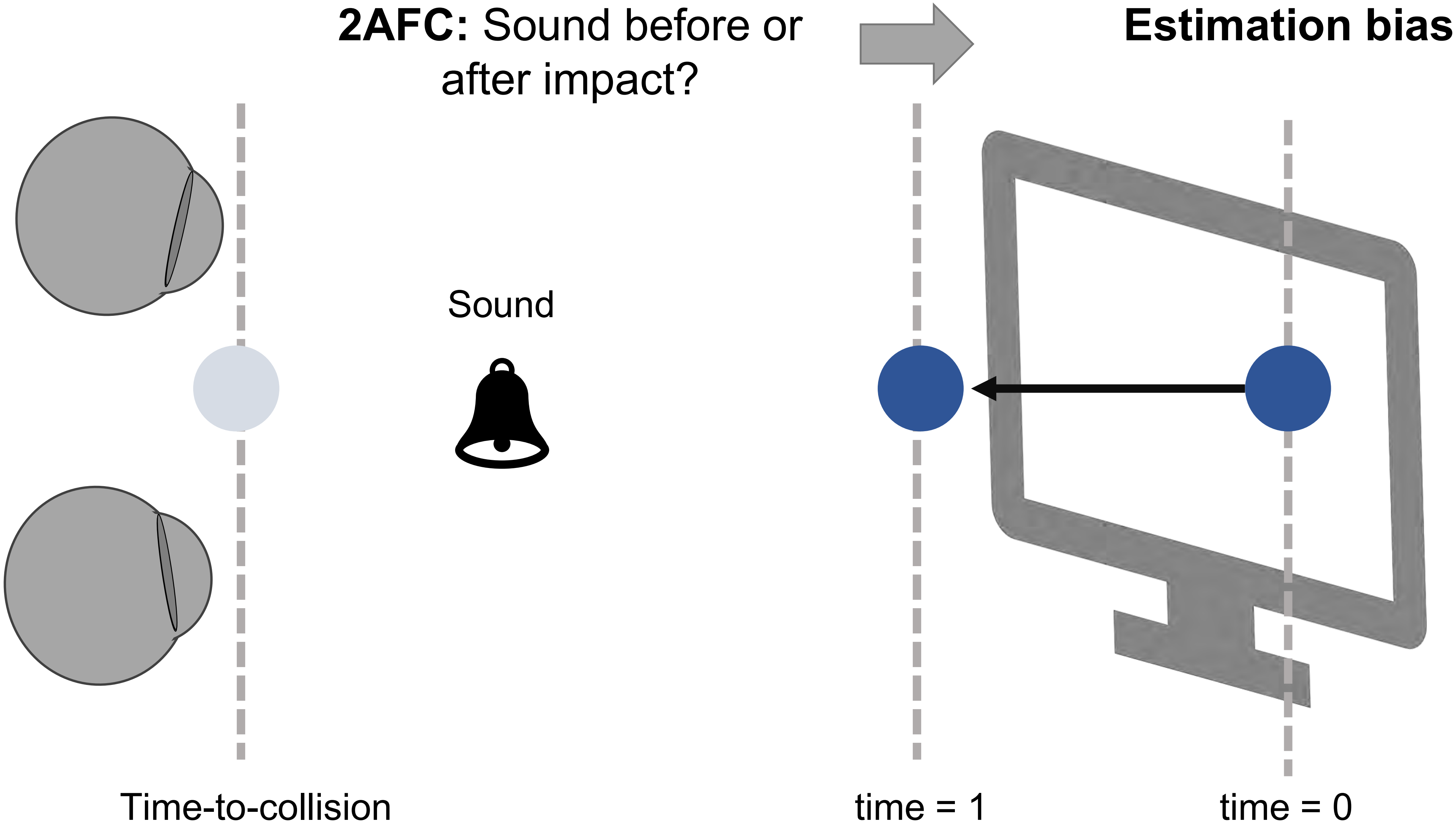



Credit: https://www.pxfuel.com/en/free-photo-ohgvi

Regan, D. "Binocular information about time to collision and time to passage." Vision Research 42.22 (2002): 2479-2484.

2AFC: Sound before or after impact?

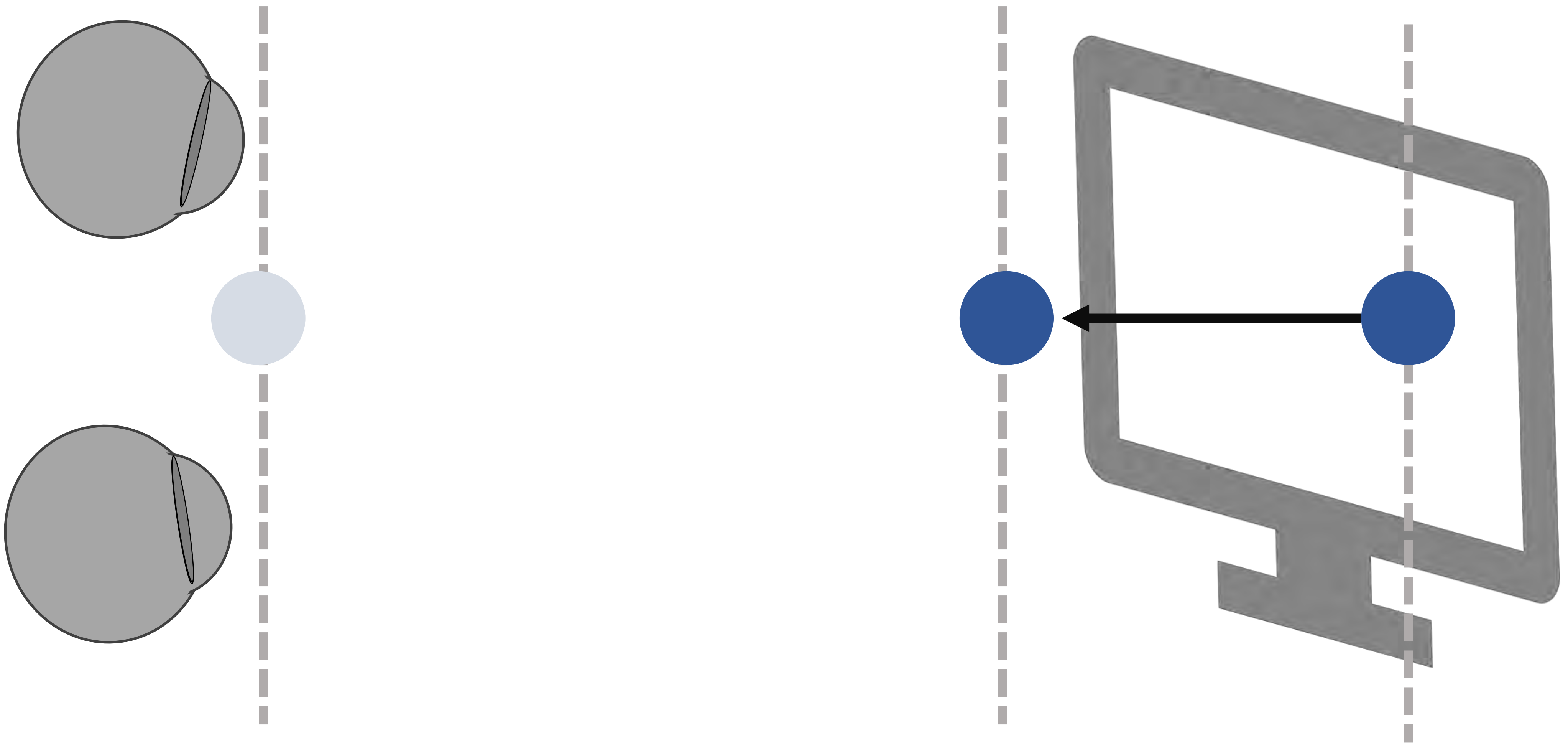
Estimation bias



Gray, Robert, and David Regan. "Accuracy of estimating time to collision using binocular and monocular information." *Vision research* 38.4 (1998): 499-512.

2AFC: TTC larger than mean?

TTC threshold



Time-to-collision

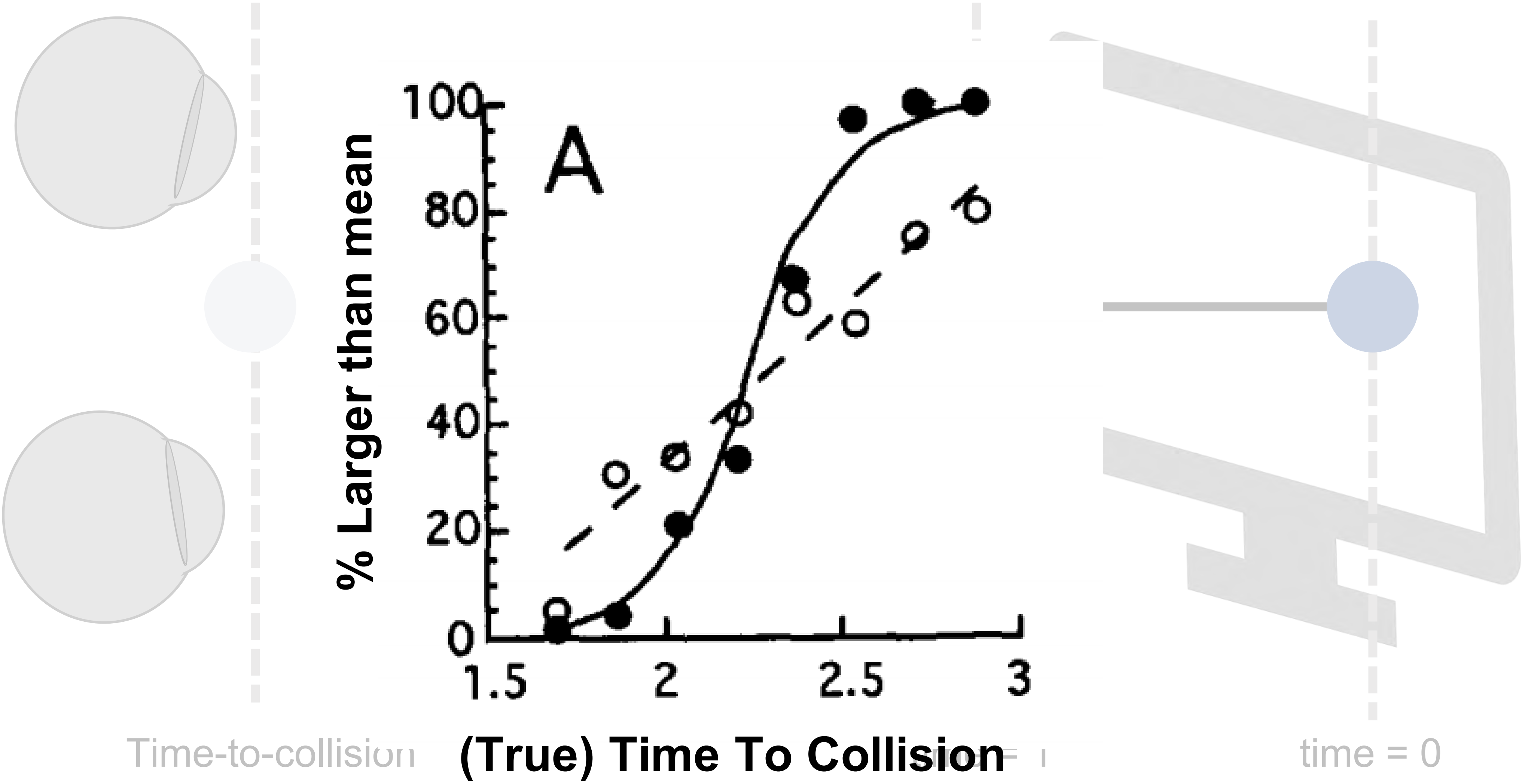
time = 1

time = 0

Gray, Robert, and David Regan. "Accuracy of estimating time to collision using binocular and monocular information." *Vision research* 38.4 (1998): 499-512.

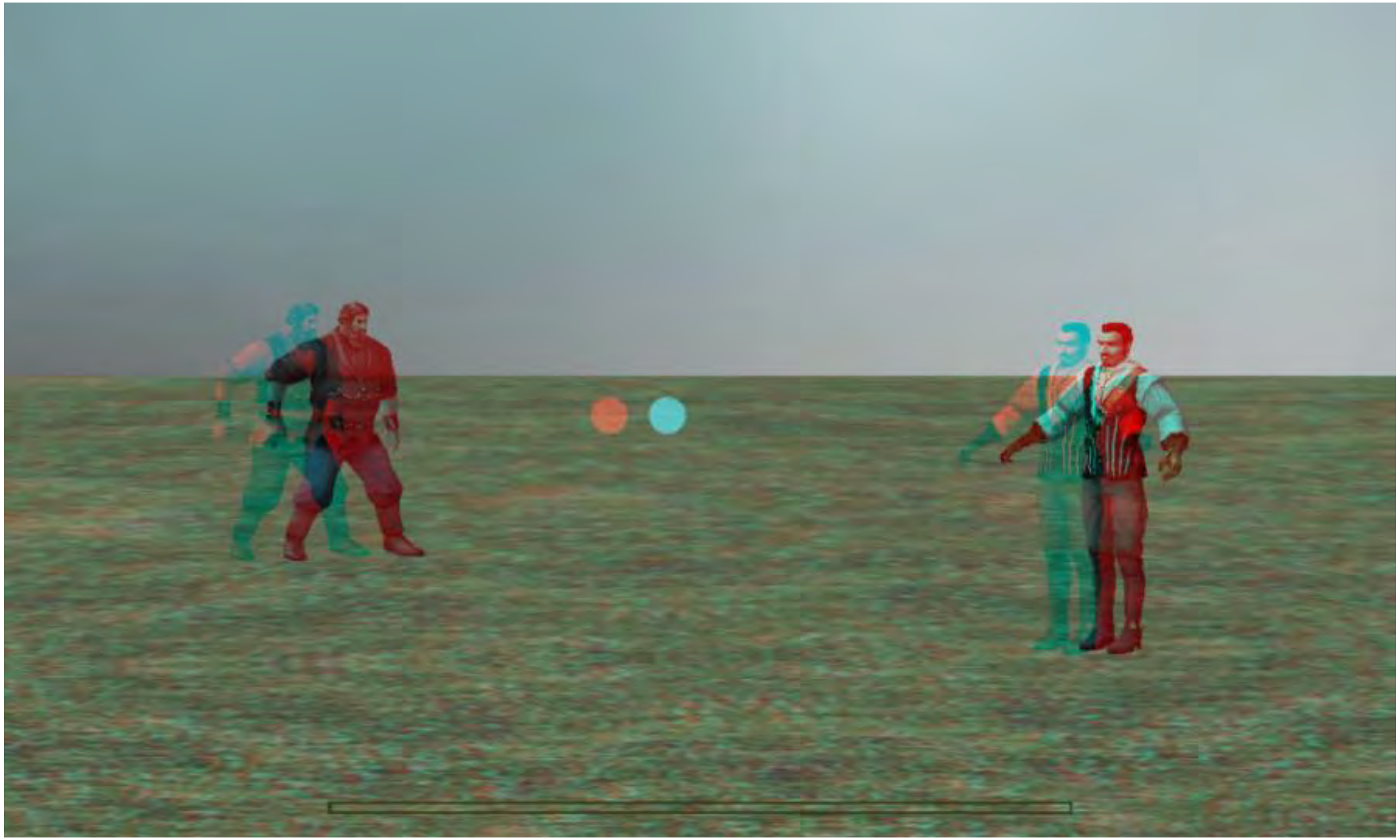
2AFC: TTC larger than mean?

TTC threshold



Gray, Robert, and David Regan. "Accuracy of estimating time to collision using binocular and monocular information." *Vision research* 38.4 (1998): 499-512.

Trajectory estimation



TU Delft Kellnhofer, Petr, et al. "Optimizing disparity for motion in depth." *Computer Graphics Forum*. EGSR 2013.

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Accommodation cue

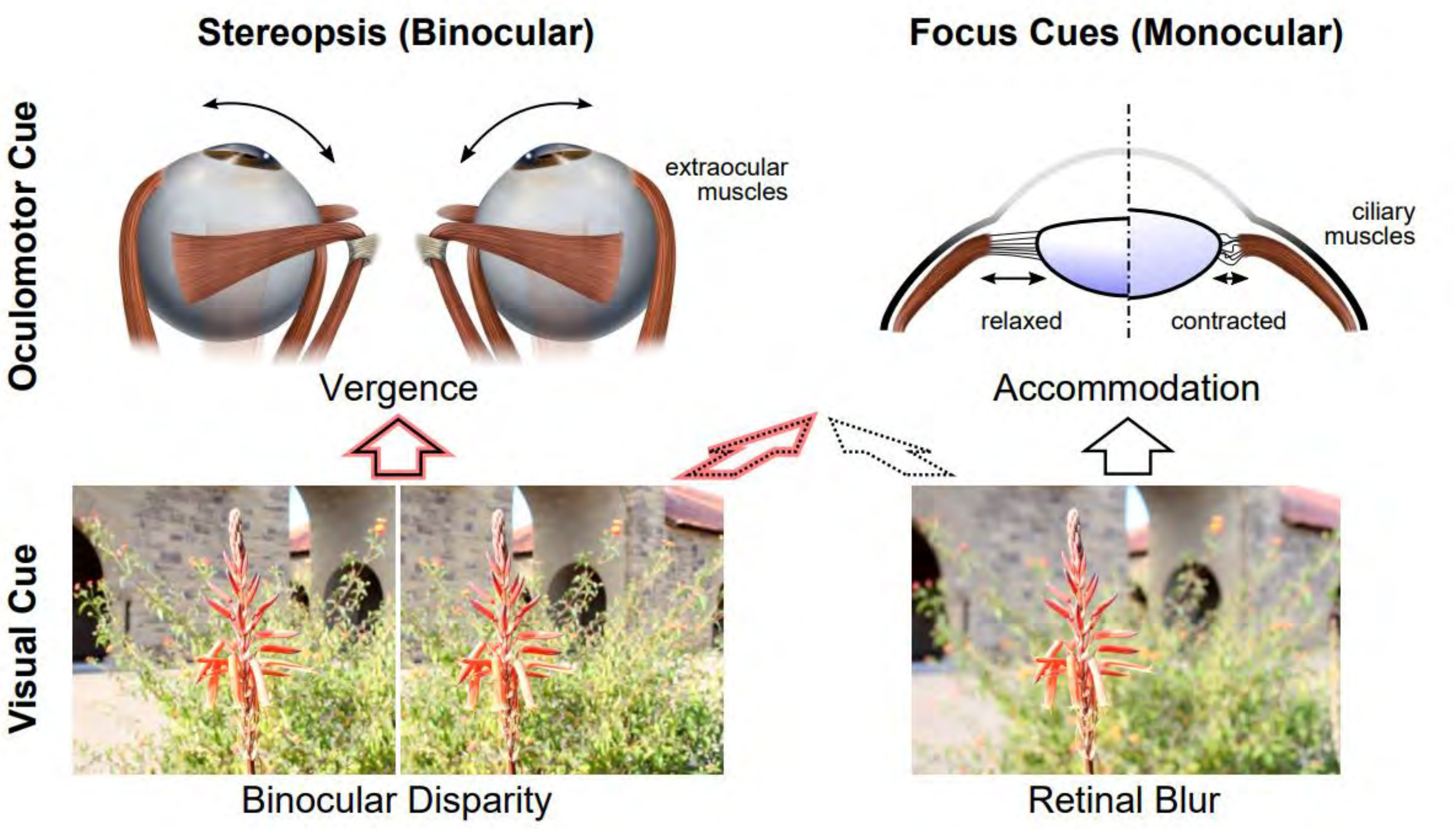
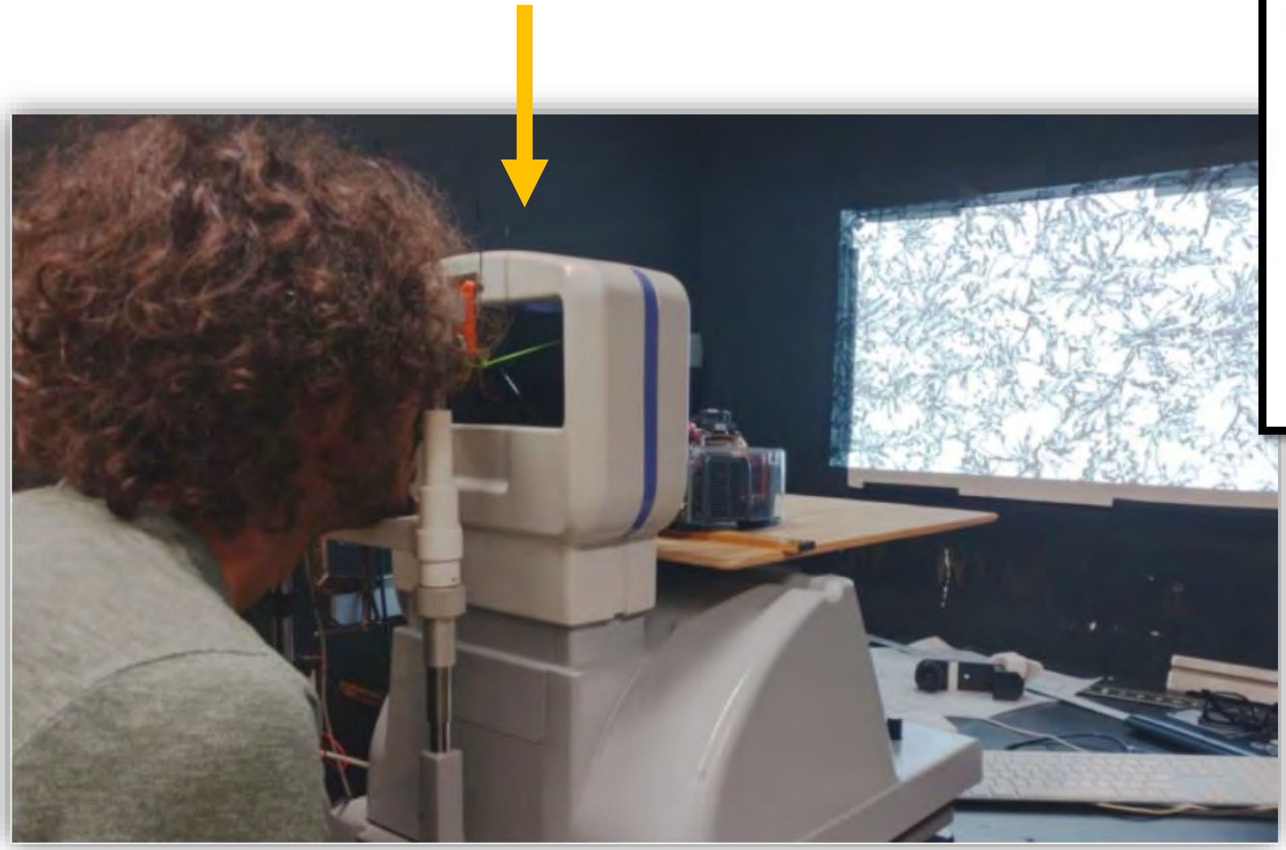
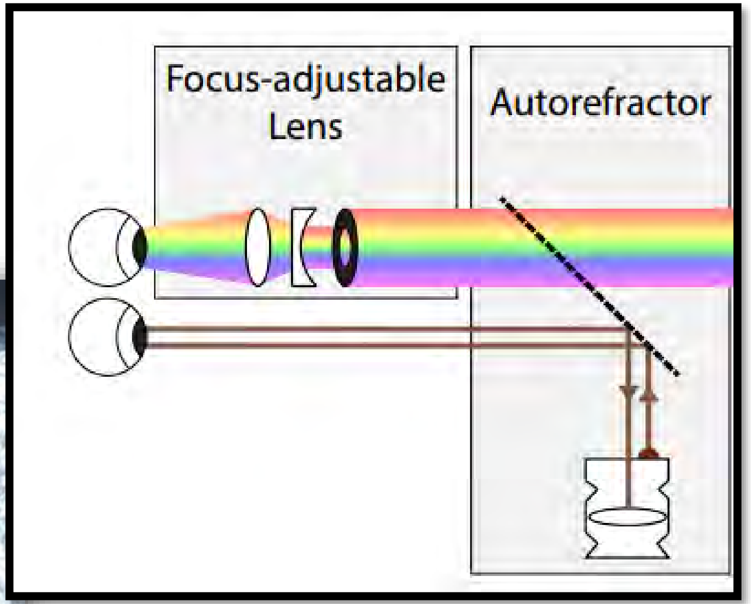


Image credit: Konrad, Robert, et al. "Accommodation-invariant computational near-eye displays." ACM SIGGRAPH 2017.

Measuring accommodation

Possible but costly…





Autorefractor

Measures infrared light reflected from the retina.

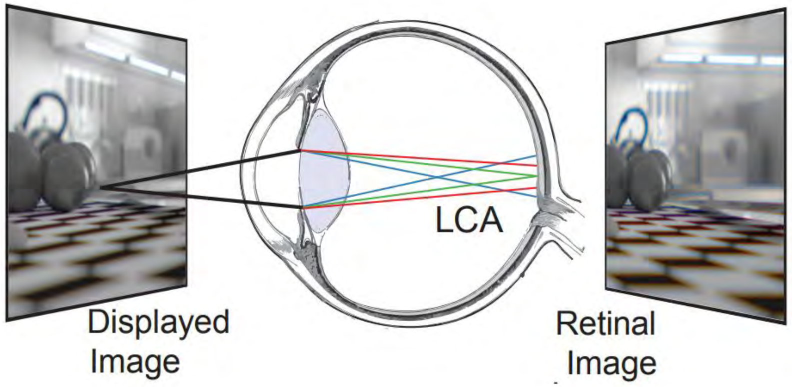
Cholewiak, Steven A., et al. "Chromablur: Rendering chromatic eye aberration improves accommodation and realism." *ACM Transactions on Graphics (TOG)* 36.6 (2017): 1-12.

Accommodation control

- **Software methods**
  - **Depth-of-Field** [1]
  - **Chromatic-aberration** [2]
  - **Remove accommodation cue** [3]
  - … but with a limited effect [4]
- **Hardware methods**
  -> Special displays.

[1]

[2]

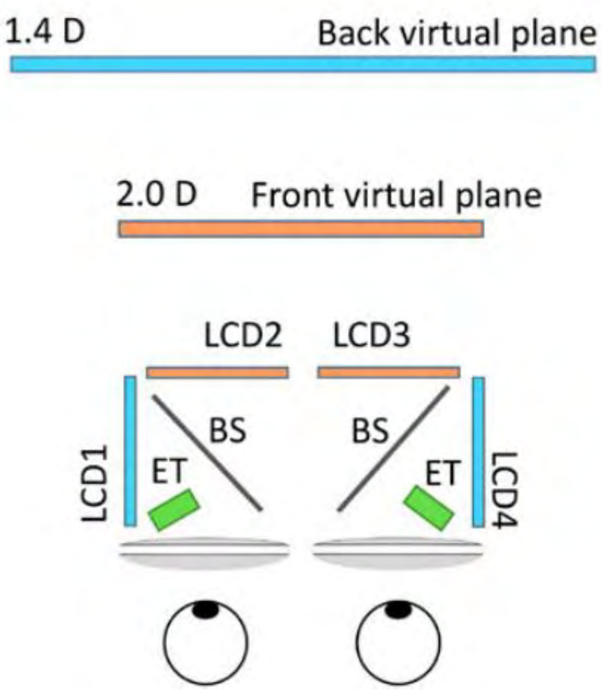


[3]

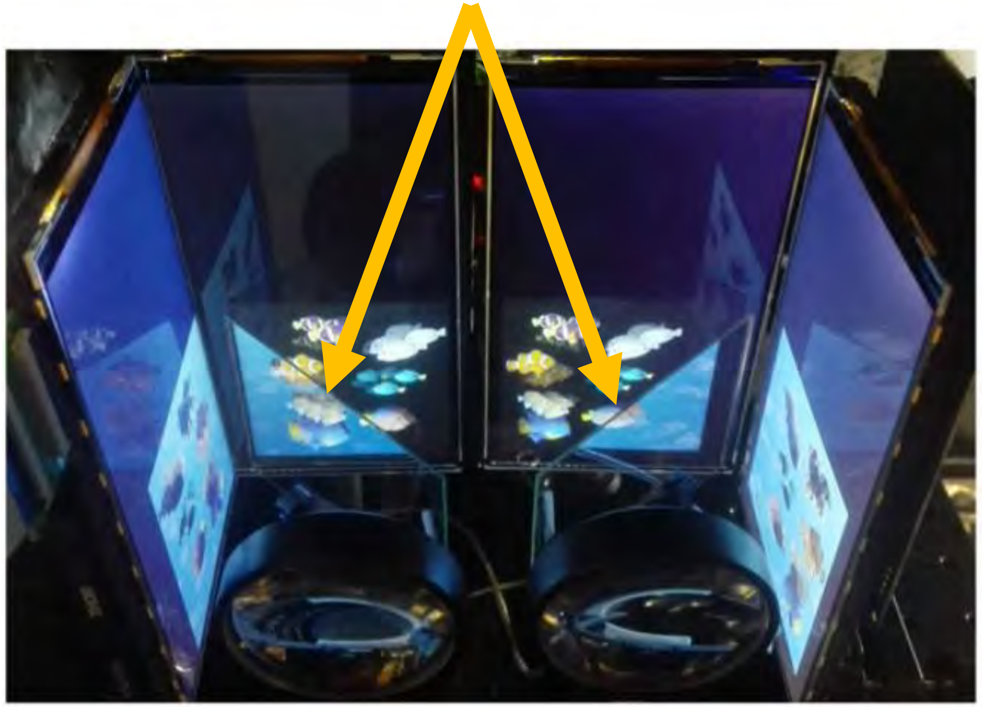
[1] Duchowski, Andrew T., et al. "Reducing visual discomfort of 3D stereoscopic displays with gaze-contingent depth-of-field." ACM SAP 2014.
[2] Cholewiak, Steven A., et al. "Chromablur: Rendering chromatic eye aberration improves accommodation and realism." *ACM SIGGRAPH 2017.*
[3] Konrad, Robert, et al. "Accommodation-invariant computational near-eye displays." ACM SIGGRAPH 2017.
[4] March, Joseph, et al. "Impact of correct and simulated focus cues on perceived realism." ACM SIGGRAPH Asia 2022.

Displays

- Multiplane
  - **Additive**



Beam splitter (Half-mirror)

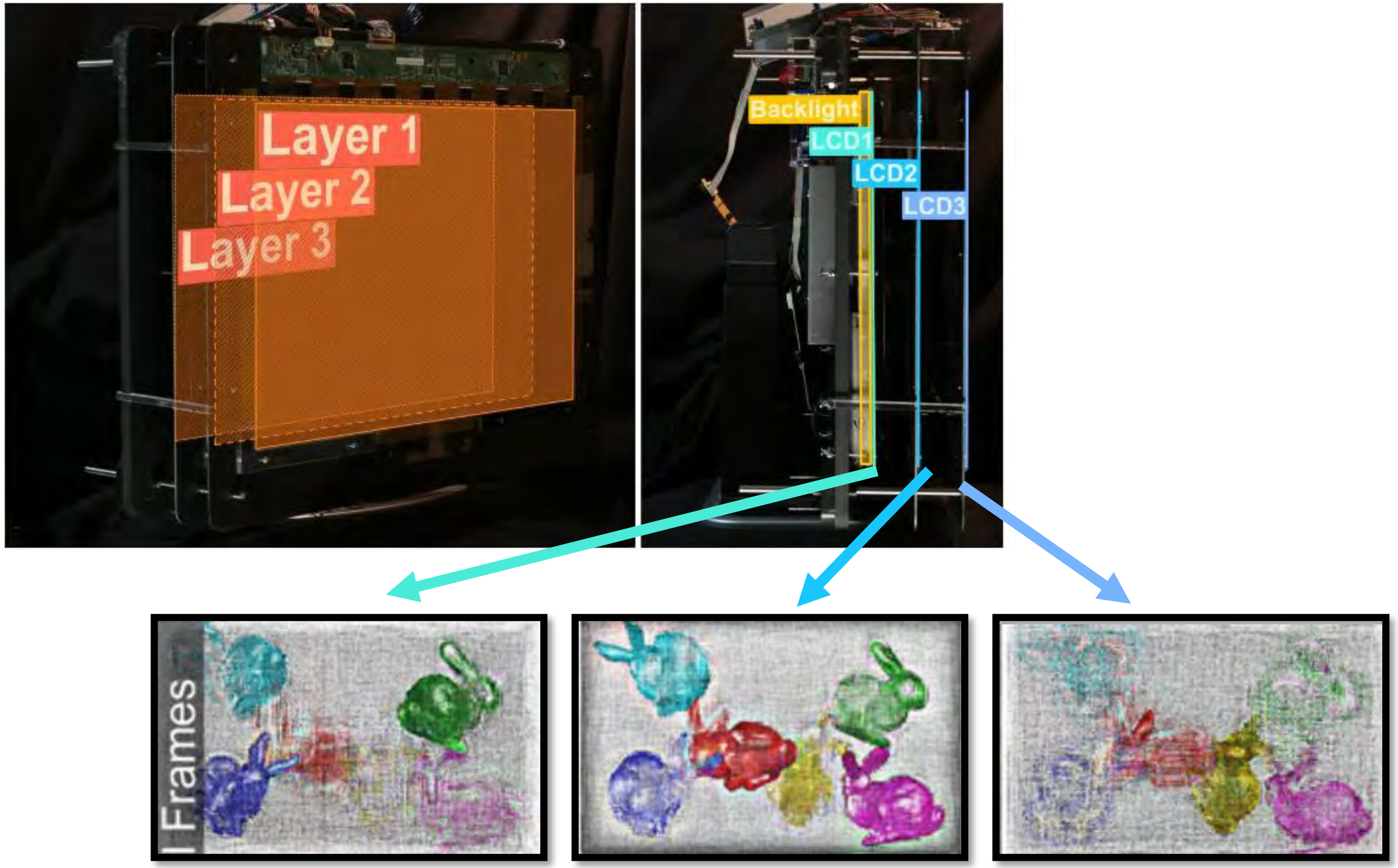


…discrete focal planes.

Matsuda, Nathan, Alexander Fix, and Douglas Lanman. "Focal surface displays." *ACM Transactions on Graphics (TOG)* 36.4 (2017).

Displays

- Multiplane
  - Additive
  - **Multiplicative**



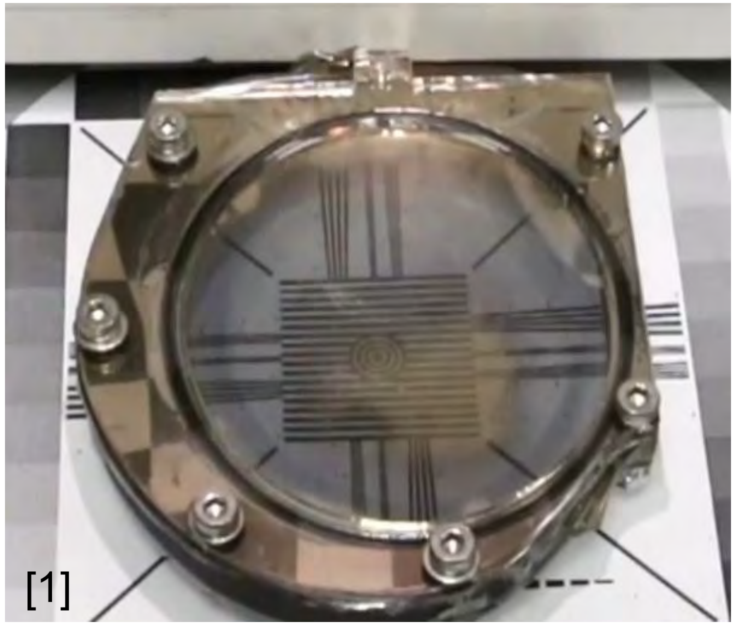
…costly optimization.

- G. Wetzstein, D. Lanman, M. Hirsch, R. Raskar. Tensor Displays: Compressive Light Field Synthesis using Multilayer Displays with Directional Backlighting. SIGGRAPH 2012.
- A. Maimone, G. Wetzstein, D. Lanman, M. Hirsch, R. Raskar, H. Fuchs. Focus 3D: Compressive Accommodation Display. SIGGRAPH 2013.

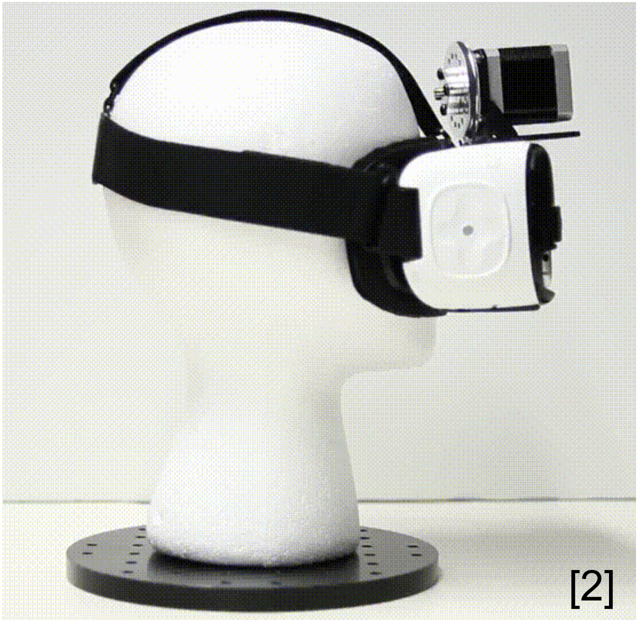
Displays

- Multiplane
  - Additive
  - Multiplicative
- **Varifocal**

Variable lens power



Variable lens offset

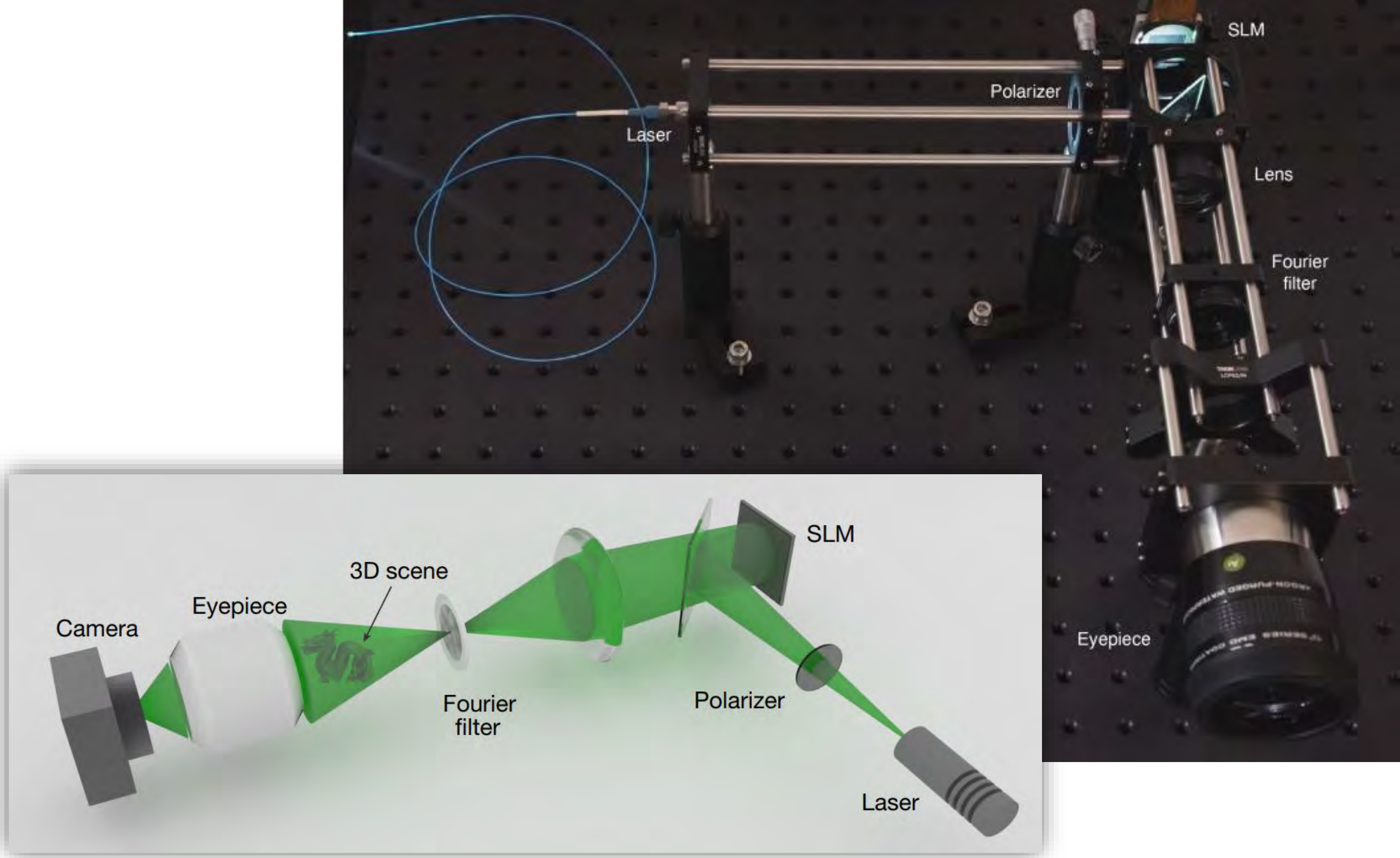


…mechanical parts.

[1] Dunn, David, et al. "Wide field of view varifocal near-eye display using see-through deformable membrane mirrors." IEEE TVCG 2017..
[2] N. Padmanaban et al. “Optimizing virtual reality for all users through gaze-contingent and adaptive focus displays”, Proceedings of the National Academy of Sciences, 2017.

Displays

- Multiplane
  - Additive
  - Multiplicative
- Varifocal
- **Holographic**



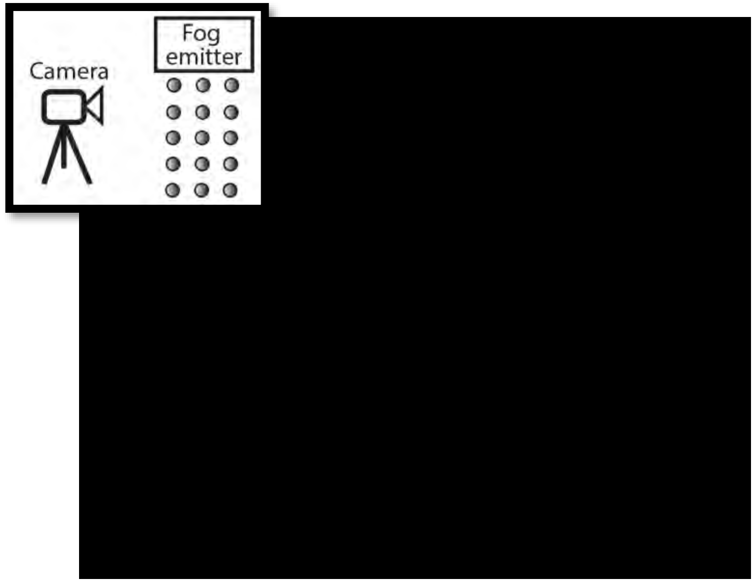
…computation cost and image quality.

Shi, Liang, et al. "Towards real-time photorealistic 3D holography with deep neural networks." Nature 591.7849 (2021).

Displays

- Multiplane
  - Additive
  - Multiplicative
- Varifocal
- Holographic
- **Volumetric**

Participating media



Credit: Tokuda et al. 2017

Volume sweep

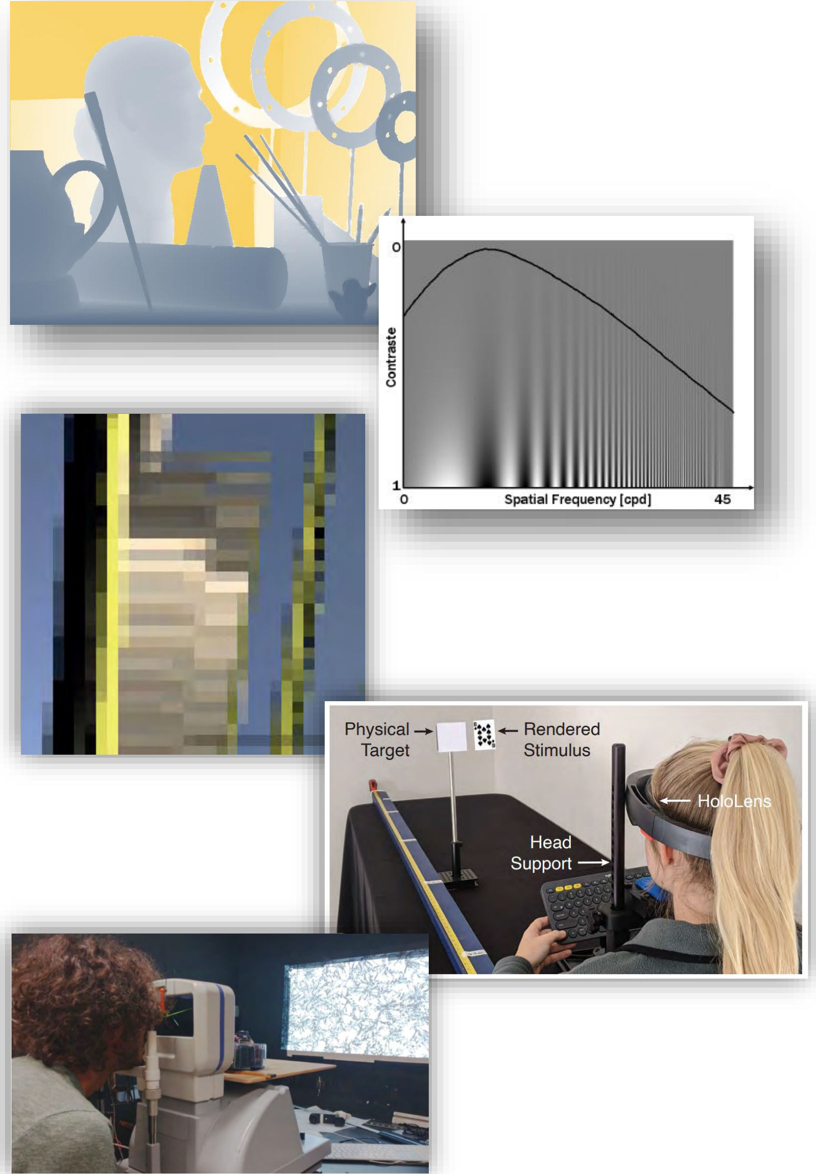
Credit: Voxon Photonics

…lack of occlusions.

Tokuda, Yutaka, et al. "MistForm: Adaptive shape changing fog screens." CHI 2017.

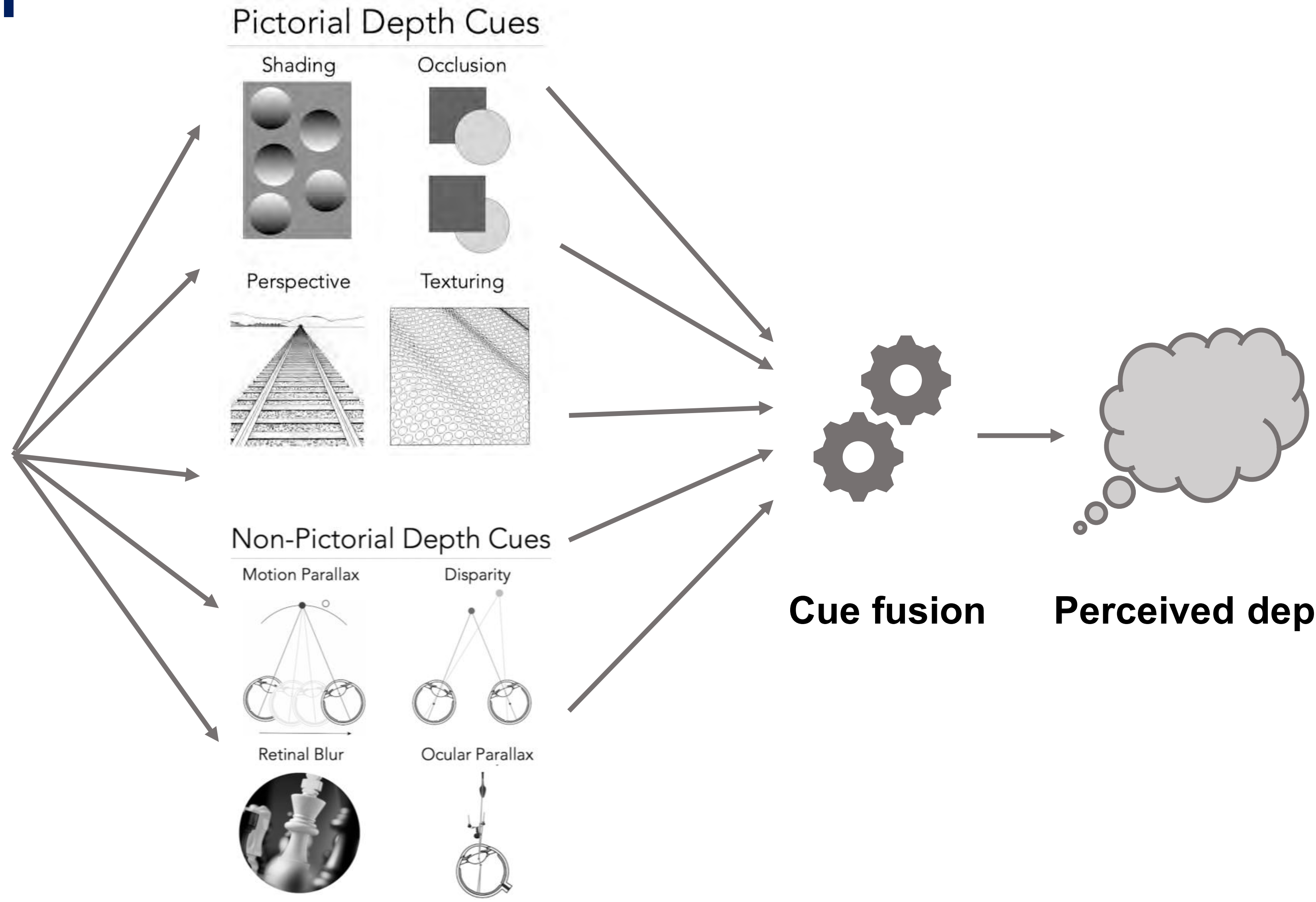
Summary

- **Binocular vision**
- **Depth sensitivity**
- **Subjective qualities**
- **Task performance**
- **Accommodation**



“Dream model”

Credit: Sachin C Nair @ pexels.com

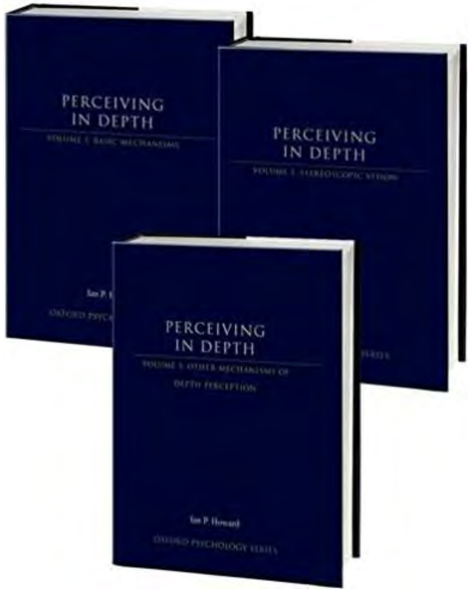


Cue extraction

Cue fusion

Perceived depth

Seeing in Depth



…in more depth

Howard, I. P., & Rogers, B. J. (2002).
Seeing in depth.
University of Toronto Press.

Thank you for your attention!

Petr Kellnhofer

- https://kellnhofer.xyz

TU Delft

Overview

Good practices for user studies

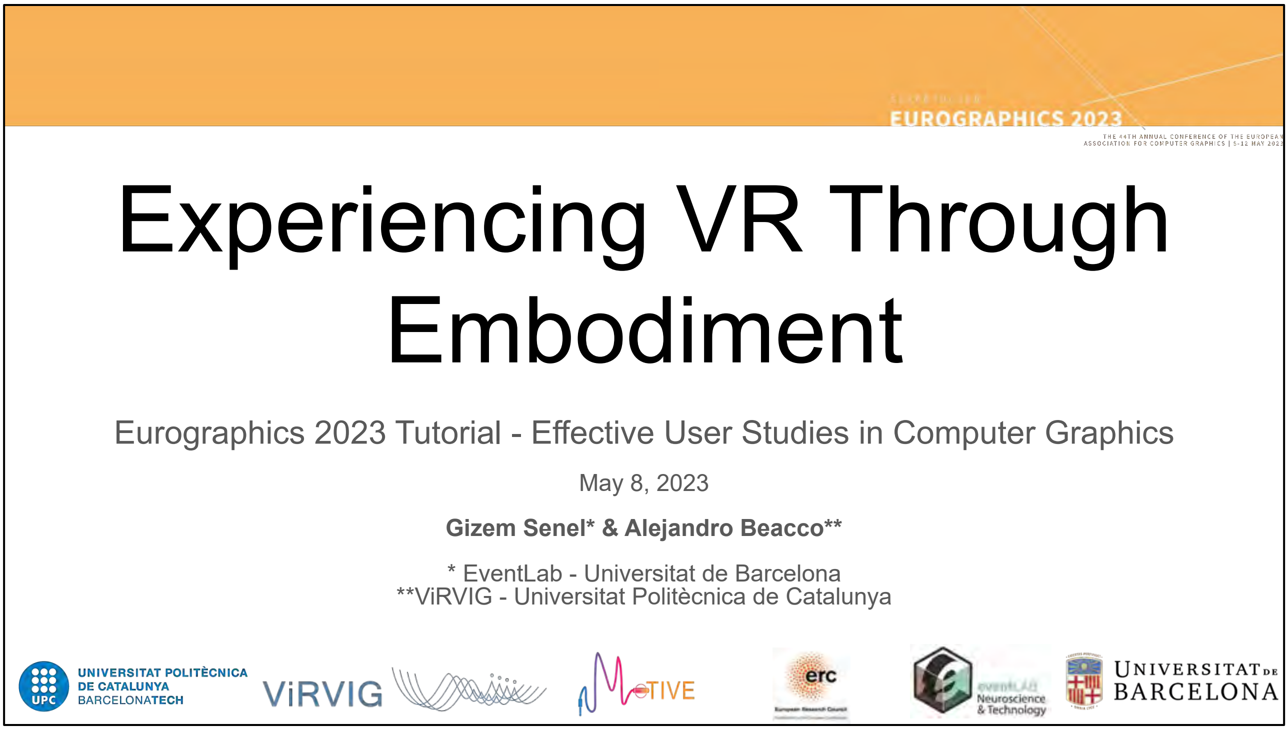
Experiencing virtual reality through embodiment

Developing computational models with mathematical and neurological insights

Virtual characters

Seeing in depth

Audio in virtual reality



EUROGRAPHICS 2023

THE 44TH ANNUAL CONFERENCE OF THE EUROPEAN
ASSOCIATION FOR COMPUTER GRAPHICS | 8-12 MAY 2023

Experiencing VR Through Embodiment

Eurographics 2023 Tutorial - Effective User Studies in Computer Graphics

May 8, 2023

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* EventLab - Universitat de Barcelona
**ViRVIG - Universitat Politècnica de Catalunya

This session of the tutorial series is about how to achieve “Effective User Studies” when “Experiencing Virtual Reality Through Embodiment”.
This talk is part of the work done in the EventLab, which is lead by Mel Slater at Universitat de Barcelona, and it is also part of the European Research Council project called Motive.

Outline

1. Introduction
2. The Illusions of VR
3. An Embodiment Open Source Library for Unity
4. Measuring Presence
5. Open Questions
6. Conclusions

Slater et al (2022). A Separate Reality: An Update on Place Illusion and Plausibility in Virtual Reality. Frontiers in Virtual Reality, 81

So, this is the outline of the presentation.
I will first give you an introduction about how virtual reality can be experienced either from 360 videos or real time 3D rendered environments
Secondly, I will describe what we call the illusions of VR, which concepts like presence or body ownership introduced through several examples.
Thirdly, I'll give you a quick overview of an open source library that easily allows conducting embodiment experiments with Unity.
Then I will review different methods of measuring presence, showing the particularities and difficulties of each one of them.
And finally, I will try to answer to some related open questions and give our conclusions.

Just as a quick note, I want to say that most of the things I will be saying today come from this paper we published last year:
M Slater, D Banakou, A Beacco, J Gallego, F Macia-Varela, R Oliva. (2022) A Separate Reality: An Update on Place Illusion and Plausibility in Virtual Reality. Frontiers in Virtual Reality, 81

1. Introduction

Let’s begin with the introduction then.

Up until now, in this tutorial series about user studies with a focus in VR, you must have seen different “types of methodologies” (Sandra should have talked to you about this).

You should also have seen “computational models with mathematical and neurological insights” by Qi Sun.

And Petr should have explained to you how we are able to properly see content in depth.

What I want to talk now first is about how there are different approaches when it comes to how we can experience virtual reality…

1. Introduction - 360º Videos

https://vr.youtube.com/

We can experience virtual reality from 360 degrees images or videos, which can be stereoscopic or not, and sometimes the video can be recorded from a first person perspective.
In any of those cases, using some head rotational tracking you can change your point of view by just turning your head, and if you look down you might see a body.
Although some technologies are starting to let you add a little bit of parallax effect and move the head with positional tracking, this is limited and you are tight to a fixed position, the one from which the video was recorded.

1. Introduction - 3D Interactive content

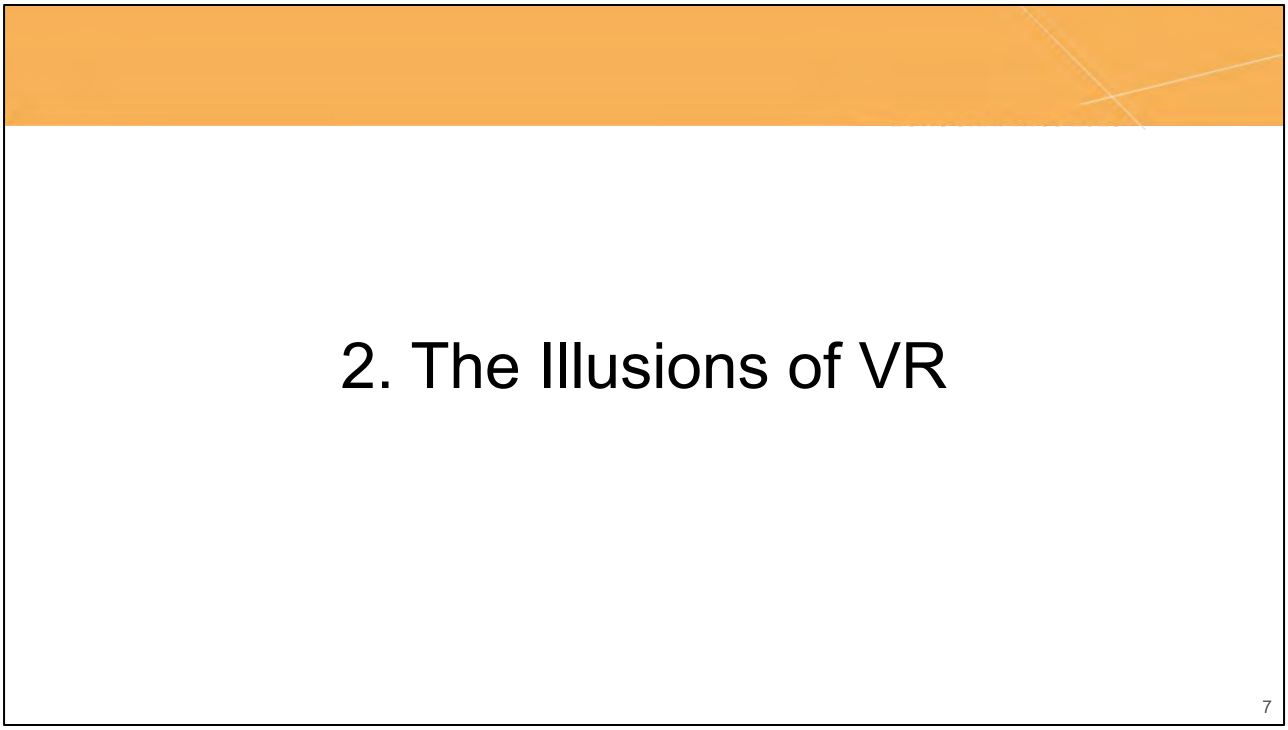
Sony Interactive Entertainment - Horizon: Call of the Mountain

The other big trend is then to use real-time 3D rendered environments.
In these, you can freely move around, change your position and point of view, as the scene is continually rendered from a different perspective.
This allows for higher levels of interaction and immersion.
But in many applications, like almost every video game released out there, when you look down you only have some floating hands and nobody at all to look at.

1. Introduction - Embodiment

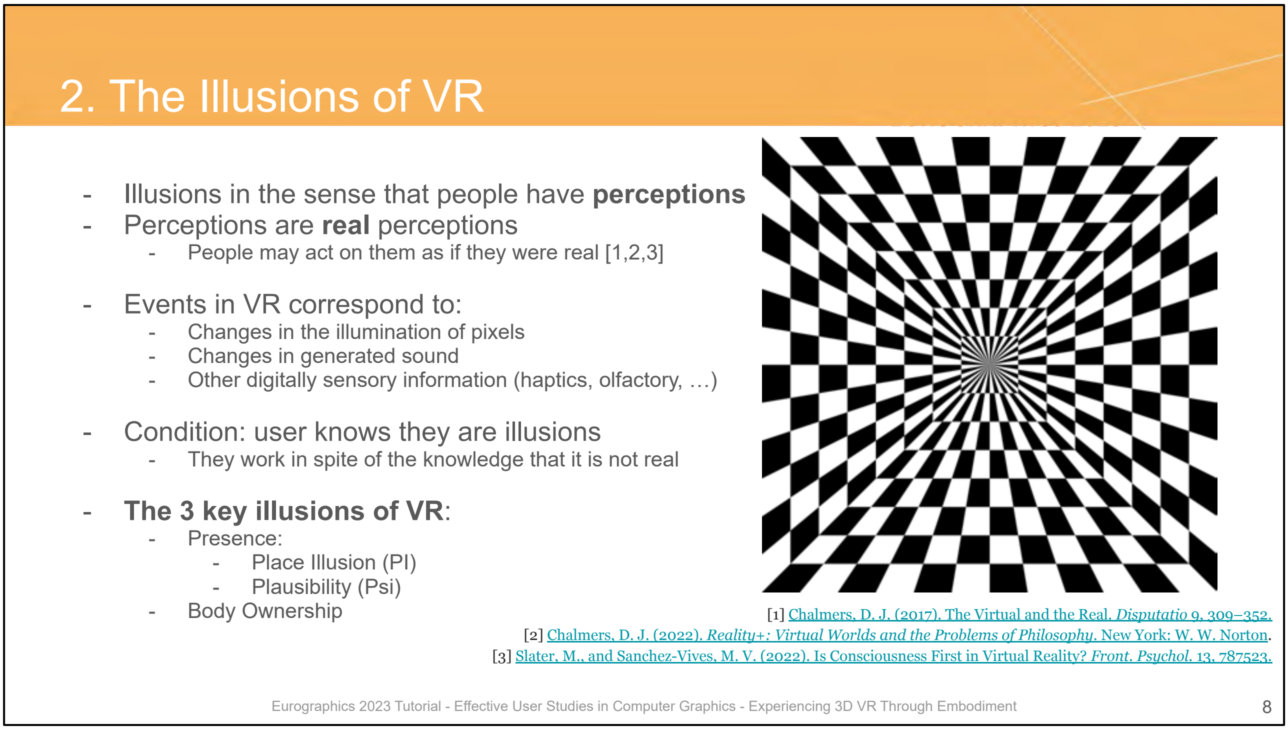
[Video]

Later, Rachel McDonnell will talk to you about how we interact with virtual characters.
But what I want to focus here on is on how we can have more than just floating hands.
In VR we can have a different self-representation, our virtual avatar that can be anyone we can imagine.
And whenever we combine this with multisensory integration of different tracking capabilities we achieve what we call "embodiment".
Here, for example, we are embodied as Mark Knopfler from the Dire Straits and experiencing a virtual concert as being him.



2. The Illusions of VR

Let’s then talk about the illusions of VR.



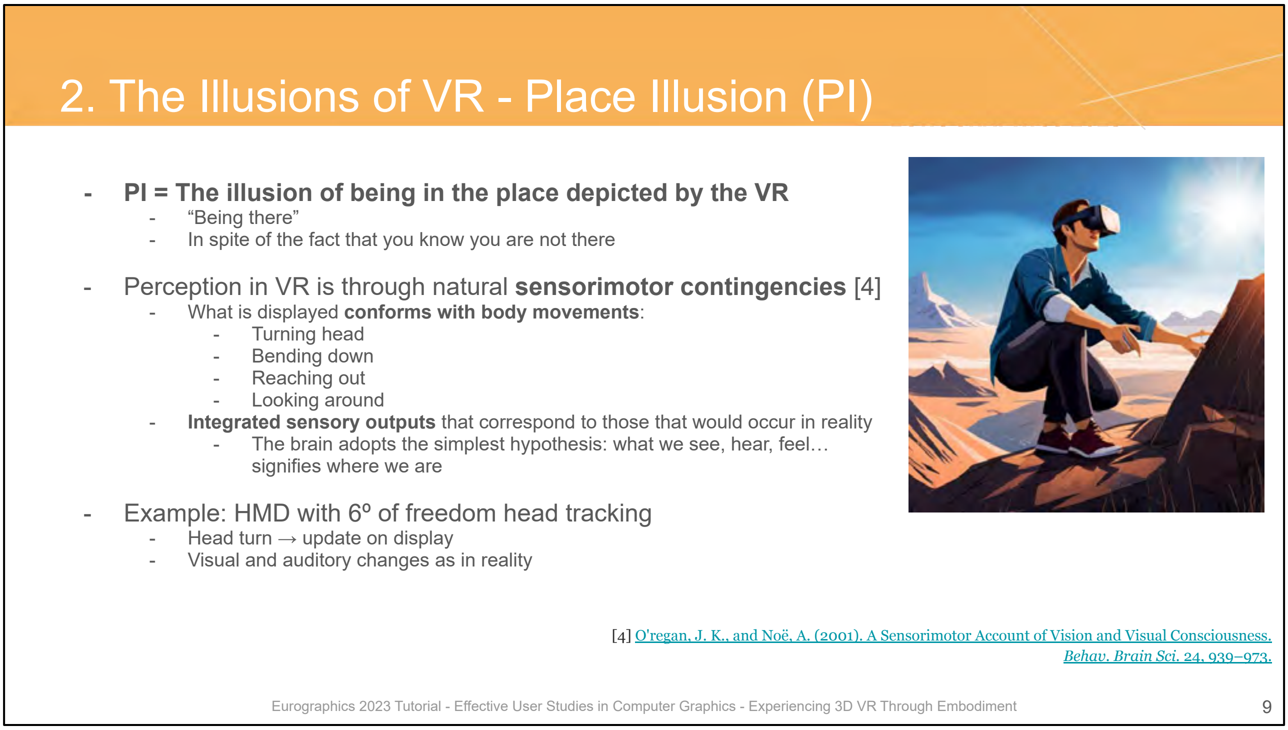
2. The Illusions of VR

- Illusions in the sense that people have **perceptions**
- Perceptions are **real** perceptions
    - People may act on them as if they were real [1,2,3]
- Events in VR correspond to:
    - Changes in the illumination of pixels
    - Changes in generated sound
    - Other digitally sensory information (haptics, olfactory, …)
- Condition: user knows they are illusions
    - They work in spite of the knowledge that it is not real
- **The 3 key illusions of VR**:
    - Presence:
        - Place Illusion (PI)
        - Plausibility (Psi)
    - Body Ownership

[1] Chalmers, D. J. (2017). The Virtual and the Real. *Disputatio* 9, 309–352.
[2] Chalmers, D. J. (2022). *Reality+: Virtual Worlds and the Problems of Philosophy*. New York: W. W. Norton.
[3] Slater, M., and Sanchez-Vives, M. V. (2022). Is Consciousness First in Virtual Reality? *Front. Psychol.* 13, 787523.

We talk about illusions in the sense that people have perceptions.
If this perceptions come from digital sources we can say they come from a different reality.
But perceptions are always real perceptions and people may react to them as if what they perceive was real.
Then, the events in VR correspond to changes in how the pixels of the HMD are illuminated, changes in the sound that is generated, or changes in any other digital source such as haptics.
The main condition here is that, whoever is inside the VR, knows that they are illusions.
The illusions work in spite knowing that they are not real.

So, there are 3 key illusions we consider in VR: “place illusion” and “plausibility”, which conform what we call “presence”. And “body ownership”.
Let’s see these and a few other concepts…



2. The Illusions of VR - Place Illusion (PI)

- **PI = The illusion of being in the place depicted by the VR**
  - “Being there”
  - In spite of the fact that you know you are not there
- Perception in VR is through natural **sensorimotor contingencies** [4]
  - What is displayed **conforms with body movements**:
    - Turning head
    - Bending down
    - Reaching out
    - Looking around
  - **Integrated sensory outputs** that correspond to those that would occur in reality
    - The brain adopts the simplest hypothesis: what we see, hear, feel… signifies where we are
- Example: HMD with 6º of freedom head tracking
  - Head turn → update on display
  - Visual and auditory changes as in reality

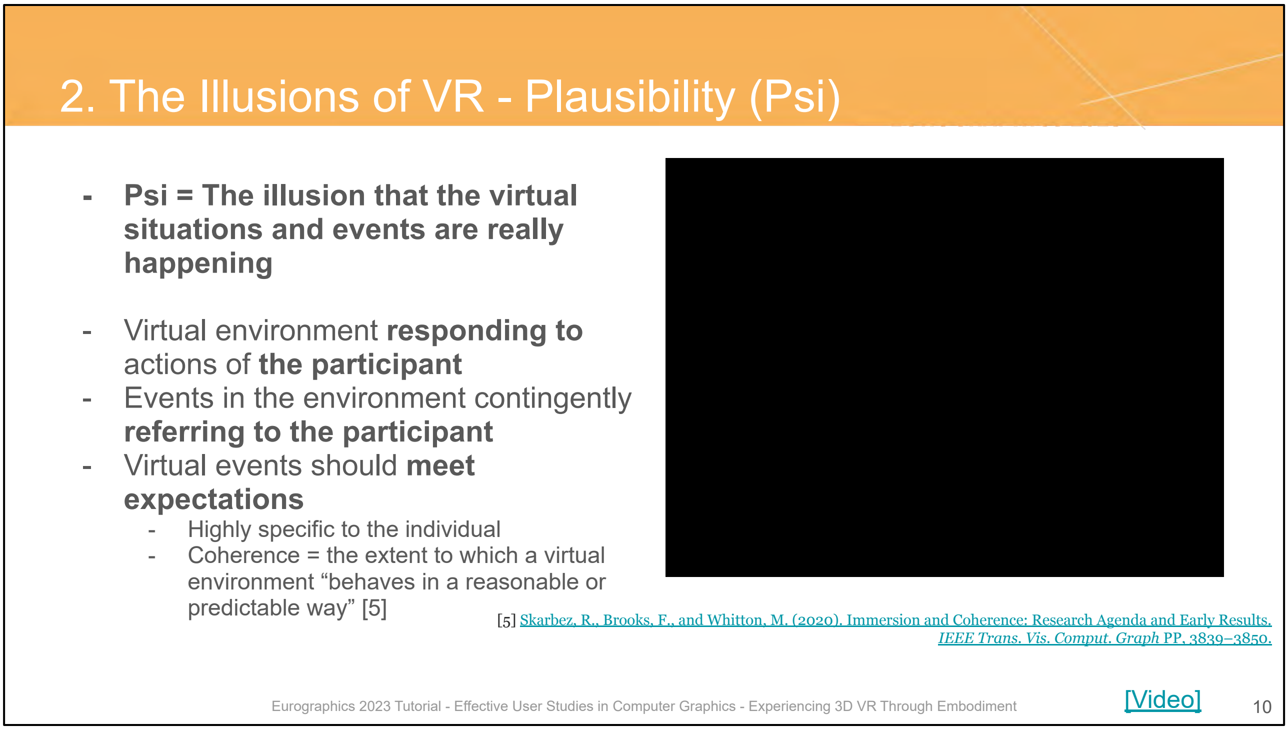
[4] O'regan, J. K., and Noë, A. (2001). A Sensorimotor Account of Vision and Visual Consciousness. *Behav. Brain Sci.* 24, 939–973.

Place Illusion is “the illusion of being in the place depicted by the VR”, “being there”, even if you know that you are not there.

In our whole lives, we perceive things using our bodies, whenever we turn our head, our visual images change in a predictable way.
That determines the probability for our sense of place, the probability that I am in the place I see, hear and touch.

In VR, we also perceive things through natural sensorimotor contingencies, following much the same rules as in the physical reality.
What appears in the screen conforms with our movements when turning our head, bending down, reaching out, looking around, etc.
And when the integrated sensory outputs correspond to those that we would experience in reality, our brain adopts the simple hypothesis: what we see, hear, feel… signifies where we are.

This is why Place Illusion, in the sense we are describing here, cannot be experienced with a desktop screen, because when we turn our head away, we see a different reality.



2. The Illusions of VR - Plausibility (Psi)

- **Psi = The illusion that the virtual situations and events are really happening**

- Virtual environment **responding to** actions of **the participant**
- Events in the environment contingently **referring to the participant**
- Virtual events should **meet expectations**
    - Highly specific to the individual
    - Coherence = the extent to which a virtual environment “behaves in a reasonable or predictable way” [5]

[5] Skarbez, R., Brooks, F., and Whitton, M. (2020). Immersion and Coherence: Research Agenda and Early Results. *IEEE Trans. Vis. Comput. Graph* PP, 3839–3850.

[Video]

Now, Plausibility is “the illusion that the situations and events that are happening in the virtual world are really happening”.

Therefore, a virtual environment will be plausible if it responds to the actions of the participant like having a virtual character looking back at you.
It will be plausible if the virtual events make references to the participant, like another virtual character suddenly smiling at you.
And it will be plausible if you are simulating a situation in which the participant has the expertise and that simulation meets his expectations.
But this is mainly subjective and highly specific each person.
Plausibility also relates to the concept of “coherence” introduced by Skarbez et al..
Coherence could be defined as the extent to which a virtual environment “behaves in a reasonable or predictable way”.
But it’s a slightly different thing that we won’t be exploring today.

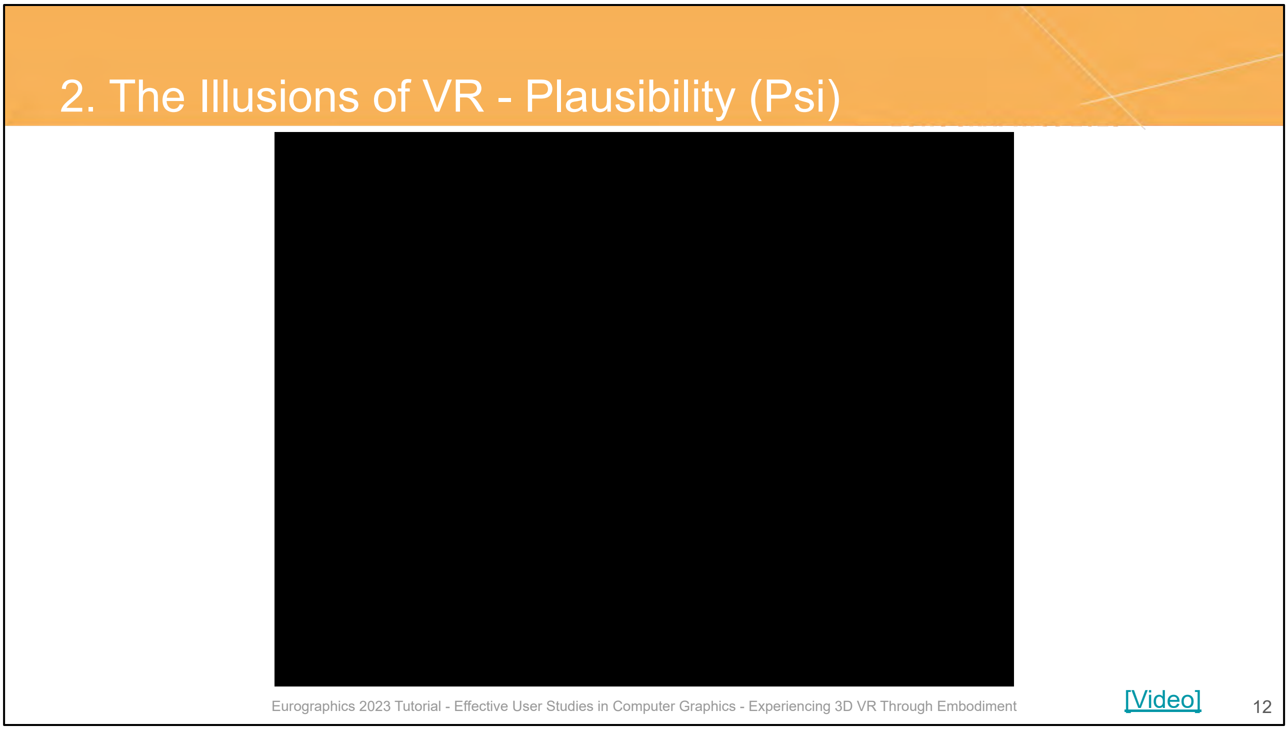
2. The Illusions of VR - Plausibility (Psi)

- **Example:** An experiment with medical doctors illustrated **failure of Plausibility**
  - Doctor interacts with patients who unreasonably demand antibiotics
  - A failure of plausibility - **computer on their desk could not be used.**

[6] Pan, X., Slater, M., Beacco, A., Navarro, X., Bellido Rivas, A. I., Swapp, D., et al. (2016). The Responses of Medical General Practitioners to Unreasonable Patient Demand for Antibiotics - A Study of Medical Ethics Using Immersive Virtual Reality. *PLoS ONE* 11

To better understand what Plausibility refers to, here is an example illustrating its failure.
In this study, medical doctors were interacting in VR with virtual patients demanding for antibiotics.
Ignoring what the study was about… what I want to tell you is that many of the participating doctors complained that they were not able to use the computer on their virtual desk, as that is what they would typically do in reality.
So, as you can see, plausibility is an exceedingly complex topic.

But plausibility does not mean necessarily ‘realistic’, these are not equivalent terms at all.



2. The Illusions of VR - Plausibility (Psi)

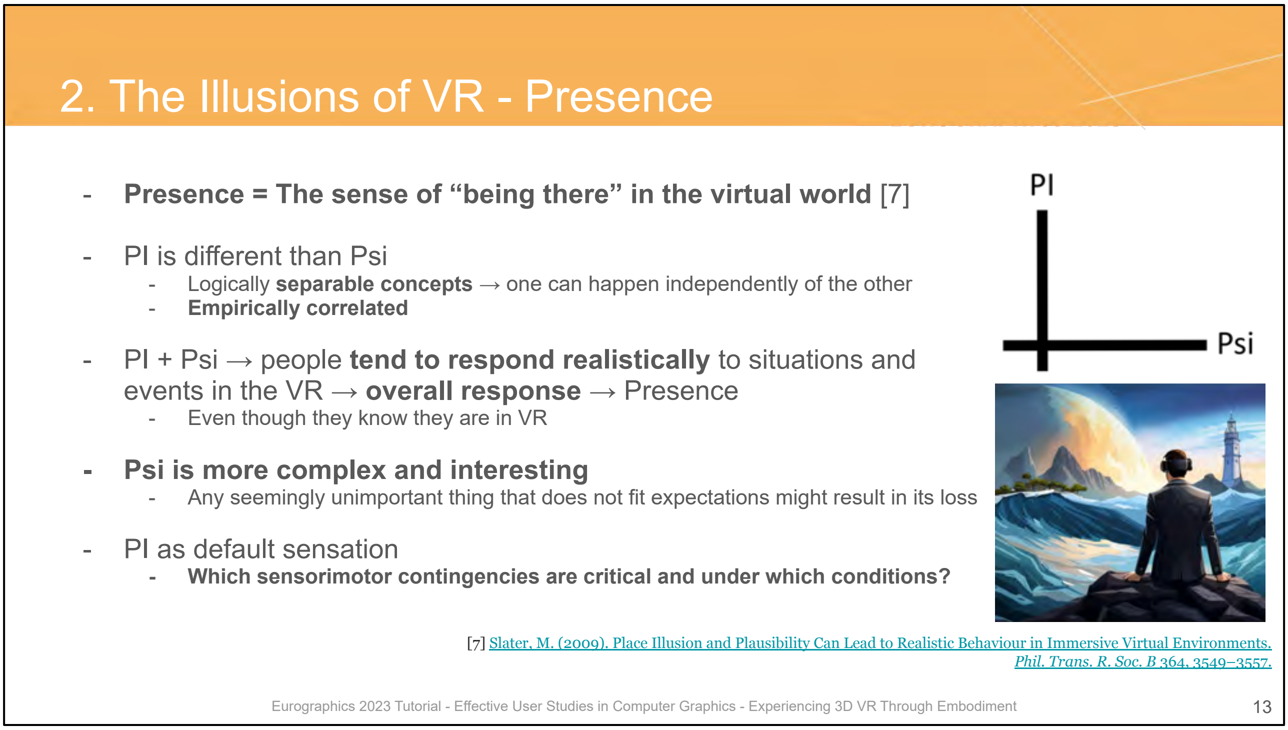
[Video]

For example in this virtual environment taken from a cognitive behavioural therapy for people with a fear of heights, a big “flying” whale appeared between the buildings.

But participants simply accepted this without comments nor failure of plausibility.

Or in a virtual chess game, when making a move the pieces where “flying” automatically to the selected spot, but this was not found to be odd.

Participants were stating that “in this world that is the way things are”.



2. The Illusions of VR - Presence

- **Presence = The sense of “being there” in the virtual world** [7]
- PI is different than Psi
  - Logically **separable concepts** → one can happen independently of the other
  - **Empirically correlated**
- PI + Psi → people **tend to respond realistically** to situations and events in the VR → **overall response** → Presence
  - Even though they know they are in VR
- **Psi is more complex and interesting**
  - Any seemingly unimportant thing that does not fit expectations might result in its loss
- PI as default sensation
  - **Which sensorimotor contingencies are critical and under which conditions?**

[7] Slater, M. (2009). Place Illusion and Plausibility Can Lead to Realistic Behaviour in Immersive Virtual Environments. *Phil. Trans. R. Soc. B 364, 3549–3557.*

We have defined Place illusion and Plausibility.
These are two orthogonal axes that conform the overall response that we call like that, presence, which is “the sense of ‘being there’ in the virtual world”.

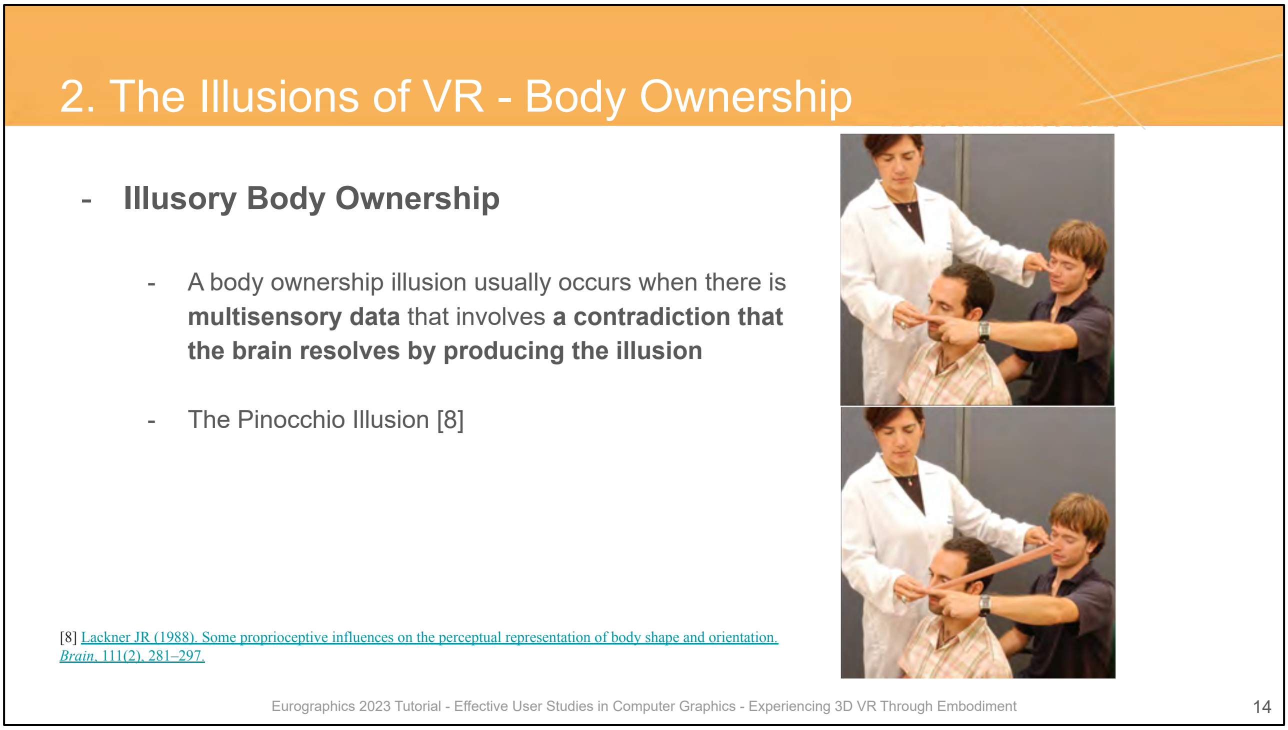
But place illusion and plausibility are different, they are logically separable concepts, since one could happen without the other.
For example you could experience a strong place illusion in a virtual world but the virtual characters could not respond to your actions.
Or the opposite, you could be interacting with a virtual character that seems very real, but do it on a desktop setup…
And although place illusion and plausibility can be correlated empirically, they have been found to be different.

When we experience both place illusion and plausibility at the same time, people tend to respond realistically to what happens in the virtual reality.
And remember they still know that they are in VR and that things are not really happening.

After many years of research, from our point of view, Plausibility seems to be more complex and interesting than Place Illusion, since any small detail can make it fail.
A typical VR setup with an HMD, head-tracking and stereo, provides place illusion as

a default sensation.

So a major question for future research will be to find which sensorimotor contingencies are critical and under which conditions.



2. The Illusions of VR - Body Ownership

- **Illusory Body Ownership**
  - A body ownership illusion usually occurs when there is **multisensory data** that involves **a contradiction that the brain resolves by producing the illusion**
  - The Pinocchio Illusion [8]

[8] Lackner JR (1988). Some proprioceptive influences on the perceptual representation of body shape and orientation. *Brain*, 111(2), 281–297.

The third main illusion of VR is illusory body ownership.

That is an illusion that happens when there is multisensory data related to your body that involves a contradiction.
The brain then resolves that by producing the illusion itself.
Take the famous Pinocchio Illusion as an example.
In here the participant is guided by the experimenter to touch the nose of someone else while the experimenter is also touching the participant’s actual nose.
This proprioception illusion is resolved by the brain giving the sense of having the nose growing longer, as happened to Pinocchio when he told a lie.

2. The Illusions of VR - Body Ownership

- **Illusory Body Ownership = The illusion that the virtual body is their own**
  - A life-sized virtual body
  - First person perspective (1PP)
  - Real-time body tracking
    - **Visuomotor synchrony**
    - Visuotactile synchrony

- **Embodiment = The process of replacing a person's body by a virtual one**

[Video]

So, when using an HMD, if we have a first person perspective, if we look towards ourselves and see a life-sized virtual body replacing our own, and if we have a real-time body tracking so that when we move the virtual body moves synchronously and in correspondence with our own movements, we then have a body ownership illusion.
That is "the illusion that the virtual body is our own", again despite knowing that it is not, and even if the virtual body is not similar at all to us.
This involves a multisensory integration of the first person perspective view of the body plus the visuomotor or visuotactile synchrony.
Then, what we call "embodiment" is the actual process of replacing a person's body by a virtual one.

2. The Illusions of VR - Body Ownership

Based on Rubber Hand Illusion [9]

[9] Botvinick, M., and Cohen, J. (1998). Rubber Hands 'feel' Touch that Eyes See. *Nature* 391, 756.

[Video]

All this is also based on the famous Rubber Hand Illusion experiment which you all might know by now.

In this classic and very simple experiment, the participant sits by a table onto which a rubber hand is placed in an anatomical plausible position, more or less parallel to his real hand.

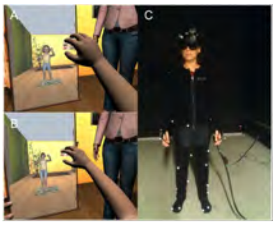
While the real hand is hidden, the experimenter taps and strokes the rubber hand and the real hand synchronously.

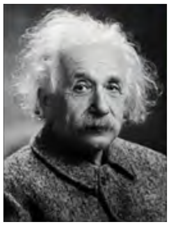
The brain resolves this conflict by creating the illusion of owning the rubber hand.

2. The Illusions of VR - Body Ownership

- Ownership over a virtual body has been **demonstrated multiple times**
- Moreover, changing the type of body can lead to:
  - Physiological
  - Behavioural
  - Attitudinal
  - Cognitive

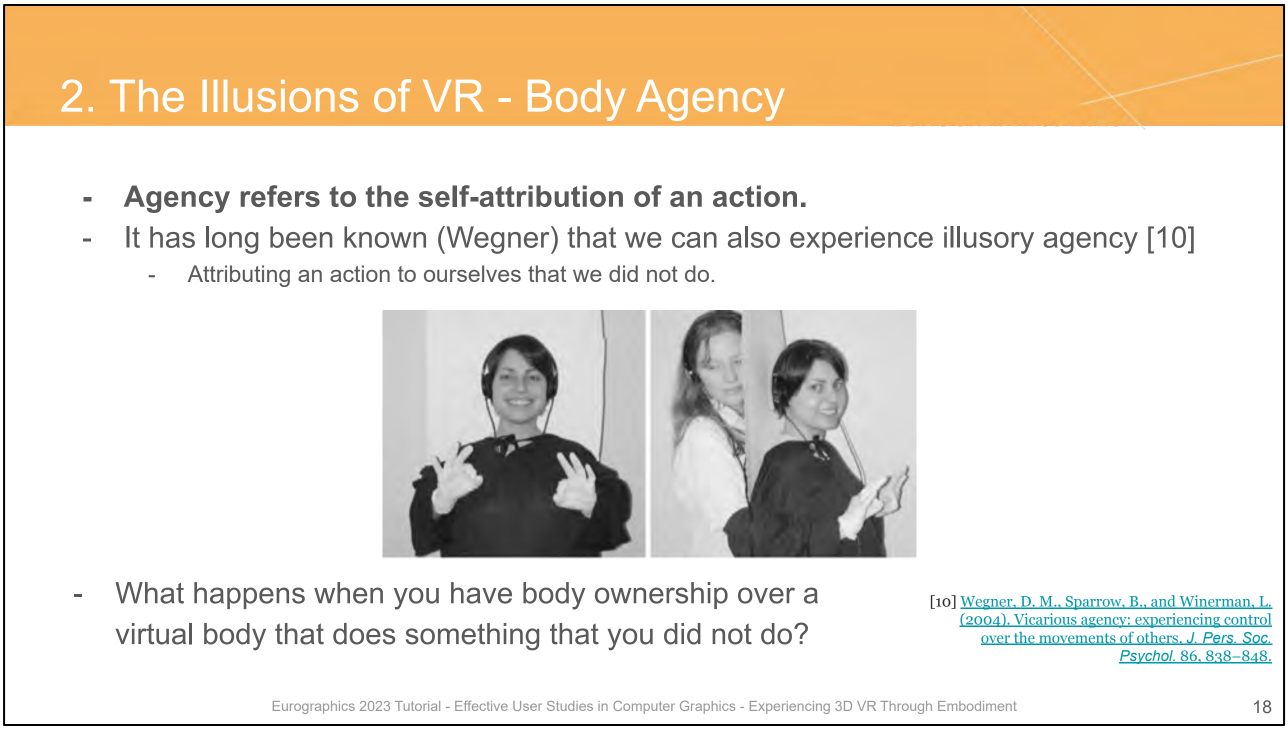
  … changes in the participant





Banakou, Groten, Slater (2013) PNAS
Peck, Seinfeld, Aglioti, Slater (2013) Consc. & Cogn
Maister, Slater, Sanchez-Vives, Tsakiris (2015) TiCS
Matamala et al (2019) Journal of Pain
Banakou et al (2020) J Royal Soc. Open

Here it might be important to note that ownership over a virtual body has been demonstrated multiple times, and moreover, that changing the type of body can lead to physiological, behavioural, and other kind of changes in the participant, so it is something that must be really taken into account.



2. The Illusions of VR - Body Agency

- **Agency refers to the self-attribution of an action.**
- It has long been known (Wegner) that we can also experience illusory agency [10]
  - Attributing an action to ourselves that we did not do.
- What happens when you have body ownership over a virtual body that does something that you did not do?

[10] Wegner, D. M., Sparrow, B., and Winerman, L. (2004). Vicarious agency: experiencing control over the movements of others. *J. Pers. Soc. Psychol.* 86, 838–848.

Now, “body agency” is another term that you will find out there, which refers to the self-attribution of an action that we really haven’t done.
“Agency” is then another illusion that can happen over the actions of others.
So, if we have body ownership over a virtual body, we might experience illusory agency when the virtual body does something that we haven’t done.

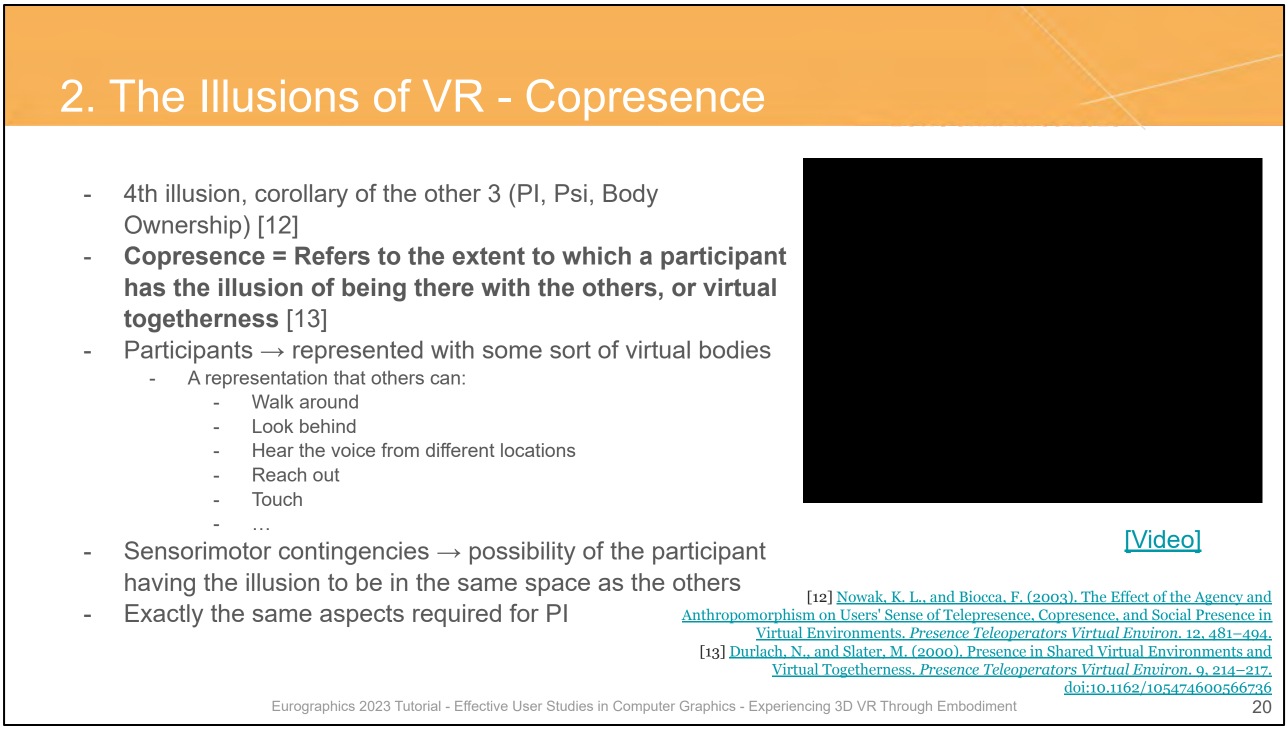
2. The Illusions of VR - Body Agency

- **Example:** Illusory agency over an act of speaking [11]
- At some point the virtual body unexpectedly uttered some words (45) with appropriate lip sync → agency over the speaking
- After the exposure → voice shifted towards of the higher frequency voice of the virtual body

[11] Banakou, D., and Slater, M. (2014). Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking. *Proc. Natl. Acad. Sci. U.S.A.* 111, 17678–17683.

[Video]

In this example, a virtual body perceived from a first person perspective and that moves synchronously with the real body conforms the body ownership illusion. At some point, the virtual body unexpectedly says some words with appropriate lip sync, words that the participant doesn’t pronounce. This caused a subjective illusion of agency over the act of speaking. Actually, after the exposure some participants shifted their voice towards the higher frequency voice of the virtual body.



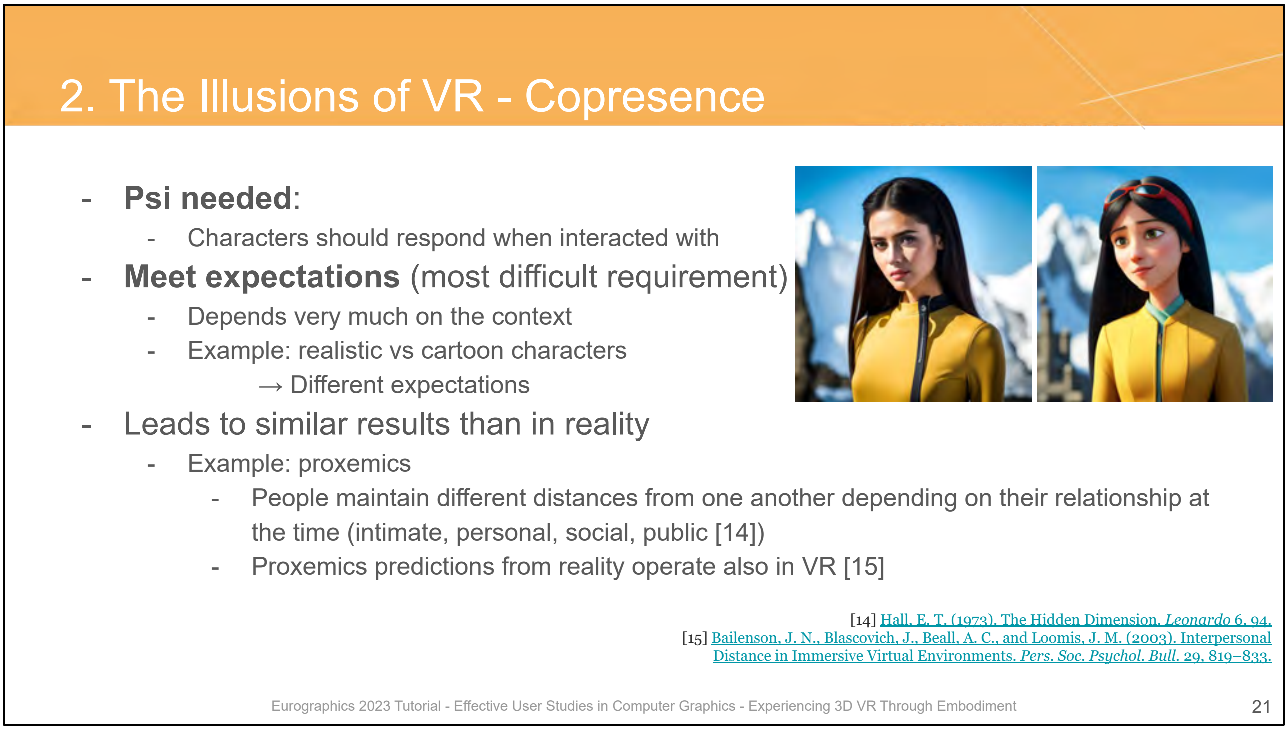
2. The Illusions of VR - Copresence

- 4th illusion, corollary of the other 3 (PI, Psi, Body Ownership) [12]
- **Copresence = Refers to the extent to which a participant has the illusion of being there with the others, or virtual togetherness** [13]
- Participants → represented with some sort of virtual bodies
  - A representation that others can:
    - Walk around
    - Look behind
    - Hear the voice from different locations
    - Reach out
    - Touch
    - …
- Sensorimotor contingencies → possibility of the participant having the illusion to be in the same space as the others
- Exactly the same aspects required for PI

[Video]

[12] Nowak, K. L., and Biocca, F. (2003). The Effect of the Agency and Anthropomorphism on Users' Sense of Telepresence, Copresence, and Social Presence in Virtual Environments. *Presence Teleoperators Virtual Environ.* 12, 481–494.
[13] Durlach, N., and Slater, M. (2000). Presence in Shared Virtual Environments and Virtual Togetherness. *Presence Teleoperators Virtual Environ.* 9, 214–217. doi:10.1162/105474600566736

We could consider a 4th illusion, corollary to the other 3 main illusions, which is "Copresence".
"Copresence" refers to "the extent to which a participant has the illusion of being there with the others".
It's like "virtual togetherness".
In this case, participants must be represented with some sort of virtual body, one that others should be able to walk around, look behind, hear, reach out, touch, etc.
Also sensorimotor contingencies must be fulfilled so that participants have the illusion of being all in the same space.
As you can notice, these are all requirements that Place Illusion already has.



2. The Illusions of VR - Copresence

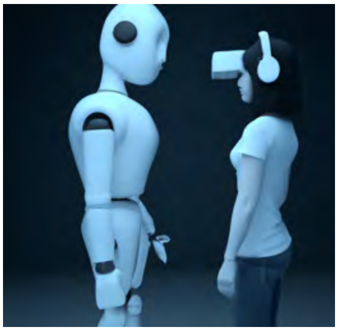
- **Psi needed**:
  - Characters should respond when interacted with
- **Meet expectations** (most difficult requirement)
  - Depends very much on the context
  - Example: realistic vs cartoon characters
    → Different expectations
- Leads to similar results than in reality
  - Example: proxemics
    - People maintain different distances from one another depending on their relationship at the time (intimate, personal, social, public [14])
    - Proxemics predictions from reality operate also in VR [15]

[14] Hall, E. T. (1973). The Hidden Dimension. *Leonardo* 6, 94.
[15] Bailenson, J. N., Blascovich, J., Beall, A. C., and Loomis, J. M. (2003). Interpersonal Distance in Immersive Virtual Environments. *Pers. Soc. Psychol. Bull.* 29, 819–833.

And to have Plausibility in a shared environment, characters should then respond to our actions.
But meeting the expectations of every participant is going to be the most challenging requirement, as expectations depend very much on the context and each person.
For example, people will not have the same expectations in an application using cartoon characters rather than realistic characters.

The fun thing about achieving copresence is that it leads to similar results that we have in reality.
For example, it has been found that in virtual reality people maintain the same distances with others than in real life, what it’s called proxemics.

2. The Illusions of VR - Copresence

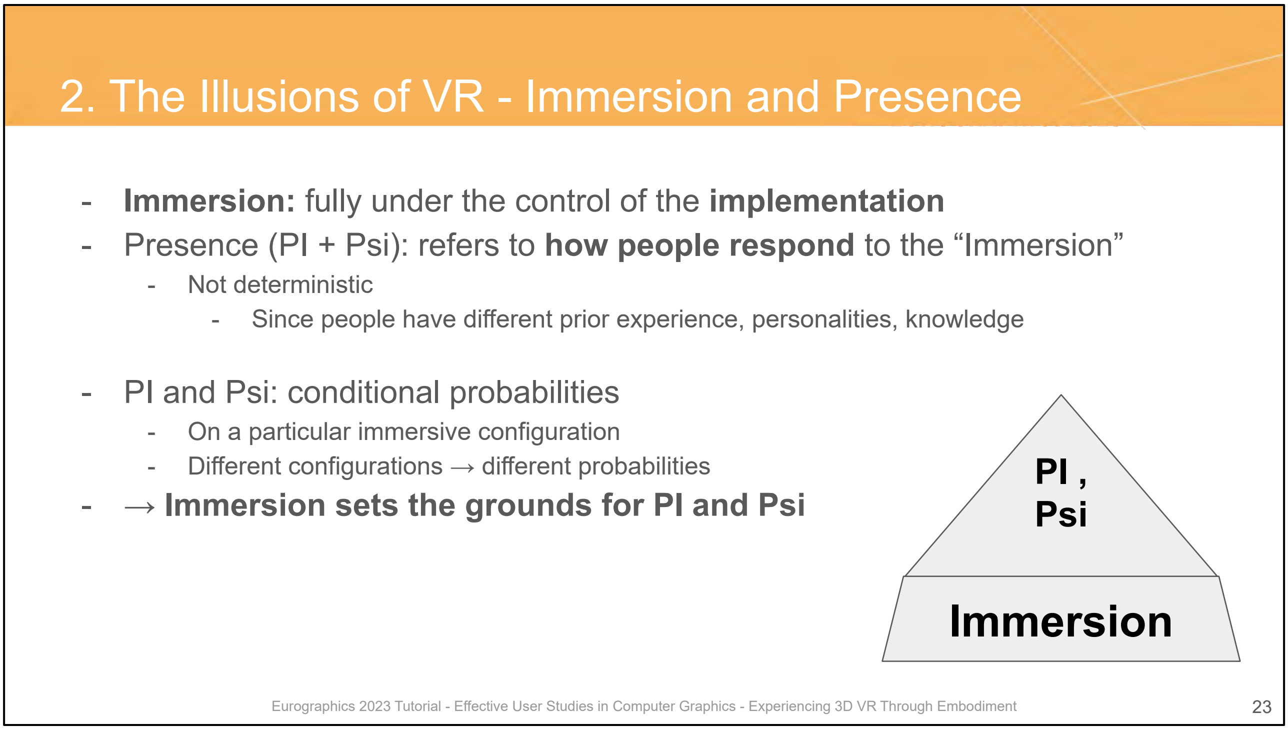


- Only remote participants meeting in VR?
- Applies to meeting AI controlled characters?
- Same issue: Do participants feel together with such representations?

- Not a separate phenomenon from PI, Psi or Body Ownership
  - PI + Psi + Body Ownership → copresence

- **Can occur whether the others are human controlled, AI controlled or any in between**

But is copresence something that only applies to remote participants meeting in VR?
Or does it also applies to share the virtual environment to AI controlled characters?
Do we feel together with such characters?
In fact, this is not a separate phenomenon from Place illusion, Plausibility or Body Ownership.
All three are needed to obtain copresence, and that can happen despite of who is controlling the other characters.



2. The Illusions of VR - Immersion and Presence

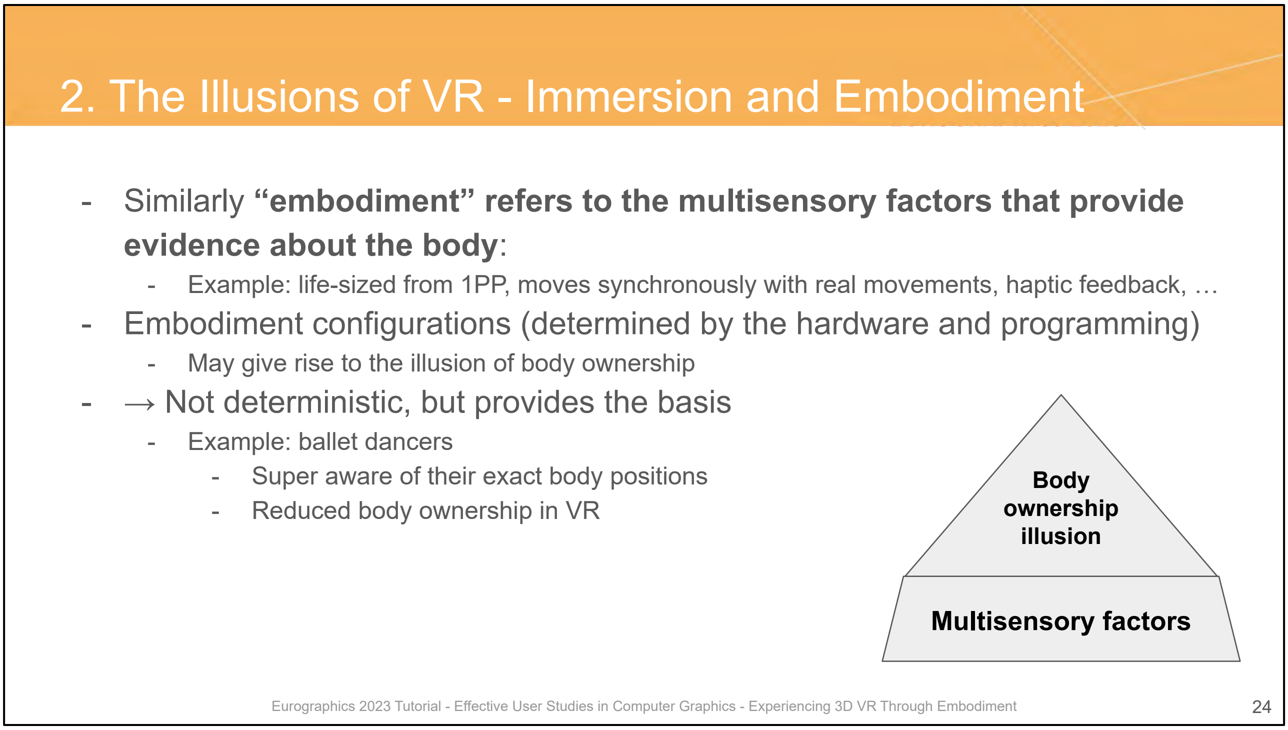
- **Immersion:** fully under the control of the **implementation**
- Presence (PI + Psi): refers to **how people respond** to the “Immersion”
  - Not deterministic
    - Since people have different prior experience, personalities, knowledge
- PI and Psi: conditional probabilities
  - On a particular immersive configuration
  - Different configurations → different probabilities
- **→ Immersion sets the grounds for PI and Psi**

PI ,
Psi

Immersion

Now, to be more clear on some concepts, let’s compare immersion and presence.
“Immersion” depends on the hardware you are using, the resolution, and it is fully under the control of the implementation.

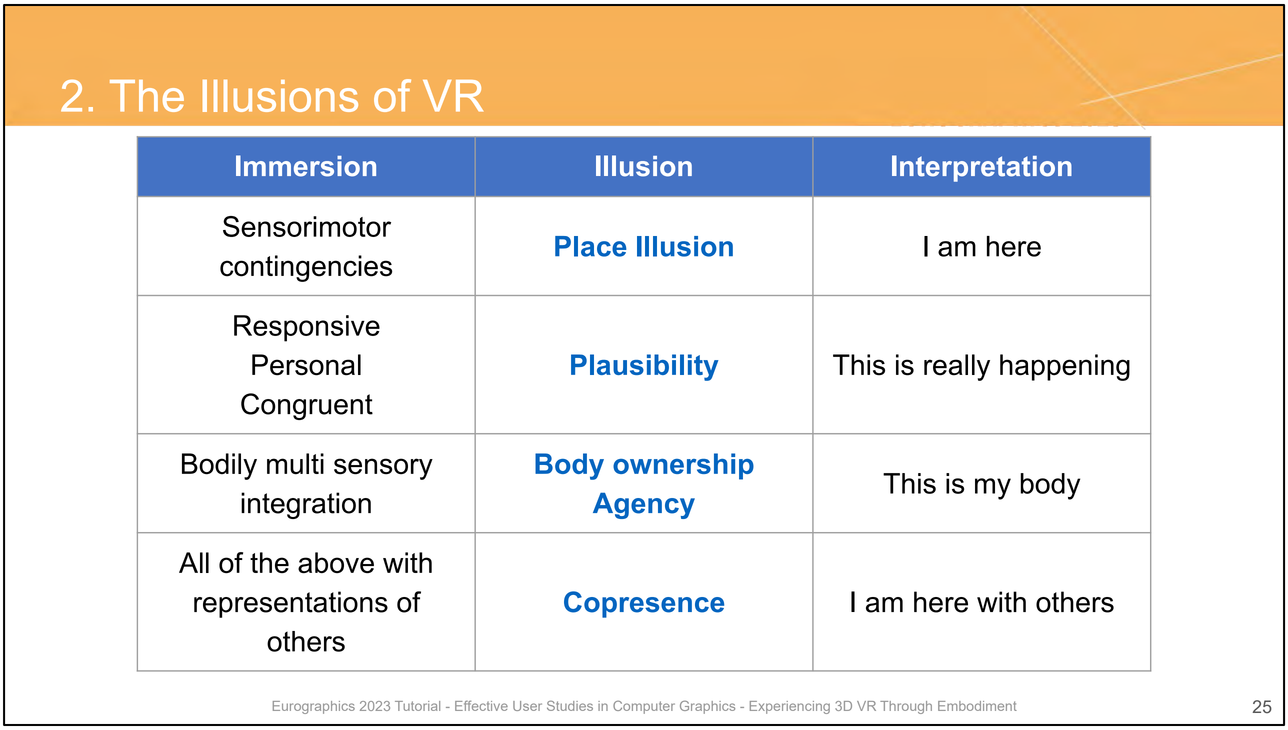
“Presence” refers then to how people respond to that “immersion”.
And that is not deterministic, since people have different prior experience, personalities and knowledge.
We can think about Place Illusion and Plausibility as conditional probabilities that depend on a particular immersive configuration.
Different configurations will cause different probabilities.
Therefore, we can say that “Immersion sets the grounds for Place Illusion and Plausibility”.



2. The Illusions of VR - Immersion and Embodiment

- Similarly **“embodiment” refers to the multisensory factors that provide evidence about the body**:
    - Example: life-sized from 1PP, moves synchronously with real movements, haptic feedback, …
- Embodiment configurations (determined by the hardware and programming)
    - May give rise to the illusion of body ownership
- → Not deterministic, but provides the basis
    - Example: ballet dancers
        - Super aware of their exact body positions
        - Reduced body ownership in VR

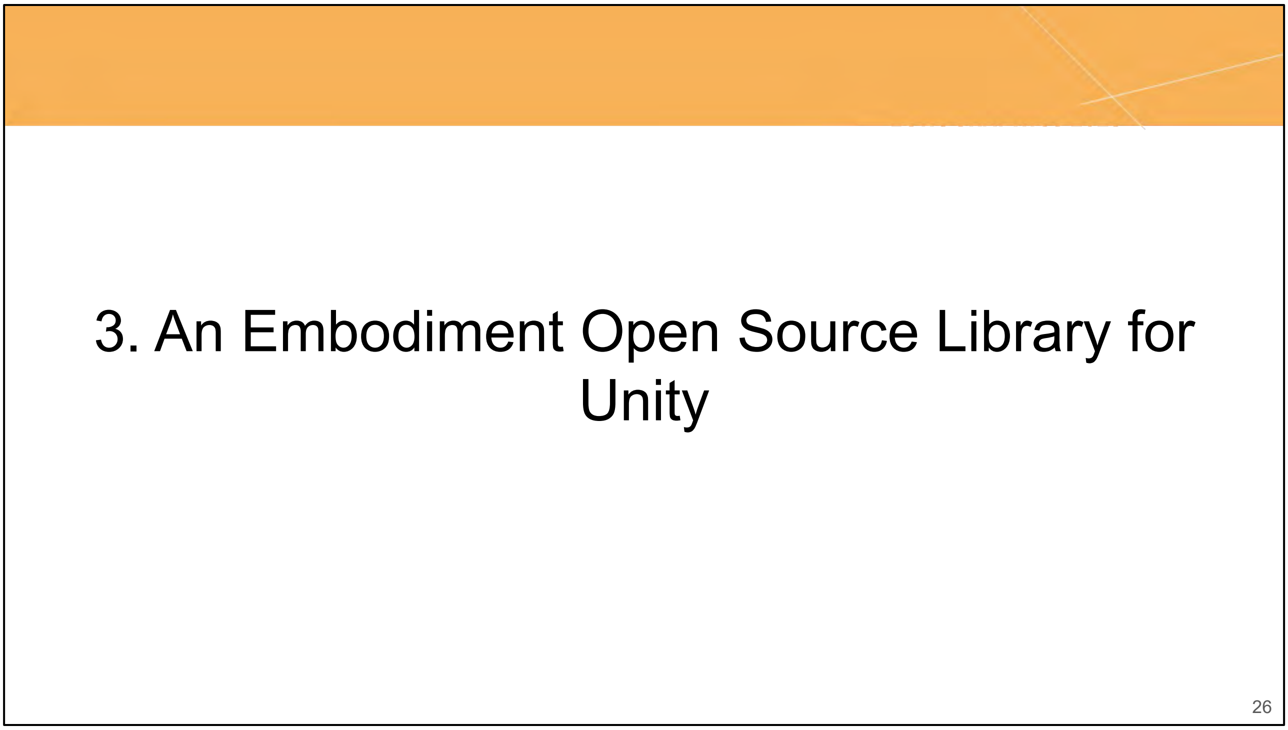
In a similar way, “embodiment” refers to the multisensory factors that provide evidence about the body.
The different embodiment configurations will be determined by the hardware and the programming.
These are not deterministic, but will provide the basis for the body ownership illusion they may cause.
For example, ballet dancers are super aware of their exact body position, so they experience a reduced body ownership in VR.



2. The Illusions of VR

Immersion	Illusion	Interpretation
Sensorimotor contingencies	**Place Illusion**	I am here
Responsive Personal Congruent	**Plausibility**	This is really happening
Bodily multi sensory integration	**Body ownership** **Agency**	This is my body
All of the above with representations of others	**Copresence**	I am here with others

So here you have a table that summarises the four illusions we have described. You can quickly check how they refer to the immersion and how we can interpret them.

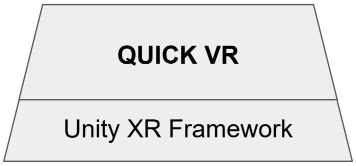


3. An Embodiment Open Source Library for Unity

Now that you know the basis of embodiment, let me introduce you to an open source library for Unity that will allow you to quickly develop experiments involving being embodied in a virtual avatar.

3. An Embodiment Open Source Library for Unity

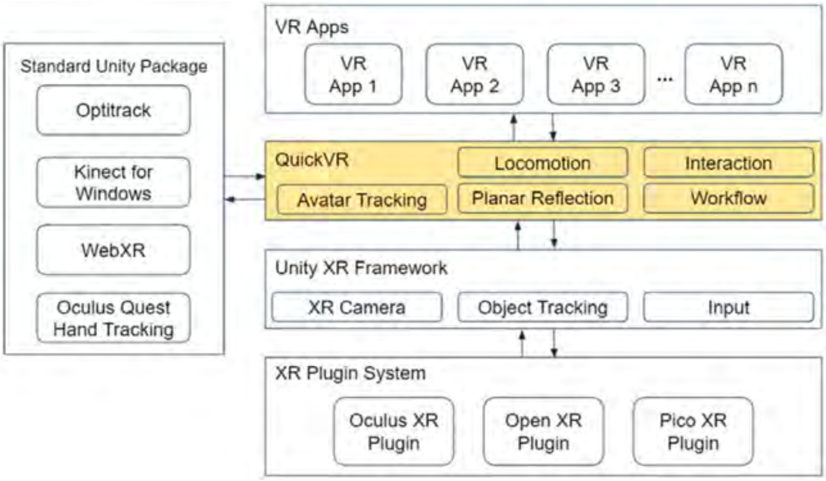
- **QuickVR: A Standard Library for virtual embodiment in Unity** [16]
  - Open source
  - Offers **embodiment** in a virtual character
  - **Supports** out of the box **any VR device** that implements the Unity XR Framework
  - **High level features**
    - Embodiment
    - Body tracking
    - Stereo planar reflections (mirror)
    - Simplified logic coding
    - Locomotion (direct, teleport, walk in Place)
    - Interaction with the environment
  - **Easy to use**
  - **Extensible**
  - **Customizable**



[16] R. Oliva, A. Beacco, X. Navarro and M. Slater. 2022. QuickVR: A Standard library for virtual embodiment in Unity Frontiers in Virtual Reality. 3:937191.

It is called QuickVR, and we have a publication that describes most of the library.
It is open source, and it is a library for Unity that offers embodiment in a virtual character with out of the box support for almost any VR device…
Any device that implements the XR Unity Framework.
While the Unity XR Framework is focused on giving us low level functionality such as stereo rendering, device tracking or input management, QuickVR focuses on higher level features.
Therefore QuickVR will provide you things like embodiment, body tracking, stereo planar reflections (meaning a mirror), a methodology that simplifies the logic coding for your experiments or user studies, locomotion and interaction with the environment.
All this will allow you to quickly prototype any new VR application in just a few hours or days and to reduce drastically your production times.
And moreover, QuickVR is very easy to use by coding novices, and it is also very easy to extend and customize if you are a more experienced programmer.

3. An Embodiment Open Source Library for Unity



Standard Unity Package
Optitrack
Kinect for Windows
WebXR
Oculus Quest Hand Tracking

VR Apps
VR App 1
VR App 2
VR App 3
...
VR App n

QuickVR
Locomotion
Interaction
Avatar Tracking
Planar Reflection
Workflow

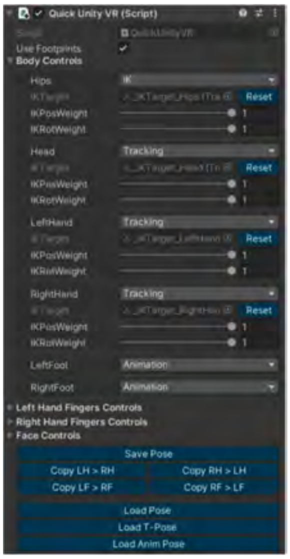
Unity XR Framework
XR Camera
Object Tracking
Input

XR Plugin System
Oculus XR Plugin
Open XR Plugin
Pico XR Plugin

As I said, QuickVR is built on top of the Unity XR Framework.
That means it doesn't need to know about each specific implementation of a specific provider, but it acts directly on the common framework.
This way, we only need to install the corresponding plugin for the desired device and it will be recognized by Unity and, by extension, by QuickVR.
If your device is not yet supported through the Unity XR Framework, QuickVR is designed so that it can be easily extended to support it.

3. An Embodiment Open Source Library for Unity

- **Main feature = Embodiment**
  - **Only** add component QuickUnityVR (to a Humanoid avatar)
- At start:
  - Calibration? **We only require the participant to look forward**
  - Assumption: avatar of similar height and proportions
- At runtime: IK to compute poses
  - Custom basic two bone IK solver → fine control of the IK step
- Update mode of each IK chain can be modified:
  - Tracking (default): tracking data provided by the VR system
  - IK: application → target set manually or by code
  - Animation: driven by the animation



Quick Unity VR (Script)

Use Footprints ✓

Body Controls

Hips: IK

IKPosWeight: 1

IKRotWeight: 1

Head: Tracking

IKPosWeight: 1

IKRotWeight: 1

LeftHand: Tracking

IKPosWeight: 1

IKRotWeight: 1

RightHand: Tracking

IKPosWeight: 1

IKRotWeight: 1

LeftFoot: Animation

RightFoot: Animation

Left Hand Fingers Controls

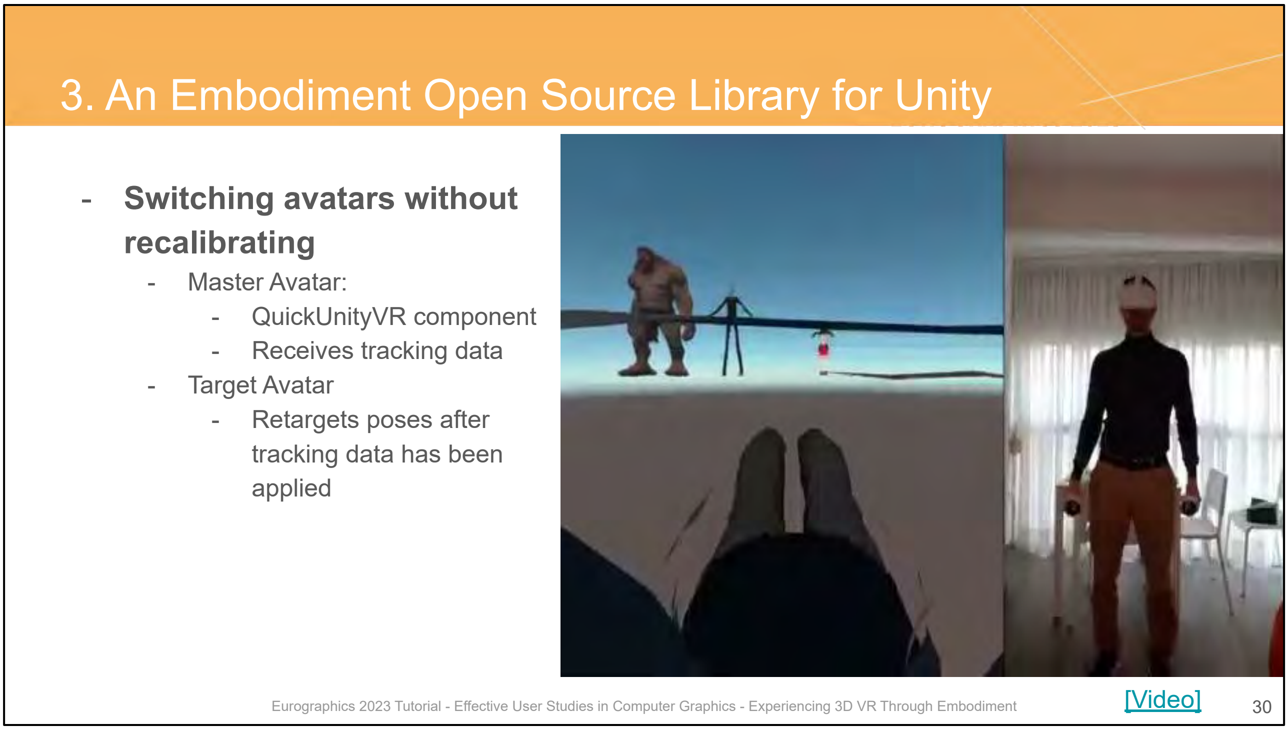
Right Hand Fingers Controls

Face Controls

But the main feature of QuickVR is embodiment.
And to achieve it, you only need to add one component called QuickUnityVR to any Humanoid Avatar and click on play.

At start QuickVR will recognize which device you are wearing and run an almost negligible calibration process, which only requires the participant to look forward.
The assumption we make here is that the avatar has similar height and proportions than the participant.

At runtime, a basic IK solver computes the poses with a fine control of the IK step.
Which means that we can easily modify the update mode of each IK chain depending on what we want to do.
We can select to update different body parts using data from the tracking, or using data or code from the application, or even using an animation, thus achieving any configuration we could need, like for example combining your upper body controlled using tracking data and the lower body part using some animation controller.



3. An Embodiment Open Source Library for Unity

- **Switching avatars without recalibrating**
  - Master Avatar:
    - QuickUnityVR component
    - Receives tracking data
  - Target Avatar
    - Retargets poses after tracking data has been applied

[Video]

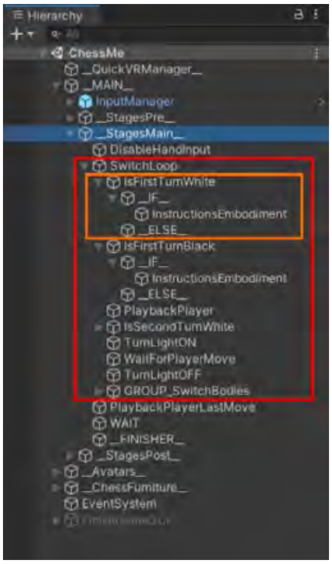
Another nice feature that QuickVR offers is the ability to be embodied in different avatars throughout the same virtual experience by seamlessly switching from one to another, without the need of recalibrating.

For that we define a master avatar that has the QuickUnityVR component and all the IK computations

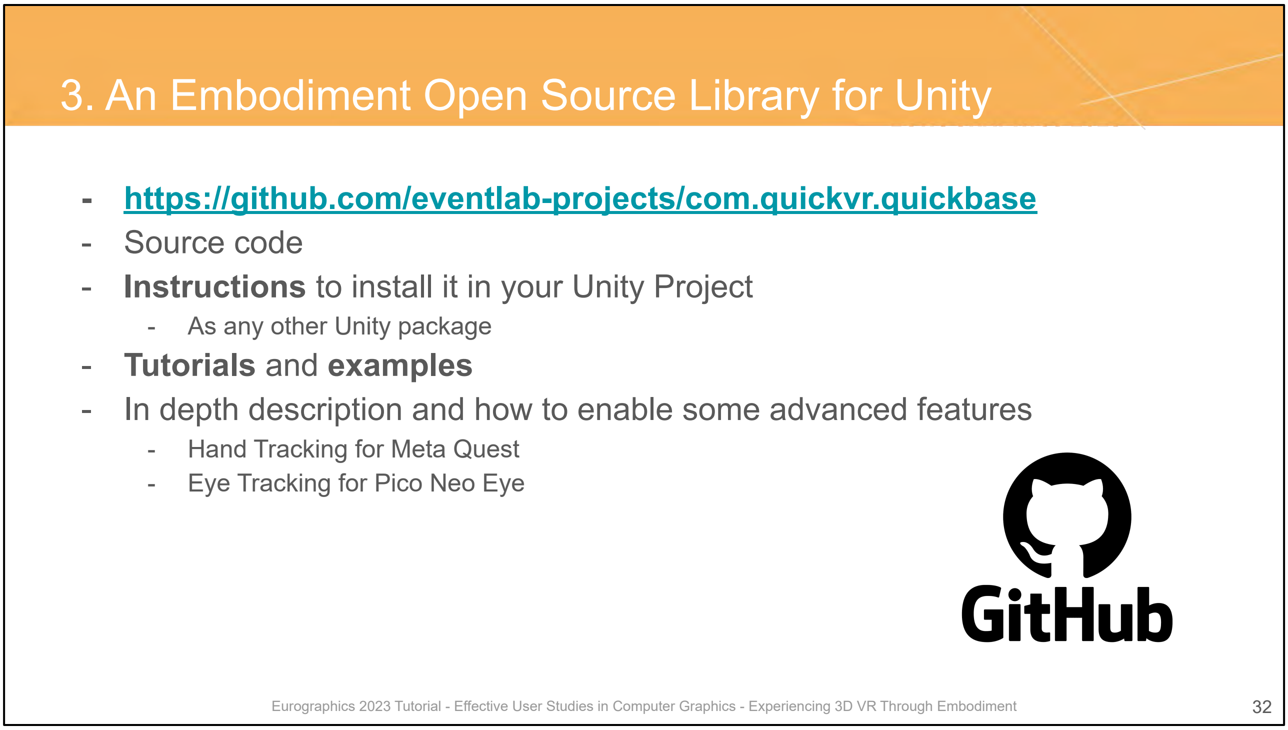
We then copy the pose of that master avatar to the final target avatar, no matter its size or proportions, where we also place our camera.

3. An Embodiment Open Source Library for Unity

- **Workflow system → logic pieces**
- **QuickStages** in the scene hierarchy
- Some **predefined stages**
  - Fade in, fade out
  - Scene loading
  - Calibration
  - …
- Highly **customizable**
  - 3 main functions: Init, CoUpdate (main coroutine), Finish
- Conditional blocks or loops



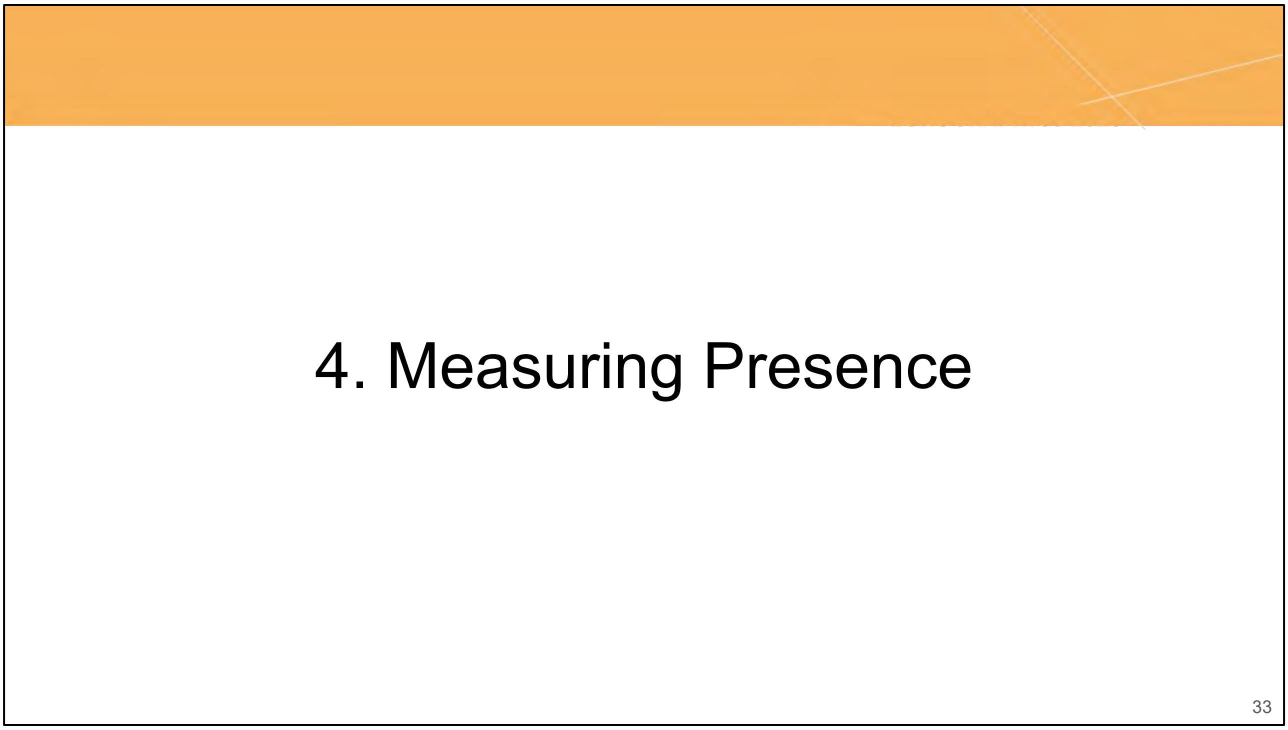
As mentioned before, one important feature of QuickVR is its workflow system and its simplified logic coding.
When you design many experiments, you realize how many parts of it are repeated or very similar within the same or different experiments.
The idea then is that you can divide the workflow of an experiment in small different logic pieces or stages, for which we define what we call QuickStages.
Therefore, for each one of the pieces we can have a corresponding QuickStage, and in Unity, these appear as components of GameObjects within the scene hierarchy.
That will allow you to easily enable, disable or reorder the stages at your convenience.
QuickVR offers some predefined stages, such as having the camera to fade in or fade out, managing and loading different scenes, giving calibration instructions to the participant, etc.…
But this workflow can also be highly customizable by extending or creating your own QuickStages.
For that you only need to reimplement 3 main functions that are executed for each stage, corresponding to what happens at the beginning, during and at the end of the stage.
And of course, if you are wondering it, we can have conditional blocks and loops with nested stages in it.



3. An Embodiment Open Source Library for Unity

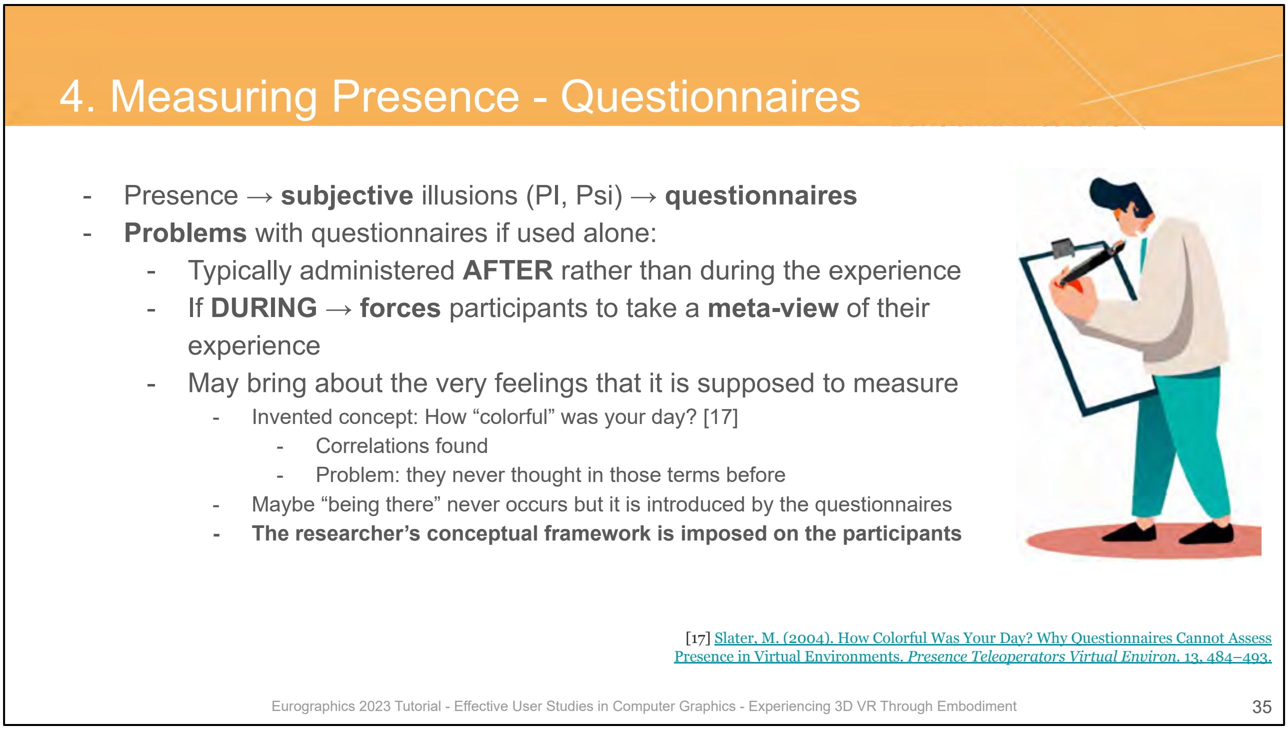
- **https://github.com/eventlab-projects/com.quickvr.quickbase**
- Source code
- **Instructions** to install it in your Unity Project
    - As any other Unity package
- **Tutorials** and **examples**
- In depth description and how to enable some advanced features
    - Hand Tracking for Meta Quest
    - Eye Tracking for Pico Neo Eye

So, having said all that, you can all give it a try by going to the github repository of QuickVR.
Along with the source code you will find there instructions to install it in your Unity projects.
You will see it is as easy as installing any other Unity package.
You will also find tutorials and examples to start using the library, and some in depth descriptions and explanations on how to use some advanced features.



4. Measuring Presence

Now that you know how you could easily program an application that has embodiment and what is the illusion of presence, let’s see what methods we can use to measure it, since one could say that having a stronger feeling of presence means our application is somehow better.



4. Measuring Presence - Questionnaires

- Presence → **subjective** illusions (PI, Psi) → **questionnaires**
- **Problems** with questionnaires if used alone:
  - Typically administered **AFTER** rather than during the experience
  - If **DURING** → **forces** participants to take a **meta-view** of their experience
  - May bring about the very feelings that it is supposed to measure
    - Invented concept: How “colorful” was your day? [17]
      - Correlations found
      - Problem: they never thought in those terms before
    - Maybe “being there” never occurs but it is introduced by the questionnaires
    - **The researcher’s conceptual framework is imposed on the participants**

[17] Slater, M. (2004). How Colorful Was Your Day? Why Questionnaires Cannot Assess Presence in Virtual Environments. *Presence Teleoperators Virtual Environ.* 13, 484–493.

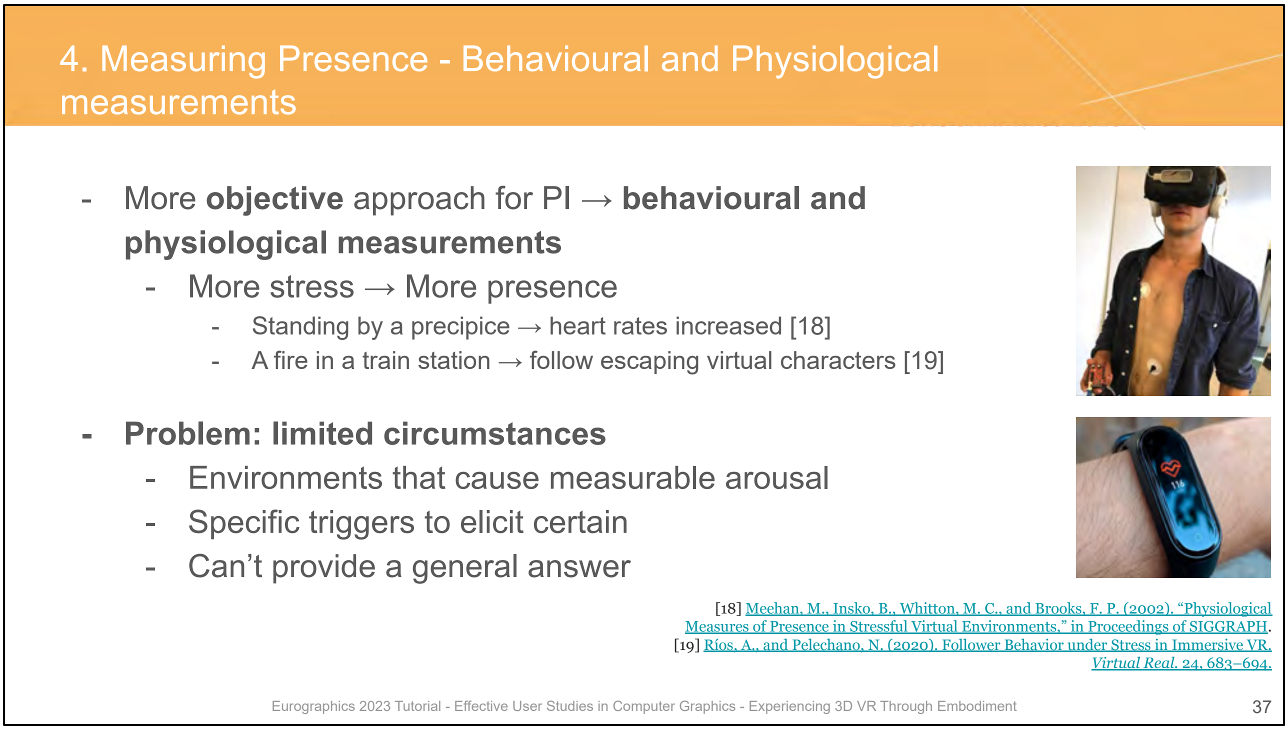
As we have seen presence is based on subjective illusions, and therefore the most common way to elicit them is through questionnaires.
But I’m not here to talk to you about the specific questions you should ask to the participants.
For that there is a lot of literature out there already…
What I want is to show you which are the problems of using only questionnaires in general.

For example, questionnaires are typically administered after the experience, which can cause participants to forget what they were really feeling at specific conditions, or to be quite imprecise on their answers.
And if the questionnaires are administered during the experience, then you are forcing the participants to take a meta-view of their experience, distracting them and dragging them out of the experience itself.
Actually, we have to be very careful with questions, since they may bring about the very feelings that they are supposed to measure.

In 2004 Mel Slater carried out an experiment where he was asking participants about “the colorfulness of their day”, which is a completely invented concept, so he was asking them: “How ‘colorful’ was your day?”.
He then found in the results correlations between this and other factors such as their daily activities, sleep pattern, etc. .
But the problem is that before been introduced to this idea participants never thought in terms of a day being ‘colorful’.

So, similarly, maybe “being there” never occurs but it is something that is introduced by the questionnaires.

The point here, then, is that using questionnaires we are imposing on the participants our conceptual framework.



4. Measuring Presence - Behavioural and Physiological measurements

- More **objective** approach for PI → **behavioural and physiological measurements**
  - More stress → More presence
    - Standing by a precipice → heart rates increased [18]
    - A fire in a train station → follow escaping virtual characters [19]
- **Problem: limited circumstances**
  - Environments that cause measurable arousal
  - Specific triggers to elicit certain
  - Can't provide a general answer

[18] Meehan, M., Insko, B., Whitton, M. C., and Brooks, F. P. (2002). "Physiological Measures of Presence in Stressful Virtual Environments," in Proceedings of SIGGRAPH.
[19] Ríos, A., and Pelechano, N. (2020). Follower Behavior under Stress in Immersive VR. *Virtual Real.* 24, 683–694.

A more objective approach is then to use behavioural and physiological measurements.
Behavioural measures can be things like "distance towards another agent", "how many times the participant looks at something".
Physiological measures include things such as the heart-rate, the skin conductivity or your brain activation.

This allows us to determine things such as having more stress implies having a stronger feeling of presence, because the participant is reacting strongly to the environment.
For example when standing by a virtual precipice we can measure how the heart rate increases, or when simulation a fire in a train station we can check if the participant follows the other escaping characters.

The problem of these measures is that they can only be used in limited circumstances.
That is in environments that cause such a measurable arousal with a positive or negative effect.
Otherwise, we can't use these measures, except when we use specific triggers to cause certain responses.
So, the main drawback is that behavioural and physiological measurements can't provide a general answer.

4. Measuring Presence - Breaks in Presence (BIP)

- **Break in Presence (BIP) = Some event that breaks consistency or expectation**
  - Glitch
  - Bug
  - Change in frame rate
  - Bumping into a (real) wall
  - …

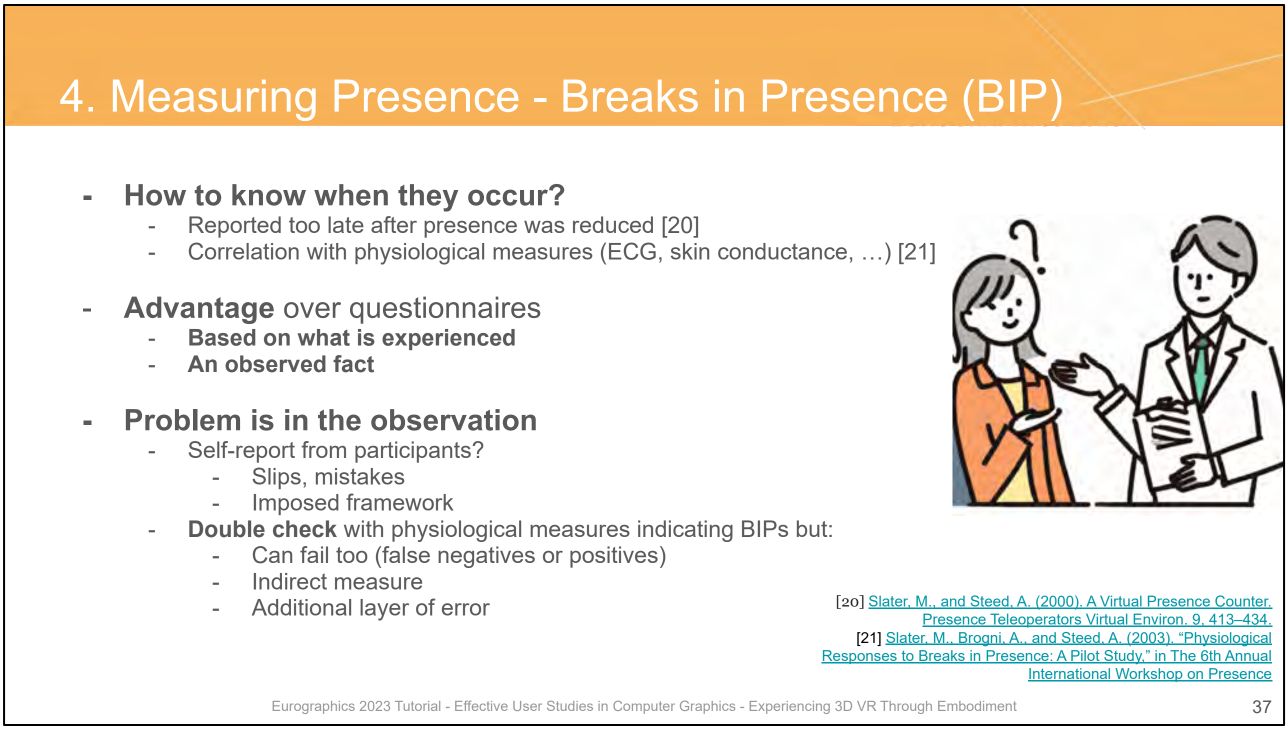
- We can **count** the number of failures and their occurrence through time [20]

- Relate to presence questionnaire:
  - Number of BIPs should correlate inversely with post-experience presence questionnaire scores

[20] Slater, M., and Steed, A. (2000). A Virtual Presence Counter. *Presence Teleoperators Virtual Environ. 9, 413–434.*

Let’s see another measure.
Have you ever been playing a game in VR and suddenly bumped into a real wall?
Or have you experimented a momentary reduced framerate?
Well, when this happens you suffer a “Break in Presence”, cause presence is based on sensorimotor contingencies.
And in the case of an event that breaks the consistency of what you see or your expectations, you lose your sense of presence, which can be recovered or not, depending on the event…

So, we can count the number of failures and their occurrence through time.
Moreover, we can relate these breaks in presence with the responses to some presence questionnaire, and we should find that they are inversely correlated:
Whenever there is a higher presence score, there should be less breaks in presence, and vice-versa.



4. Measuring Presence - Breaks in Presence (BIP)

- **How to know when they occur?**
  - Reported too late after presence was reduced [20]
  - Correlation with physiological measures (ECG, skin conductance, …) [21]
- **Advantage** over questionnaires
  - **Based on what is experienced**
  - **An observed fact**
- **Problem is in the observation**
  - Self-report from participants?
    - Slips, mistakes
    - Imposed framework
  - **Double check** with physiological measures indicating BIPs but:
    - Can fail too (false negatives or positives)
    - Indirect measure
    - Additional layer of error

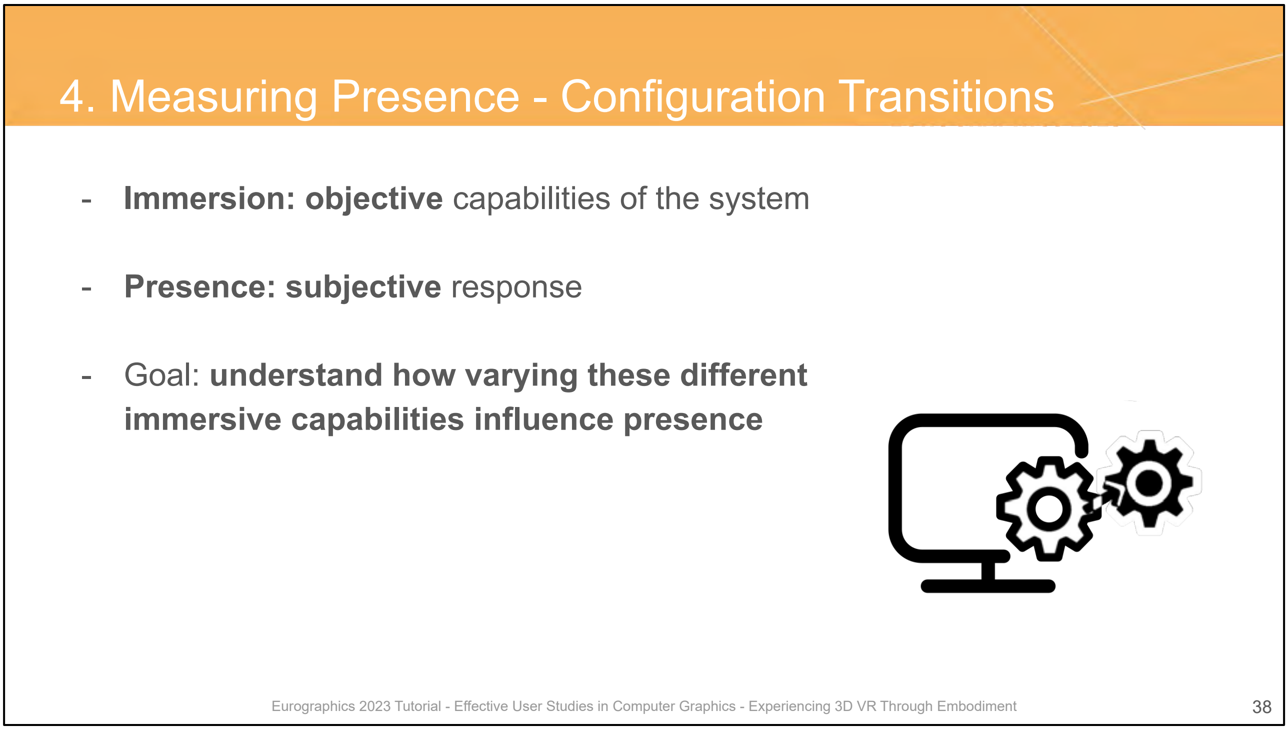
[20] Slater, M., and Steed, A. (2000). A Virtual Presence Counter. Presence Teleoperators Virtual Environ. 9, 413–434.

[21] Slater, M., Brogni, A., and Steed, A. (2003). “Physiological Responses to Breaks in Presence: A Pilot Study,” in The 6th Annual International Workshop on Presence

The major issue with counting breaks in presence is knowing when they occur. Because when a break in presence is verbally reported by a participant, it is already too late, because the break happens before the report itself, and therefore presence has already diminished.
What has been found though is that physiological measures such as ECG or skin conductance correlates somehow with break in presence..

What is then the advantage of counting breaks in presence over questionnaires? Well, breaks in presence are intrinsically based on what the participants are experiencing during the VR exposure.
They are a sudden failure in the system, an observed fact.

The problem is mainly in the observation.
Should we let the participants to self report them?
In that case they might forget to report an occurrence, or the opposite, maybe they feel impelled to report something, as if we are again imposing our framework on them.
Then it would be better to use physiological measures indicating a break in presence for a double layer of assessment.
But these measures can have false negatives or false positives indicating breaks in presence.
And doing so, we have to keep in mind that we will be creating an indirect measure, which will also add another layer of possible errors.



4. Measuring Presence - Configuration Transitions

- **Immersion: objective** capabilities of the system
- **Presence: subjective** response
- Goal: **understand how varying these different immersive capabilities influence presence**

A different measure to assess presence is through configuration transitions.
What is that?
Well, as you must know, when you are designing applications, studies or experiments, many times you have to deal with many different factors at the same time.
In the end, what you try to do is to understand the tradeoffs between all those factors that could be or not included in your designs.
With presence it's the same…
Virtual reality has the power to deliver the place illusion, we could say is the default purpose of the VR.
But how different factors are influencing over the sense of presence?
We somehow need a way to measure that influence.

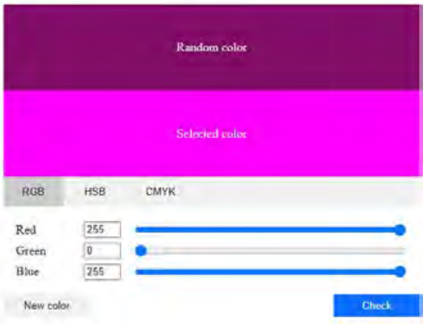
And we have seen that while immersion is based on the objective capabilities of our system, our configuration…
… Presence is a subjective response.
Then our goal should be to understand how varying these different immersive capabilities or factors can influence presence.

4. Measuring Presence - Configuration Transitions

- Color matching example
- Analogous method to asses PI or Psi [22]
    - First exposure at highest level - pay attention to PI + Psi
    - Training
    - Exposed with lowest levels → asked to match inicial PI + Psi

- **Configuration:** a set of factors levels
- **A change in a factor is a transition** from one configuration to another

- **Participants are never asked their opinions or to give rating scales**
- Method premised on **observable events only**
    - Participant's decisions
    - Matches
    - Not the meanings!



Red 255
Green 0
Blue 255

[22] Slater, M., Spanlang, B., and Corominas, D. (2010a). Simulating Virtual Environments within Virtual Environments as the Basis for a Psychophysics of Presence. *ACM Trans. Graph.* 29, 92.

Now, think about the typical game or experiment where you ask participants to match two colors:
you show a color to the participant and ask him to change the RGB values of another color so that it gets as similar as possible to the first color.
Configuration transitions are based on that.

For example, you can have 4 different varying factors like the type of illumination, the field of view, the display type, and the self-representation of the participant.
You first expose participants to the highest level of presence configuration and ask them to pay attention to their sense of place illusion and plausibility.
Then you train them over the 4 factors and how to change the levels.
And finally, you expose them to the lowest level of presence configuration and ask them to change the factors until they match their initial sense of place illusion and plausibility.

A configuration is therefore a set of factor levels.
And a transition is a change in one of the factors, that is, going from one configuration to another.

The nice thing about configuration transitions is that participants are never asked their opinions or to give any rating scale.
They are a method premised only on observable events.
It is entirely based on the participants' decisions, and the only important thing is the matches that they make, not why.

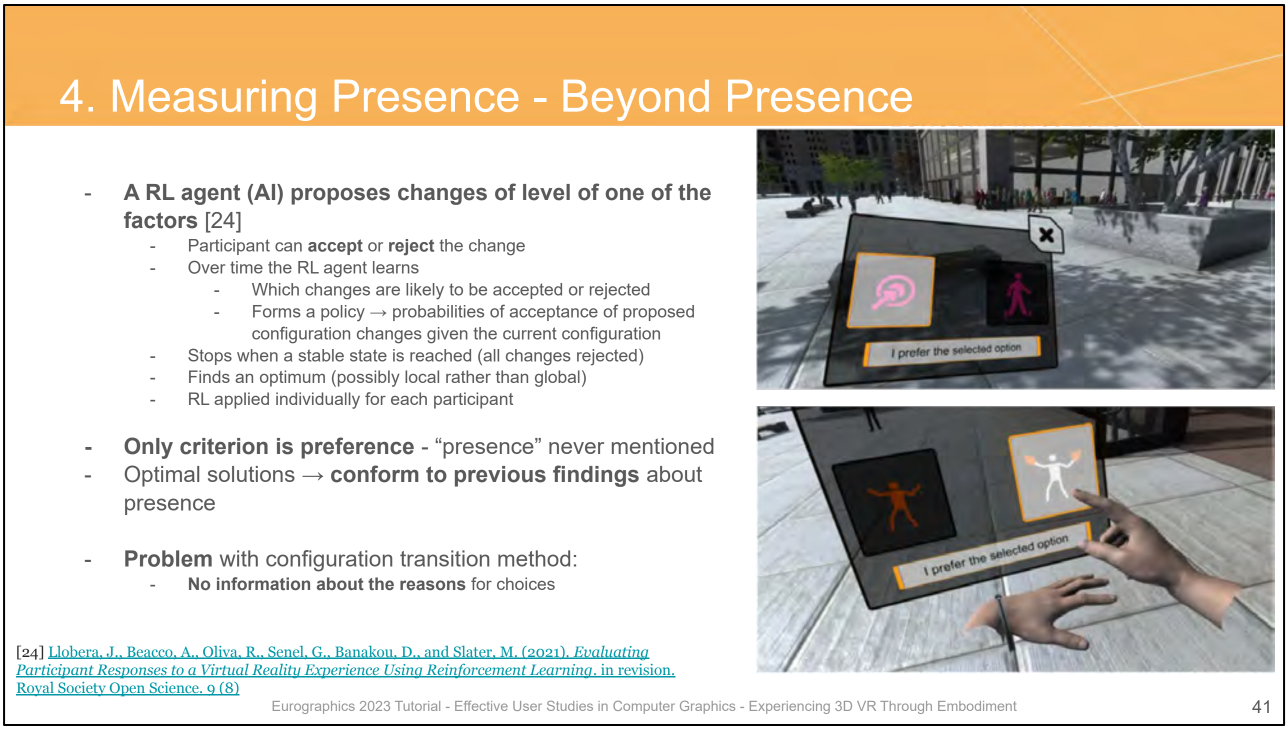
4. Measuring Presence - Beyond Presence

- **Configuration transitions to evaluate impact of several factors** [23]
  - Participants could change a factor level in any direction → no order assumption
  - **Goal: maximize "preference"** (instead of improve presence)
  - Transition from A to B because they prefer B to A
    - No reason needed
  - No need to first experience an optimal configuration → **no a priori assumption**
  - Coherent results across participants → **fits the idea of not imposing criteria** of researchers (such as presence) on participants

[23] Murcia-López, M., Collingwoode-Williams, T., Steptoe, W., Schwartz, R., Loving, T. J., and Slater, M. (2021). "Evaluating Virtual Reality Experiences through Participant Choices," in 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR) (IEEE), 747–755.

But we can go further beyond presence and use configuration transition to evaluate the impact of several factors.
Participants could change the level of a factor in any direction, with no order assumption.
Their goal should then be to maximize their "preference", avoiding imposing a concept such as presence.
If they transition from one configuration to another, it should only be because they prefer it, without giving any reason at all.

The nice thing about this is that then you don't need to expose participants to the supposedly best configuration, you don't have to make a priori assumptions.
And it has been found that such methods can give coherent results across participants, which fits the idea of not imposing our framework or bias participants.



4. Measuring Presence - Beyond Presence

- **A RL agent (AI) proposes changes of level of one of the factors** [24]
  - Participant can **accept** or **reject** the change
  - Over time the RL agent learns
    - Which changes are likely to be accepted or rejected
    - Forms a policy → probabilities of acceptance of proposed configuration changes given the current configuration
  - Stops when a stable state is reached (all changes rejected)
  - Finds an optimum (possibly local rather than global)
  - RL applied individually for each participant
- **Only criterion is preference** - "presence" never mentioned
- Optimal solutions → **conform to previous findings** about presence

- **Problem** with configuration transition method:
  - **No information about the reasons** for choices

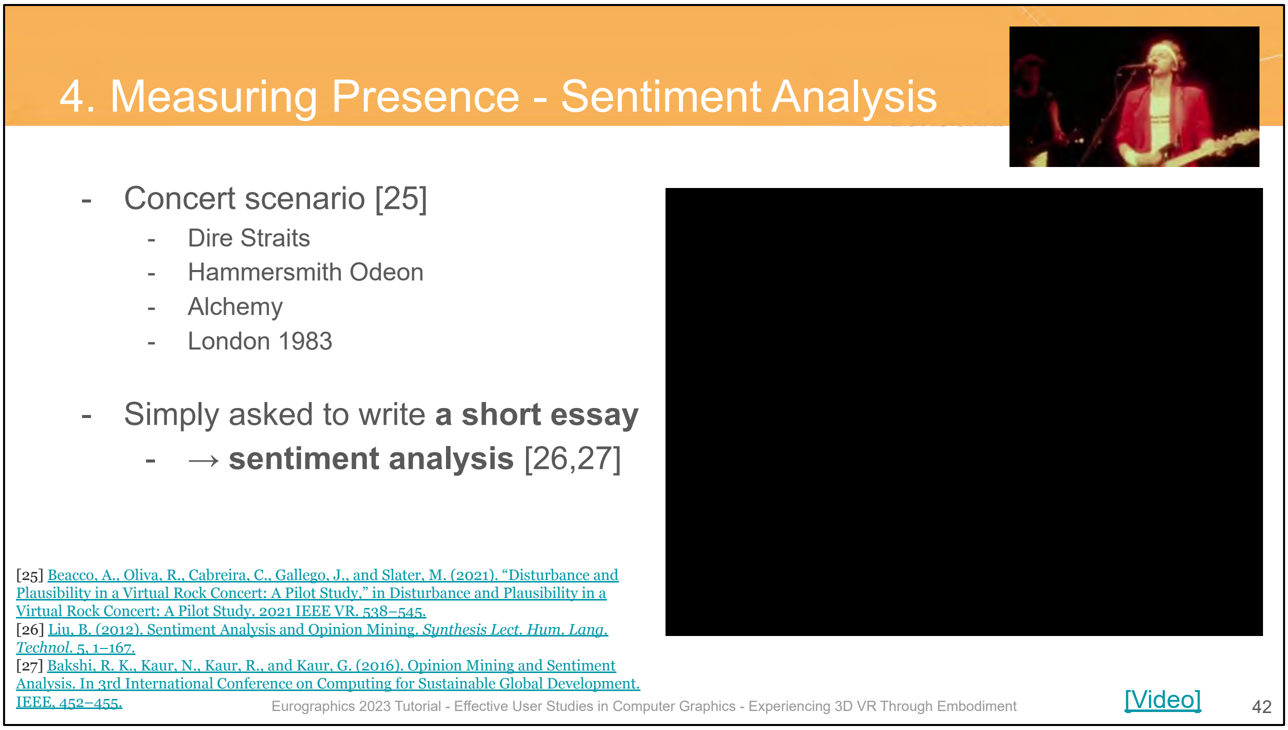
[24] Llobera, J., Beacco, A., Oliva, R., Senel, G., Banakou, D., and Slater, M. (2021). *Evaluating Participant Responses to a Virtual Reality Experience Using Reinforcement Learning*, in revision. Royal Society Open Science. 9 (8)

In this example here we went even a little bit further.
Here participants do not even have to think about a possible change in the configuration, nor to do it, but a Reinforcement Learning agent proposes it for them.
Then participants only need to decide if they accept or reject the change, based on their preference.

The reinforcement learning agent learns over time which changes are likely to be accepted or not, and forms a policy based on probabilities.
Then it only stops when all changes are rejected - that is, when a stable state is reached.
We find an optimum state that pleases the participant, possibly a local maximum rather than a global one, but optimum.

Here again, the only criterion is preference, which is good, and the concept of "presence" was never mentioned to the participants
Moreover, we found out that the optimal solutions reached from this experiment conform to previous findings about presence in the literature.

But, the main problem with configuration transition methods is that, although based either on matching states or simply on preference, it does not give any information about the reasons for participant's choices.



4. Measuring Presence - Sentiment Analysis

- Concert scenario [25]
  - Dire Straits
  - Hammersmith Odeon
  - Alchemy
  - London 1983
- Simply asked to write **a short essay**
  - → **sentiment analysis** [26,27]

[25] Beacco, A., Oliva, R., Cabreira, C., Gallego, J., and Slater, M. (2021). "Disturbance and Plausibility in a Virtual Rock Concert: A Pilot Study," in Disturbance and Plausibility in a Virtual Rock Concert: A Pilot Study. 2021 IEEE VR. 538–545.

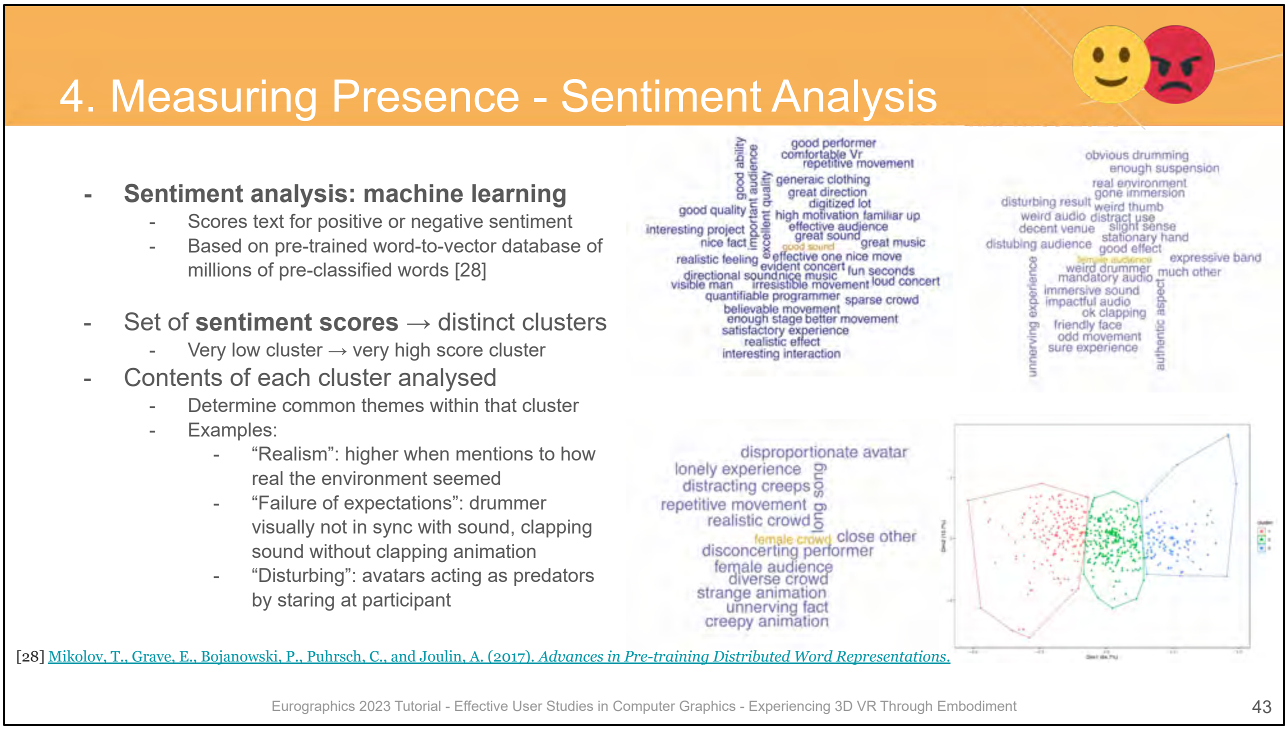
[26] Liu, B. (2012). Sentiment Analysis and Opinion Mining. *Synthesis Lect. Hum. Lang. Technol.* 5, 1–167.

[27] Bakshi, R. K., Kaur, N., Kaur, R., and Kaur, G. (2016). Opinion Mining and Sentiment Analysis. In 3rd International Conference on Computing for Sustainable Global Development. IEEE. 452–455.

[Video]

Now the last method I want to introduce to you is "sentiment analysis", but I'll try to illustrate it through another example study.
For this project we did recreate a Dire Straits concert from 1983, and we put participants in the crowd to virtually attend the concert.

The point is that this was exploratory.
We'd never done anything like this before and wanted to find out what would happen.
The very first presence questionnaires were based on what participants (in the 1990s) told us about their experiences.
We were interested in the same here - let's listen to them first before we impose our own concepts.
Therefore, the only thing we asked participants is to write a short essay about their experience after the VR exposure.
Then we took all the answers and applied sentiment analysis over them.



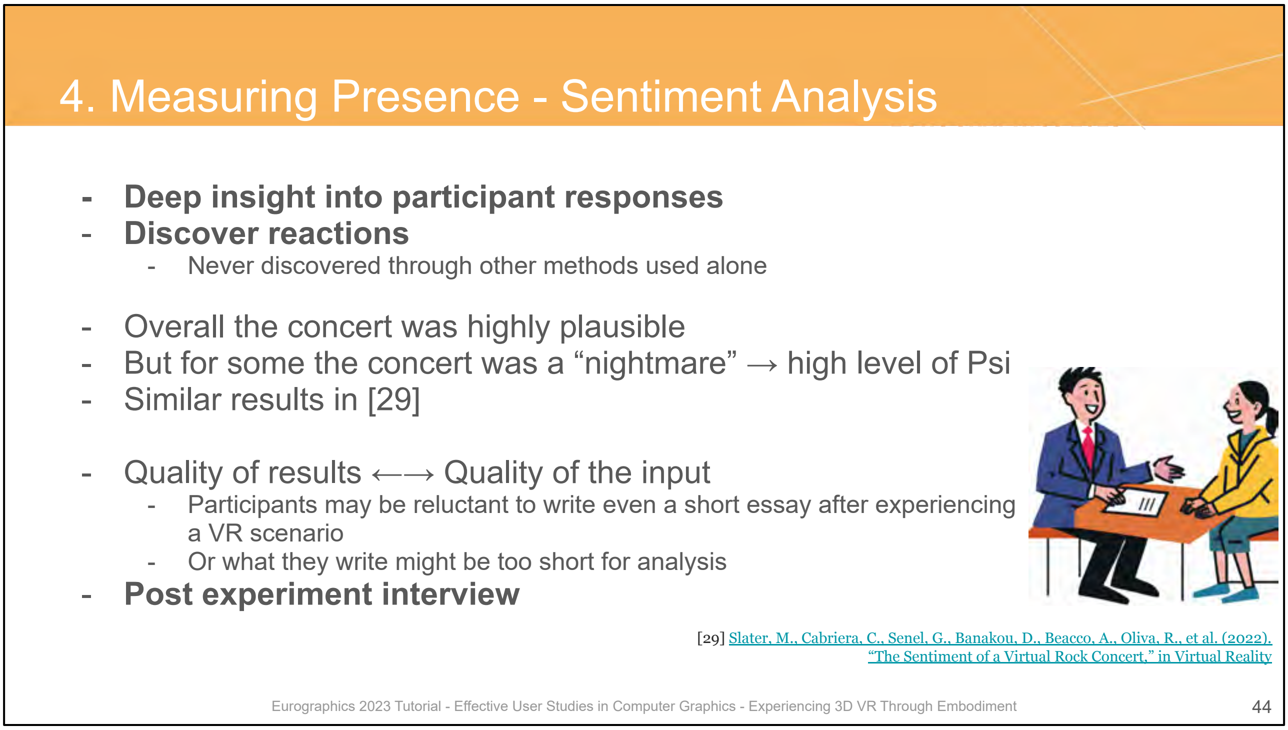
4. Measuring Presence - Sentiment Analysis

- **Sentiment analysis: machine learning**
  - Scores text for positive or negative sentiment
  - Based on pre-trained word-to-vector database of millions of pre-classified words [28]
- Set of **sentiment scores** → distinct clusters
  - Very low cluster → very high score cluster
- Contents of each cluster analysed
  - Determine common themes within that cluster
  - Examples:
    - “Realism”: higher when mentions to how real the environment seemed
    - “Failure of expectations”: drummer visually not in sync with sound, clapping sound without clapping animation
    - “Disturbing”: avatars acting as predators by staring at participant

[28] Mikolov, T., Grave, E., Bojanowski, P., Puhrsch, C., and Joulin, A. (2017). *Advances in Pre-training Distributed Word Representations.*

If you’re wondering what sentiment analysis, it is a machine learning method that scores a piece of text with a positive or negative sentiment value.
It is based on pre-trained word-to-vector databases with millions of pre-classified words.

So, for each sentence of each essay we are able to get a sentiment score.
This allows us to perform a cluster analysis and find different clusters of terms going from a very low to a very high sentiment score.
Then the contents of each cluster were then analyzed to determine the common themes within that cluster.
We found clusters such as “realism”, with higher score when mentions of how real the environment seemed.
A “failure of expectations” cluster, related to thinkings like having the drummer visually not in sync with the sound, or hearing clapping sounds without the crowd having a clapping animation, things like that…
Or a “Disturbing” cluster, with respect to things like having crowd avatars acting as predators by starting at the participant.
That, by the way, was totally unexpected for us, since it depicts something that we haven’t deliberately programmed, it just happened by accident.



4. Measuring Presence - Sentiment Analysis

- **Deep insight into participant responses**
- **Discover reactions**
    - Never discovered through other methods used alone

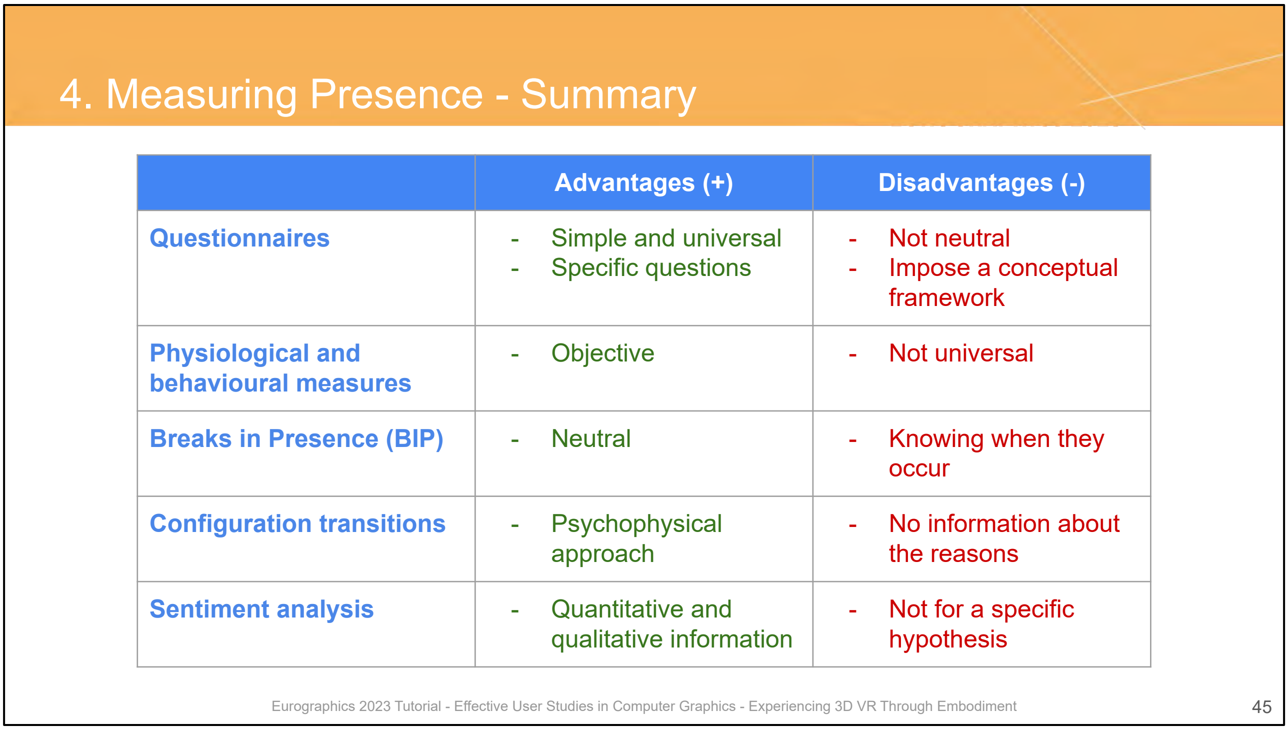
- Overall the concert was highly plausible
- But for some the concert was a “nightmare” → high level of Psi
- Similar results in [29]

- Quality of results ←→ Quality of the input
    - Participants may be reluctant to write even a short essay after experiencing a VR scenario
    - Or what they write might be too short for analysis
- **Post experiment interview**

[29] Slater, M., Cabriera, C., Senel, G., Banakou, D., Beacco, A., Oliva, R., et al. (2022). “The Sentiment of a Virtual Rock Concert,” in Virtual Reality

So sentiment analysis allowed us to get deep insight into how and why participants responded to the concert experience.
We discovered reactions that we would never have discovered through other methods used alone, such as questionnaires.
We found that the concert was highly plausible, but that for some participants it was more like a nightmare, as some felt really disturbed by the crowd.
This implies a high level of plausibility, since without that illusion there would be no reason to be disturbed.
And we got similar results in another publication.

But in the end, the quality of the results when using a sentiment analysis, highly depends on the quality of the input, that is, the quality of the essays.
After the VR experience, participants may be very reluctant to write something.
Or maybe what they write is too short for analysis, or they might forget to report something.
Then a more promising approach is to record what participants say in a post-experiment interview, maybe informal, rather than asking them to write something.



4. Measuring Presence - Summary

	Advantages (+)	Disadvantages (-)
Questionnaires	- Simple and universal - Specific questions	- Not neutral - Impose a conceptual framework
Physiological and behavioural measures	- Objective	- Not universal
Breaks in Presence (BIP)	- Neutral	- Knowing when they occur
Configuration transitions	- Psychophysical approach	- No information about the reasons
Sentiment analysis	- Quantitative and qualitative information	- Not for a specific hypothesis

This slide summarizes what we have seen of all methods.

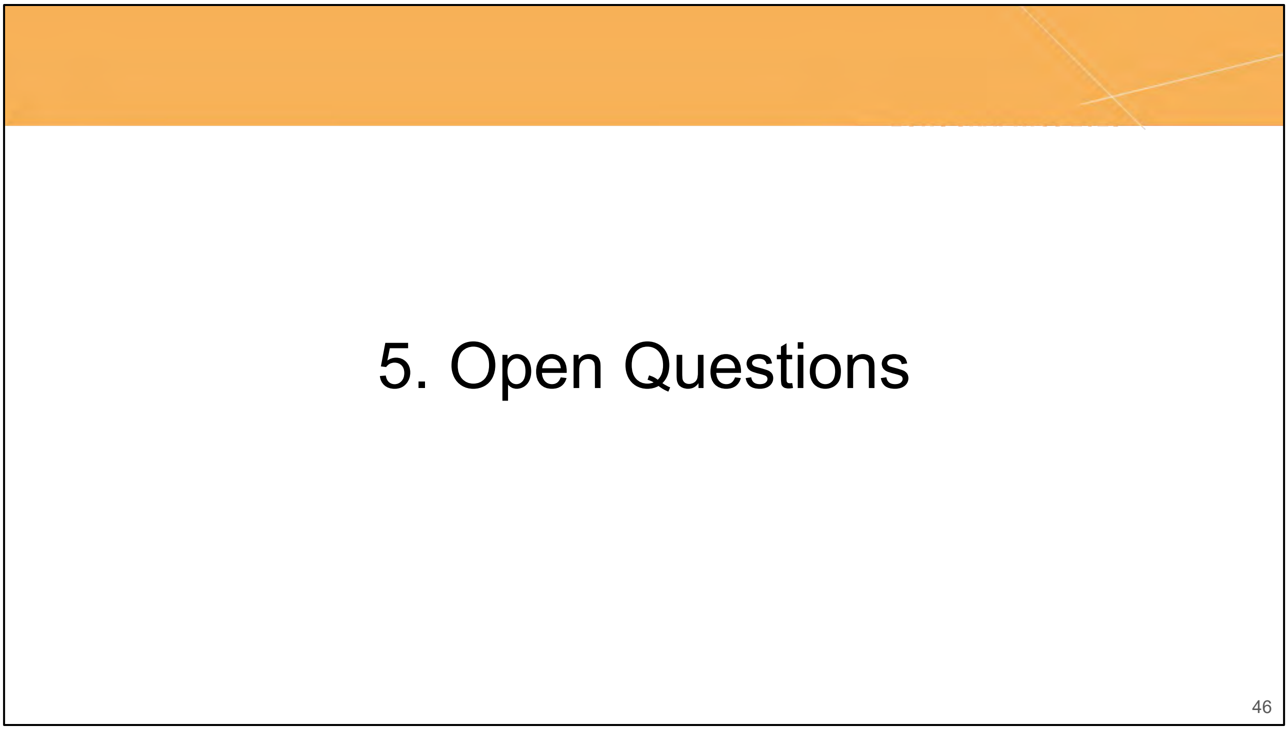
Questionnaires are simple and universal, since they are applicable to any concept and any scenario and they can help answer specific questions.
But they are not neutral and not ideal to find out what happens from the point of view of the participants.
They impose a conceptual framework on them.

Physiological and behavioural measures are objective, but not universal.
They require specific events or conditions to induce responses to the participants.
Those conditions must be really well-understood.

Breaks in Presence are neutral, but have the problem of really knowing when they occur.

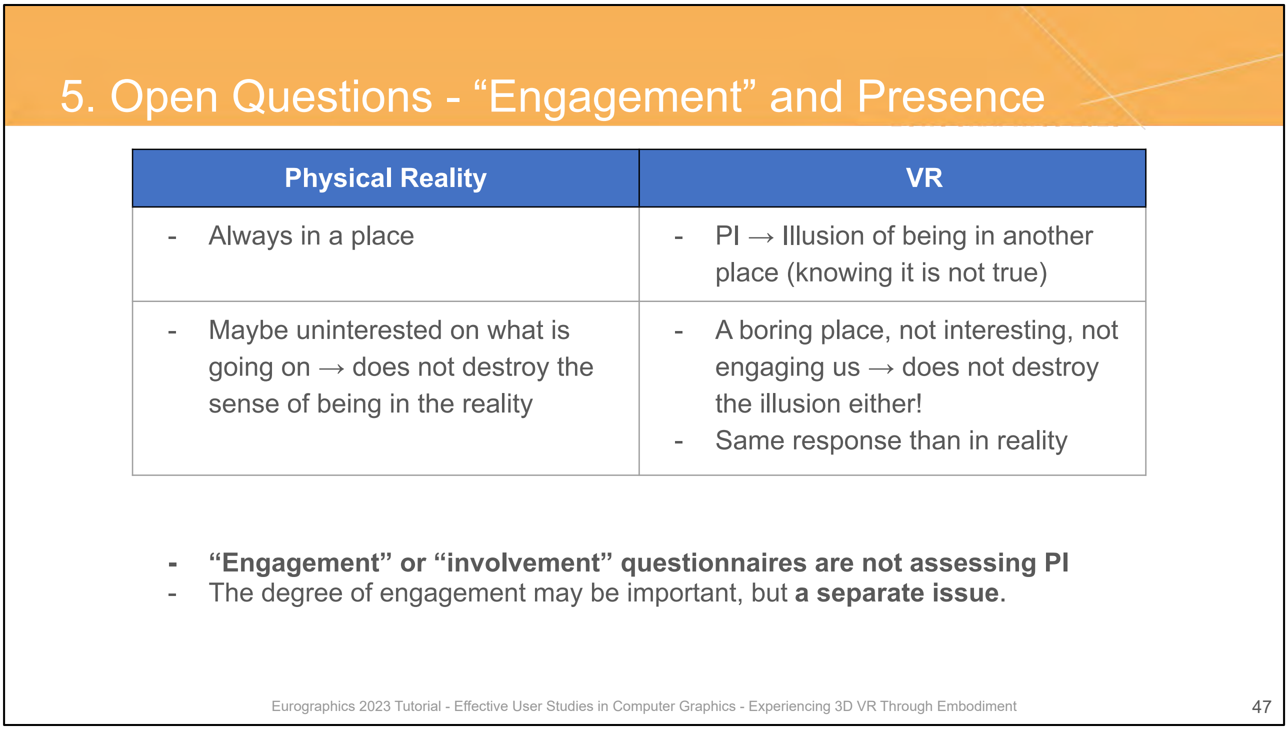
Configuration transitions are nice psychophysical approaches to quantifying presence.
But they don’t give any information about the reasons why participants chose them.

And Sentiment analysis finds a good quantitative and qualitative information about the responses to a scenario.
But it is not properly suited to demonstrate a specific hypothesis.



5. Open Questions

And before giving our conclusions, lets answer to some related open questions…



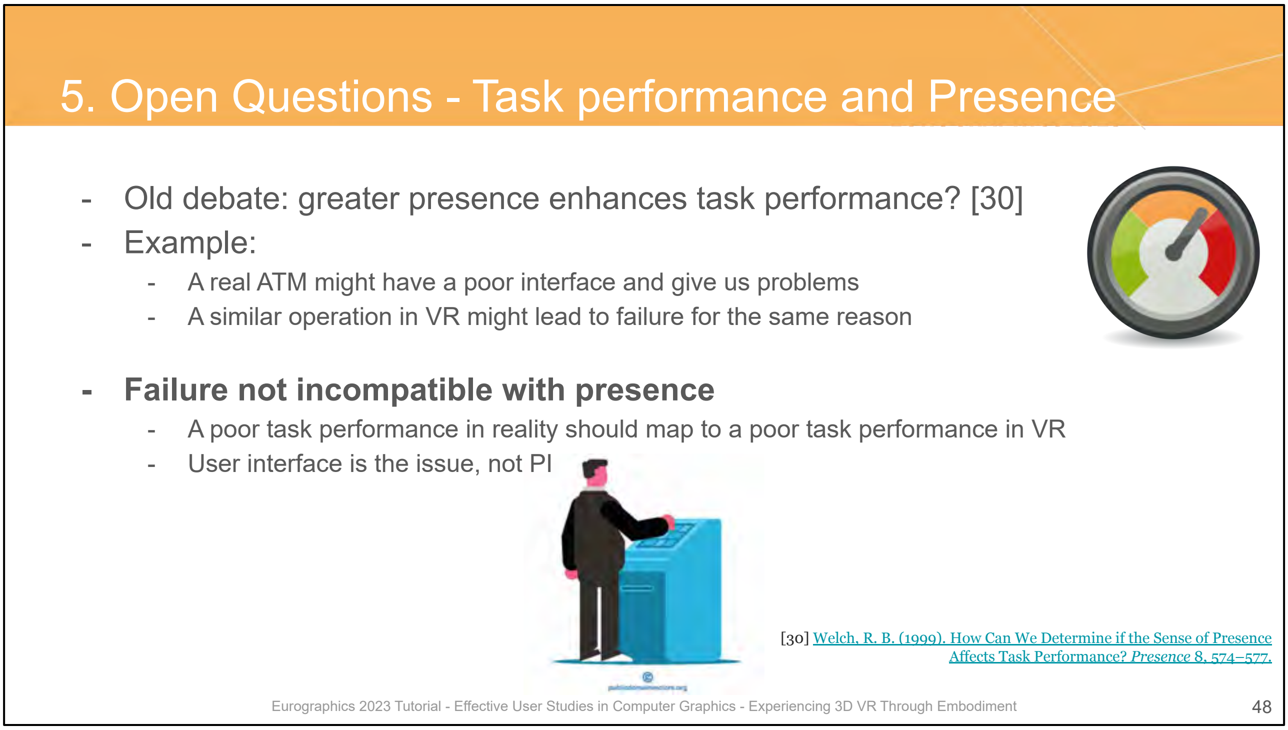
5. Open Questions - “Engagement” and Presence

Physical Reality	VR
- Always in a place	- PI → Illusion of being in another place (knowing it is not true)
- Maybe uninterested on what is going on → does not destroy the sense of being in the reality	- A boring place, not interesting, not engaging us → does not destroy the illusion either! - Same response than in reality

- **“Engagement” or “involvement” questionnaires are not assessing PI**
- The degree of engagement may be important, but **a separate issue**.

There are many studies out there that claim that if participants are more engaged or involved in their application, that is more likely to produce a higher sense of place illusion and presence…
But let’s think about this for a minute.
In physical reality we are always in a place.
What happens in reality might not be interesting, but that does not mean that we don’t feel like we are there, in the reality.
Similarly, in virtual reality the place illusion happens when we feel that we are in that other place, even though we know it is not true.
But like in reality, being a virtual boring place, one that is not interesting or that is not engaging us… does not mean that the illusion is broken and that we don’t feel we are there.

Therefore, questionnaires including categories such as “engagement”, or “involvement”, are not really assessing for place illusion.
Probably the degree of engagement may be important, but we consider this to be a separate problem.



5. Open Questions - Task performance and Presence

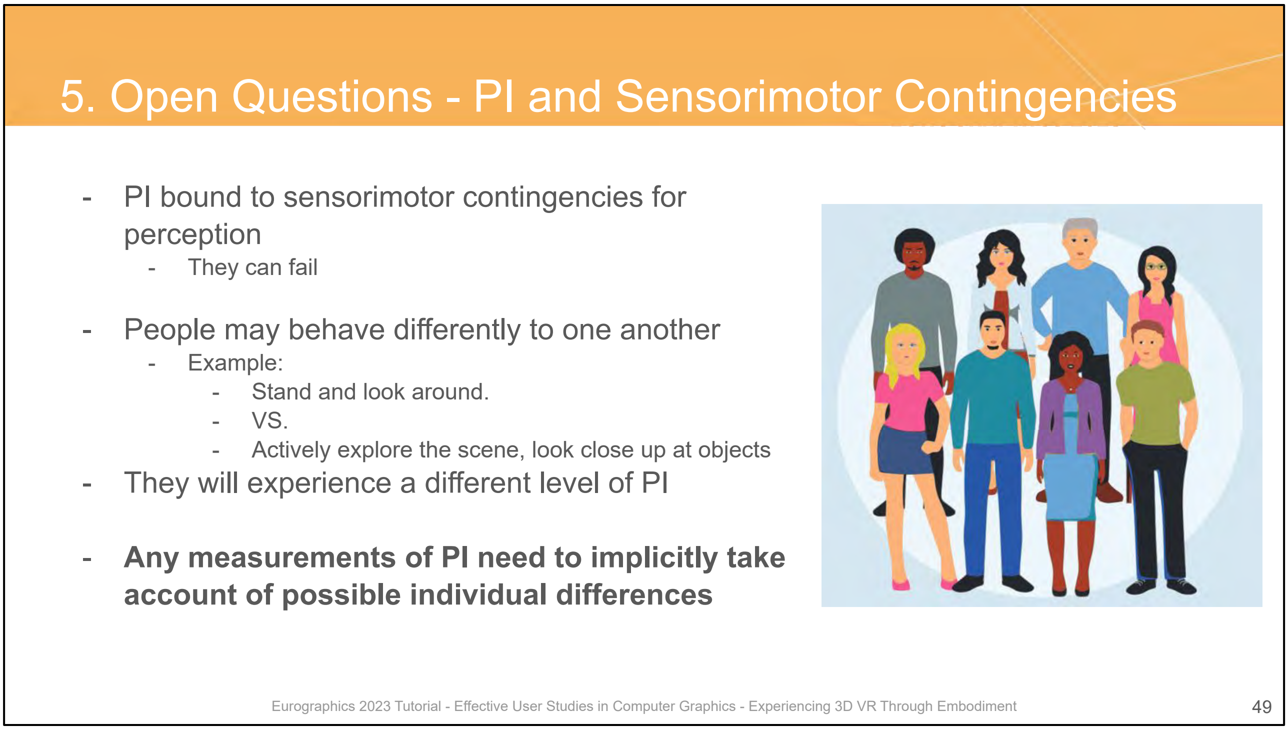
- Old debate: greater presence enhances task performance? [30]
- Example:
  - A real ATM might have a poor interface and give us problems
  - A similar operation in VR might lead to failure for the same reason

- **Failure not incompatible with presence**
  - A poor task performance in reality should map to a poor task performance in VR
  - User interface is the issue, not PI

[30] Welch, R. B. (1999). How Can We Determine if the Sense of Presence Affects Task Performance? *Presence* 8, 574–577.

There is also an old debate around whether having a greater presence enhances task performance.
But take a real ATM as an example.
It might have a very poor interface and give us lots of problems to use it.
Carrying on a similar operation in virtual reality might also lead to a failure due to the same reasons, in this case, a bad user interface.

Therefore, our position here is that failure is not incompatible with presence, because a poor task performance in reality should also be mapped to a poor task performance in VR.



5. Open Questions - PI and Sensorimotor Contingencies

- PI bound to sensorimotor contingencies for perception
  - They can fail
- People may behave differently to one another
  - Example:
    - Stand and look around.
    - VS.
    - Actively explore the scene, look close up at objects
- They will experience a different level of PI
- **Any measurements of PI need to implicitly take account of possible individual differences**

We have also seen that place illusion is bound to sensorimotor contingencies for perception, and that these can fail.
Also, different people may behave differently in the virtual world.
While one might just stand and look around, another individual could actively explore the scene and look close up at objects.
Those would be two different ways of experiencing the scene and therefore they will experience a different level of place illusion.
Therefore, in our opinion, any measurements of place illusion need to implicitly take into account the possible differences between individuals.
Any expected value of place illusion will be a function of the sensorimotor contingencies, but any observed value would vary around the expected one due to the individual differences.

5. Open Questions - PI and Psi

- **PI is part of what VR is** (though it can fail)
  - If fails, can re-form
- **Psi requires deliberate design**
  - If fails, does not re-form
    - Example: if you realise that a virtual human is unaware of you, you lose interest and move on [31]

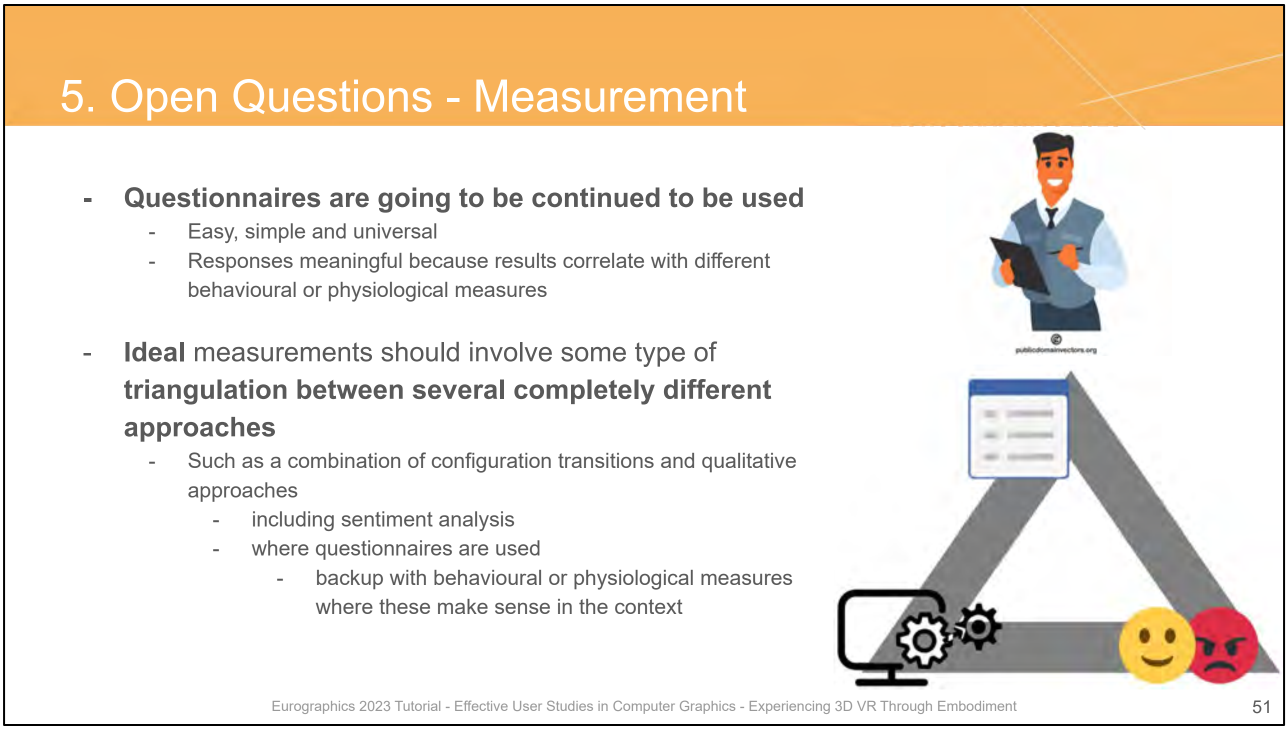
- **Research should focus on Psi:**
  - Under what conditions do people take events and situations in the VR as actually happening?
  - When does it fail?

[31] Garau, M., Ritter-Widenfeld, H., Antley, A., Friedman, D., Brogni, A., and Slater, M. (2004). *Temporal and Spatial Variations in Presence: A Qualitative Analysis, 7th International Conference on Presence.* Valencia, Spain).

When it comes to designing your virtual experiences, we've seen that place illusion might be experienced by default.
But despite that, we might also experience a low plausibility by default.
Place illusion is part of what VR is, though it can fail.
But plausibility requires a deliberate design so that participants buy into your scenario.
And that does not necessarily mean using photorealism nor realism, because a VR scene can be anything, even something that can't happen in real life.

In any case, if place illusion fails momentarily it is likely to re-form again, because sensorimotor contingencies can be recovered.
However, if plausibility fails it won't re-form, and participants will lose interest…

Therefore, we insist that future research should focus more on plausibility, trying to know under what conditions do people take events and situations in the VR as actually happening, and when does it fail.

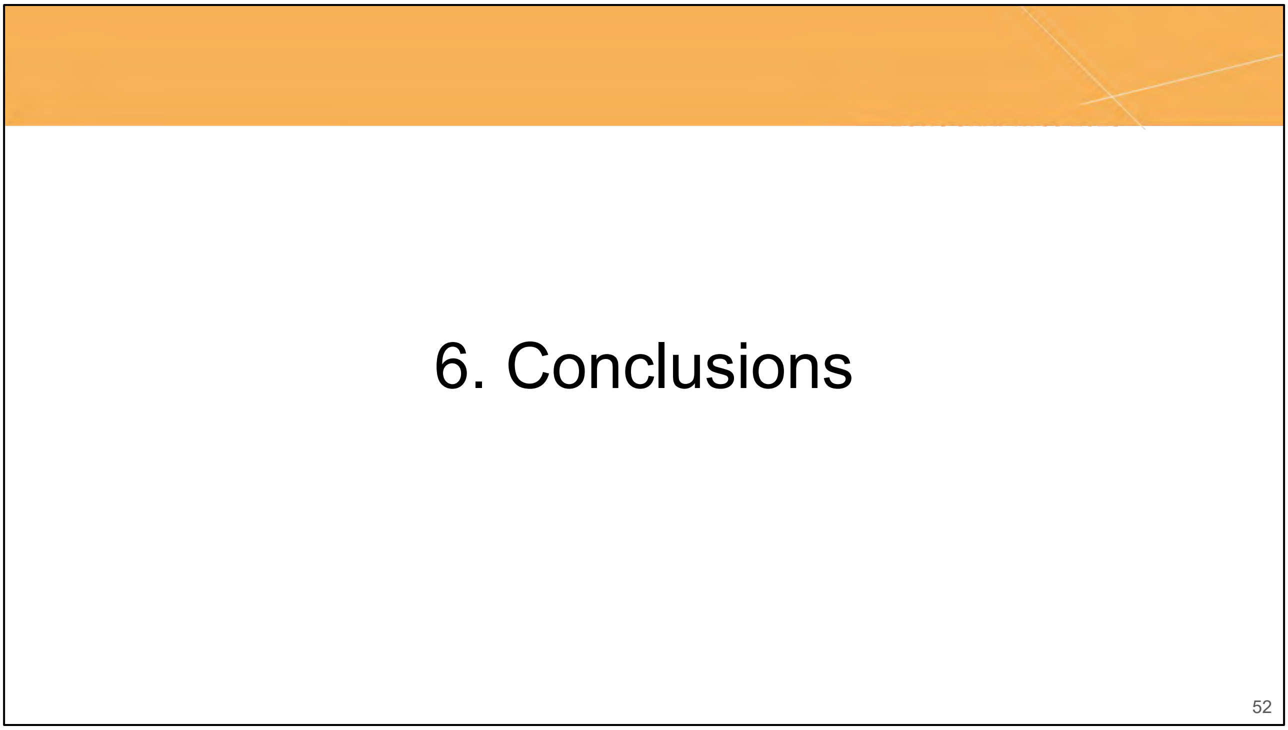


5. Open Questions - Measurement

- **Questionnaires are going to be continued to be used**
  - Easy, simple and universal
  - Responses meaningful because results correlate with different behavioural or physiological measures
- **Ideal** measurements should involve some type of **triangulation between several completely different approaches**
  - Such as a combination of configuration transitions and qualitative approaches
    - including sentiment analysis
    - where questionnaires are used
      - backup with behavioural or physiological measures where these make sense in the context

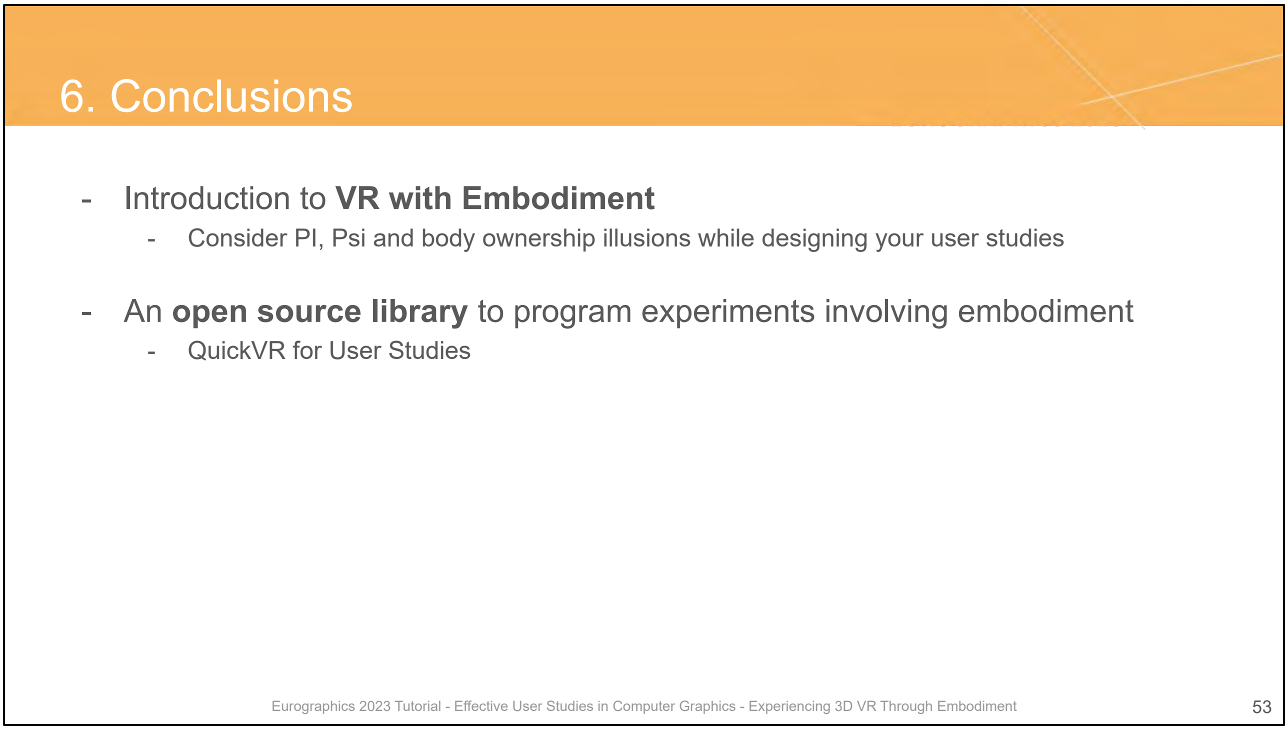
And coming back to the measuring problem, after all, we think that questionnaires are going to be continued to be used
Because we've seen they are easy, simple and universal.
And also their responses are meaningful because the results correlate with different behavioural or physiological measures.

But in the end, we also think that the ideal measurements should involve some type of triangulation between several completely different methods
For example a combination of configuration transitions and qualitative approaches, including sentiment analysis to find possible reasons for the choices of the participants.
Questionnaires can also be used, but backed up with behavioural or physiological measures where these make sense in the context.



6. Conclusions

I will now give you our final conclusions.
We have talked a lot about presence and related concepts.
But the way I see, many of the conclusions we got can be generalized and applied to any general user studies so that we are able to perform them more effectively.

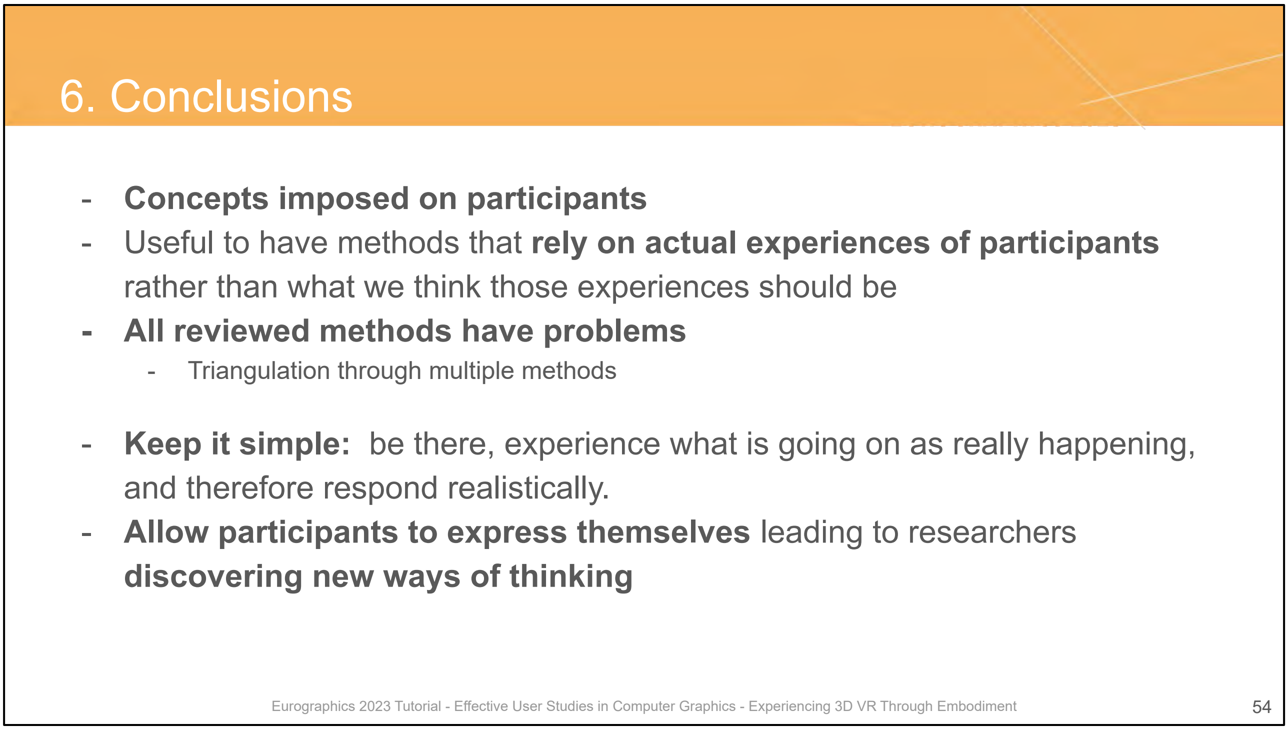


6. Conclusions

- Introduction to **VR with Embodiment**
    - Consider Pl, Psi and body ownership illusions while designing your user studies
- An **open source library** to program experiments involving embodiment
    - QuickVR for User Studies

We have introduced you how VR can be differently experienced through embodiment. You need to understand its importance, and consider presence and body ownership when designing your user studies. Design experiments that promote these illusions, specially Plausibility, to ensure participants respond realistically to the virtual environment.

We have also presented to you QuickVR, an open source library that you can already use to program your own experiments or user studies that involve embodiment into a 3D virtual avatar.
Using QuickVR, you can focus on gathering valuable insights into user behaviour and responses in virtual environments.



6. Conclusions

- **Concepts imposed on participants**
- Useful to have methods that **rely on actual experiences of participants** rather than what we think those experiences should be
- **All reviewed methods have problems**
  - Triangulation through multiple methods
- **Keep it simple:** be there, experience what is going on as really happening, and therefore respond realistically.
- **Allow participants to express themselves** leading to researchers **discovering new ways of thinking**

We have seen how sometimes, unintentionally, we are imposing our research framework and concepts on the participants, probably biasing somehow the results.
It is therefore useful to have methods that rely on the actual experience of the participant rather than on what we think those experiences should be.
We have reviewed many methods to measure presence, but that can be analogously used in other user studies to measure other aspects of computer graphics.
And we have seen that they all have problems.
Then, a good way forward would be to combine psychophysical measures with qualitative methods, including sentiment analysis.
But ideally, an in general, we should try to use some triangulation through multiple methods.

In the end, we should try to keep things simple for participants.
Ask them to be there in the virtual world, or to use your application, and experience whatever you have prepared for them, so that they can respond realistically.
And additionally, we should allow them to express themselves, somehow leading us, the researchers, to discover new ways of thinking.
New ways of thinking about the effects of VR on people, or new ways of thinking about any other field we are exploring.

Acknowledgements

- **People - Event Lab**
  - **Mel Slater**
  - Domna Banakou
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  - Carlos Cabreira
  - Solène Neyret
  - Joan Llobera
  - …
- **Project**
  - Moments in Time in Immersive Virtual Environments (**MoTIVE**)
  - European Research Council Advanced Grant (742989)

Thank you.
Thank you very much for listening.
And to end with this talk, I'd like to thank and acknowledge Mel Slater and all the people of the Event Lab who had contributed to this research.
Especially the ones who participated in the ERC project MoTIVE.

Overview

Good practices for user studies

Experiencing virtual reality through embodiment

Developing computational models with mathematical and neurological insights

Virtual characters

Seeing in depth

Audio in virtual reality

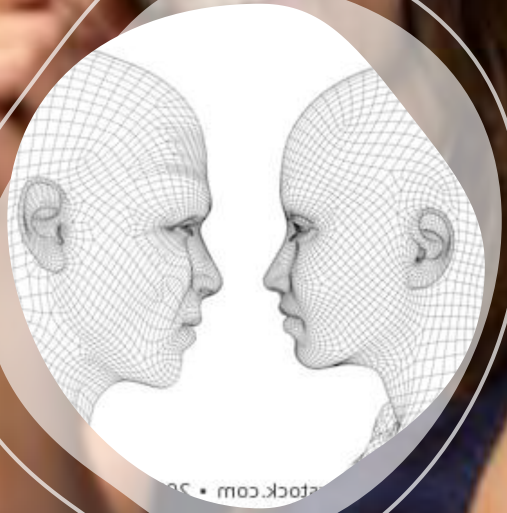
Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

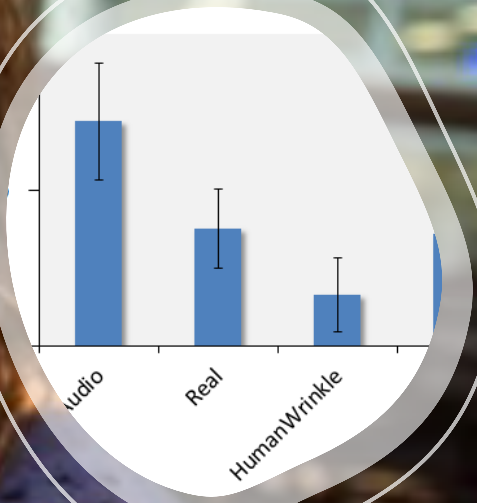
Perception of Virtual HUMANS

Rachel McDonnell
Associate Professor
Trinity College Dublin
Email: ramcdonn@tcd.ie

APPROACH


Motor Function
Sensory Function
Hand skills
Hip
Trunk
Leg
Trunk
Neck
Arm
Fingers
Hand
Face
Arm
Hand
Face
Speech
Language
Hearing
Smell
Vision
Emotions
Posture
Balance
Coordination




udio
Real
HumanWrinkle

METHODS

DIRECT (conscious) measures:

- Subjective response scales (Likert, 2AFC)
- Standardised questionnaires

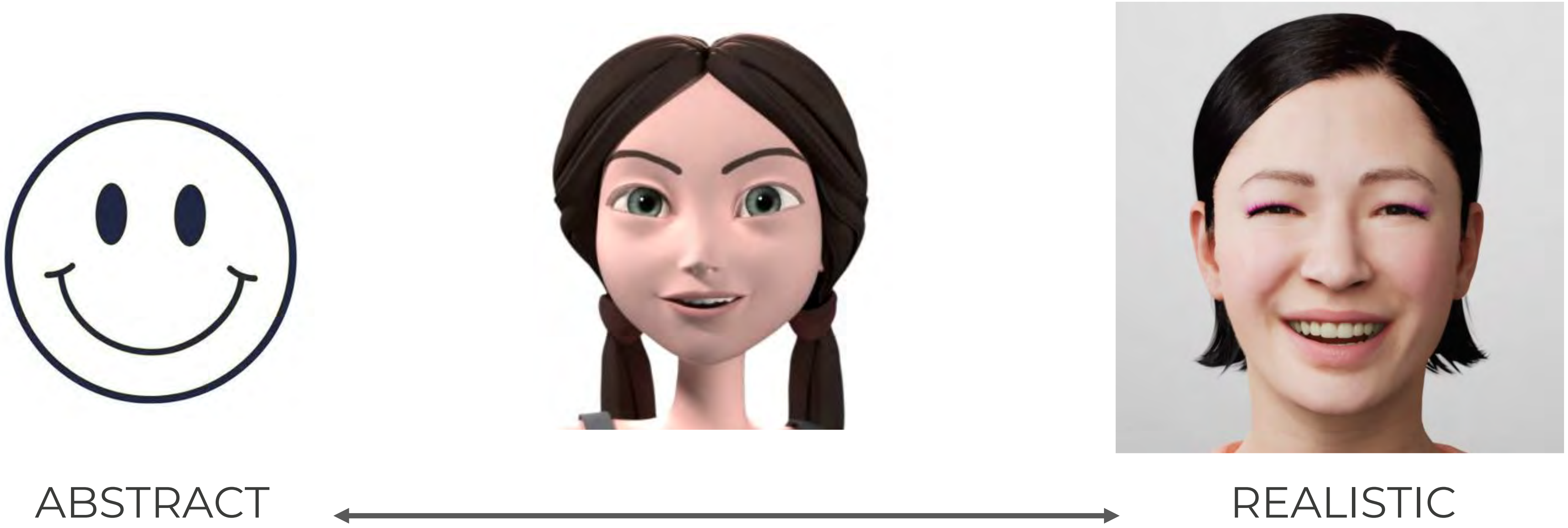
INDIRECT (subconscious) measures:

- Behaviour (decision making)
- Psychophysical response
- Bias, implicit tests (social cognition)

01

MODELING & LIGHTING

SHAPE STYLIZATION



ABSTRACT ⟷ REALISTIC

- The exact classification of a character’s level of realism or stylization is the first issue for perceptual research

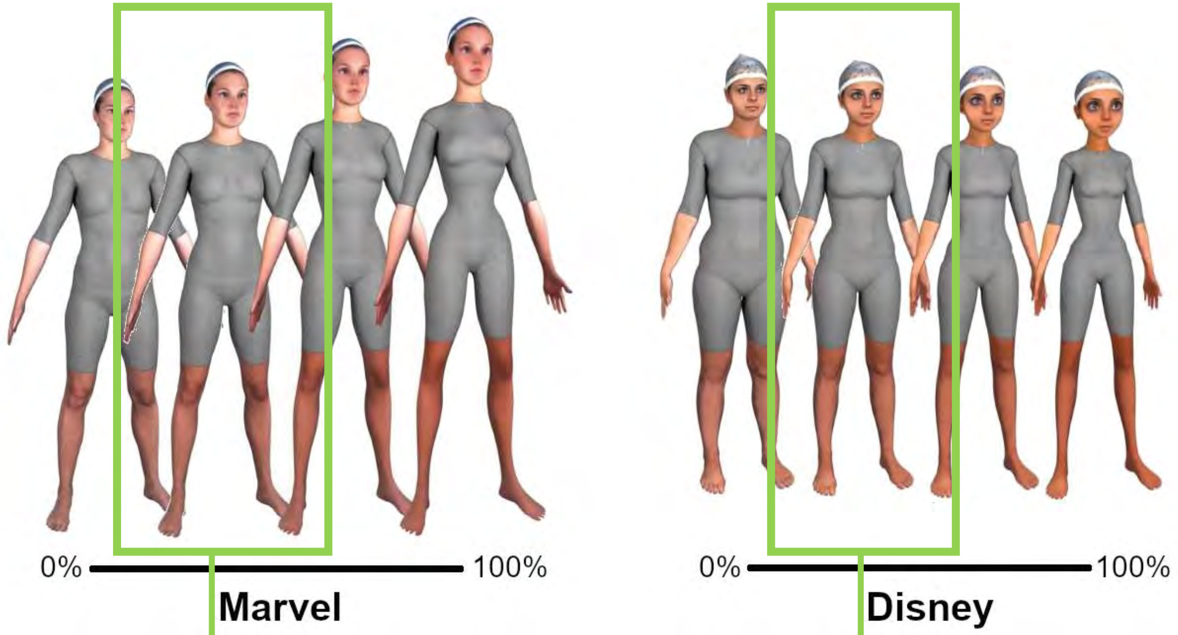
see: [McCloud, 1993; Ritchie et al. 2005]

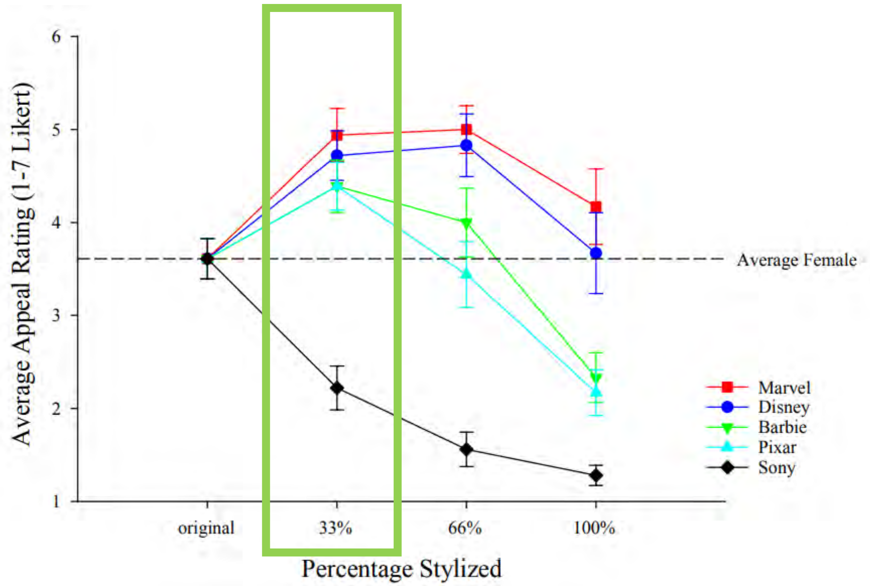
SHAPE STYLIZATION

- Shape is the main predictor or realism
- Changing the geometry is more effective for creating abstract characters than changing the texture

[Zell et al. 2015]

SHAPE STYLIZATION





Still realistic but more appealing,

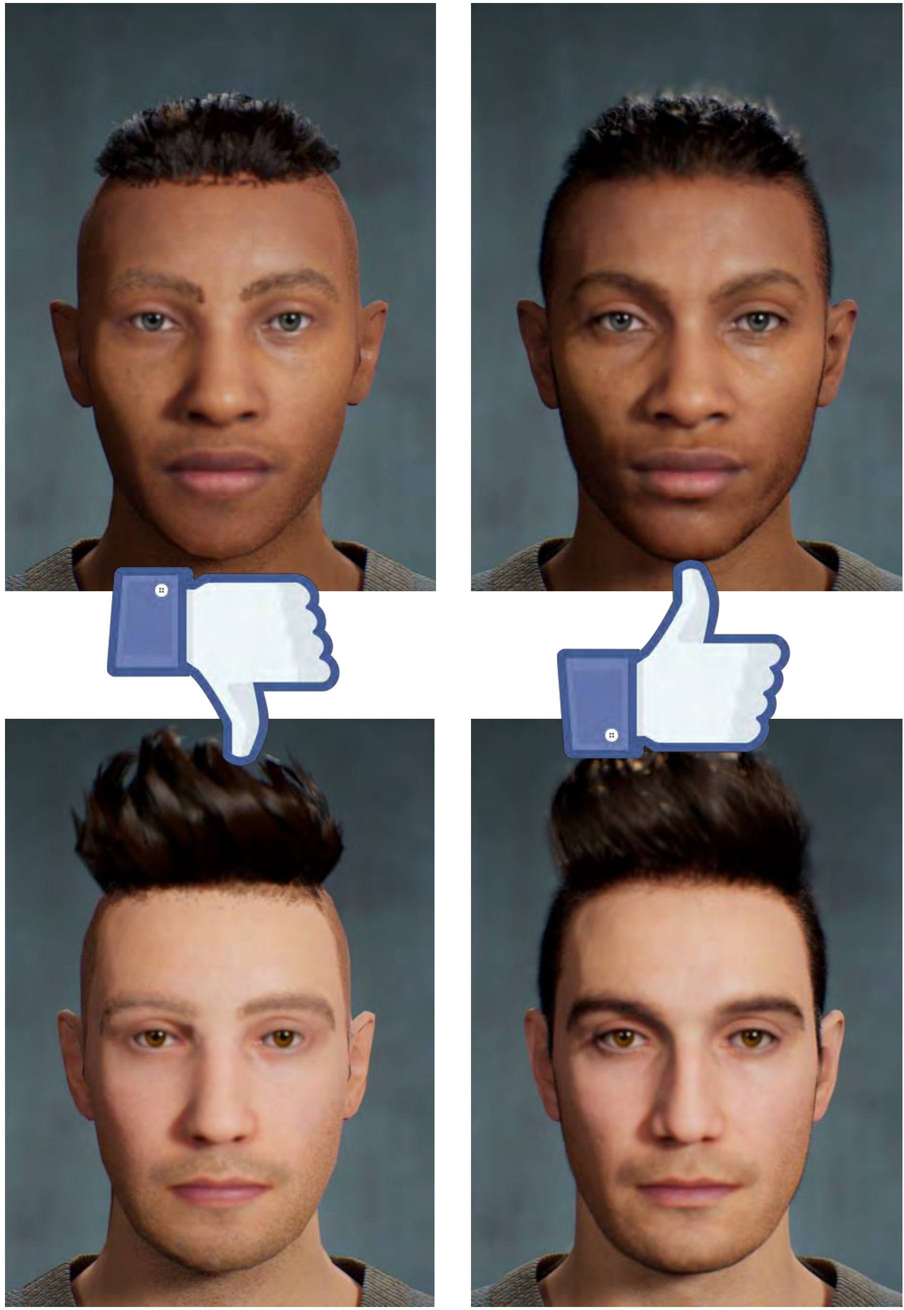
[Fleming et al. 2016]

- 33% morph was perceived in most cases as most appealing but also still as realistic.

LEVEL OF DETAIL

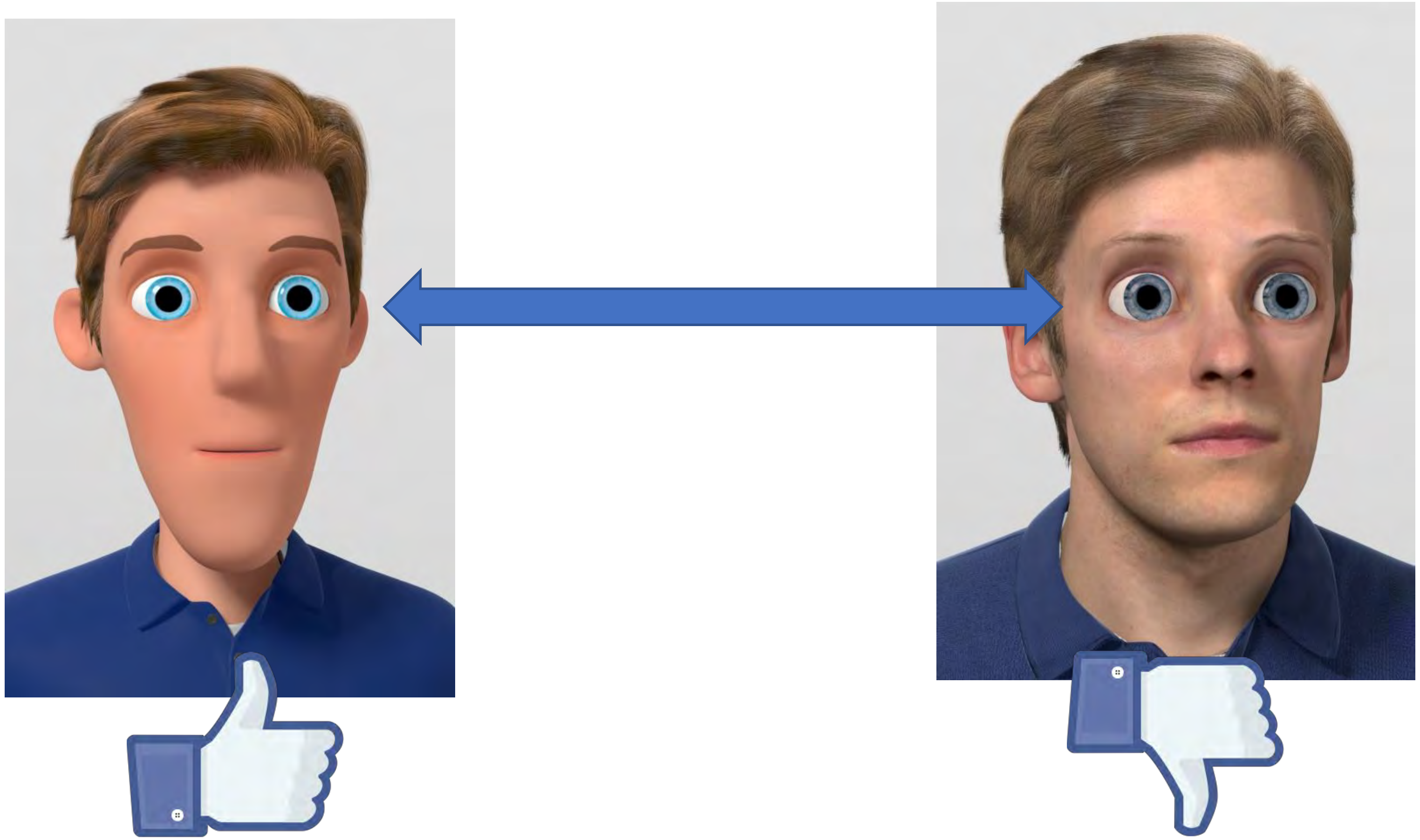
[MacDorman et al. 2009, Burleigh et al. 2013]

- Low resolution characters perceived as less realistic but also less eerie and more appealing
- Newer studies show opposite - higher levels were rated more appealing



[Higgins et al. 2022]

FACIAL PROPORTIONS



- It may seem that the eyes are of different size, but they are in fact the same size

[Seyama and Nagayama 2007; Burleigh et al. 2013]

NATURAL VARIATIONS

HIGH INTELLIGENCE

TRUSTWORTHY

DOMINANT

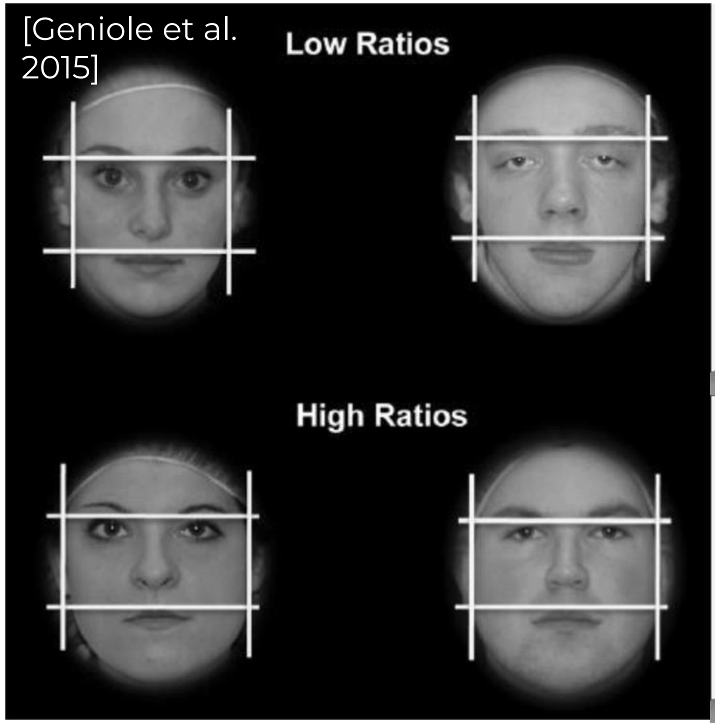
TRUSTWORTHY

- Instant personality trait judgements about based on aspects of their face

FEATURES

- Real faces
  - Wide faces: More dominant, more aggressive, less honest, less appealing
  - Large eyes: Less dominant, more honest

- Virtual faces
  - Realistic – same as real
  - Low realism/non-humanoid - similar results except narrow faces more dominant
  - Evidence that traits alone affect outcomes

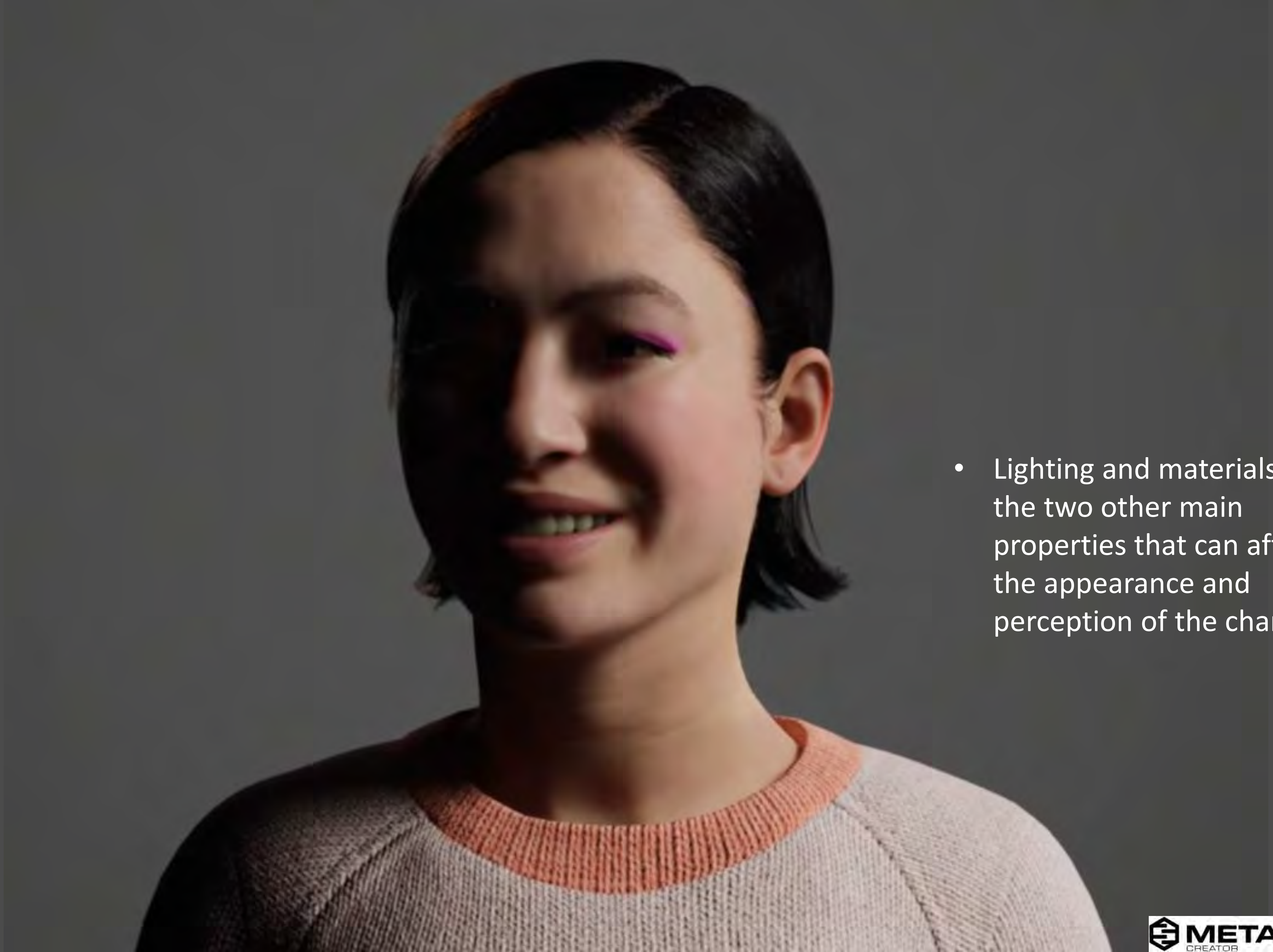

[Geniole et al. 2015]


[Ferstl & McDonnell 2018]


[Wang et al. 2013]


[Ferstl et al. 2016]

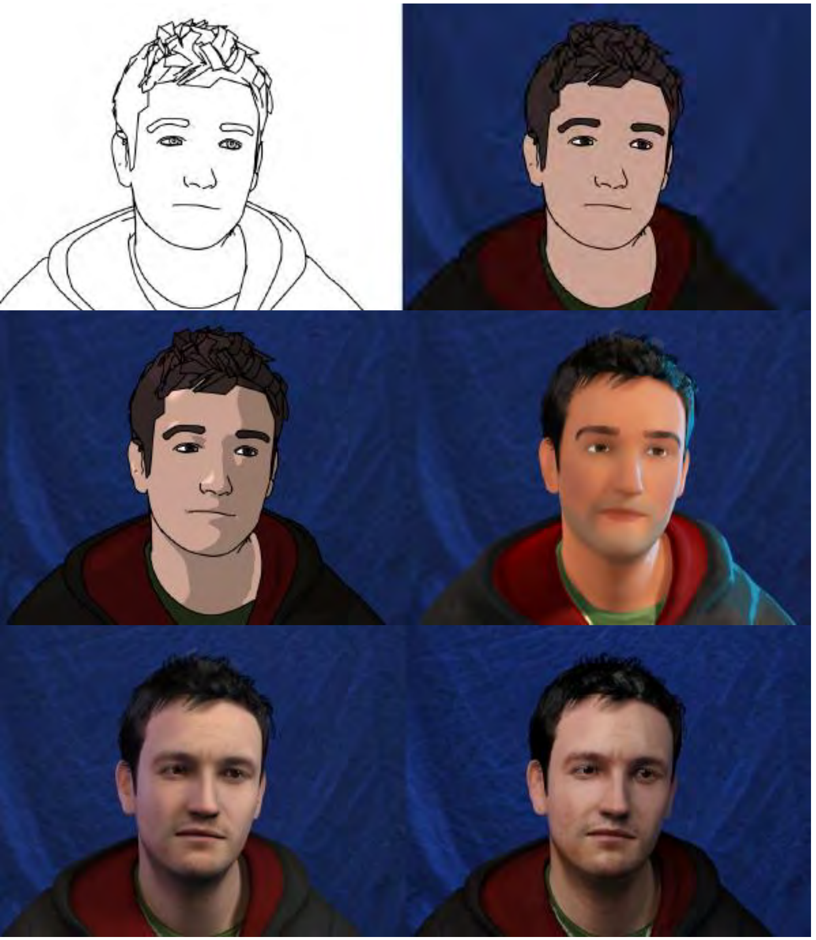

[Song & Luximon 2021]



- Lighting and materials are the two other main properties that can affect the appearance and perception of the character

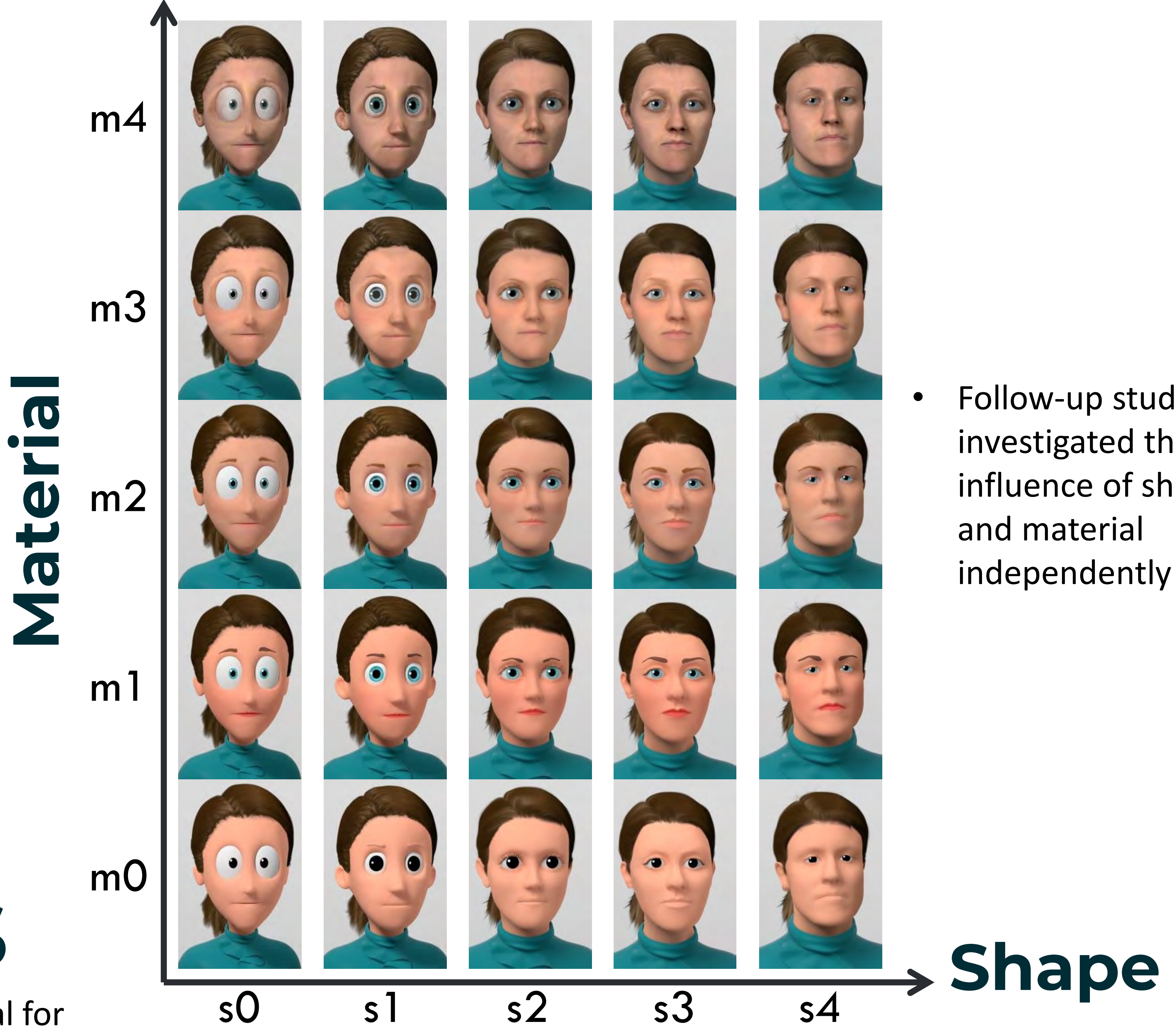
METAHUMAN
CREATOR

MATERIALS



[McDonnell 2012]

- Positive effect of realism, drop in appeal for characters rated in the as ambiguous

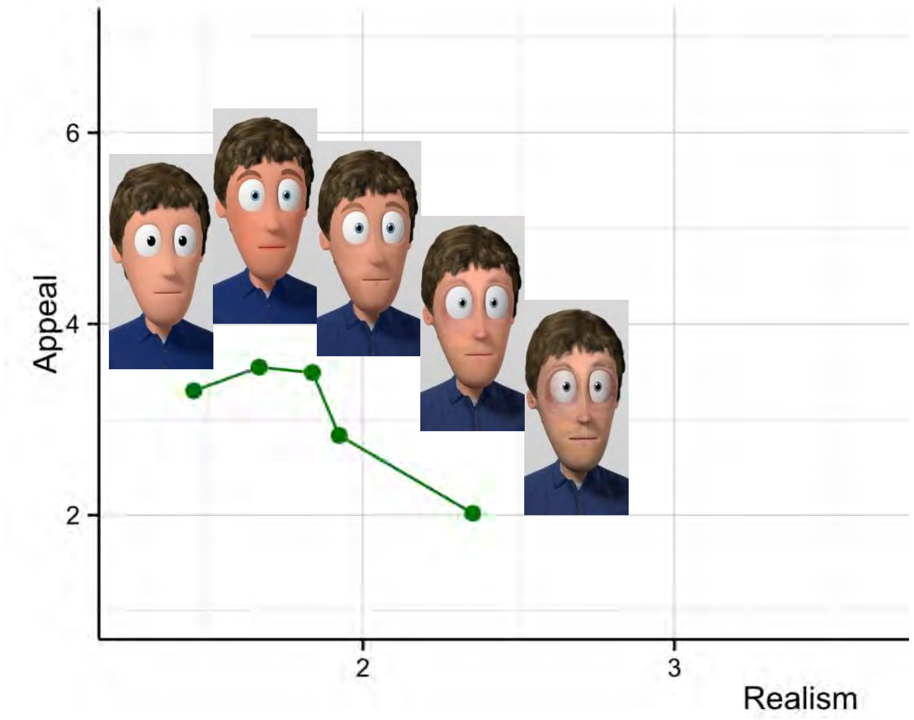


- Follow-up study investigated the influence of shape and material independently

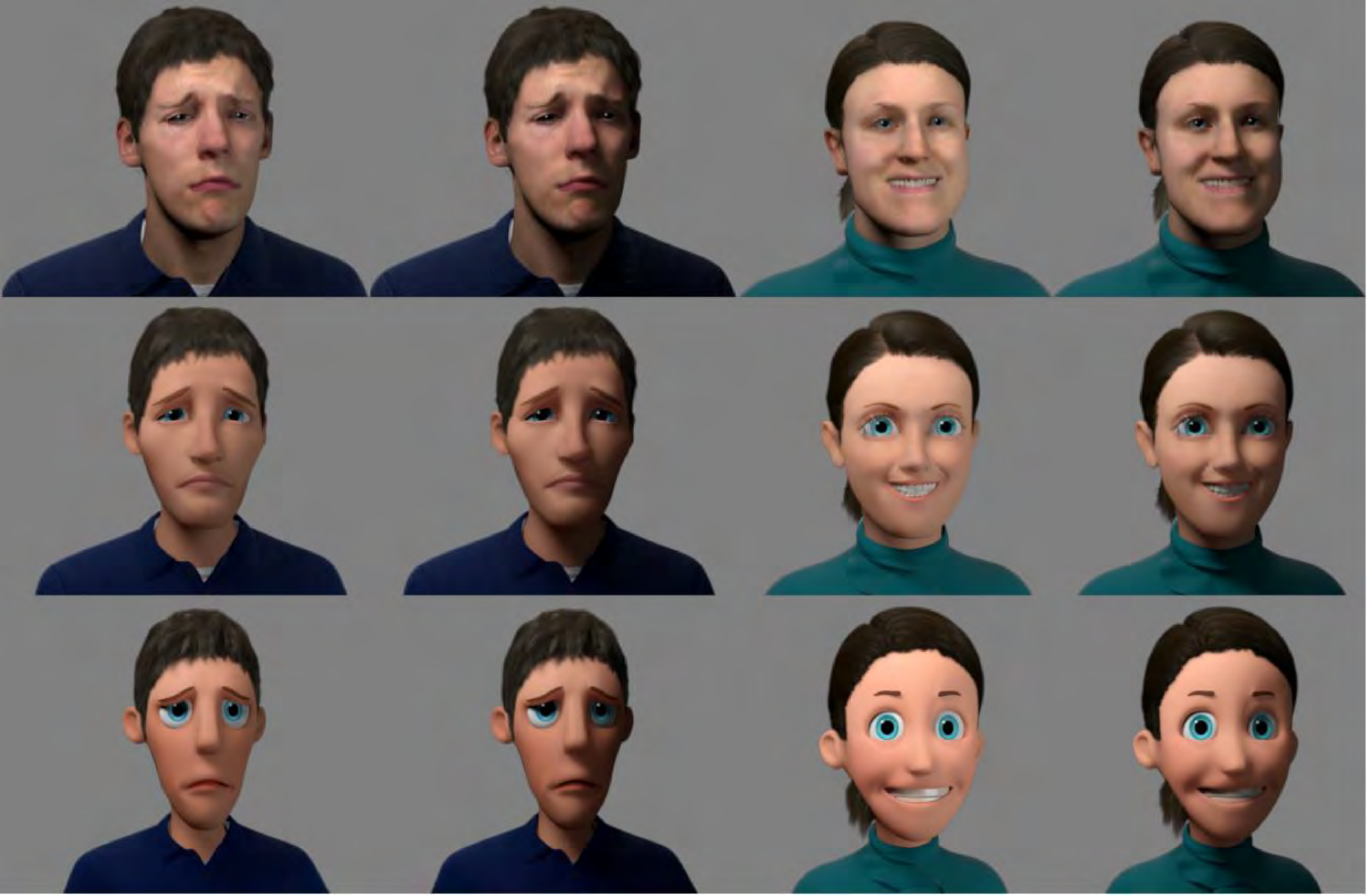
[Zell 2015]

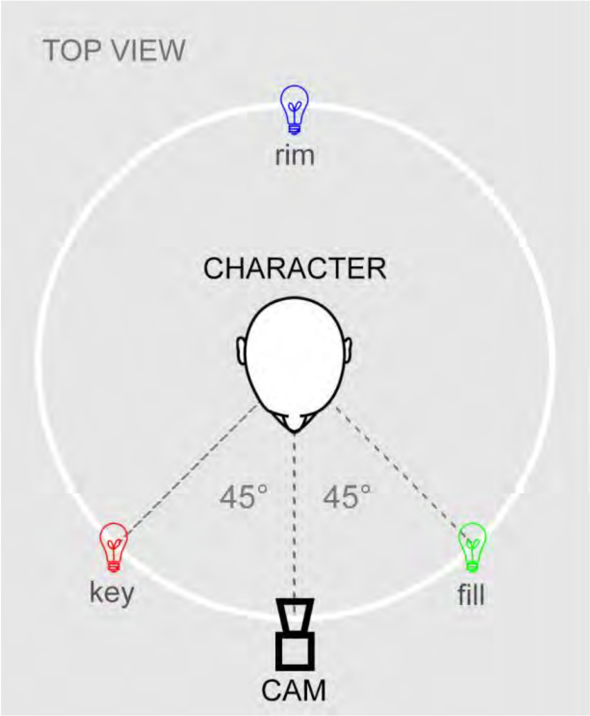
KEY FINDINGS

- Material is main predictor of appeal, attractiveness, and eeriness
- Smoother textures more appealing
- Matching style of material with shape increases appeal
- Hard-to-categorize characters more eerie



LIGHTING

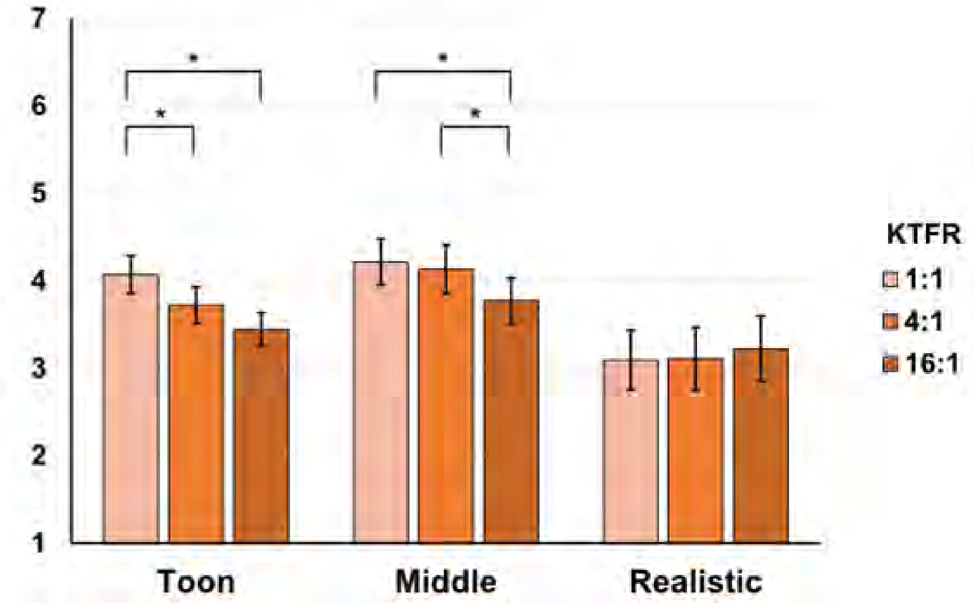


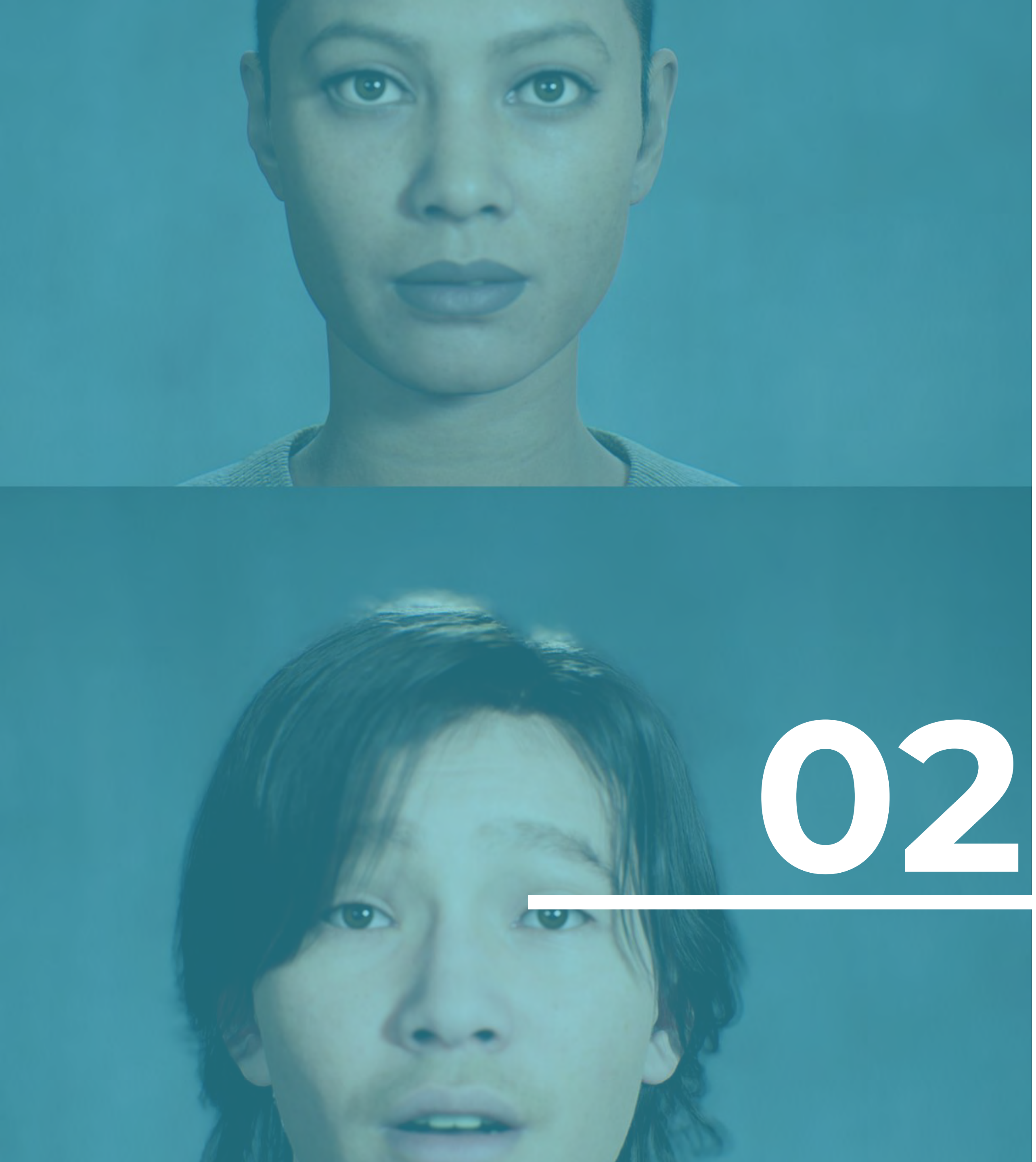


[Wisessing 2020]

KEY FINDINGS

- Brightness of light source improves appeal
- Brightness of light source does not improve eeriness
- Reduce shadow intensity to lower eeriness
- Darker shadows do not affect the appeal of realistic characters





02

SOCIAL INTERACTIONS

SOCIAL PRESENCE

- "Being with another"
- The key component is interaction – the artificial agent should notice and respond appropriately to the user
- The result is social behaviour of the user

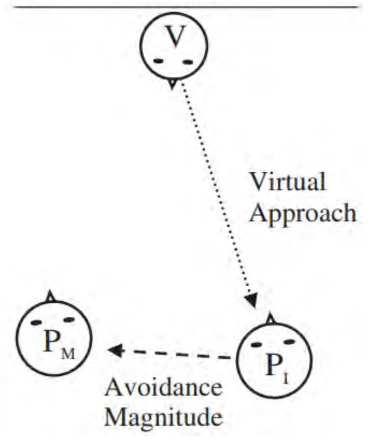
If the character is expressing behaviour (emotions, gestures, …) correctly, the social presence with the character will be stronger, behaviour closer to real life interactions

Examples:

- Proximity (personal space people leave between the character and themselves
- Mimicry (imitating character's gestures, reacting)

[Vogt et al. 2014]

[Slater et al. 2006]



[Bailenson et al. 2003]

REALISTIC ⟷ ABSTRACT

[Zibrek et al. 2019]

- In-lab
- Full embodiment
- Empathy
- Proximity

>622
participants!


www.fraps.com

QUESTIONNAIRE

Empathetic concern

“The girl I just observed made me feel concerned.”

Embodiment

3-item questionnaire

(body ownership when observed in

the mirror, when looking down, when moving)

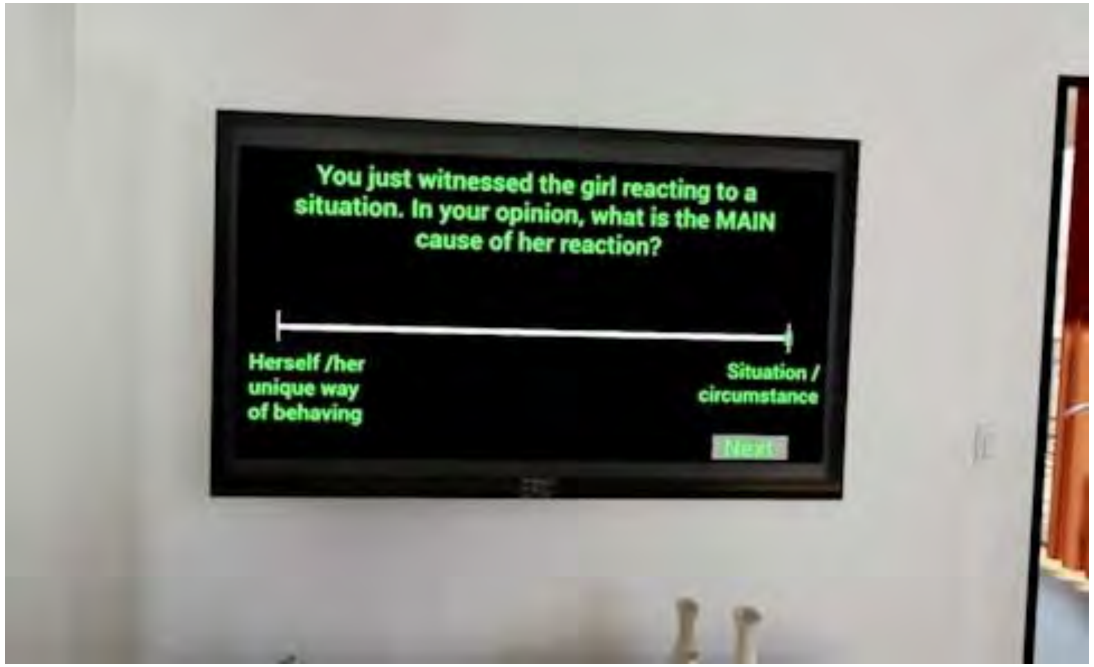
Place Illusion

“I have the sensation of being in a living room”

Social presence

5-item questionnaire

SOCIAL PRESENCE QUESTIONNIARE (Bailenson et al. 2005)

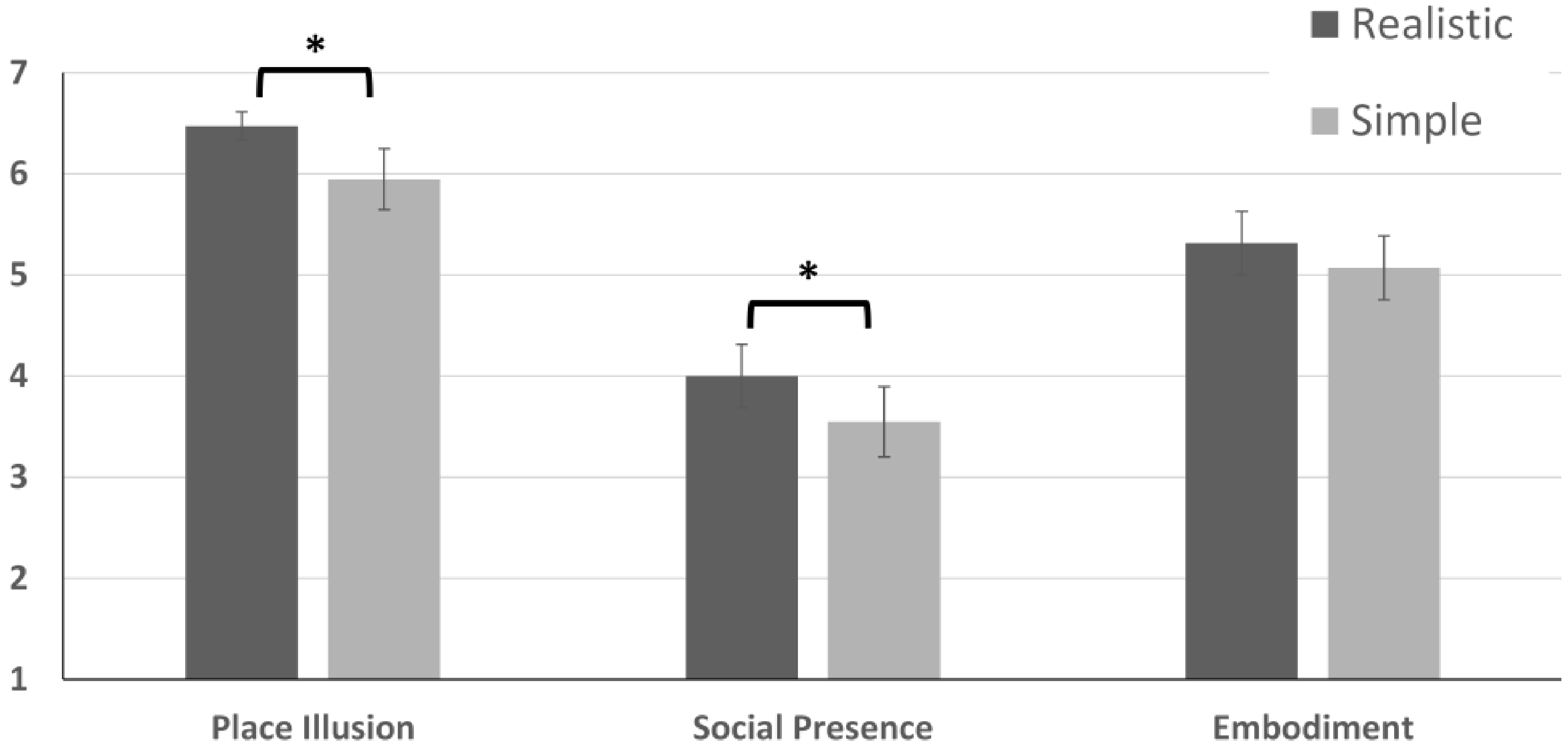


You just witnessed the girl reacting to a situation. In your opinion, what is the MAIN cause of her reaction?

RESULTS

H1: Realistic style increased place illusion and social presence ✓

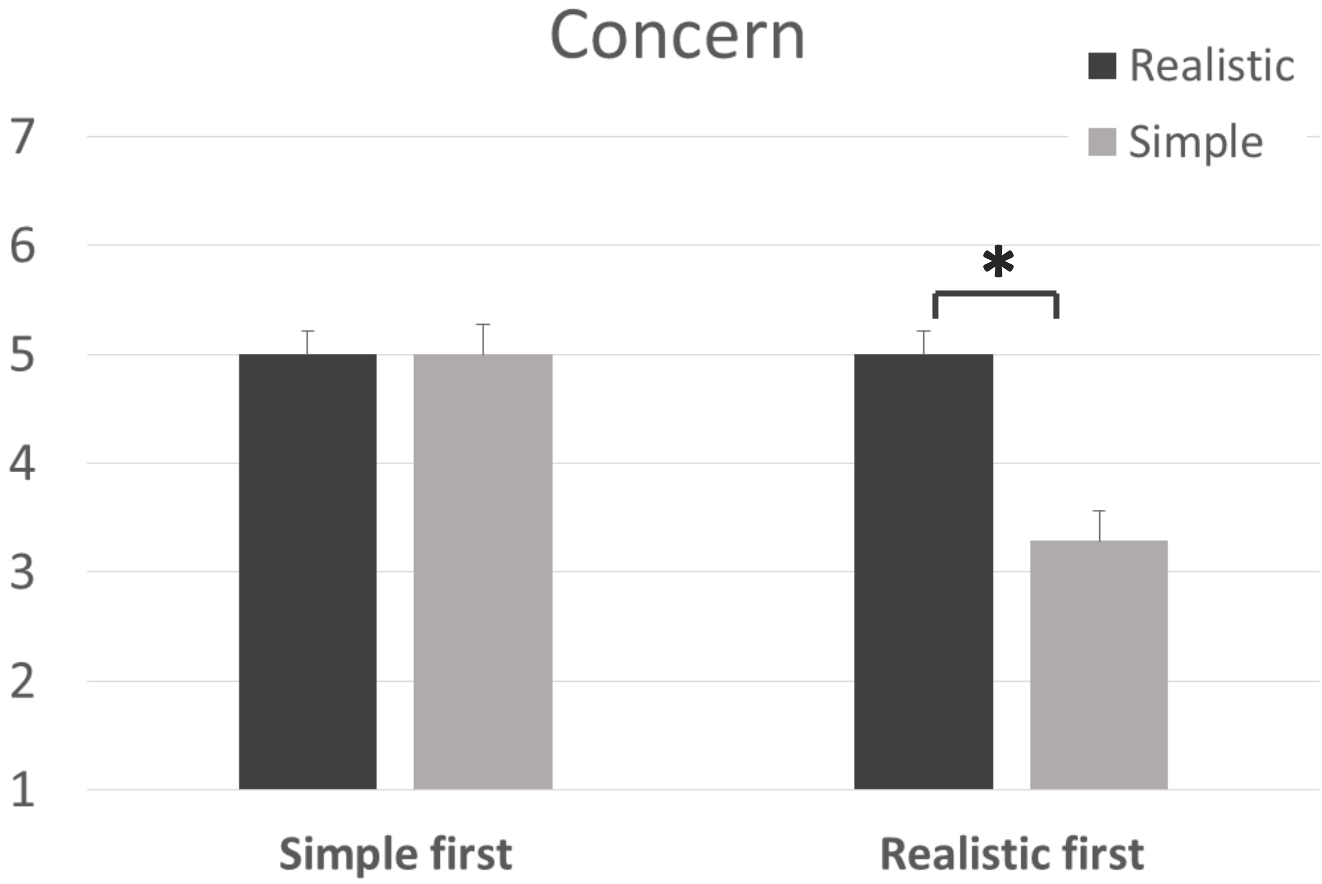
(Social presence effect only when using embodiment)



RESULTS

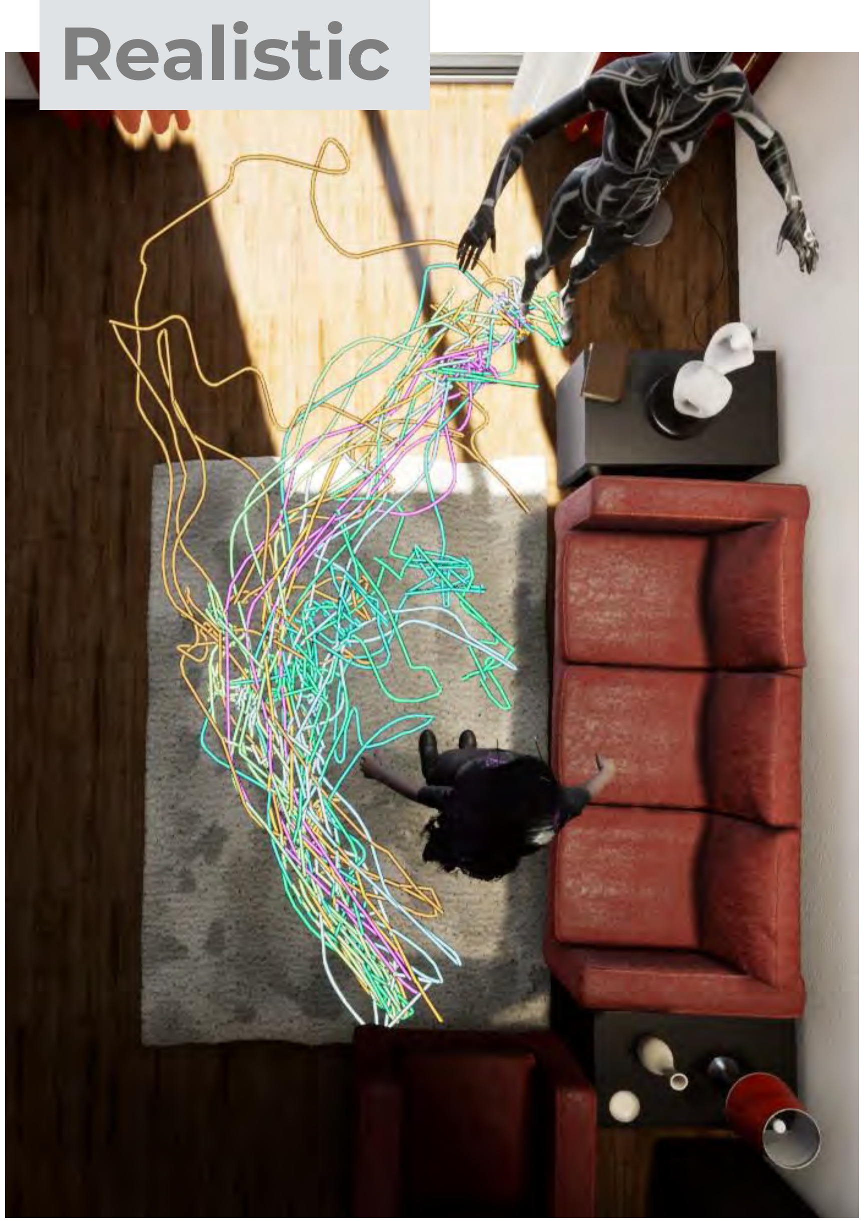
✗ ✓ H2: Realistic style will increase the empathetic response of participants

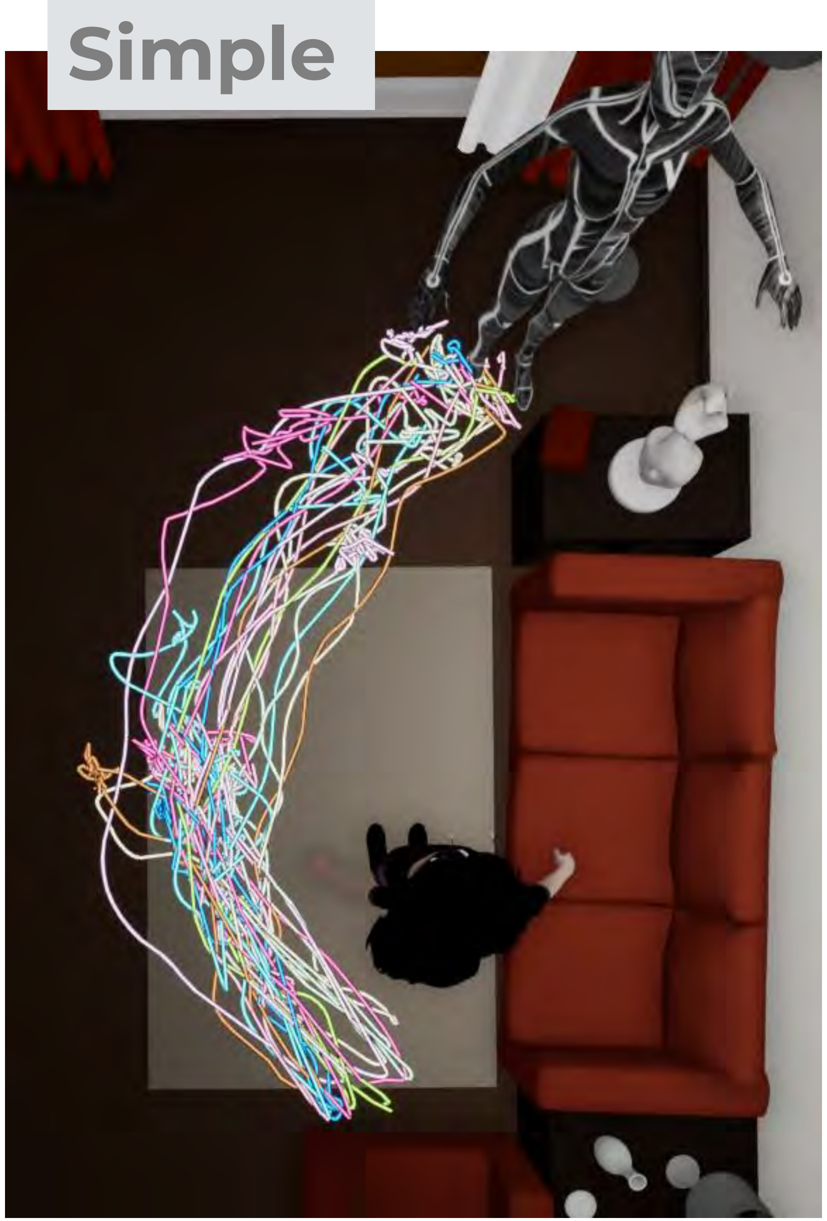
Higher concern for sad photorealistic character



RESULTS

- ✗ H3: Realistically rendered character will increase proximity distance

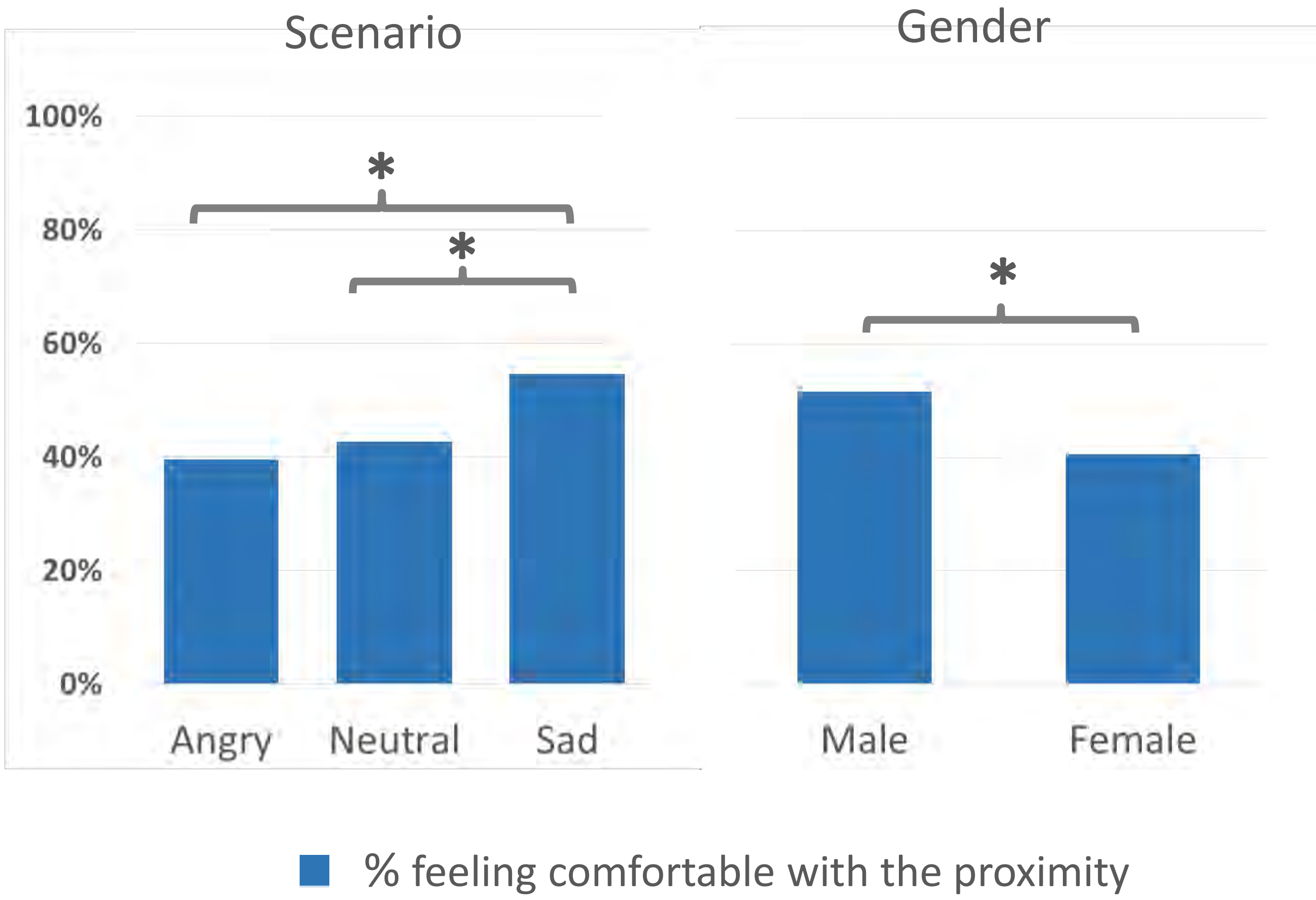




RESULTS

Proximity

- ✗ No difference according to realism
- ✓ Comfortable with Sad character
- ✓ Effect of gender
- ✓ Interesting character (zombie)



BODY OWNERSHIP

- Body Ownership
  the illusory perception a person might have that an artificial body or body part is their own, and is the source of their sensations [Tsakiris 2010]

- Representation?
  - Realism does not affect ownership when congruent visuo-tactile and visuomotor cues are provided [Maselli & Slater 2013]
  - Higher ownership for self-avatars [Gorisse et al. 2019]
  - Behaviour modification [Yee et al. 2007]

synchronous visuotactile stimulation

[Kokkinara & Slater 2014]

visuotactile synchrony

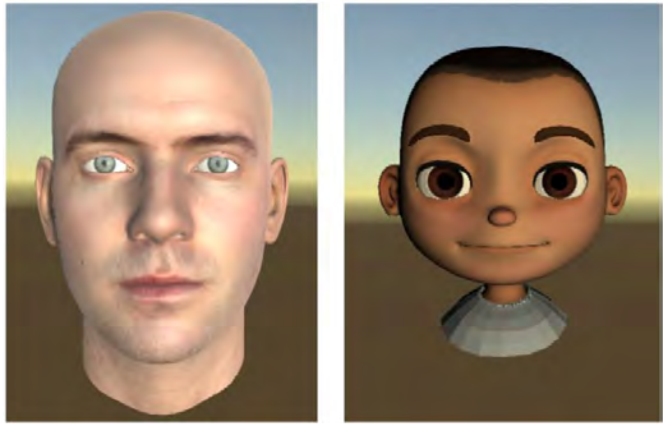
visuomotor

FACE OWNERSHIP

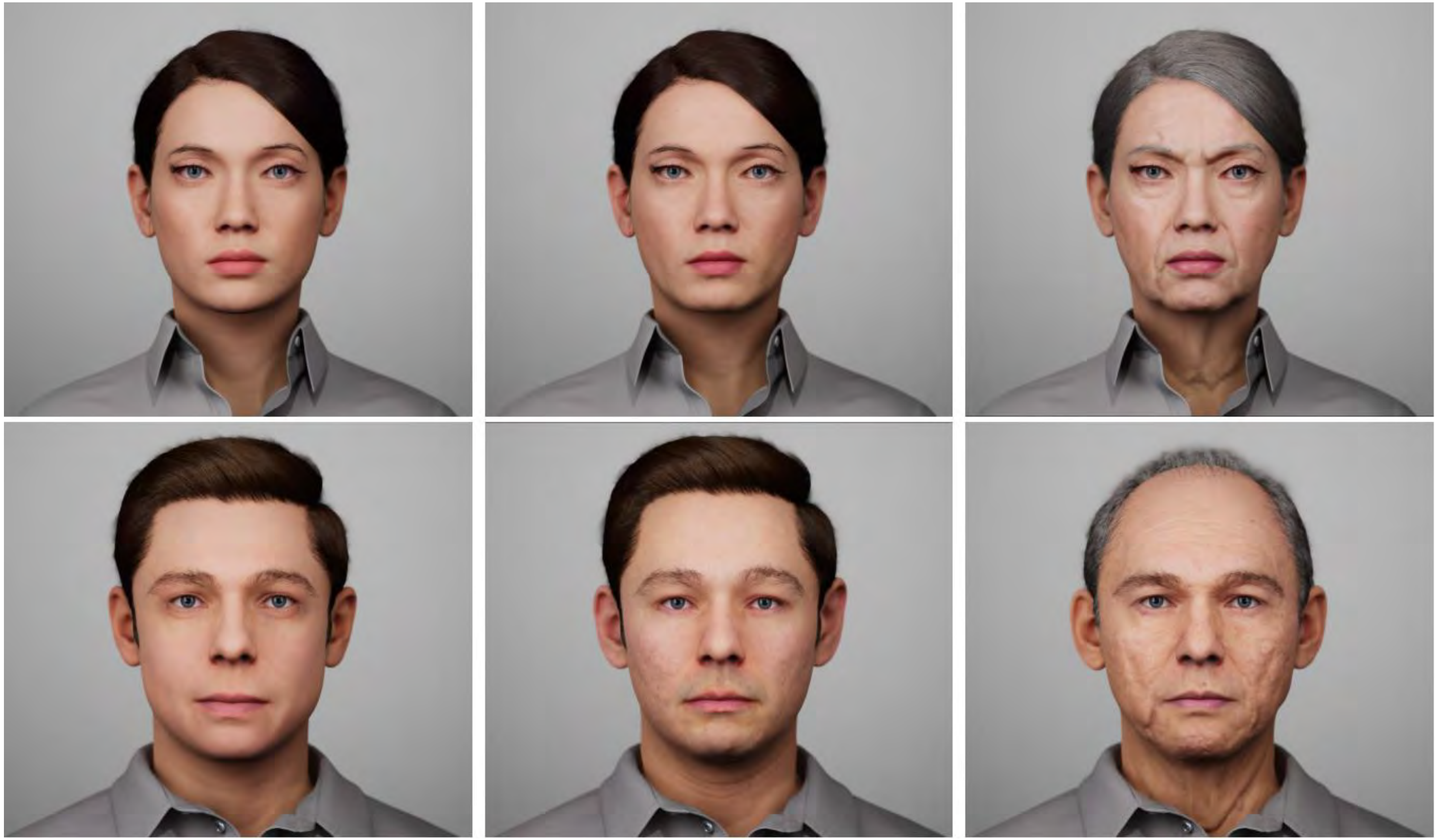
- Fewer studies on face ownership
- Real-time tracking
    - High levels of ownership

- Representation
    - Cartoon and Realistic equal ownership [Kokkinara & McDonnell 2015]
    - Realistic higher ownership than cartoon (but lower agency) [Ma et al. 2022]

[Ma et al. 2022]



[Kokkinara & McDonnell 2015]



- Facial ownership levels similar regardless of avatar age [Jordan et al., IEEE VR, 2023]

AVATAR VIDEO-CONFERENCING

Can avatars be used effectively in video-conferencing?
Do cartoon representations inhibit valenced conversations?

[Higgins et al. 2021]

AVATAR VIDEO-CONFERENCING

Can avatars be used effectively in video-conferencing?
Do cartoon representations inhibit valenced conversations?

MOOD INDUCTION PHASE

CONVERSATION

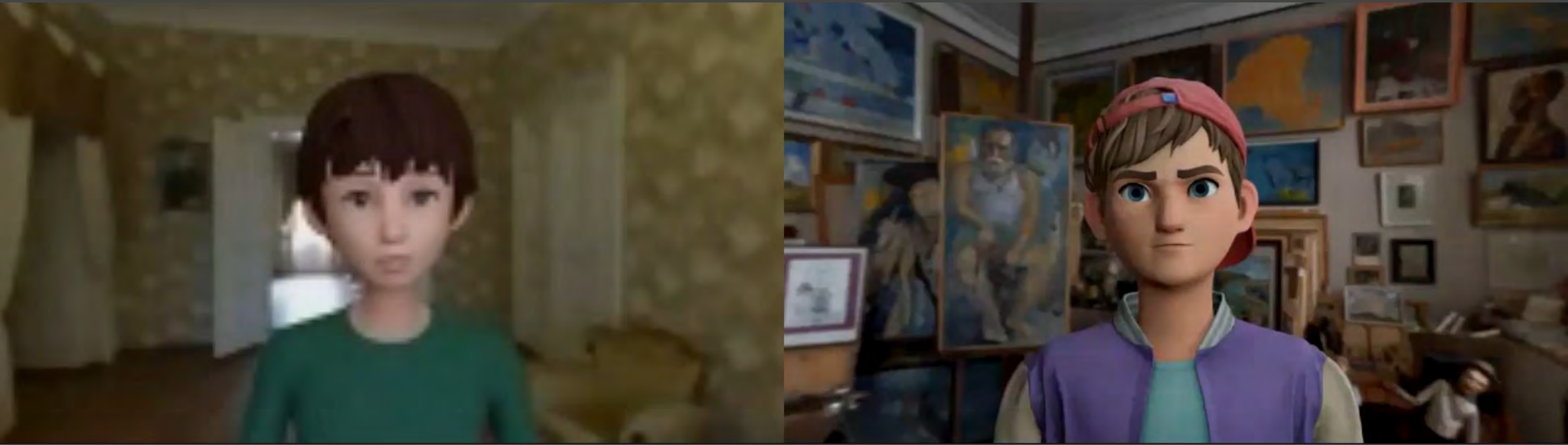
QUESTIONNAIRE

[Higgins et al. 2021]

Participant

Experimenter

Excerpt of conversation following the positive valence video



Participant

Experimenter

Excerpt of conversation following the negative valence video

RESULTS

- ✓ Avatars can be effective for remote collaboration
- ✓ Cartoon avatars appropriate for positive & negative valence conversations
- ✓ Fatigue scores were low
- ✓ Higher social presence than non-video conditions

03

CONCLUSION

Complexity of interactions

- Render style, lighting, materials, shape

Virtual human appearance affects how we behave

- Social distance
- Trustworthy
- Ethical implications?

Future lots of interactions with virtual humans

- More studies needed!

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Overview

Good practices for user studies

Experiencing virtual reality through embodiment

Developing computational models with mathematical and neurological insights

Virtual characters

Seeing in depth

Audio in virtual reality

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

Effective User Studies in Computer Graphics: **Audio in Virtual Reality**

Mauricio Flores Vargas

Auditory Feedback

Essential component in the perception of our environment.

Influences how we perceive and interact with the world.

Localization information

Environmental cues

Emotional expression

Object Attributes

Spatial Audio

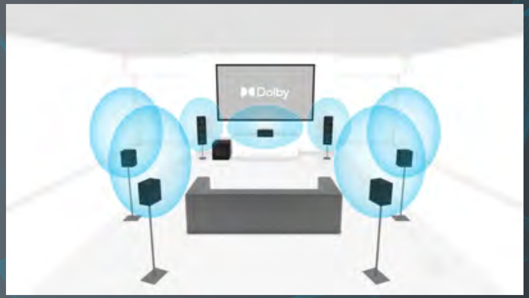
Allows listeners to perceive sounds coming from multiple directions around them.

3D audio? = Adding vertical components to provide height information.

2D Surround

+

Height Info



360˚ Immersive

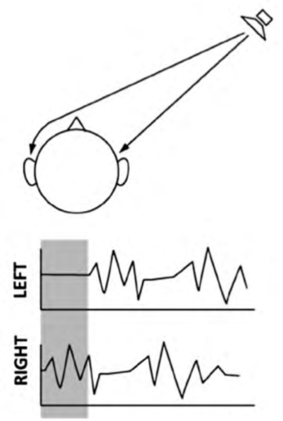
https://www.dolby.com/about/support/guide/speaker-setup-guides/

Sound Source Localization

> Locate sounds using a set of perceptual features to estimate a sound source's specific position and distance.

Interaural Time Difference (ITD)

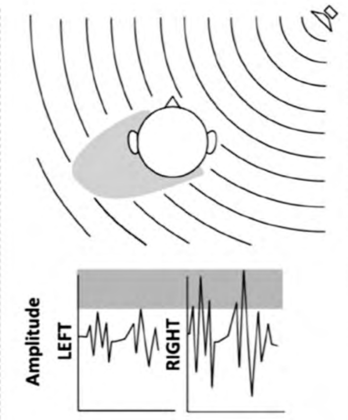
Delayed arrival of the signal to the ear furthest from the source.



(Sennheiser, J., 2004)

Interaural Level Difference (ILD)

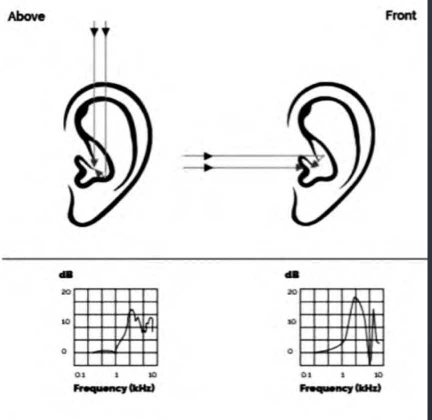
Level difference of the signal caused by the head occlusion.



(Sennheiser, J., 2004)

Monoaural Cues

Spectral deviation of the signal caused by our body (HRTF!).



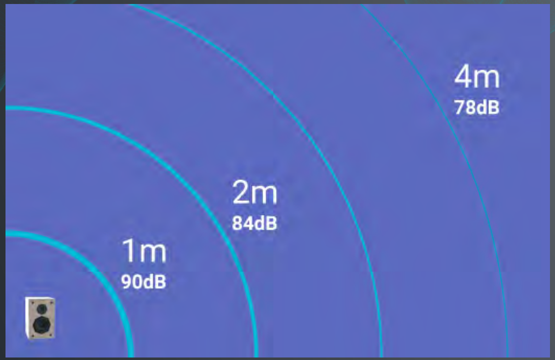
(Sennheiser, J., 2004)

Distance

Ability to perceive the distance of sound sources from the listener.

Amplitude Attenuation

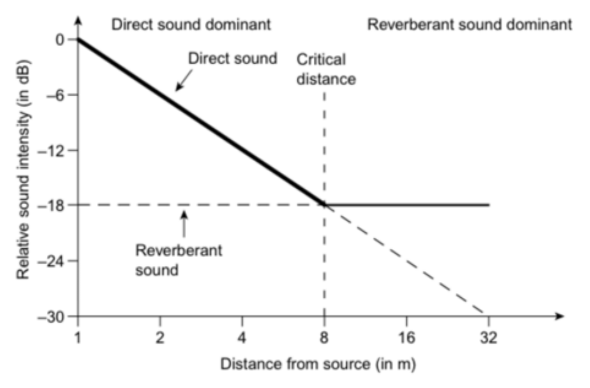
Sound level decreases as the distance to the listener increases.



(Resonance audio 2018)

Direct-to-Reverberant Ratio

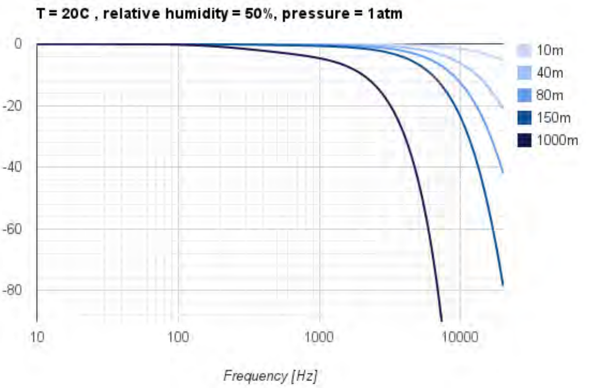
Difference between the direct signal and acoustic reverberation levels (indoors).



(Kaplanis, Neofytos & Velzen, José, 2012)

Frequency absorption

High-frequency decay with distant sounds (outdoors).



(T.wozniak , 2014)

Externalization

> Perception that sounds appear to come from outside our head.

Externalized

Sound source

Listener

Internalized

Listener

Signal will be externalised as long as it has clear perceptual cues.

Room Auralization

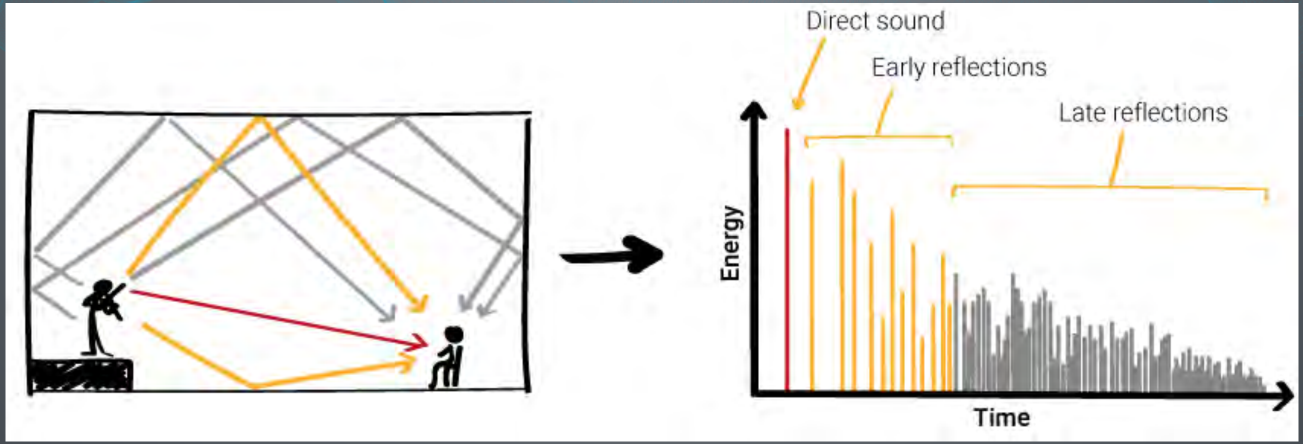
> Simulation of the acoustic response of a space or environment.

Early Reflections

First sound reflections to reach the listener's following the direct sound.

Reverberation

First sound reflections to reach the listener's following the direct sound.



(Ateliercrescendo, 2021)

Audio in VR

Replace the existing sounds in the environment with virtual ones.

Spatial Audio in Immersive Visual Environments

Presence

Sense of “being there” experienced in IVEs.

Plausibility

Situations and events in an IVE are really happening.

Interaction

Correlated reactions between the user and the IVE.

Embodiment

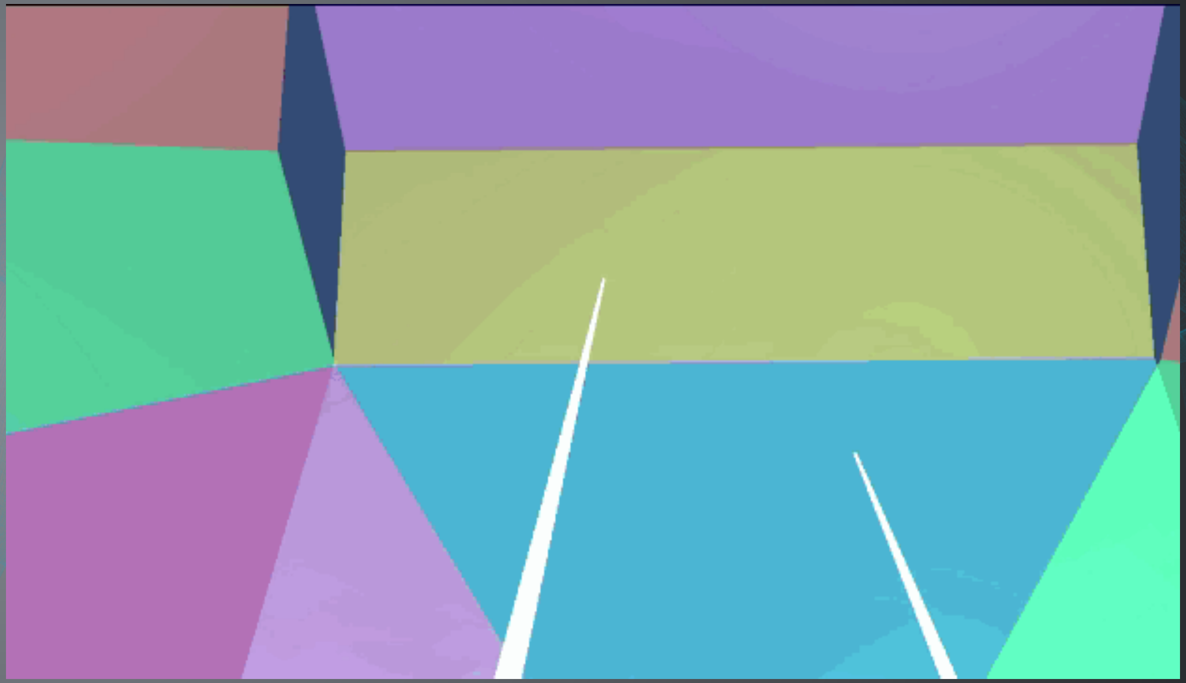
Perception of avatar an as one's own body.

Benefits of Audio feedback in VR

- Audio feedback is omnidirectional.
- Provides a constant stream of information as it is always turned on.
- Does not clutter the limited visual real-estate.
- Additional dimension of feedback for multisensory integration in VR.
- Provides shorter interaction times compared to visual feedback.

Uses of Audio feedback in VR

- Action-based audio feedback on interactions.
- Direct users’ gaze and attention.
- Create environment sounds or soundscapes.
- Provide information about the virtual environment.
- Maximise the immersiveness of VR environments.



Audio Rendering Techniques in VR

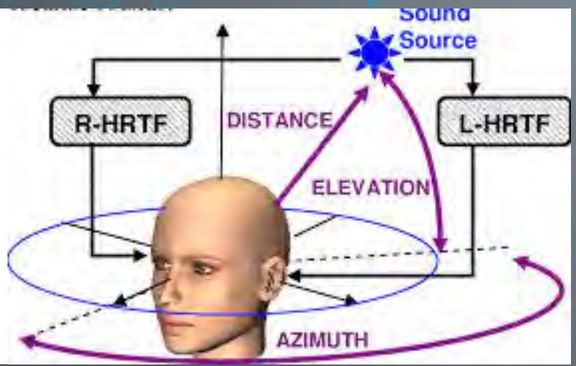
Binaural

- Capture designed to mimic the position of the human ears and reproduced over headphones.
- HRTF convolution is crucial for rendering. Spatial accuracy depends on the listener's physical attributes.

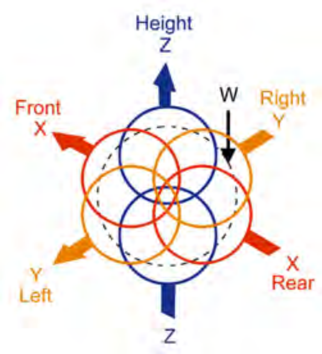
Ambisonics

- Capture of a full 360˚ sound field using a spherical mic array reproduced over multiple channels.
- Spatialization accuracy depends on the number of channels used for rendering (ambisonics orders).

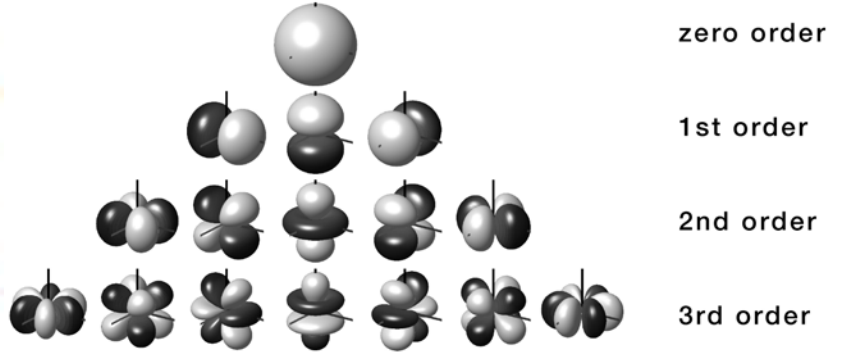
Dummy head Neumann, NA).



(Faller et al., 2007)



(Trail Mix Studios, NA).

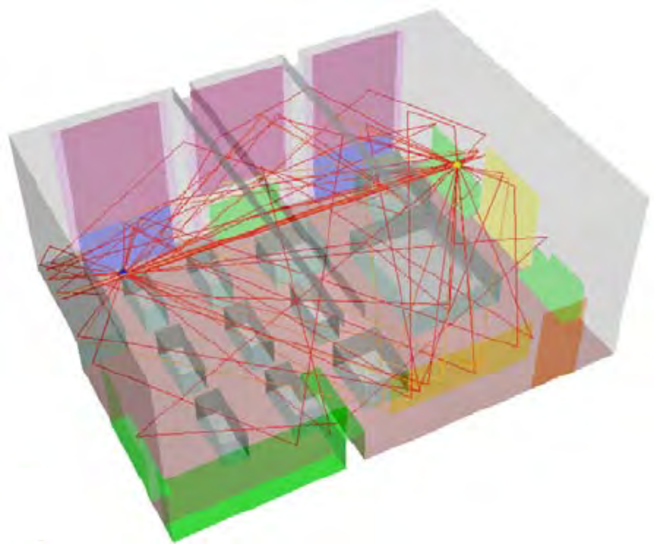


(Zotter et al., 2019)

Acoustic Modelling Techniques in VR

Geometric Acoustics

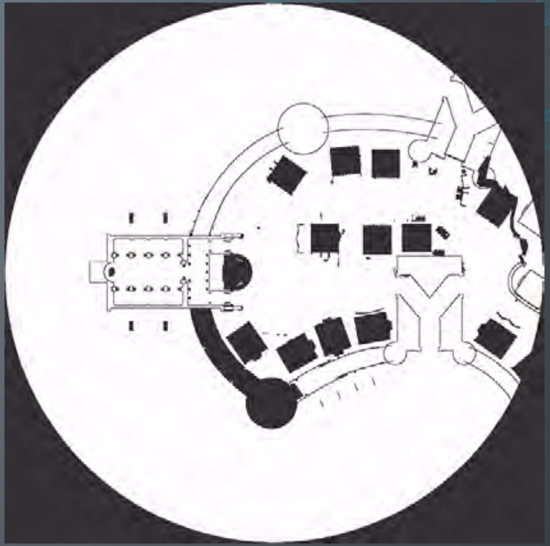
Ray-based simulation that depicts sound travelling from the sound source to the listener, reflecting and scatting off surfaces.



(Pelzer et al., 2014)

Wave Acoustics

Wave-based simulation that uses uniform discrete grids which update pressure amplitude in each cell at each time-step.



(Kevinasg,NA)

Spatial Audio Tools

Spatial Audio Plugin Suites

- VST plugins for DAWs & Video Editing software.
- Track head position using plugins and head-tracking devices (Waves NX, RJ Lab, Supperware).
- Track head position in game engines and transfer data via OSC or UDP.
- Mainly 3 DOF content and 360˚ video.

IEM Plug-in Suite

Noise Makers

Blue Ripple Sound

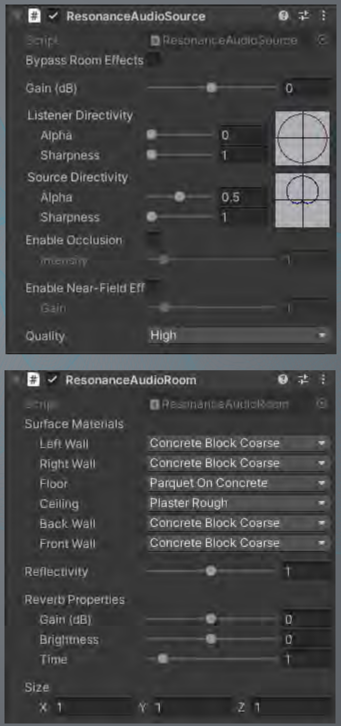
DearVR

Spatial Audio Tools

Audio Spatializers

- Audio plugin SDK for game engines and audio middleware.
- Track head position directly in the Game engine using mainly HMDs.
- Higher level of Interactive design (IVEs and 6DOF).
- Integration with VR platforms (Oculus & Steam).

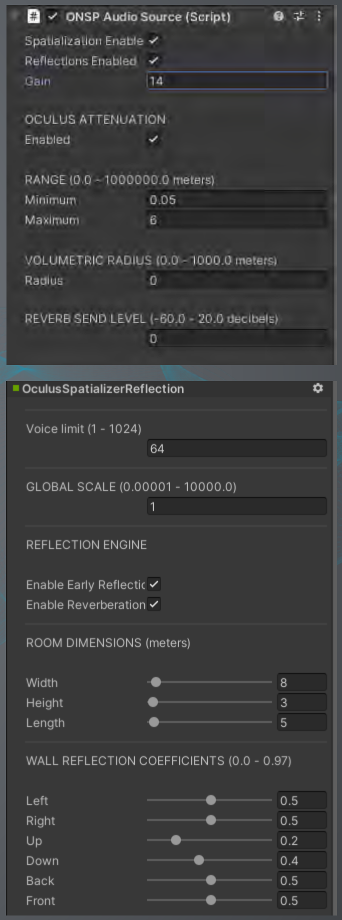
Resonance



ResonanceAudioSource
Script: ResonanceAudioSource
Bypass Room Effects ☐
Gain (dB) 0
Listener Directivity
  Alpha 0
  Sharpness 1
Source Directivity
  Alpha 0.5
  Sharpness 1
Enable Occlusion ☐
  Intensity 1
Enable Near-Field Eff ☐
  Gain 1
Quality High

ResonanceAudioRoom
Script: ResonanceAudioRoom
Surface Materials
  Left Wall: Concrete Block Coarse
  Right Wall: Concrete Block Coarse
  Floor: Parquet On Concrete
  Ceiling: Plaster Rough
  Back Wall: Concrete Block Coarse
  Front Wall: Concrete Block Coarse
Reflectivity 1
Reverb Properties
  Gain (dB) 0
  Brightness 0
  Time 1
Size
  X 1 Y 1 Z 1

Oculus



ONSP Audio Source (Script)
Spatialization Enable ✓
Reflections Enabled ✓
Gain 14

OCULUS ATTENUATION
Enabled ✓

RANGE (0.0 - 1000000.0 meters)
Minimum 0.05
Maximum 6

VOLUMETRIC RADIUS (0.0 - 1000.0 meters)
Radius 0

REVERB SEND LEVEL (-60.0 - 20.0 decibels)
0

OculusSpatializerReflection
Voice limit (1 - 1024)
64

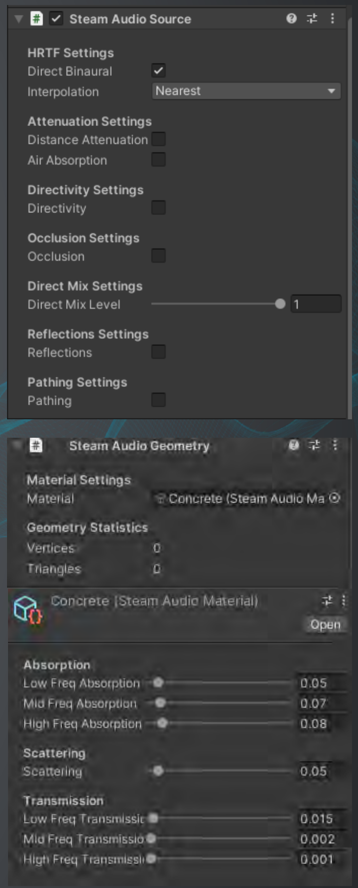
GLOBAL SCALE (0.00001 - 10000.0)
1

REFLECTION ENGINE
Enable Early Reflectic ✓
Enable Reverberation ✓

ROOM DIMENSIONS (meters)
Width 8
Height 3
Length 5

WALL REFLECTION COEFFICIENTS (0.0 - 0.97)
Left 0.5
Right 0.5
Up 0.2
Down 0.4
Back 0.5
Front 0.5

Steam



Steam Audio Source
HRTF Settings
  Direct Binaural ☑
  Interpolation Nearest
Attenuation Settings
  Distance Attenuation ☐
  Air Absorption ☐
Directivity Settings
  Directivity ☐
Occlusion Settings
  Occlusion ☐
Direct Mix Settings
  Direct Mix Level 1
Reflections Settings
  Reflections ☐
Pathing Settings
  Pathing ☐

Steam Audio Geometry
Material Settings
  Material: Concrete (Steam Audio Ma
Geometry Statistics
  Vertices 0
  Triangles 0

Concrete (Steam Audio Material)
Open
Absorption
  Low Freq Absorption 0.05
  Mid Freq Absorption 0.07
  High Freq Absorption 0.08
Scattering
  Scattering 0.05
Transmission
  Low Freq Transmissic 0.015
  Mid Freq Transmissio 0.002
  High Freq Transmissi 0.001

Spatial Audio Tools

Audio Middleware

- Ease of audio integration with Game Engines
- Comprehensive and intuitive interfaces
- Wide variety of built-in features for audio interactivity
- Real-time DSP processing effects of audio mixing

Wwise

FMOD Studio

Elias

Influence of Audio in Presence and Immersion

Audio in VR: Effects of a Soundscape and Movement-Triggered Step Sounds on Presence

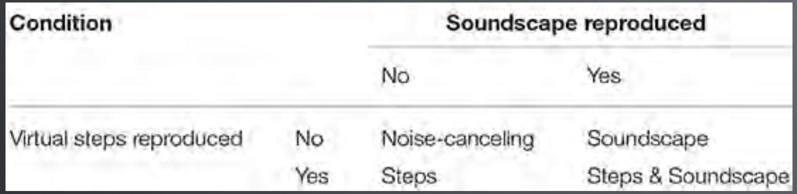
Kern and Ellermeier (2020)

Assess the effect of auditory stimuli (nature sounds and step sounds, on presence in virtual environments.

Experiment 1 Design

Condition	Noise canceling headphones?	Sounds presented in VR?
No headphones	NO	NO
Noise-canceling	YES	NO
Steps	YES	YES (virtual steps)
Soundscape	YES	YES (Soundscape)
Steps & Soundscape	YES	YES (virtual steps, Soundscape)

Experiment 2 Design



Condition		Soundscape reproduced	
		No	Yes
Virtual steps reproduced	No	Noise-canceling	Soundscape
	Yes	Steps	Steps & Soundscape

Results

- **Experiment 1**
  - Soundscape influenced perceived presence and realism.
  - Step sounds did not have a significant effect.
- **Experiment 2**
  - Both soundscape and steps sound significantly influenced perceived presence and realism.
  - Soundscape effects were larger than step sounds.
- Auditory feedback heightens the sense of presence in VR.

Previous Audio – Presence Studies

	Presence [0–100]			**Presence [1–5]**	**Presence [1–7]**
	Hendrix and Barfield, 1996	Dinh et al., 1999	Larsson et al., 2007	Hendrix and Barfield, 1996	Larsson et al., 2007
No Sound	45.45 (19.42)	63.4 (18.6)	49.15 (3.99)	3.45 (0.82)	4.45 (0.21)
Sound	56.09 (21.00)	69.3 (16.1)	57.57 (4.34)	2.73 (0.90)	5.21 (0.26)

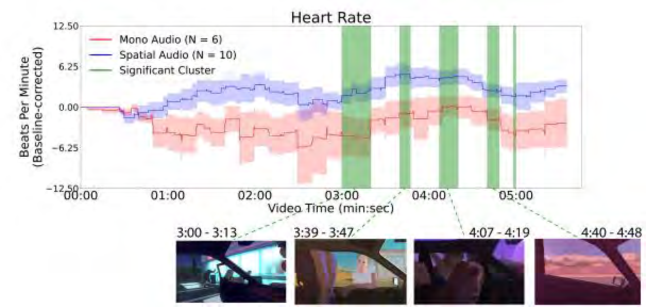
Moved By Sound: How head-tracked spatial audio affects autonomic emotional state and immersion-driven auditory orienting response in VR Environments

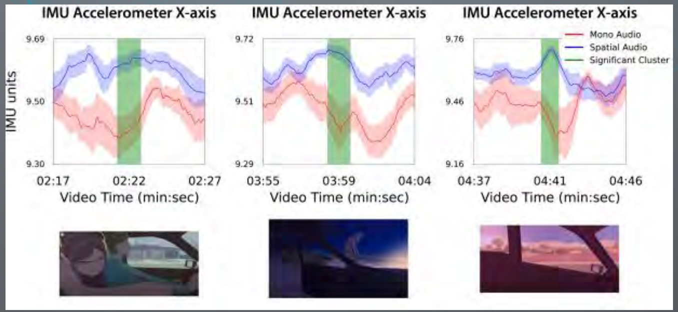
Warp et al. (2022)

Determine whether head-tracked spatial audio exerts an effect on physiologically measured emotional response.

Examine the extent to which the spatial characteristics of the audio can increase the sense of immersion in a VR experience.

EmteqPRO VR headset





Results

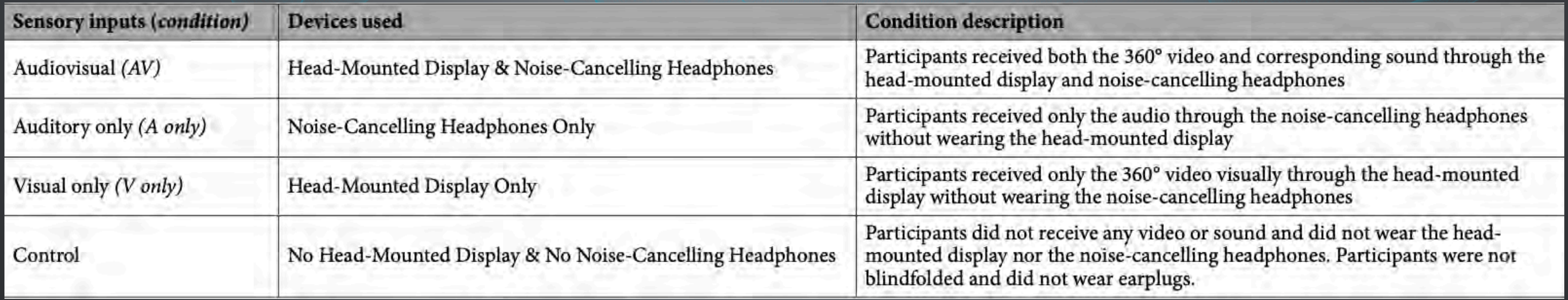
- Spatial audio favours the sense of immersion in VR environments.
- It increased the capacity for orientation prediction due to heightened localization accuracy.
- The study validates previous research on the effectiveness of head-tracked audio spatialization.
- Spatial audio can significantly affect emotional response in IVEs.
- Spatial audio with head-tracked music and sound can increase autonomic arousal and valence in VR.

Influence of Audio in Body Perception & Response

Investigating the role of auditory and visual sensory inputs for inducing relaxation during virtual reality stimulation.

> *Naef et al. (2022)*
>
> Determine which sensory aspect of immersive VR intervention is responsible for the greatest relaxation response.

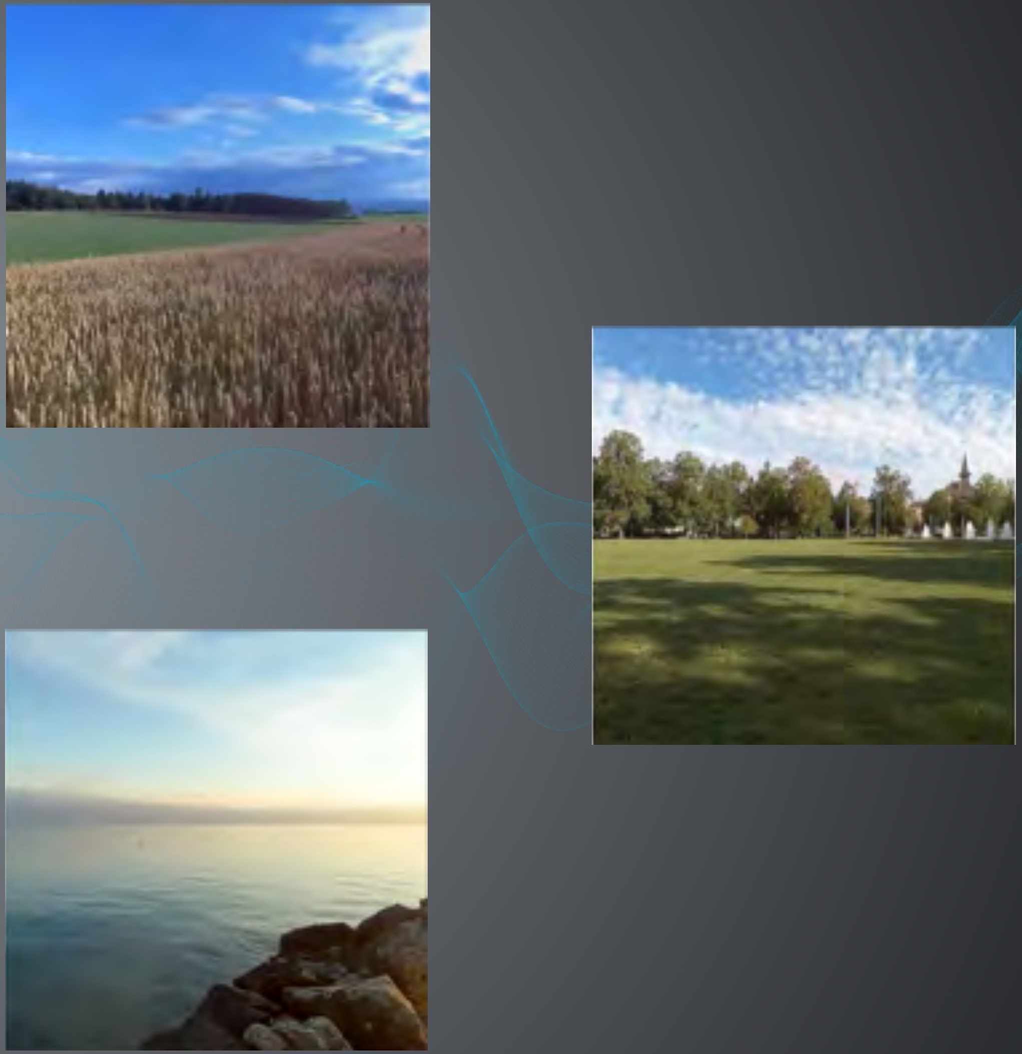
Experiment Conditions



Sensory inputs (*condition*)	**Devices used**	**Condition description**
Audiovisual (*AV*)	Head-Mounted Display & Noise-Cancelling Headphones	Participants received both the 360° video and corresponding sound through the head-mounted display and noise-cancelling headphones
Auditory only (*A only*)	Noise-Cancelling Headphones Only	Participants received only the audio through the noise-cancelling headphones without wearing the head-mounted display
Visual only (*V only*)	Head-Mounted Display Only	Participants received only the 360° video visually through the head-mounted display without wearing the noise-cancelling headphones
Control	No Head-Mounted Display & No Noise-Cancelling Headphones	Participants did not receive any video or sound and did not wear the head-mounted display nor the noise-cancelling headphones. Participants were not blindfolded and did not wear earplugs.

Results

- Participants were more relaxed after receiving audio-visual input compared to other conditions.
- The audio-visual condition caused the biggest drop in heart rate, respiration rate, and blood pressure over time.
- The occipital cortex may be activated by auditory input, indicating a significant interaction between the auditory and visual cortices during audio-visual stimulation.

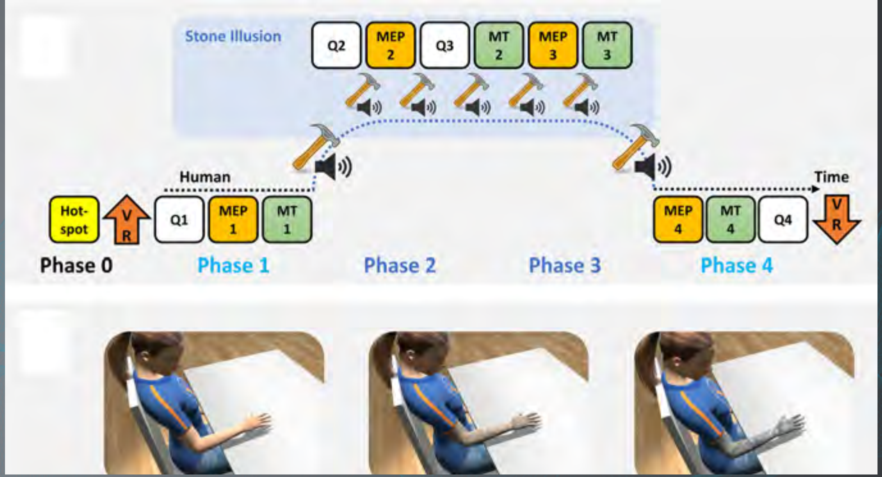


“Tricking the Brain” Using Immersive Virtual Reality: Modifying the Self-Perception Over Embodied Avatar Influences Motor Cortical Excitability and Action Initiation

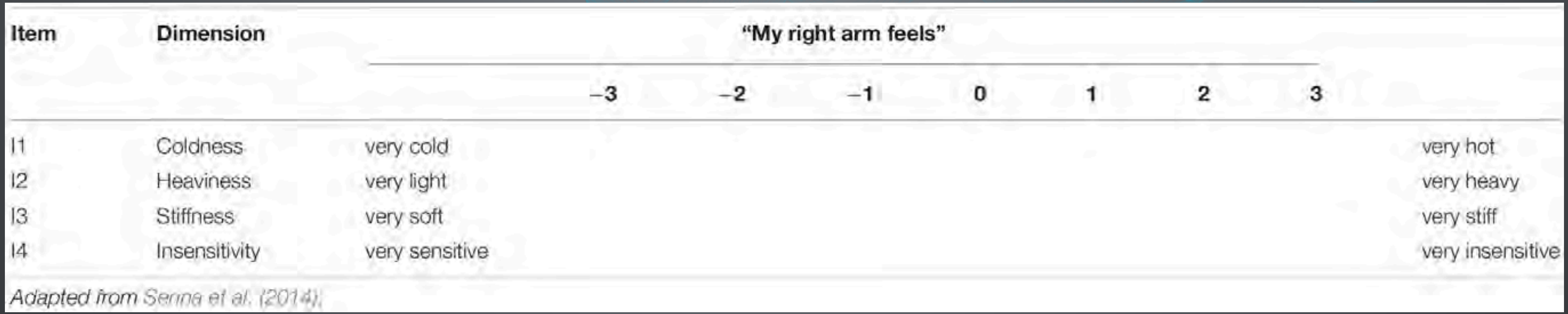
Beutler et al. (2021)

Modulating physical properties of an embodied avatar in VR to influence motor brain networks and action execution.

Experiment Design



Stone feeling questionnaire

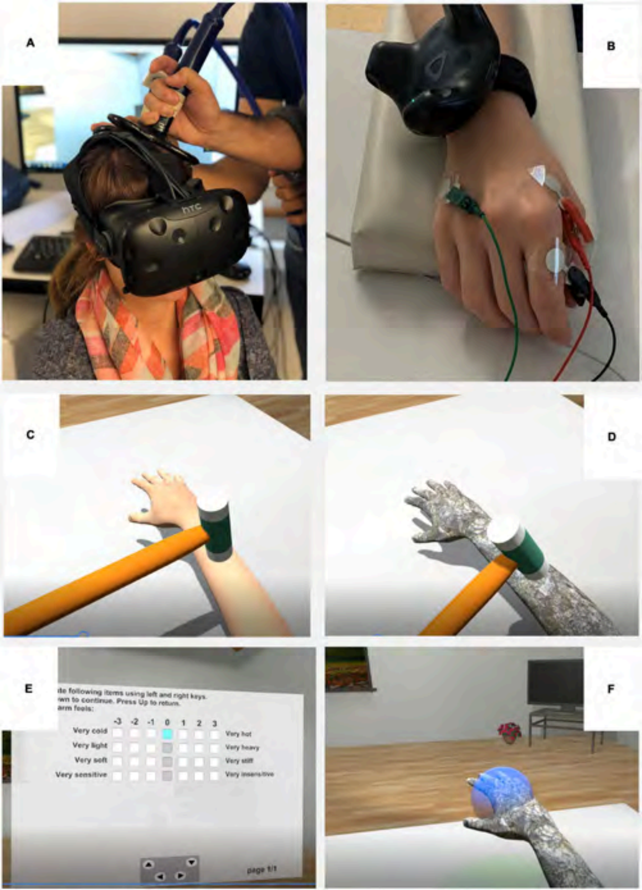


Item	Dimension	“My right arm feels”								
			−3	−2	−1	0	1	2	3	
I1	Coldness	very cold								very hot
I2	Heaviness	very light								very heavy
I3	Stiffness	very soft								very stiff
I4	Insensitivity	very sensitive								very insensitive

Adapted from Serino et al. (2014).

Results

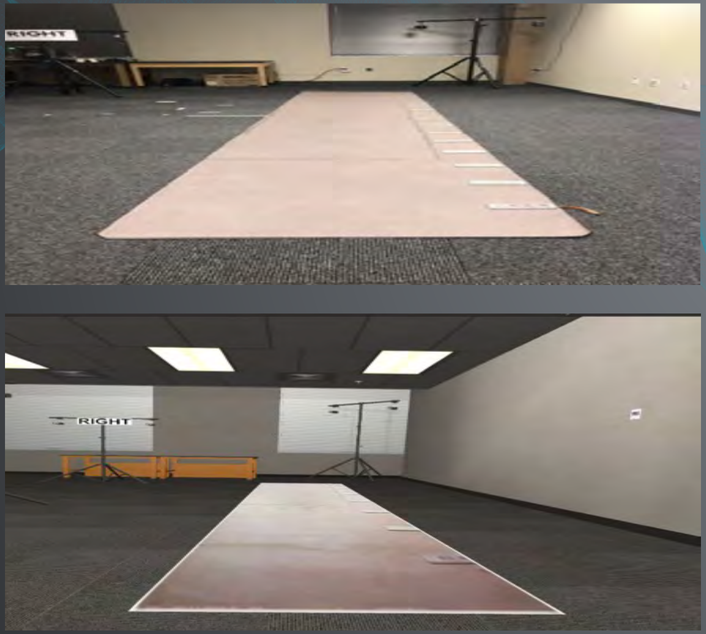
- The "stone arm illusion" was experienced by participants without affecting their feeling of body ownership.
- Body perceptions are continuously updated in the brain in response to sensory signals related to the body.
- Participants' subjective illusion strength was associated with increased motor cortical excitability and faster movement initiation.
- Immersive VR has the potential to influence motor brain networks by subtly modifying the perception of reality.



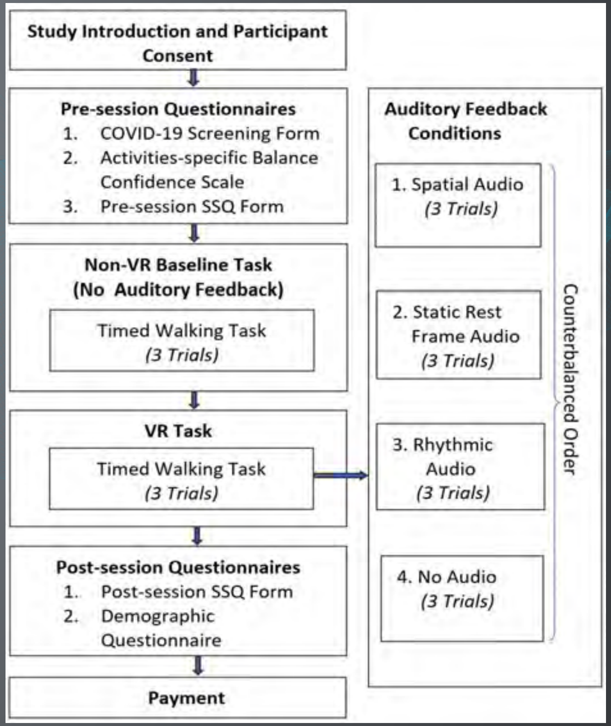
Auditory Feedback to Make Walking in Virtual Reality More Accessible

Mahmud et al. (2022)

Investigate the impact of several auditory feedback modalities on gait in VR.



Study procedure



Results

- Gait disturbance happened in VR conditions for all participants when there was no auditory feedback.
- Overall, auditory feedback conditions improved gait performance in both participant groups while immersed in VR.
- Spatial audio improved gait performance significantly compared to other auditory condition
- Participants with mobility impairments showed significantly greater improvement in gait parameters.
- Few gait parameters (e.g., velocity, cadence, step length, stride length) were affected differently for participants with MI and participants without MI.

Experiment Setup

Audio-visual Perception in VR

Spatial Sound in a 3D Virtual Environment: All Bark and No Bite?

Meghanathan et al. (2021)

Investigate the effect of auditory cues on visual searches in 3D virtual environments with both visual and auditory noise.

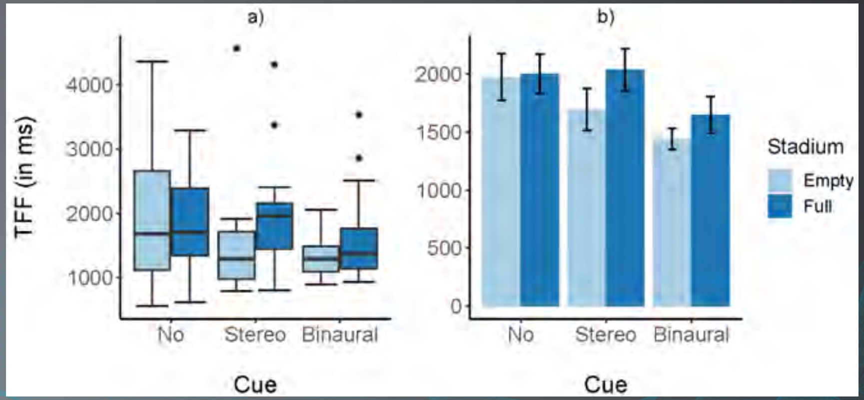
Fixation behaviour: Empty-binaural

Fixation behaviour: Full-binaural

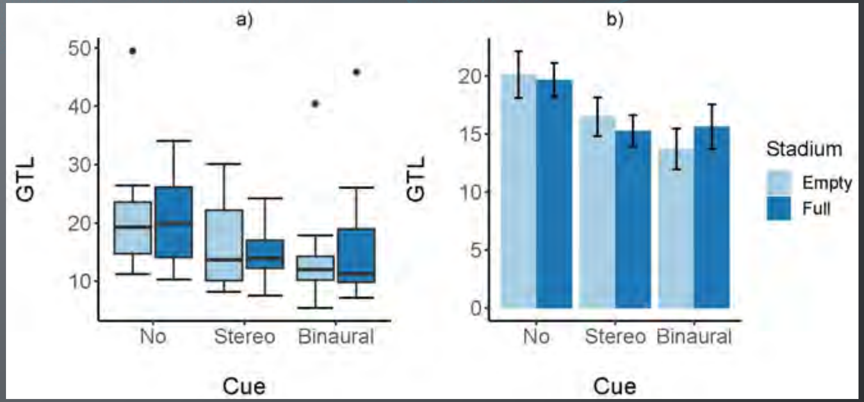
Results

- Binaural cues outperformed stereo and no auditory cues in target detection, irrespective of the environmental noise.
- Binaural cues resulted in lower time to first fixation (TFF), compared to stereo and no audio cues.
- Trials with no auditory cues showed longer search duration and search paths.
- Spatial audio can improve responsiveness and immersion in virtual environments with visual and auditory noise.

Time to first fixation



Gaze trajectory length



Generic HRTFs May be Good Enough in Virtual Reality. Improving Source Localization through Cross-Modal Plasticity

Berger et al. 2018

Investigate whether auditory source localization could be improved for users of generic HRTFs via cross-modal learning.

First-person Perspective of the Environment

Results

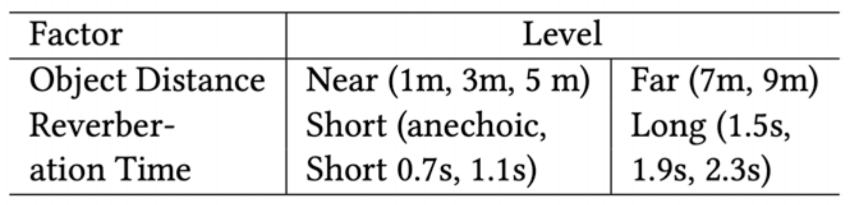
- Pairing synchronous visual stimulus with auditory feedback is enough to improve sound localization with generic HRTF in VR.
- Exposing participants for as short as 60 sec is enough to induce a measurable improvement.
- Recalibration of acoustic space does not transfer between sounds of disparate frequencies/types.
- Personalised HRTFs might not be necessary if users can recalibrate their auditory perception through Cross-modal learning.

Using Audio Reverberation to Compensate Distance Compression in Virtual Reality

Huang et al. 2021

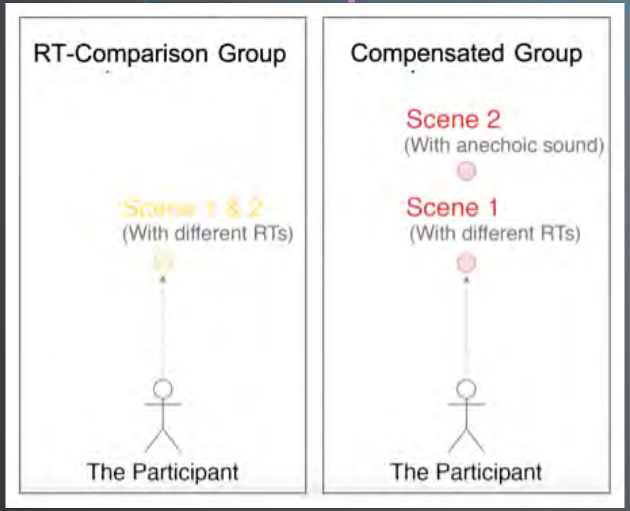
Potential of reverberation time (RT) to alter users' depth perception to address distance compression in VR.

RT-Comparison Group

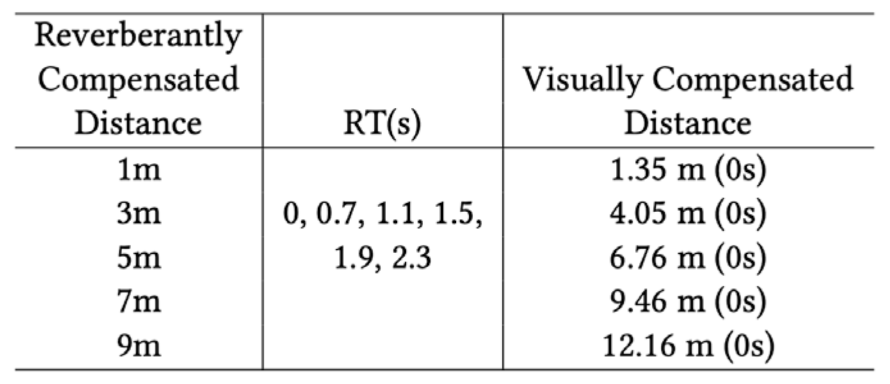


Factor	Level	
Object Distance	Near (1m, 3m, 5 m)	Far (7m, 9m)
Reverber-ation Time	Short (anechoic, Short 0.7s, 1.1s)	Long (1.5s, 1.9s, 2.3s)

Groups



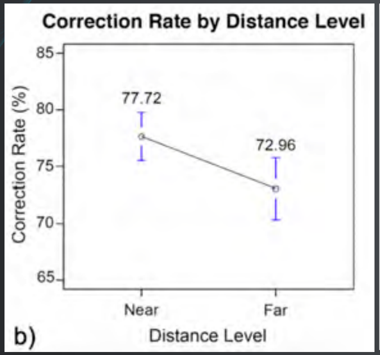
RT-Comparison Group

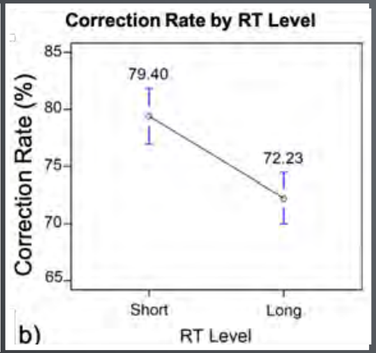


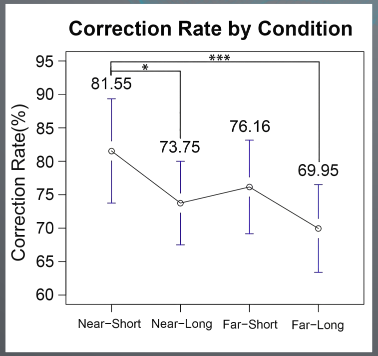
Reverberantly Compensated Distance	RT(s)	Visually Compensated Distance
1m	0, 0.7, 1.1, 1.5, 1.9, 2.3	1.35 m (0s)
3m		4.05 m (0s)
5m		6.76 m (0s)
7m		9.46 m (0s)
9m		12.16 m (0s)

Results

- RT influences how users perceive depth
  - Longer RTs = farther distances
  - Shorter RT = nearer distances
- Influence of RT was stronger in the near field (1-5m) than in the far field (5-10m).
- Excessive RT increase can cause sensory segregation.
- RT can be used to compensate for distance underestimation in VR.



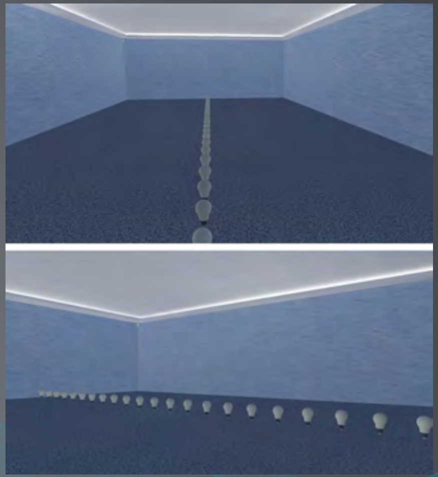


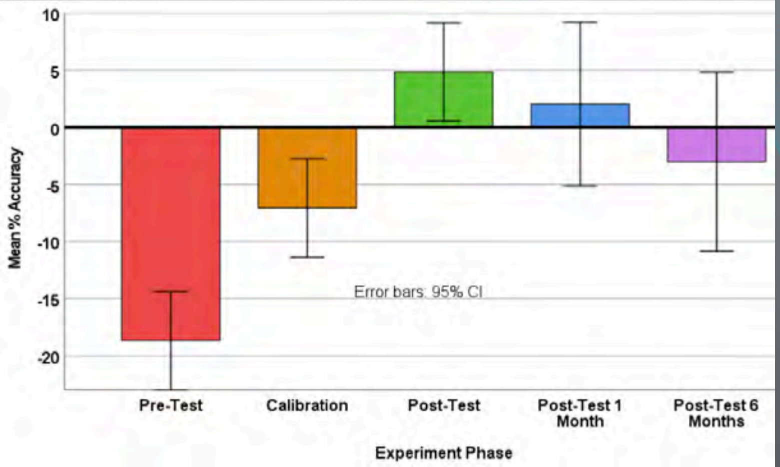


Empirical Evaluation of Calibration and Long-term Carryover Effects of Reverberation on Egocentric Auditory Depth Perception in VR

Lin et al. 2022

Examine the perceptual learning and carryover effects of RT calibration related to the depth of a target in VR.





Additional Findings:

- The calibration effect can carry over for an extended period of time. However, performance tends to degrade over time.

Conclusions

Audio and Audio-visual feedback in VR

- Heightens the illusion of Presence and Immersion in VR.
- Favourable dimension for multisensory integration.

- Allows for body-perception modulations.
- It affects users' physical and psychological responses.

- Audio-visual feedback can improve task performance in VR.
- It allows for overcoming the current limitations of VR systems.

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Thank you!

SAARBRÜCKEN

EUROGRAPHICS 2023

Effective User Studies in Computer Graphics

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