MAX PLANCK INSTITUTE
FOR HUMAN COGNITIVE AND BRAIN SCIENCES

Mind Body Emotion

BERLIN SCHOOL OF MIND AND BRAIN

HUMBOLDT-UNIVERSITÄT ZU BERLIN

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

Combining Eye-Tracking and EEG Experiments with immersive Virtual Reality

—

Challenges and Opportunities for Cognitive Neuroscientists

—

a workshop

For questions, comments, collabs, … please do not hesitate to get in touch:

klotzsche@cbs.mpg.de

Felix Klotzsche[1] & Sven Ohl[2]

[1] *Max-Planck-Institute for Human Cognitive and Brain Sciences*

[2] *Humboldt-Universität zu Berlin*

—

a workshop

Part I

1. Virtual Reality & Cognitive Neuroscience
2. Motivating an Experiment
3. VR for Experiments: Hardware & Software
4. Spatial Reference Frames
5. Eye and Head Movements in VR
6. Timings & Data Synchronization

Part II (1:00pm)

Questions & Discussion

Hands-on

For questions, comments, collabs, … please do not hesitate to get in touch:

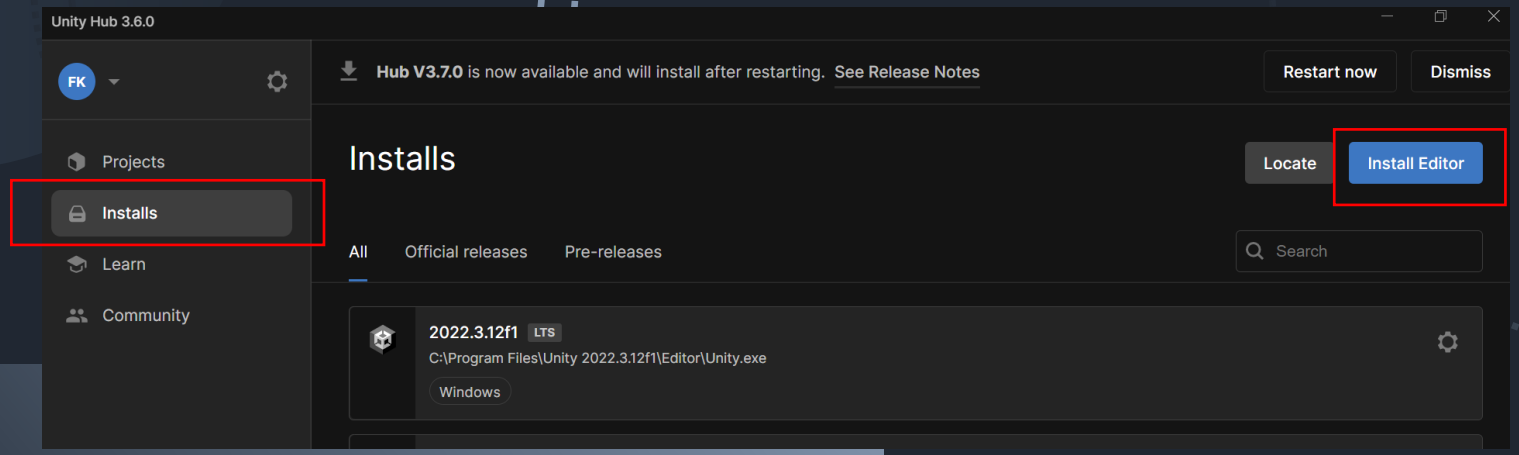
klotzsche@cbs.mpg.de

a workshop

If you want to participate in the hands-on section:

Please make sure to have Unity installed and it works on your machine.
The easiest way:

1. Install **Unity Hub**: https://unity.com/unity-hub
2. Create a Unity ID (Personal Plan): https://id.unity.com/
2. Within Unity Hub, install the latest “Official Release” (**2022.3**) of the Editor.



David Chalmers, 2017:

» Virtual reality is not a second class reality. …
In the long run, and in principle, virtual reality may well be on par with physical reality. «

Chalmers, 2017, *The Virtual and the Real*

https://aeon.co/videos/new-realities-are-imminent-how-vr-reframes-big-questions-in-philosophy

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Virtual reality:

»an immersive, interactive, computer-generated environment« (Chalmers, 2017)

… immersion:

the degree of capability of a technical device to provide sensual stimulation that resembles its real-world equivalent (Slater, 2000).

… presence:

»the human reaction to immersion« (Slater, 2000),
i.e., the subjective impression to be in a specific situation/context

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VR

Virtual Reality

experienced reality is fully computer-generated (CG)

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AR	MR	VR
Augmented Reality	Mixed Reality	Virtual Reality
artificial CG content rendered on top of the physical reality	artificial CG content rendered on top of the physical reality digital and physical objects interact	experienced reality is fully computer-generated (CG)

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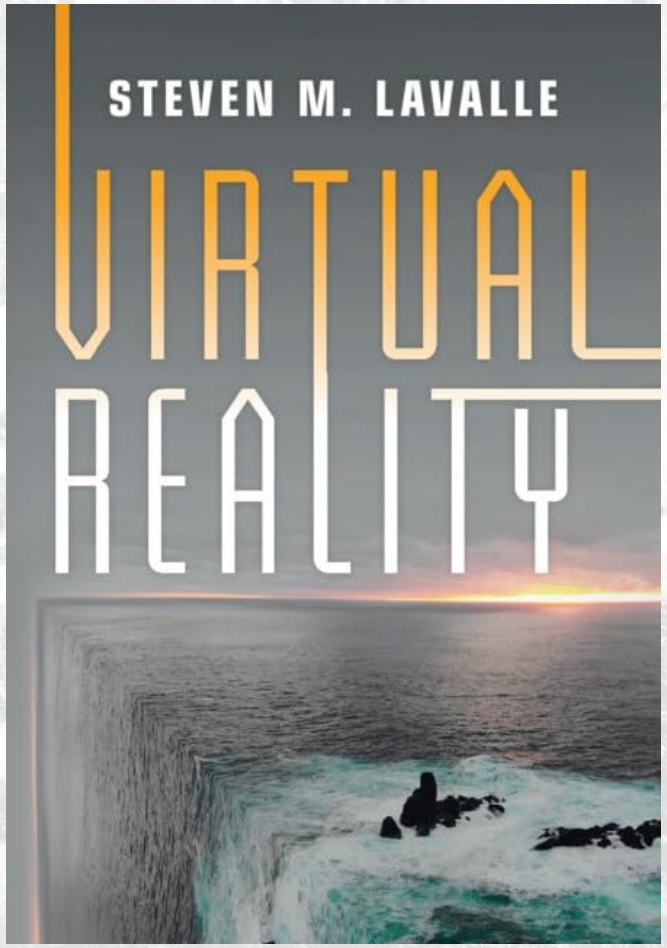
Steven LaValle (2019/2023): Virtual Reality
https://lavalle.pl/vr/

(here: Chapter 02)



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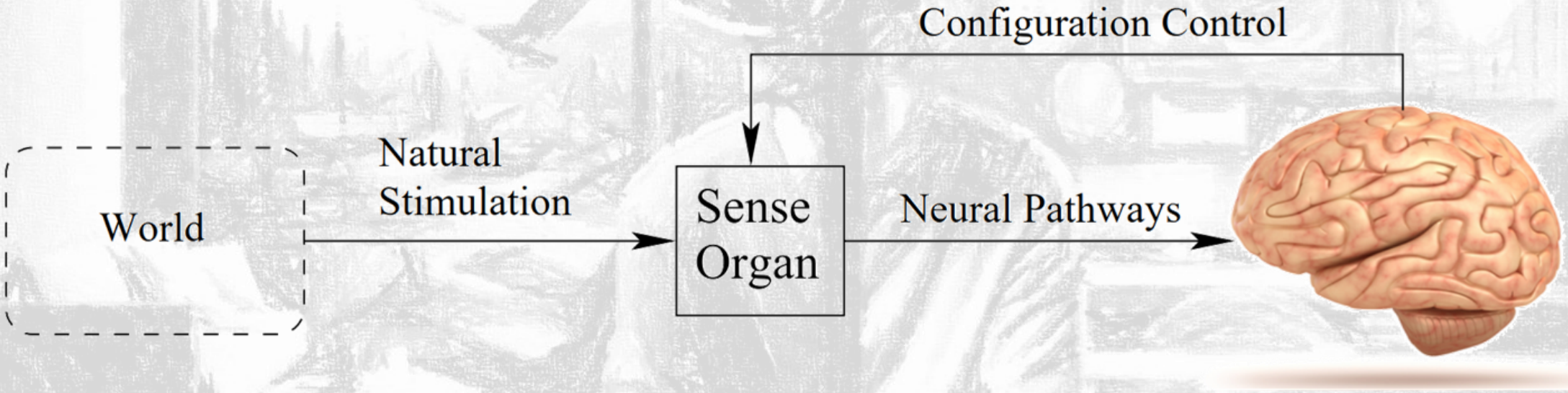

adapted from LaValle (2019): *Virtual Reality*

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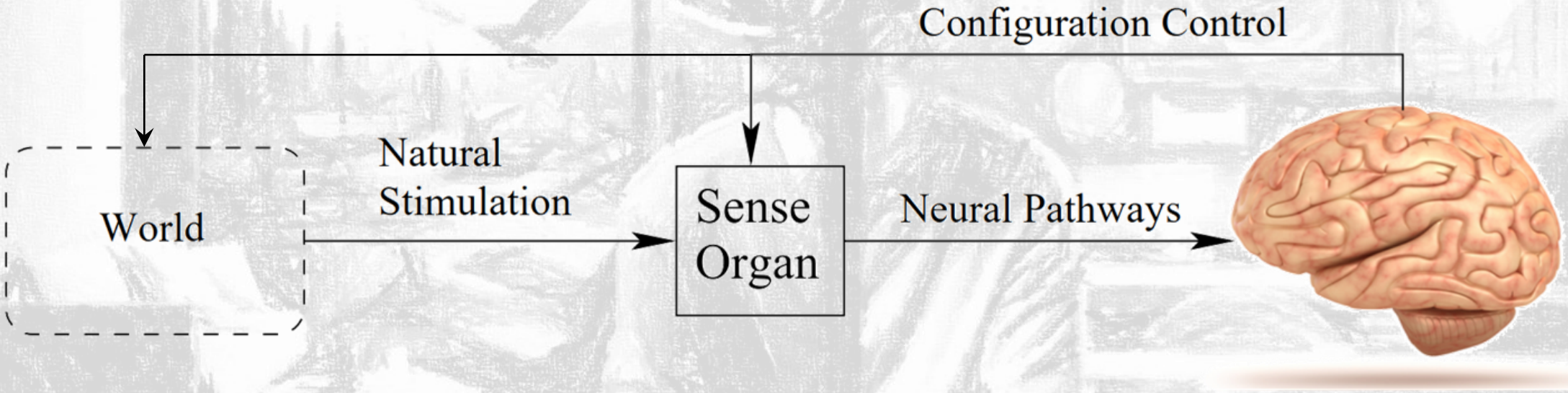

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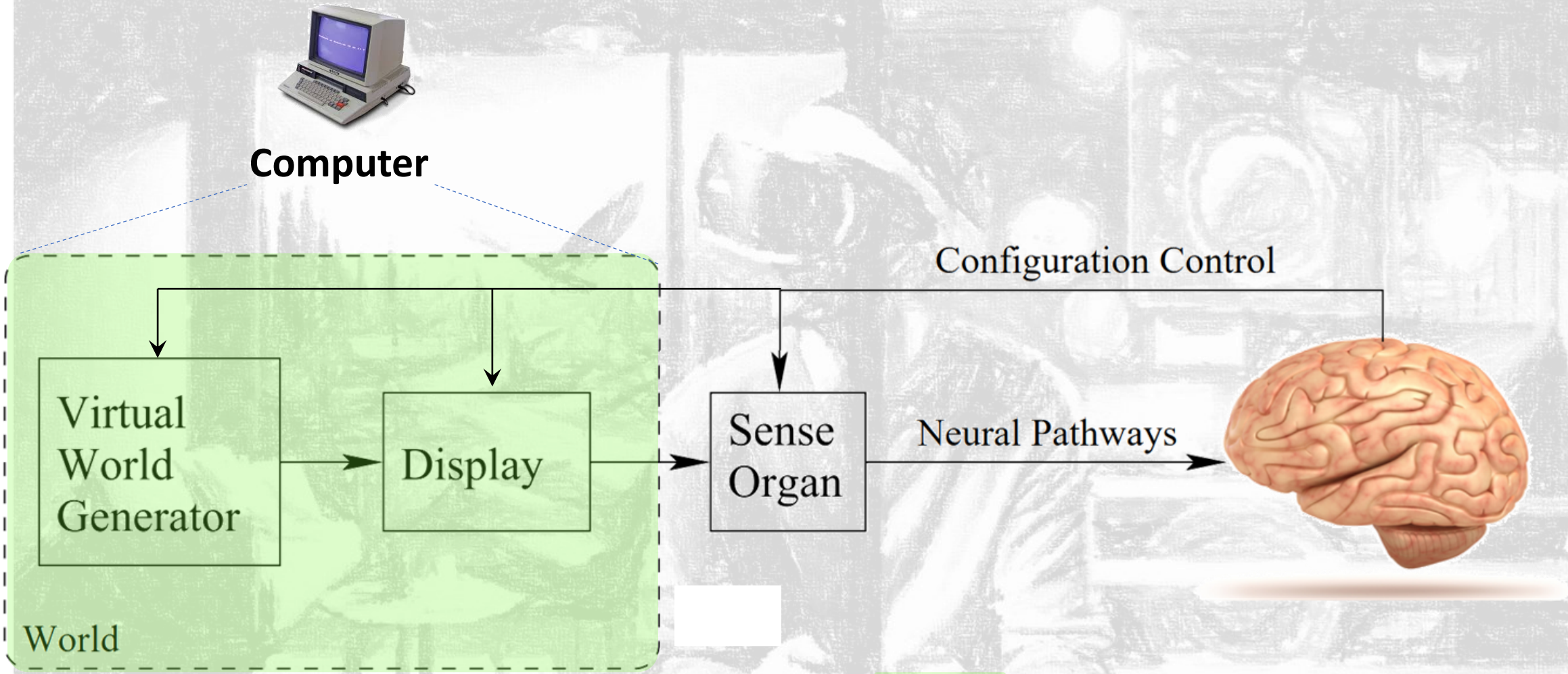

computer(-generated) stuff

adapted from LaValle (2019): *Virtual Reality*

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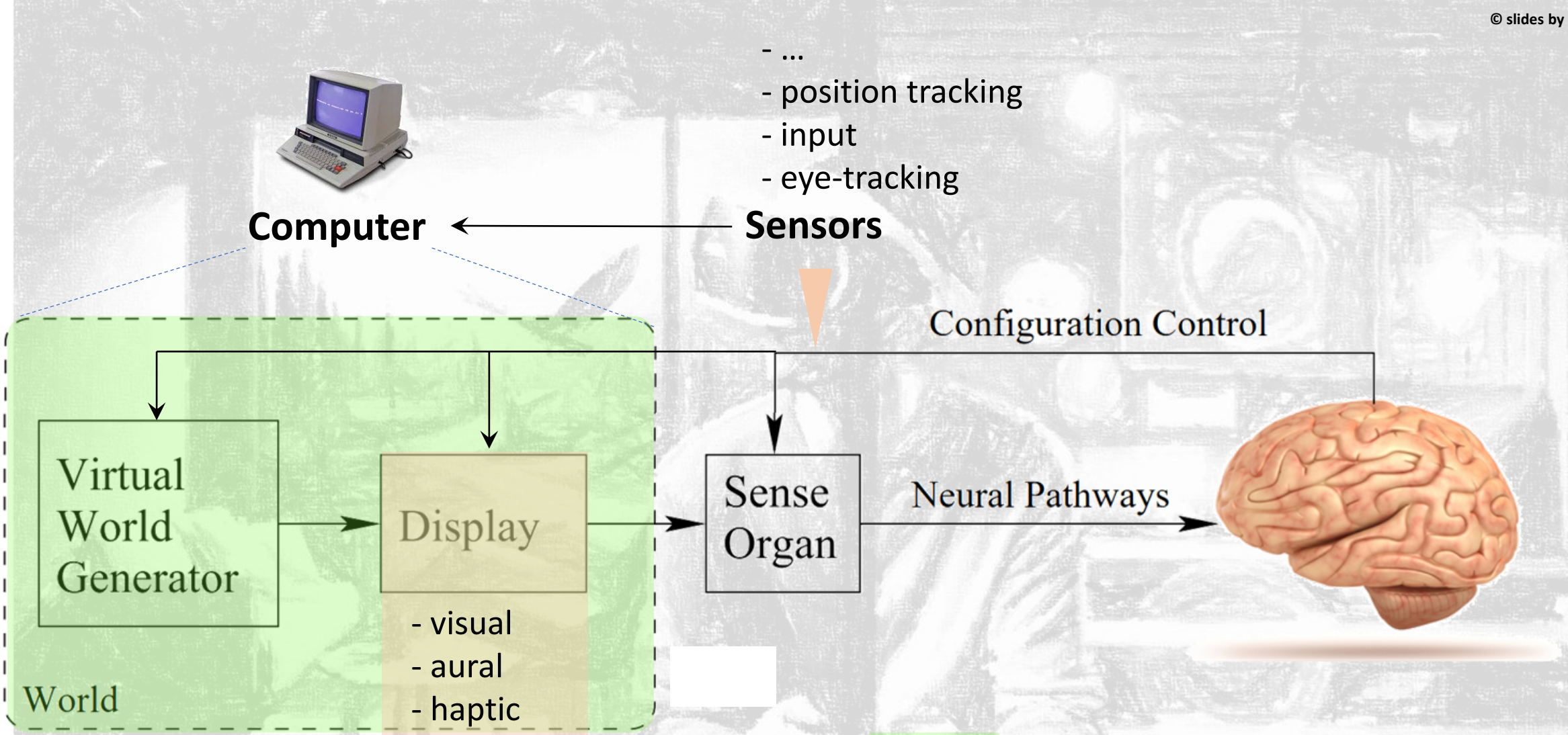

computer(-generated) stuff

computer↔human interface

adapted from LaValle (2019): *Virtual Reality*

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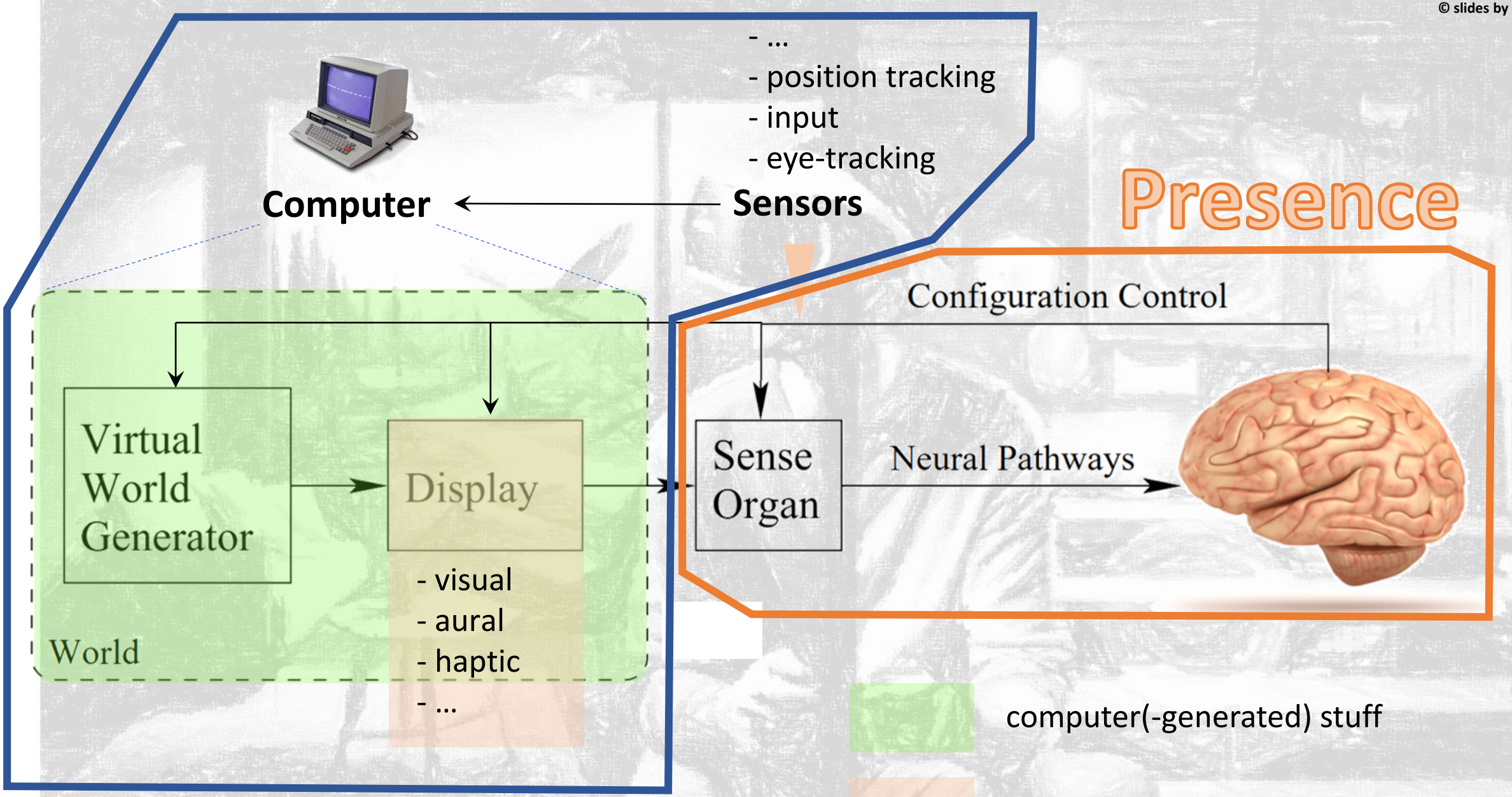
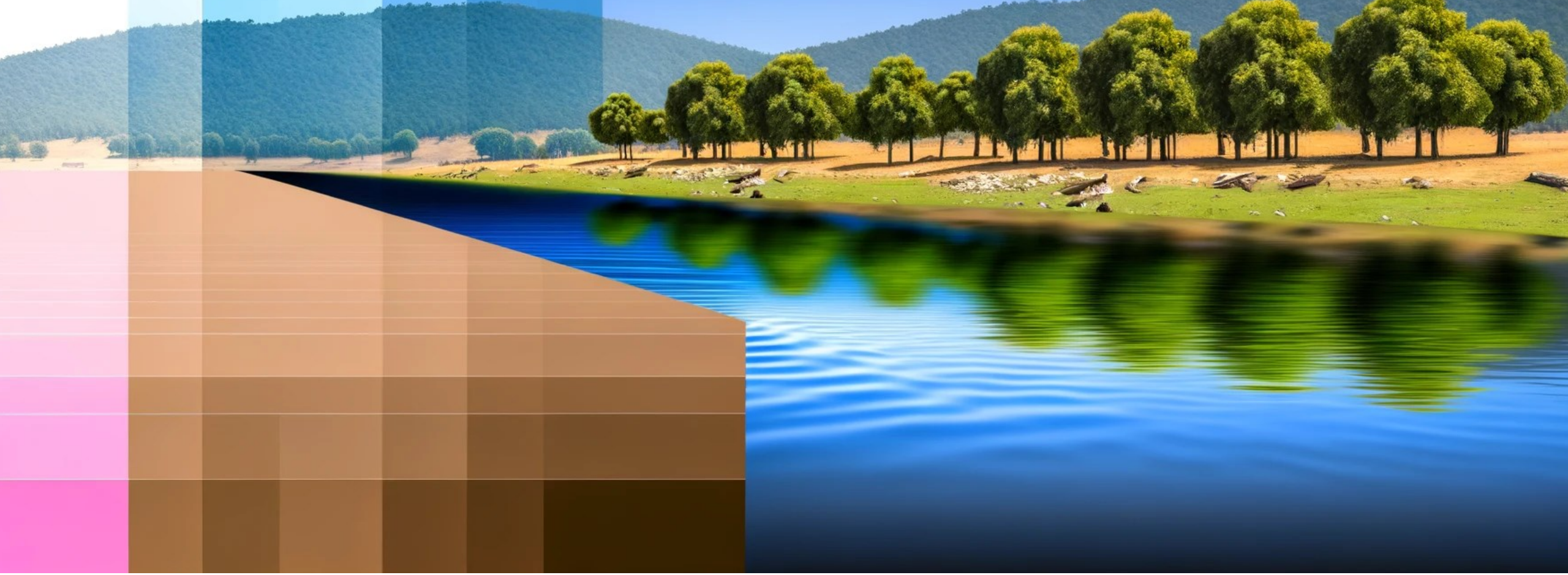


computer(-generated) stuff

computer↔human interface

adapted from LaValle (2019): *Virtual Reality*



VR as a tool for cognitive neuroscientists: Opportunities & motivation

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Naturalism

"Naturalistic paradigms can be heuristically defined as those that employ the **rich, multimodal dynamic stimuli that represent our daily lived experience** […] or that **embody relatively unconstrained interactions** with other agents, gaming environments, or virtual realities." (Sonkusare et al., 2019)

Trends in Cognitive Sciences

CellPress REVIEWS

Review

Naturalistic Stimuli in Neuroscience: Critically Acclaimed

Saurabh Sonkusare,[1,2] Michael Breakspear,[1,3,*] and Christine Guo[1]

NeuroImage 222 (2020) 117254

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

ELSEVIER

Keep it real: rethinking the primacy of experimental control in cognitive neuroscience

Samuel A. Nastase[a,*], Ariel Goldstein[a], Uri Hasson[a,b]

[a] Princeton Neuroscience Institute, Princeton University, Princeton, NJ, USA
[b] Department of Psychology, Princeton University, Princeton, NJ, USA

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Naturalism

- use case **affective sciences**:
  immersive VR to evoke “true feelings”

Behavior Research Methods
https://doi.org/10.3758/s13428-023-02241-y

ORIGINAL MANUSCRIPT

Check for updates

Immersive VR for investigating threat avoidance: The VRthreat toolkit for Unity

Jack Brookes[1] · Samson Hall[1] · Sascha Frühholz[2,3] · Dominik R Bach[1,4]

Accepted: 12 September 2023
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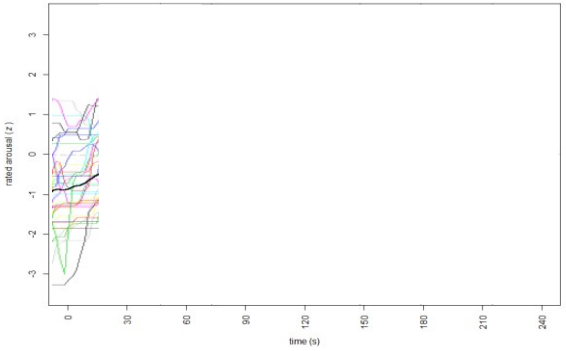
eLife

RESEARCH ARTICLE

Decoding subjective emotional arousal from EEG during an immersive virtual reality experience

Simon M Hofmann[1*†], Felix Klotzsche[1,2*†], Alberto Mariola[3,4*†], Vadim Nikulin[1,5], Arno Villringer[1,2], Michael Gaebler[1,2*]



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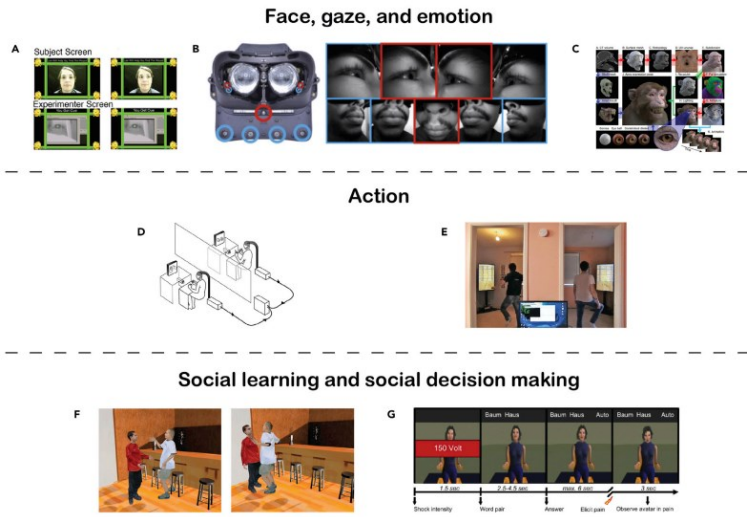
Naturalism

- use case **social interactions & cognition**:
  reproducible interactions with realistic avatars



brain sciences

MDPI

Review

Extended Reality for the Clinical, Affective, and Social Neurosciences

Thomas D. Parsons [1,2,3,*], Andrea Gaggioli [4,5] and Giuseppe Riva [4,5]

iScience

CellPress OPEN ACCESS

Review

Levels of naturalism in social neuroscience research

Siqi Fan,[1] Olga Dal Monte,[1,2] and Steve W.C. Chang[1,3,4,5,*]

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Naturalism

representing **spatial properties** of stimuli

- ❑ stereoscopic depth cues
- ❑ embedding of observer in spatiotopically congruent surrounding
- ❑ use cases:

spatial memory & attention

ARTICLES
https://doi.org/10.1038/s41562-021-01245-y
nature human behaviour
Check for updates

Multiple spatial frames for immersive working memory

Dejan Draschkow[1,2], Anna C. Nobre[1,2] and Freek van Ede[1,3]

spatial navigation

CellPress
OPEN ACCESS
Current Biology

Article

Predictive maps in rats and humans for spatial navigation

William de Cothi,[1,2,7,9,*] Nils Nyberg,[2] Eva-Maria Griesbauer,[2] Carole Ghanamé,[2] Fiona Zisch,[2,3] Julie M. Lefort,[1] Lydia Fletcher,[2] Coco Newton,[4] Sophie Renaudineau,[2] Daniel Bendor,[2] Roddy Grieves,[2,5] Éléonore Duvelle,[2,5] Caswell Barry,[1,6] and Hugo J. Spiers[2,6,7,8,*]

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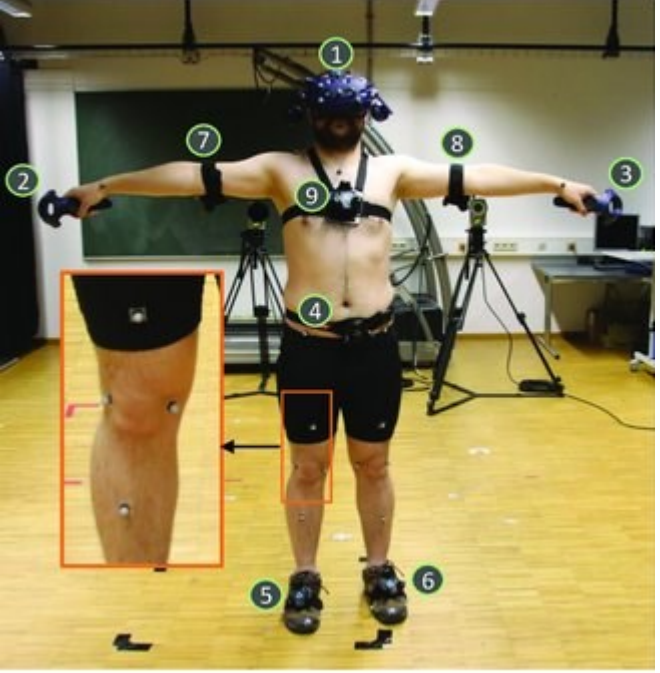
Experimental control & reproducibility

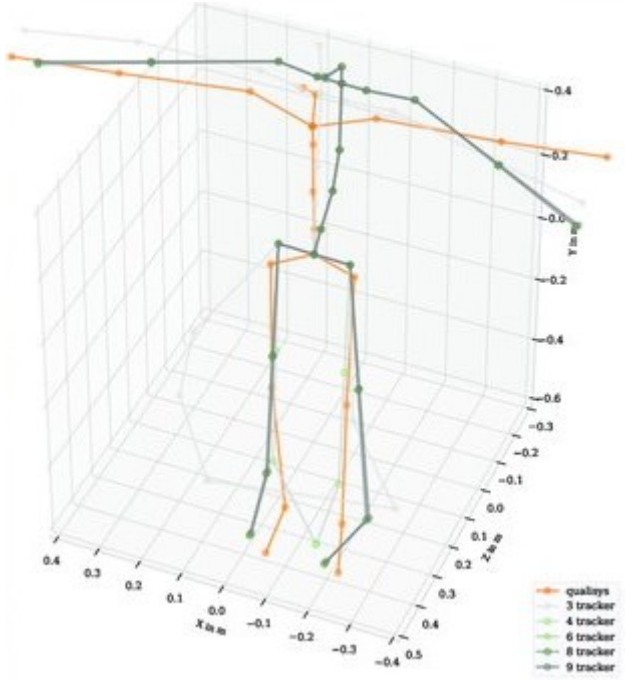
stimuli in VR are **computer-generated**

⇒ (theoretically) full control about their design and behavior

of course: still a **trade-off** between **naturalistic** stimuli and **experimental control**

but: VR makes this trade-off conceivable





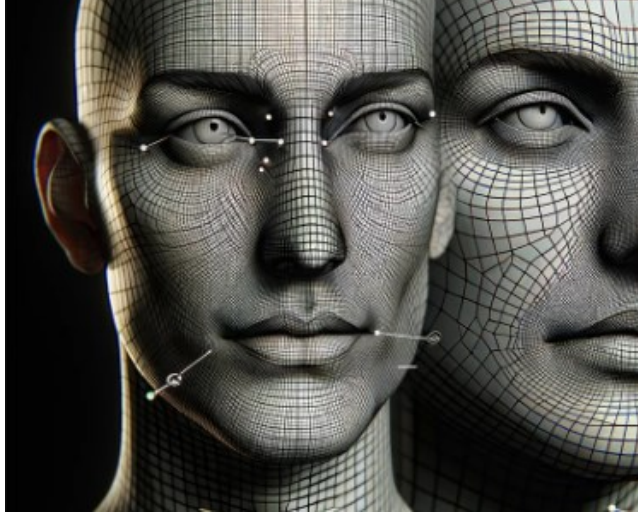
Vox et al., 2021, *Sensors,* http://dx.doi.org/10.3390/s21093145

Tracking capabilities

VR headsets allow for fairly easy, cheap and mobile tracking of

- ❑ Head
- ❑ Eyes*
- ❑ Hands*
- ❑ Face*
- ❑ Body (parts)

*: in some VR headsets



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Die pummligen Pandas
lachen und springen,
sind quietschvergnügt
und tanzen und singen.

Sie zieh'n ihre Show ab
und haben viel Spaß.
Nur einem Panda,
dem fehlt doch was!

Manche sind
anders:
Ein Suchbuch

© slides by Sven Ohl

Die pummligen Pandas
lachen und springen,
sind quietschvergnügt
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Sie zieh'n ihre Show ab
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Nur einem Panda,
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Manche sind
anders:
Ein Suchbuch

© slides by Sven Ohl

Die piekfeinen Pinguine
sind alle gleich befrackt.
Und nicht nur das, sie tanzen auch
exakt im selben Takt!

Nur einer hat ein Geheimnis
unter seinem Flügel versteckt.
Hast du schon das Küken
in der Menge entdeckt?

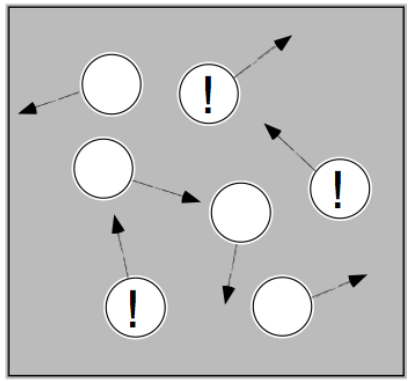
Manche sind
anders:
Ein Suchbuch

Attention moves across the sensory input just like a spotlight.
(The Spotlight of Attention)

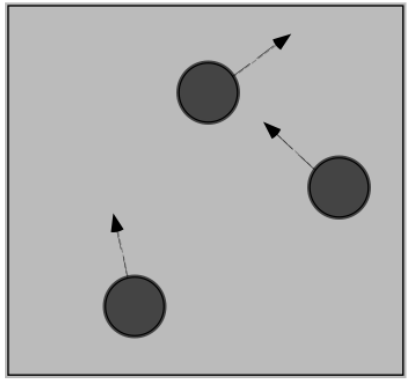
© slides by Sven Ohl

Experimental tasks to study attention

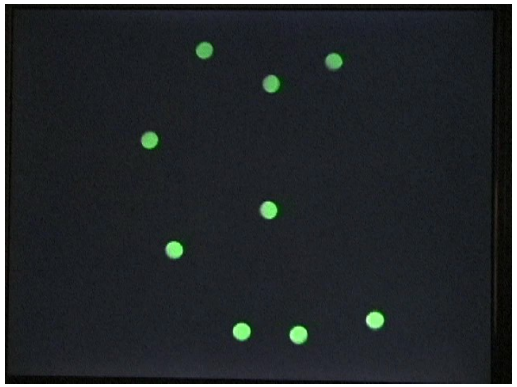
- Visual search
- Multiple object tracking



Tracking 3 balls (!)



Attention image

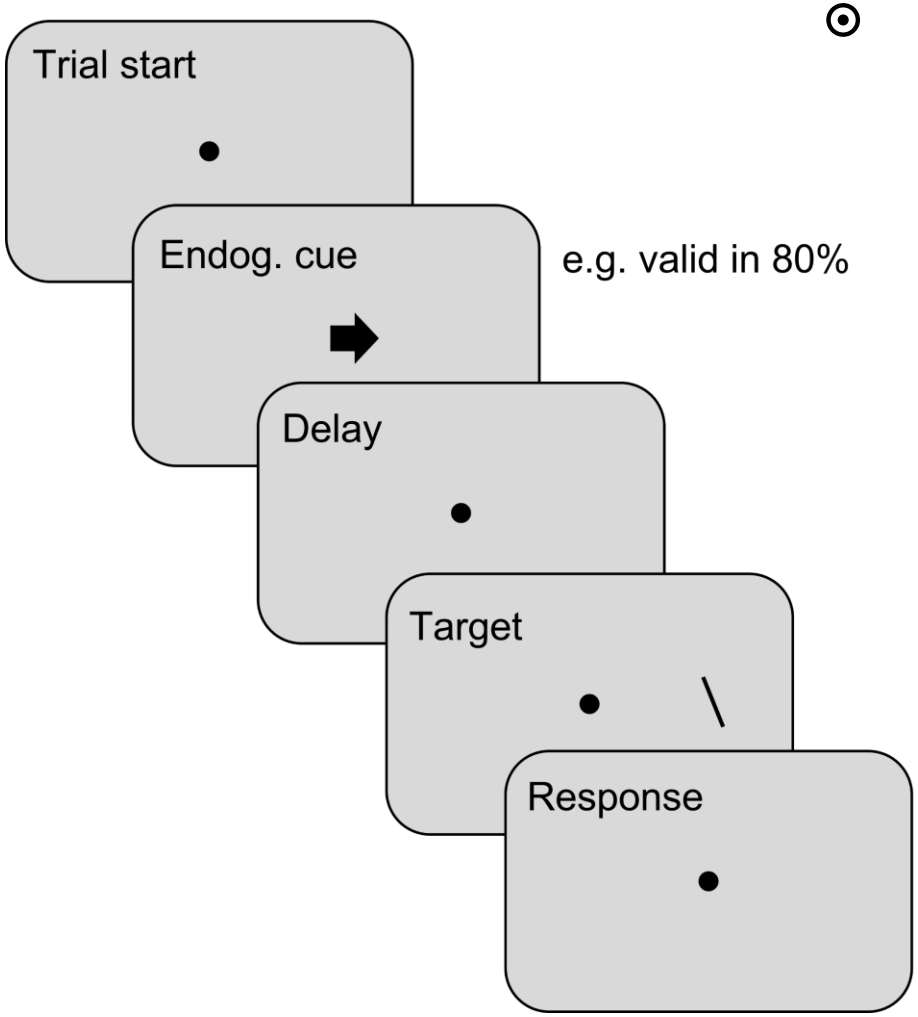


Pylyshyn & Storm, 1988; Yantis, 1992;
Intriligator & Cavanagh, 2001

- Cueing paradigms for studying spatial attention

© slides by Sven Ohl

Variants of the same task: Spatial attention



- Future directions:
  - Large field of view
  - Attending in 3D

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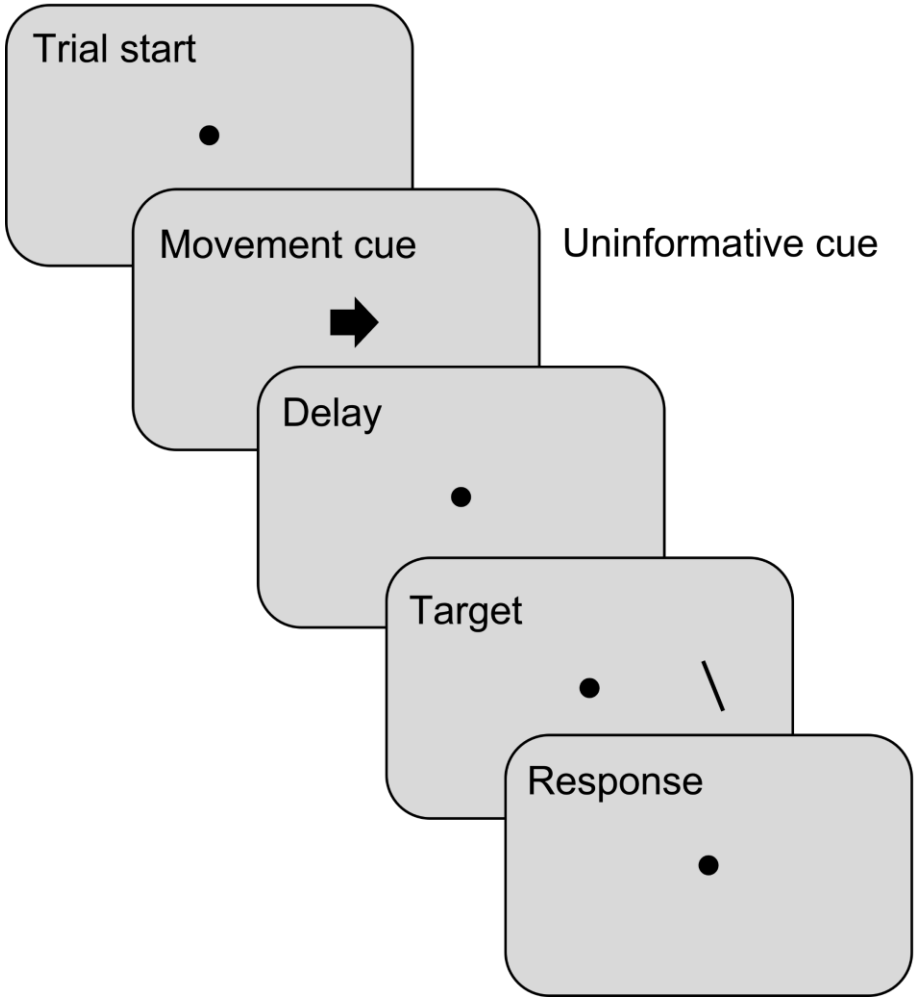
Variants of the same task: Pre-saccadic attention



- Past work: Effector-independent attention shifts [Jonikaitis & Deubel, 2011]
- Future directions:
  - Pre-saccadic attention in natural environments.
  - Add more actions

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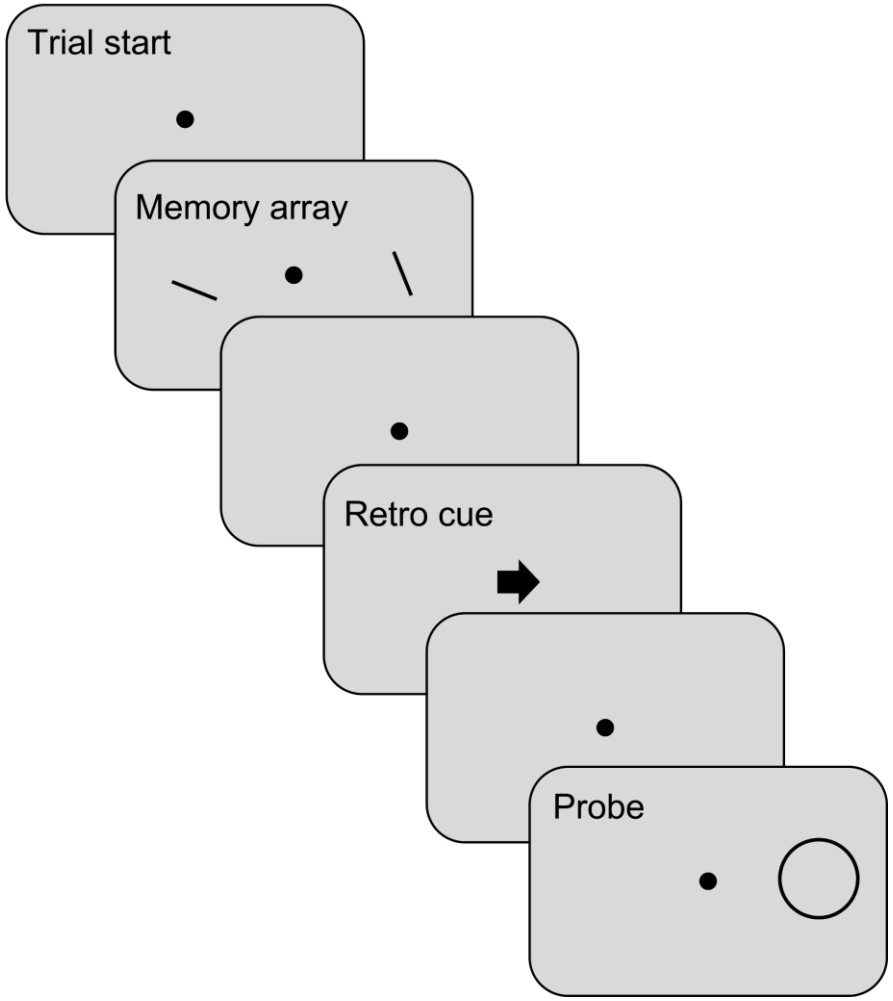
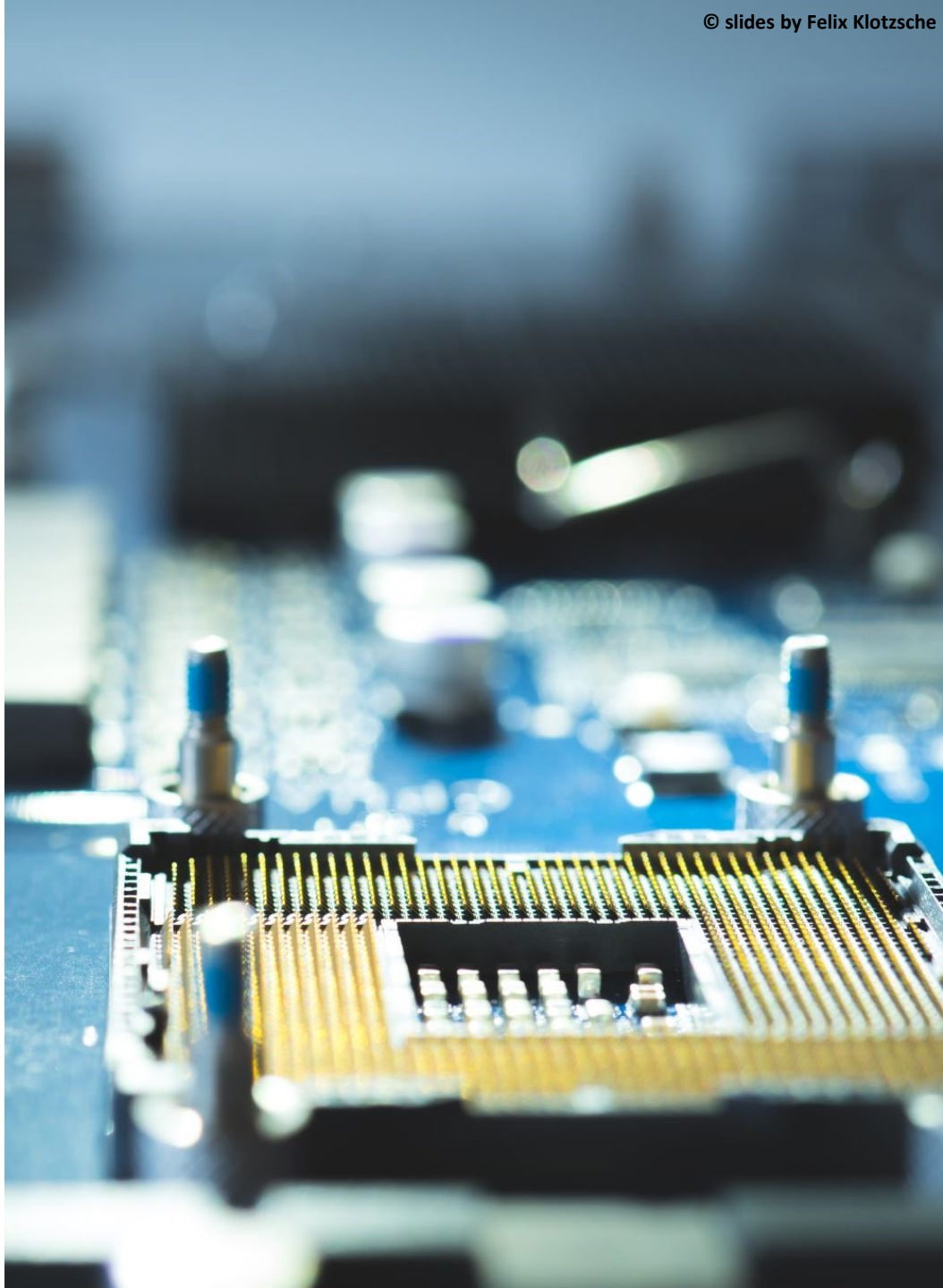
Variants of the same task: Retro-cues



- Past work:
  - Higher memory capacity for natural stimuli
    [Brady, Störmer, & Alvarez, 2016]
- Future directions:
  - Assessing the role of reference frames in natural environments

Hardware



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Hardware — (current) VR headsets

tethered

HTC Vive Pro (Eye)
https://www.computeralliance.com.au/htc-vive-pro-edition-virtual-reality-3d-headset-kit-pn-99hanw007-0

mobile

Oculus Quest Pro
https://komete-xr.com/de/products/meta-quest-pro

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Hardware — (current) VR headsets

tethered headsets with eye-tracking (selection)

		Price (est.)	ET sampling rate
	HTC Vive Pro (Eye)	**1400€**	**120Hz**
	Varjo VR/XR 3/4	**3200€+**	**200Hz**
	HP Omnicept	**1050€**	**120Hz**

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Hardware — (current) VR headsets

mobile headsets with eye-tracking (selection)

		Price (est.)	ET sampling rate
	Meta Quest Pro	**1100€**	**72Hz**
	PICO Neo 4 Enterprise	**1100€**	**60Hz**
	Vive Focus 3 + Eye-Tracker	**1700€**	**120Hz**

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Hardware — (current) VR headsets

VRcompare - The Internet's Largest VR & AR Headset Database

	Meta Quest 3	2023	$499	2 x LCD binocular	110° horizontal 96° vertical	2064x2208 per-eye
	DPVR E4C	2023	$398	Single LCD binocular	95° horizontal 95° vertical 115° diagonal	1832x1920 per-eye
	Bigscreen Beyond	2023	$999	2 x Micro-OLED binocular	102° horizontal 90° vertical	2560x2560 per-eye

https://vr-compare.com/

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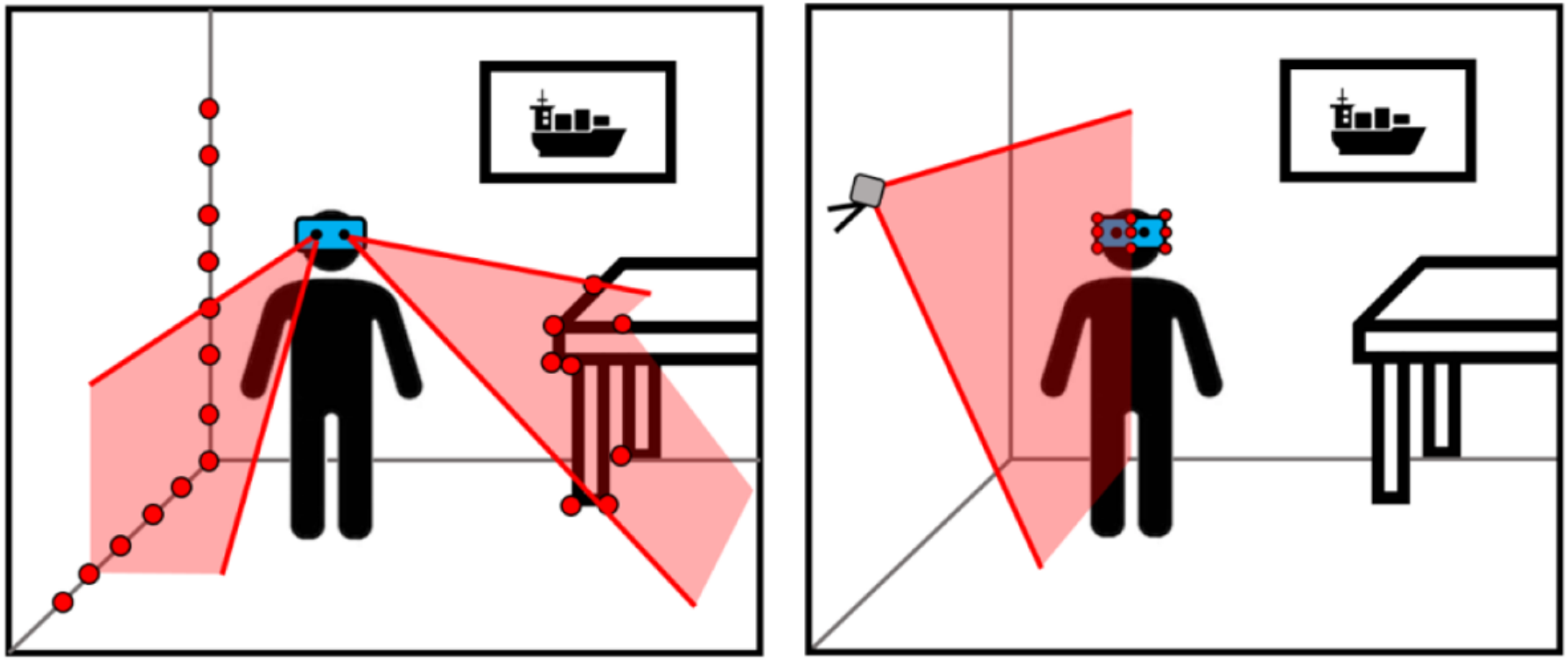
Spatial tracking



Inside-out tracking (a)

Outside-in tracking (b)

Bauer et al., 2021, *Sensors,* https://doi.org/10.3390/s21051622

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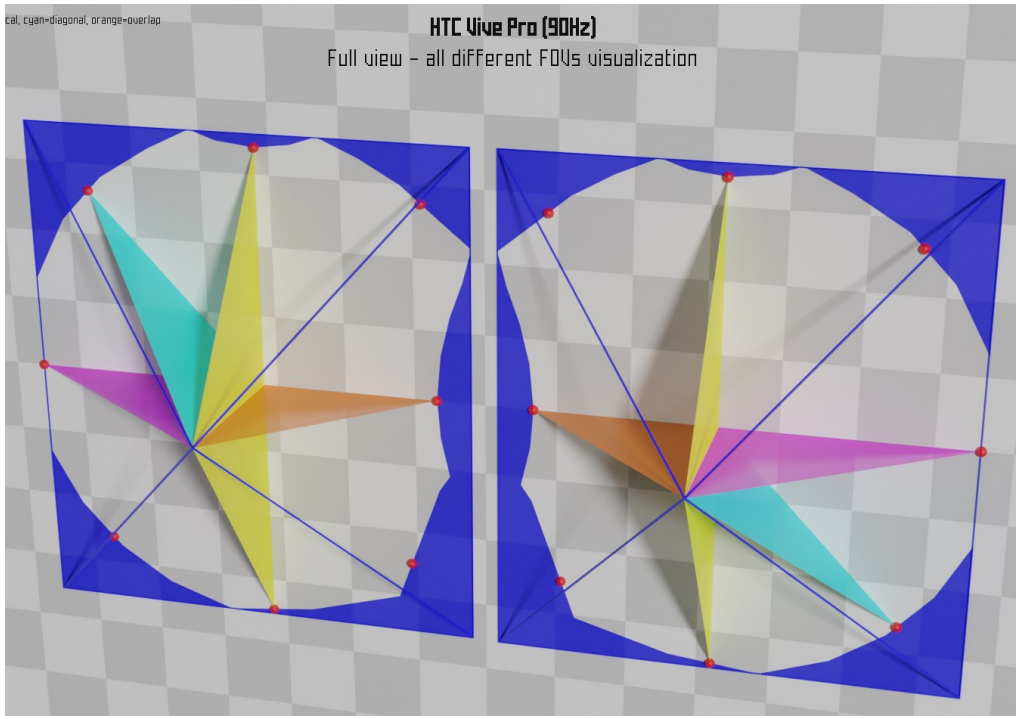
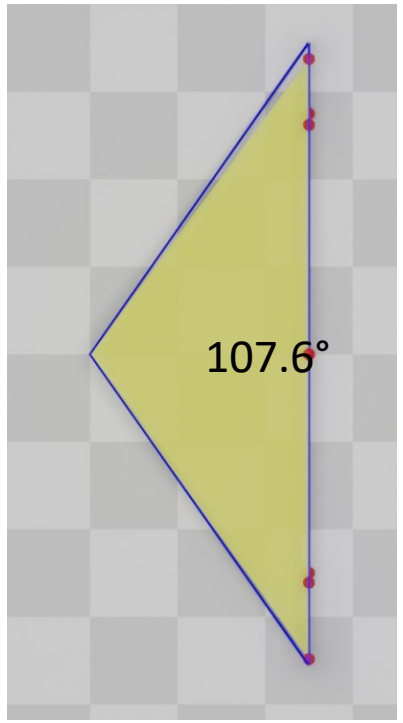
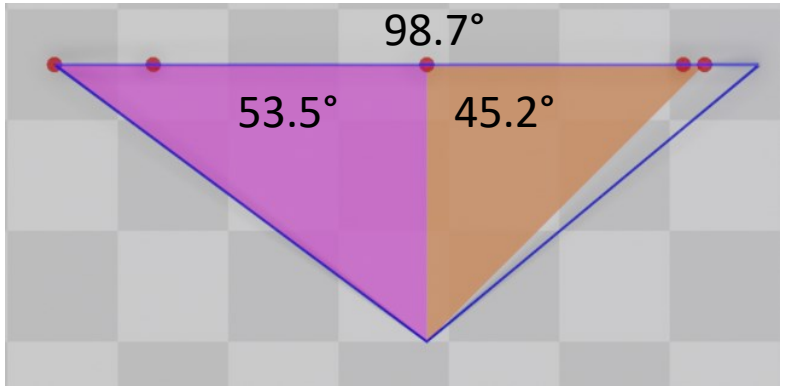
Field of view

rendered

https://www.reddit.com/r/Pimax/comments/88ae51/pimax_vs_vive_lenses_resized/





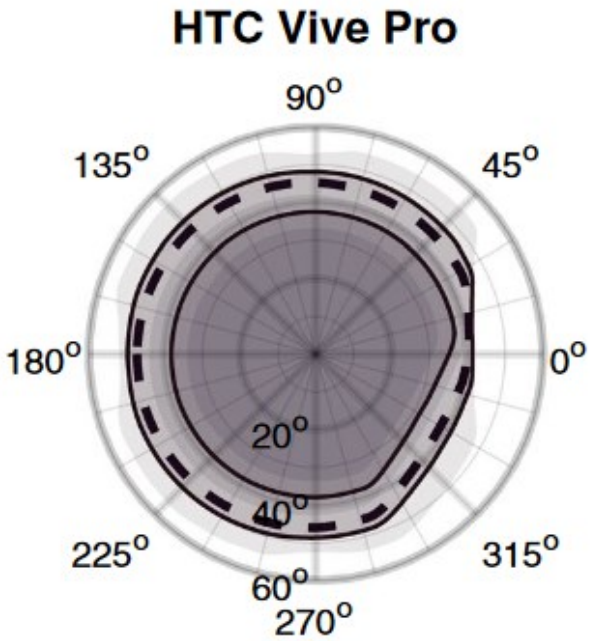


vertical and horizontal span of the rendered images (left eye)

Musil, 2023, *CC-BY-SA-4.0*
https://risa2000.github.io/hmdgdb/

Field of view

measured



Sauer et al., 2022, *Virtual Reality*
https://link.springer.com/article/10.1007/s10055-021-00619-x

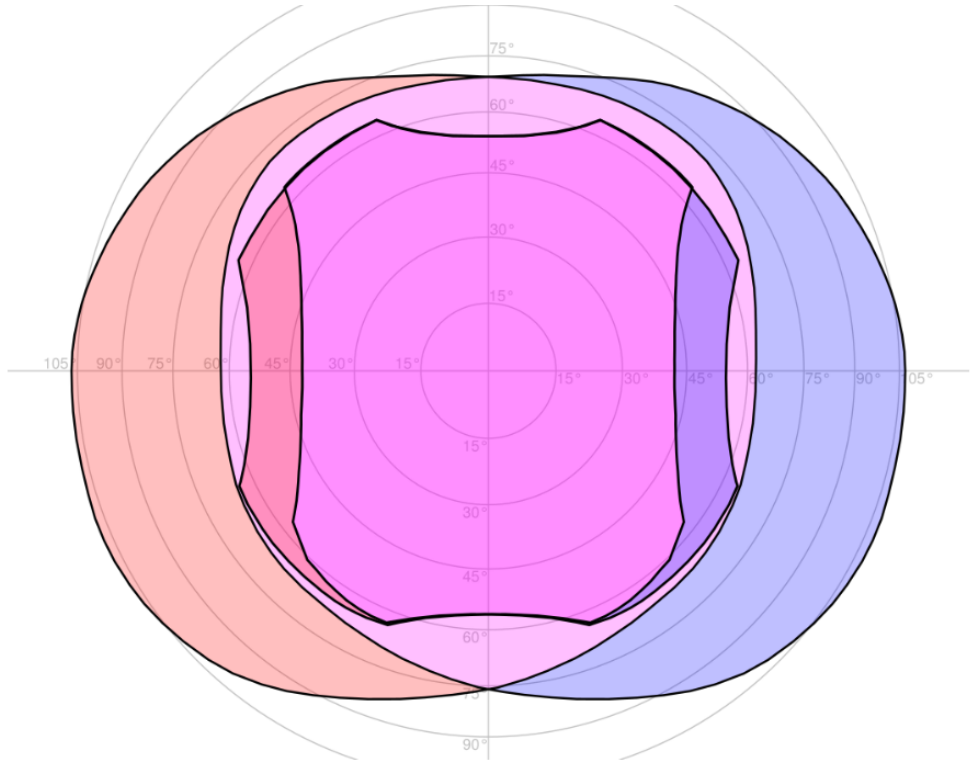


Figure 3: Maximum field of view of HTC Vive Pro (at 8mm eye relief), superimposed over average human FoV using an area-preserving projection. Numbers indicate azimuthal angle away from the forward direction. Red: left-eye FoV. Blue: right-eye FoV. Purple: binocular FoV (stereo overlap).

http://doc-ok.org/?p=1955#more-1955

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Accommodation & vergence

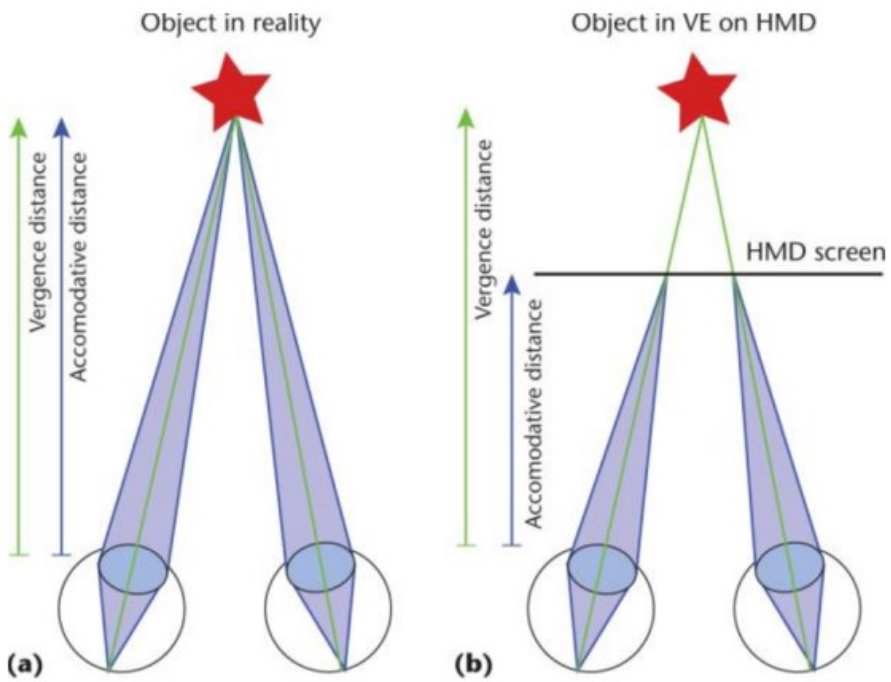

Figure 2: Vergence-Accommodation Conflict: (a) natural vision versus (b) screen based-vision.

Peillard et al., *ISMAR 2020,* https://ieeexplore.ieee.org/document/9284699

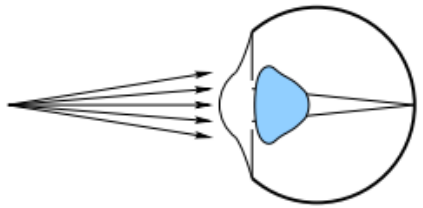

Figure 4.28: The process of accommodation: The eye muscles pull on the lens, causing it to increase the total optical power and focus the image on the retina.

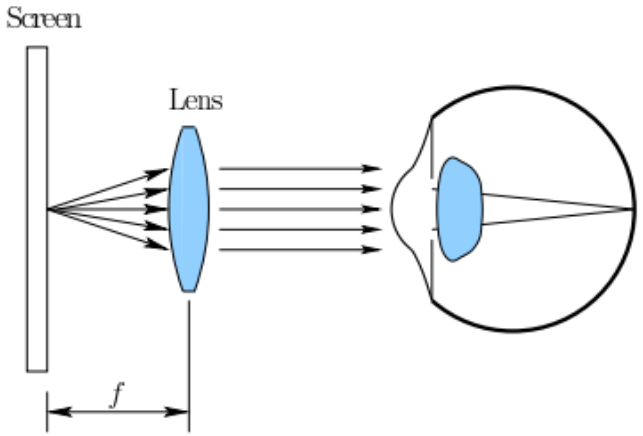

Figure 4.30: In VR headsets, the lens is placed so that the screen appears to be infinitely far away.

LaValle, 2019, *Virtual Reality*, https://lavalle.pl/vr/vrch4.pdf

© slides by Felix Klotzsche

Accommodation & vergence

VIVE Products Experiences Support

HackPerception Posted March 15, 2019

Verified Members

3.5k

,

This turns out to be a rather complex question - you can get into a real rabbit hole trying to research this. In a mathmatical sense, the lens focus at infinity but in real-world practice alot of people report that the focal distance is equivalent ~1.4-3m depending on the HMD and their testing methodology. We don't really publish a focal distance because it's not a super cut and dry number due to how human preception works.

https://forum.htc.com/topic/5356-does-the-vive-system-use-optical-infinity/

reddit r/Vive r/Vive Search Reddit

Doc_Ok · 5 mo. ago

UC Davis KeckCAVES

> "it's not a super cut and dry number due to how human preception works."

LOL what a bunch of hogwash. What they meant to say was "we don't want to publish a hard number because minor manufacturing differences can cause a large device-by-device difference, and we don't want to admit how lax our quality control standards are."

3 Reply Share ···

https://www.reddit.com/r/Vive/comments/16ewdoy/what_is_htc_vives_focal_plane_distance/

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Accommodation & vergence

VIVE Products Experiences Support

HackPerception Posted March 15, 2019

Verified Members

This turns out to be a rather

s focus at infinity

nodology. We

https://foru

John Carmack
@ID_AA_Carmack

The design focal distance for the Quest/Quest 2 optics is 1.3 meters. Some older headsets were 2.0 meters, and I have been saying that incorrectly for a while.

4:35 PM · Mar 15, 2021

redd

y meant to say was "we don't want to publish a
because minor manufacturing differences can cause a large device-by-device difference, and we don't want to admit how lax our quality control standards are."

3 Reply Share ···

https://www.reddit.com/r/Vive/comments/16ewdoy/what_is_htc_vives_focal_plane_distance/

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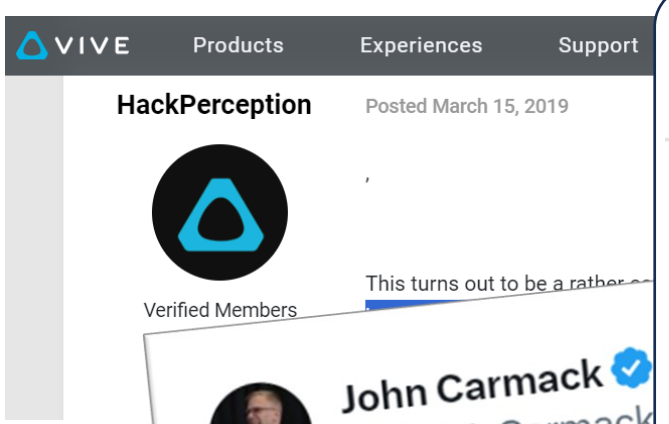
Accommodation & vergence



https://for

https://www.reddit.com/r/Vive/comments/16ewc

visionscience.com/pipermail/visionlist_visionscience.com/2021/005945.html

If you want to actually measure the focal length you'll have to follow Maarten's example and take the system apart; then you can put the Fresnel lens in an optical bench (or a lensometer if you're in an eyecare setting) and you'll have your dioptric power = 1 / focal length.

The virtual image distance can be measured by placing a positive lens (4 D should work fine) up against the Fresnel lens and in a dark room projecting the HMD image onto a white wall. Move the HMD until the image is sharp, measure the distance from wall to auxiliary lens, and apply the well-known formula:

$$1/f = 1/i + 1/s$$

where $1/f = 4$ (or whatever dioptric power you picked for your auxiliary lens), and i is the image distance, i.e., from auxiliary lens to wall, in meters.

You'll then find s, the distance from the auxiliary lens to the virtual HMD image, again in meters.

Hope this makes sense.

Best, Gislin

https://visionscience.com/pipermail/visionlist_visionscience.com/2021/005945.html

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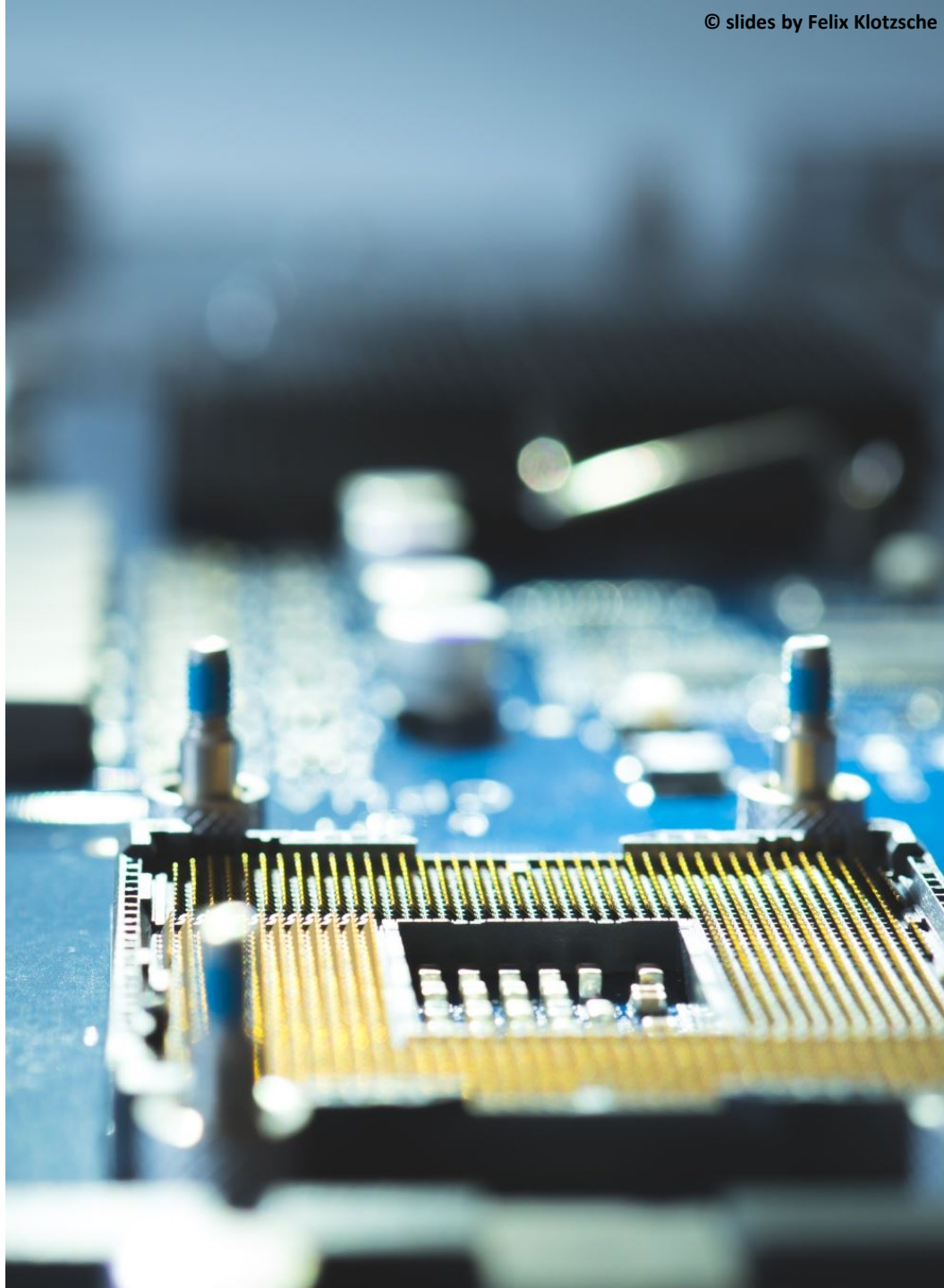
Hardware — take-aways

- https://vr-compare.com/
- Specify central aspects of your use case, research question, and possible constraints.
  - Mobility vs compute power?
  - Compatibility with the rest of your setup.
  - Peripheral vision.
  - How long should participants wear the HMD?
  - Which eye-tracking measures/quality do you need?
  - Community support.
- Do not trust the specs of the manufacturers. Try to find reports on reddit, forums, …
- Be prepared to be wrong. Have/be a supportive PI.



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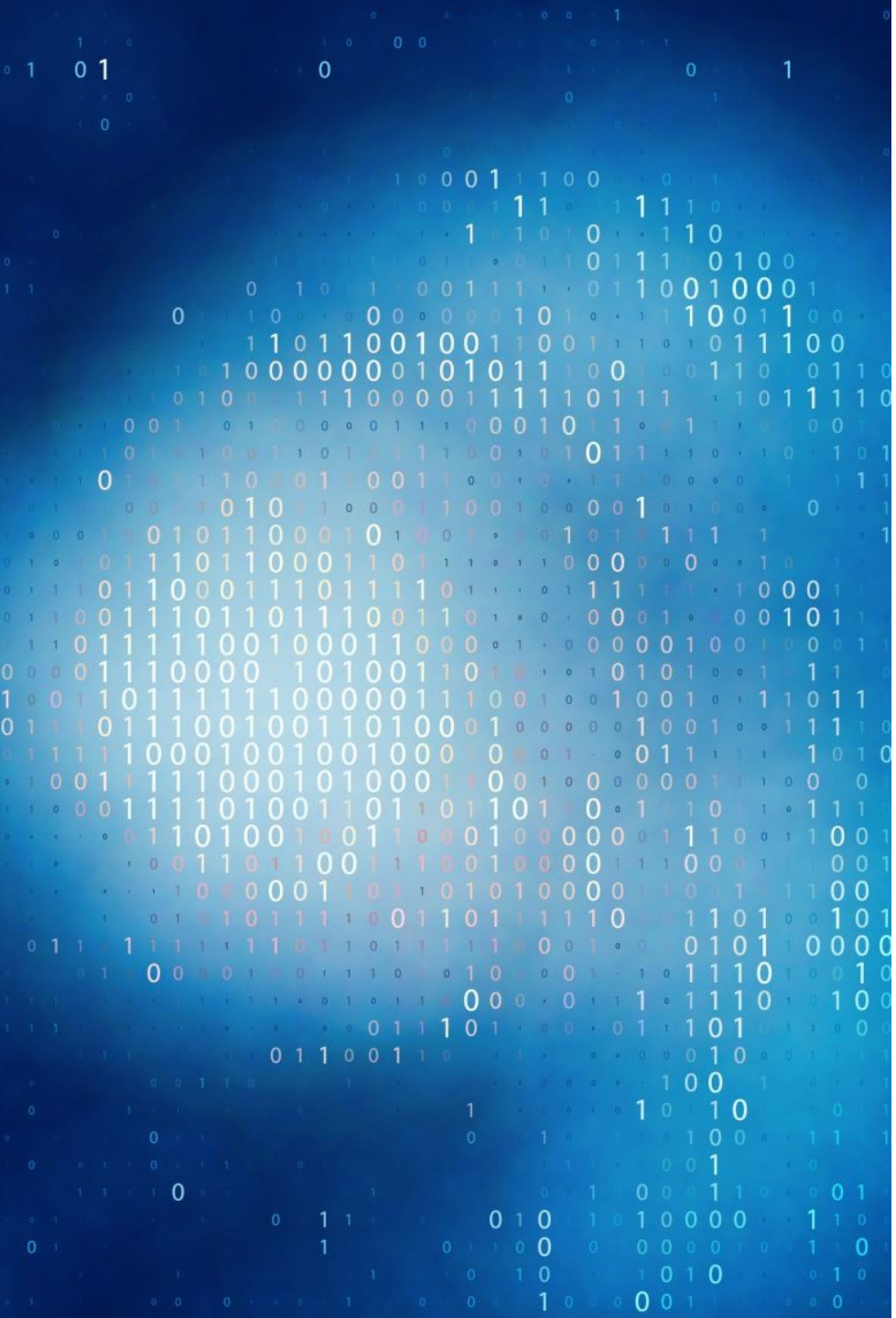

Software

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Software — Game engines

	scripting language	price model
Unity	**C#**	**free <$200k revenue**
Unreal	**C++, Verse**	**free <$1M revenue**
Godot	**GDScript, C#, C++**	**free, open source**
Vizard	**Python**	**paid, $2500?? lifetime license**

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Software — Scientific VR frameworks

VR support in Psychtoolbox (PsychVRToolbox)

http://psychtoolbox.org/docs/PsychVRToolbox

- ❑ MATLAB based
- ❑ OpenXR support
- ❑ Small user base?

Perception Toolbox for Virtual Reality (PTVR)

https://ptvr.inria.fr/

- ❑ Python based interface (Unity in the backend)
- ❑ For HTC Vive Pro
- ❑ Under active development

PsychoPy + PsychXR

http://psychxr.org/

- ❑ Python based
- ❑ OpenHMD support
- ❑ Last activity (GitHub) 3 years ago

Vizard

https://www.worldviz.com/vizard-virtual-reality-software

- ❑ Python based
- ❑ Supports many current headsets (incl eye-tracking)
- ❑ No support for mobile HMDs

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Software — Toolboxes

UXF 2.0

VR | Desktop | Web Browser

Behavior Research Methods (2020) 52:455–463
https://doi.org/10.3758/s13428-019-01242-0

Check for updates

Studying human behavior with virtual reality: The Unity Experiment Framework

Jack Brookes[1] · Matthew Warburton[1] · Mshari Alghadier[1] · Mark Mon-Williams[1,2] · Faisal Mushtaq[1,2]

Published online: 22 April 2019
© The Author(s) 2019

https://immersivecognition.com/unity-experiment-framework/

- ❑ Unity
- ❑ Useful for maneuvering trial structure & logging
- ❑ Well documented
- ❑ Last release: 2022

bmlTUX

i-Perception
Volume 11, Issue 4, July–August 2020
© The Author(s) 2020, Article Reuse Guidelines
https://doi.org/10.1177/2041669520938400

SAGE journals

Methods

bmlTUX: Design and Control of Experiments in Virtual Reality and Beyond

Adam O. Bebko and Nikolaus F. Troje

https://biomotionlab.github.io/TUX/

- ❑ Unity
- ❑ “Design and run experiments quickly”
- ❑ “Minimal code” required
- ❑ Last release: 2022

simpleXR (sXR)

https://github.com/simpleOmnia/sXR

- ❑ Unity
- ❑ “Facilitate rapid development of XR experiments”
- ❑ Under active development

vexptoolbox

Behavior Research Methods (2023) 55:570–582
https://doi.org/10.3758/s13428-022-01831-6

vexptoolbox: A software toolbox for human behavior studies using the Vizard virtual reality platform

Immo Schuetz[1,2] · Harun Karimpur[1,2] · Katja Fiehler[1,2]

Accepted: 9 March 2022 / Published online: 23 March 2022
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https://github.com/ischtz/vizard-experiment-toolbox

- ❑ Vizard
- ❑ “Randomized, trial-based experimental designs, … storing of result data, … built-in recording of eye-tracking and motion tracking data”
- ❑ Last release: 2022

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Digital Assets

Unity Asset Store

https://assetstore.unity.com/

cgtrader

https://www.cgtrader.com/

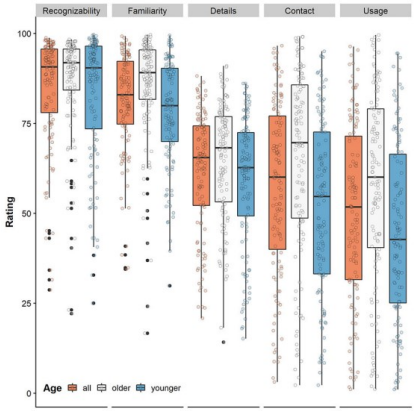
Sketchfab

https://sketchfab.com/

Objaverse-XL

A Universe of 10M+ 3D Objects

https://objaverse.allenai.org/



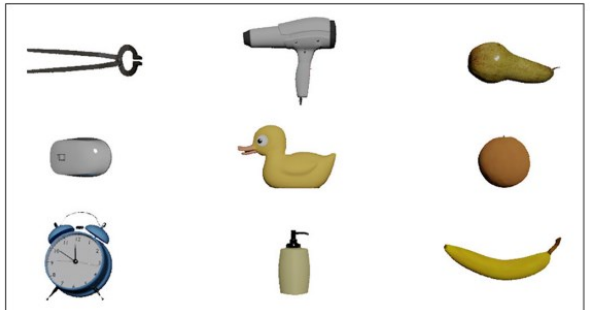


FIGURE 1 | Nine example 3D household objects from the freely available OpenVirtualObjects (OVO). (https://edmond.mpdl.mpg.de/imeji/collection/7L7t07UXD8asG_MI).

frontiers in Virtual Reality

ORIGINAL RESEARCH
published: 22 December 2020
doi: 10.3389/frvir.2020.611091

OpenVirtualObjects: An Open Set of Standardized and Validated 3D Household Objects for Virtual Reality-Based Research, Assessment, and Therapy

Johanne Tromp[1,2], Felix Klotzsche[1,2], Stephan Krohn[3], Mert Akbal[1,4], Leonardo Pohl[5], Eva M. Quinque[1,6], Julia Belger[1,6], Arno Villringer[1,2] and Michael Gaebler[1,2*]*

https://www.frontiersin.org/articles/10.3389/frvir.2020.611091/full

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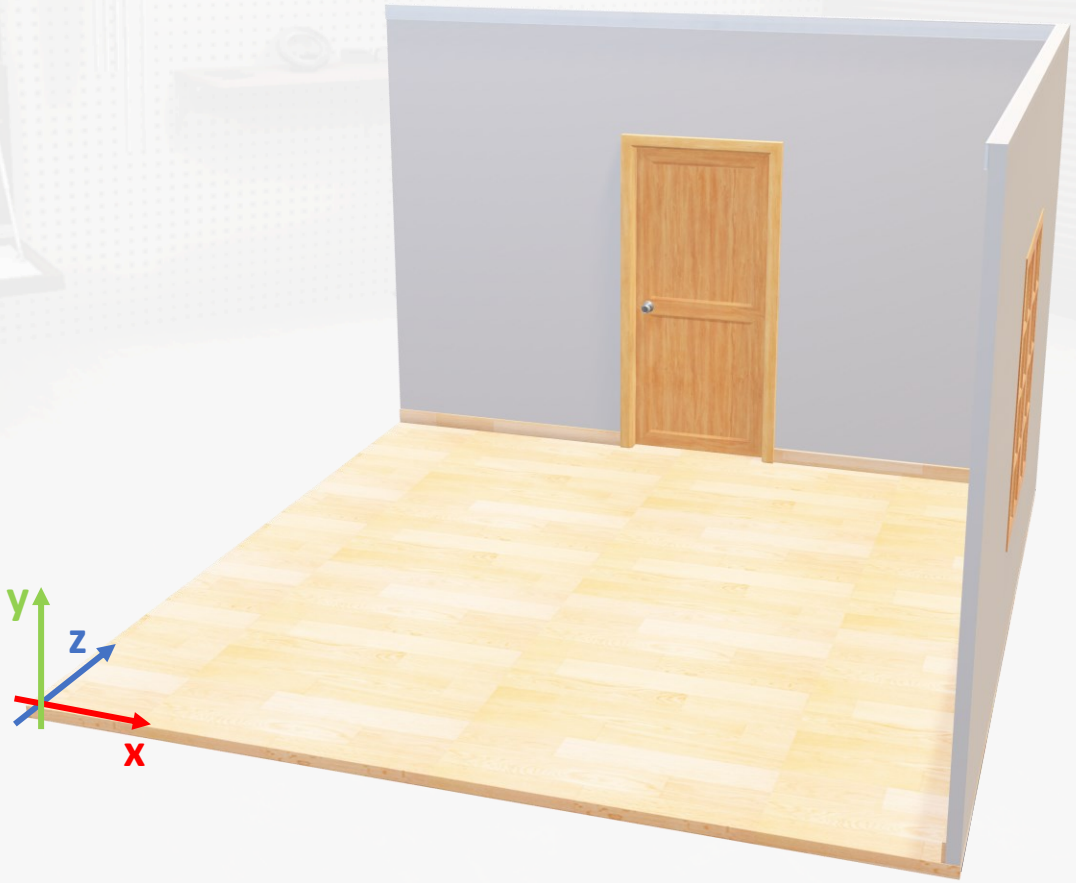
Excursus: spatial reference frames

world space

- arbitrary origin: $(0, 0, 0)^t$
- "left-handed" coordinate system, y-axis pointing up



3D models from Microsoft 3D library

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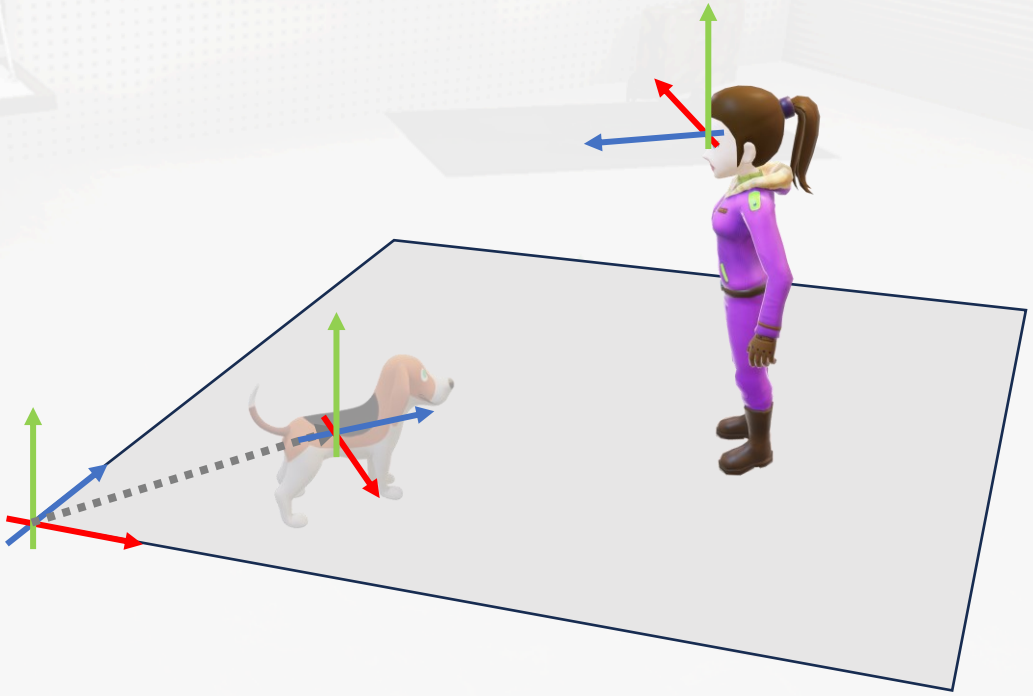
Spatial reference frames

world space

© slides by Felix Klotzsche

Spatial reference frames

world space vs local space(s)



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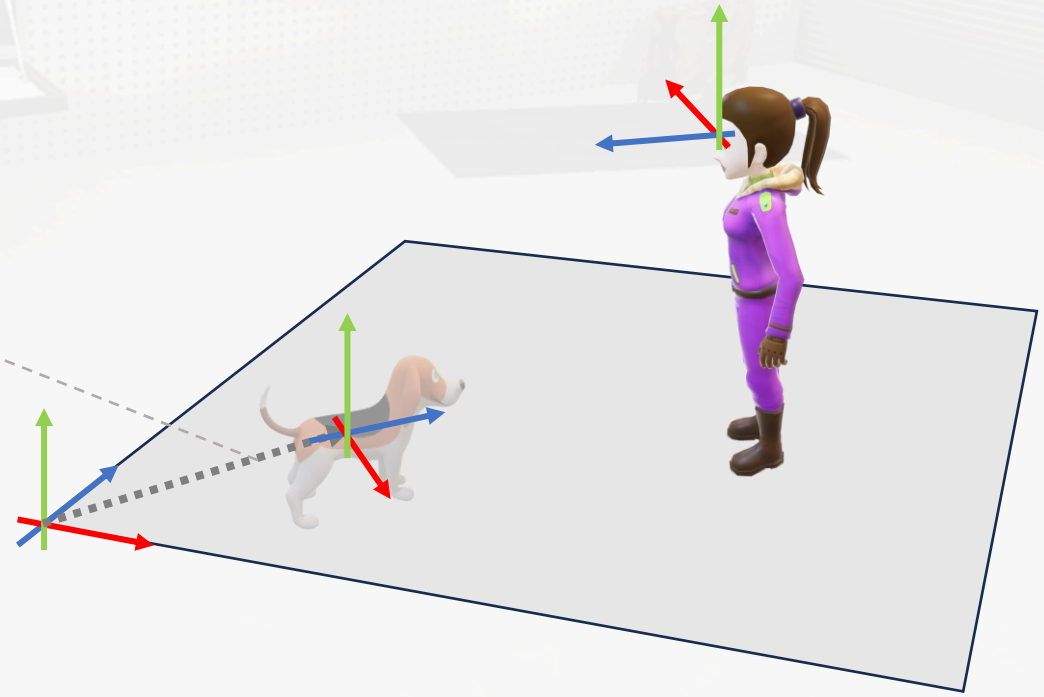
Spatial reference frames

world space vs local space(s)

pos_{dog}



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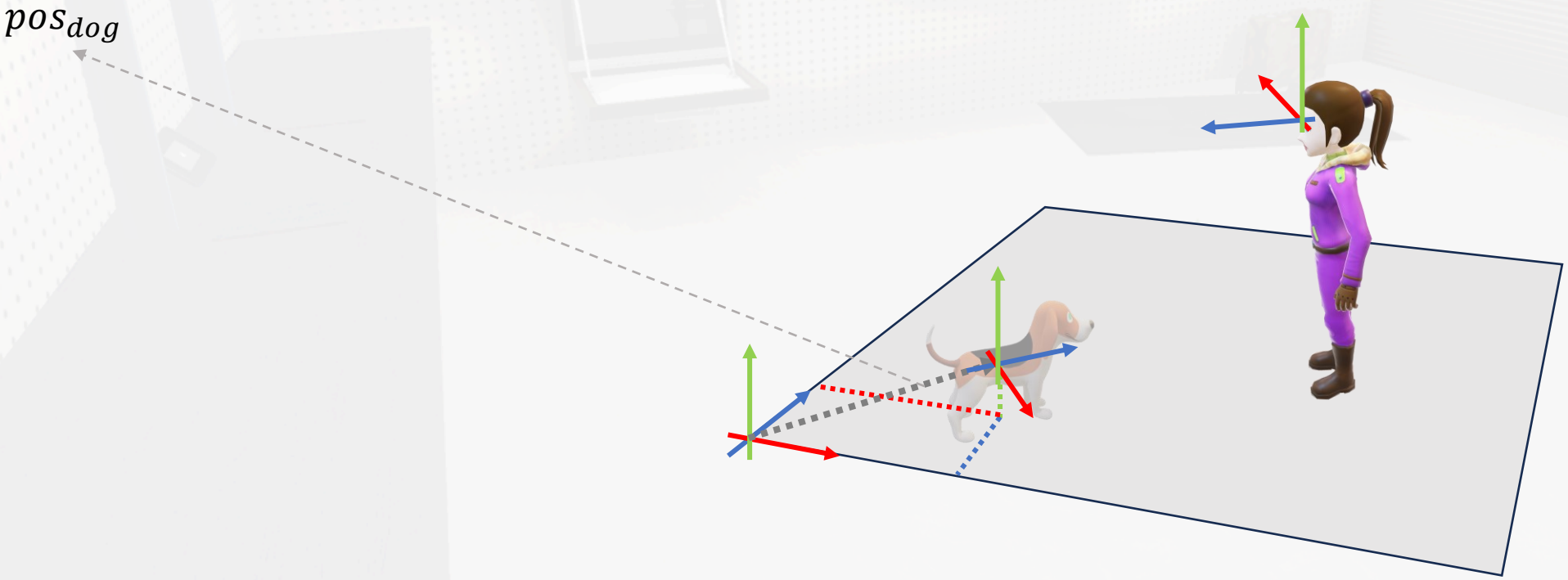
Spatial reference frames

world space vs local space(s)



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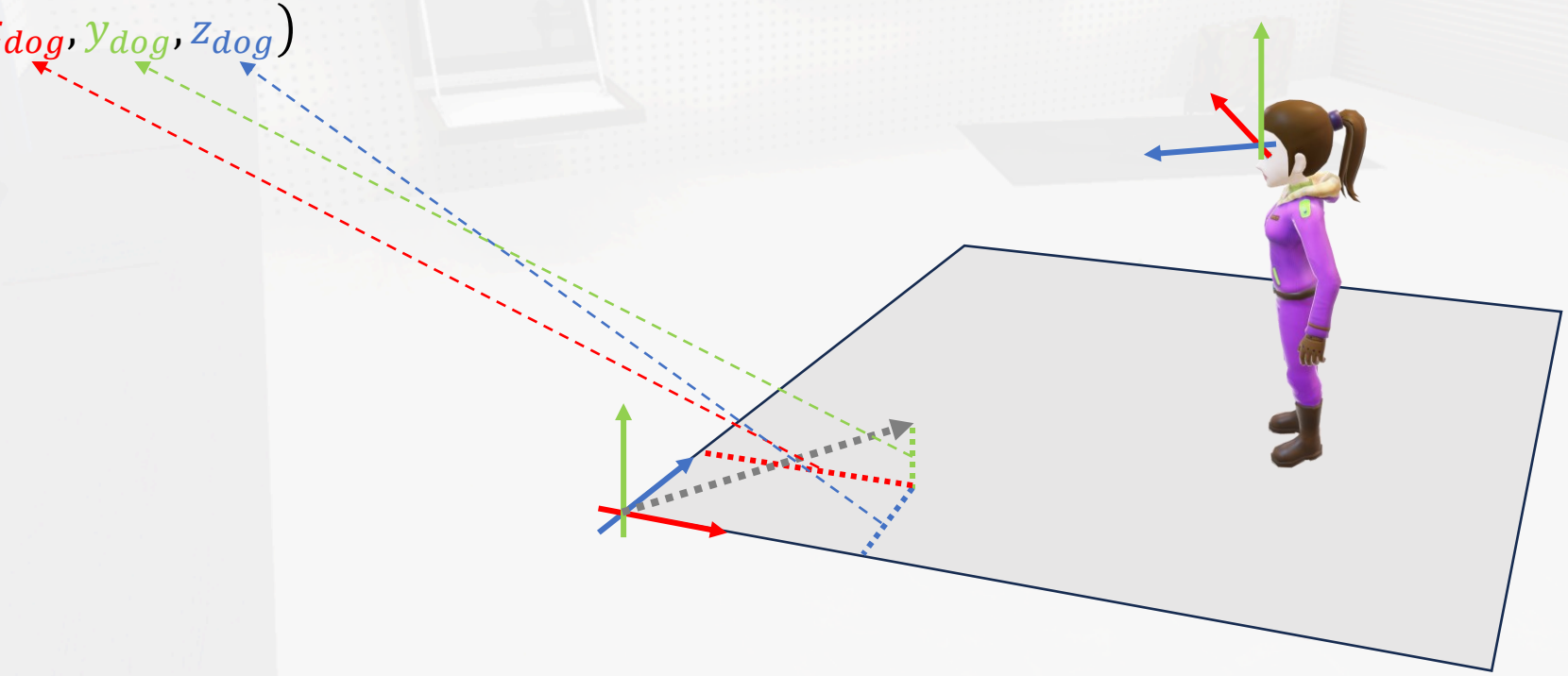
Spatial reference frames

world space vs local space(s)

$$pos_{dog} = (x_{dog}, y_{dog}, z_{dog})$$



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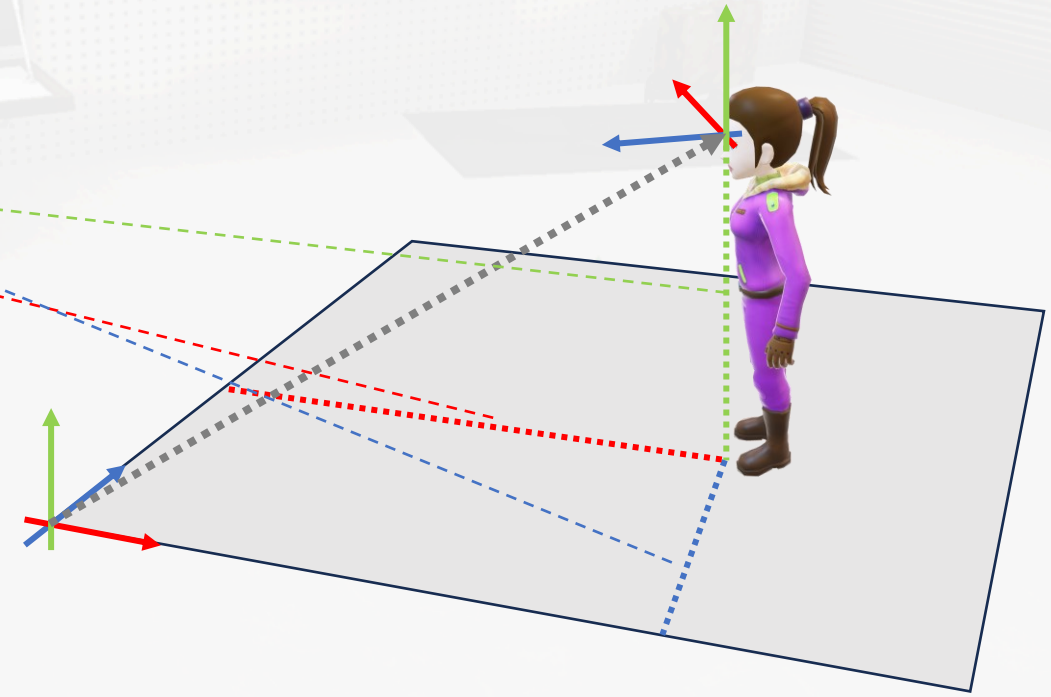
Spatial reference frames

world space vs local space(s)

$$pos_{amy} = (x_{amy}, y_{amy}, z_{amy})$$



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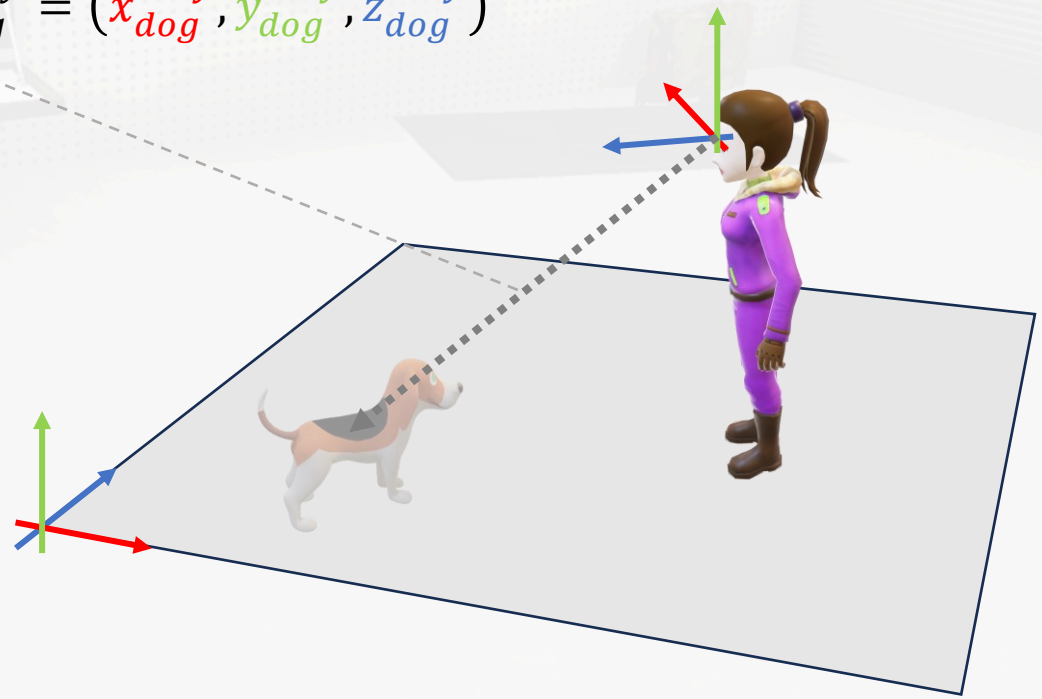
Spatial reference frames

world space vs local space(s)

$$pos_{dog} = (x_{dog}, y_{dog}, z_{dog})$$

$$pos_{amy} = (x_{amy}, y_{amy}, z_{amy})$$

$$pos_{dog}^{amy} = (x_{dog}^{amy}, y_{dog}^{amy}, z_{dog}^{amy})$$



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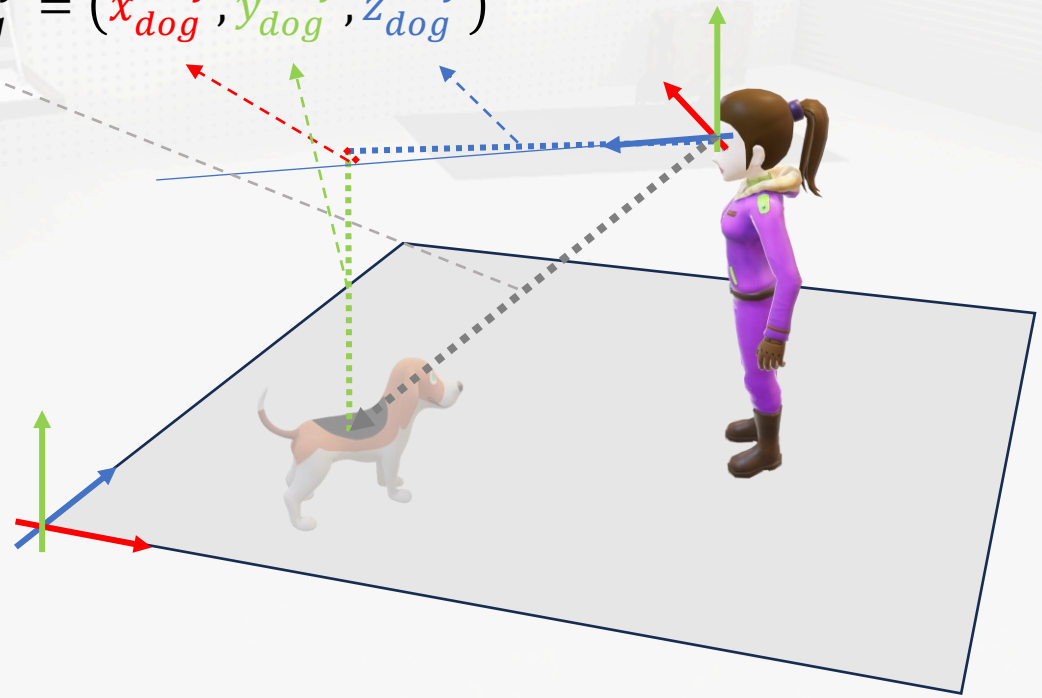
Spatial reference frames

world space vs local space(s)

$$pos_{dog} = (x_{dog}, y_{dog}, z_{dog})$$

$$pos_{amy} = (x_{amy}, y_{amy}, z_{amy})$$

$$pos_{dog}^{amy} = (x_{dog}^{amy}, y_{dog}^{amy}, z_{dog}^{amy})$$



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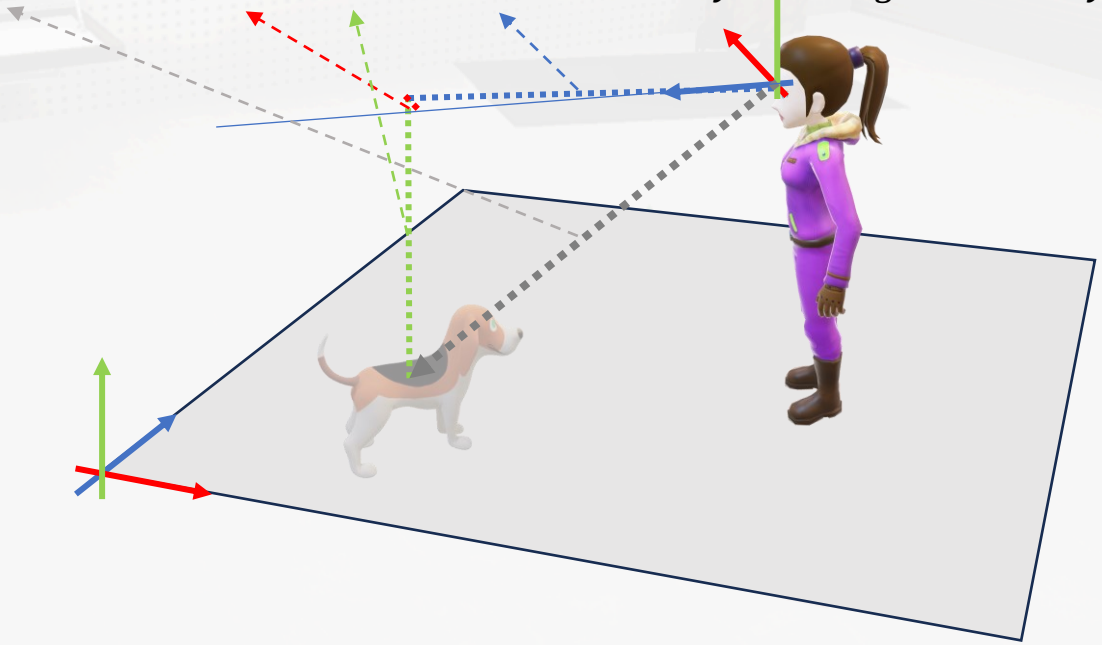
Spatial reference frames

world space vs local space(s)

$$pos_{dog} = (x_{dog}, y_{dog}, z_{dog})$$

$$pos_{amy} = (x_{amy}, y_{amy}, z_{amy})$$

$$pos_{dog}^{amy} = (x_{dog}^{amy}, y_{dog}^{amy}, z_{dog}^{amy}) = R_{amy}^{-1}(pos_{dog} - pos_{amy})$$



$$pos_{dog} = R_{amy}(pos_{dog}^{amy}) + pos_{amy}$$

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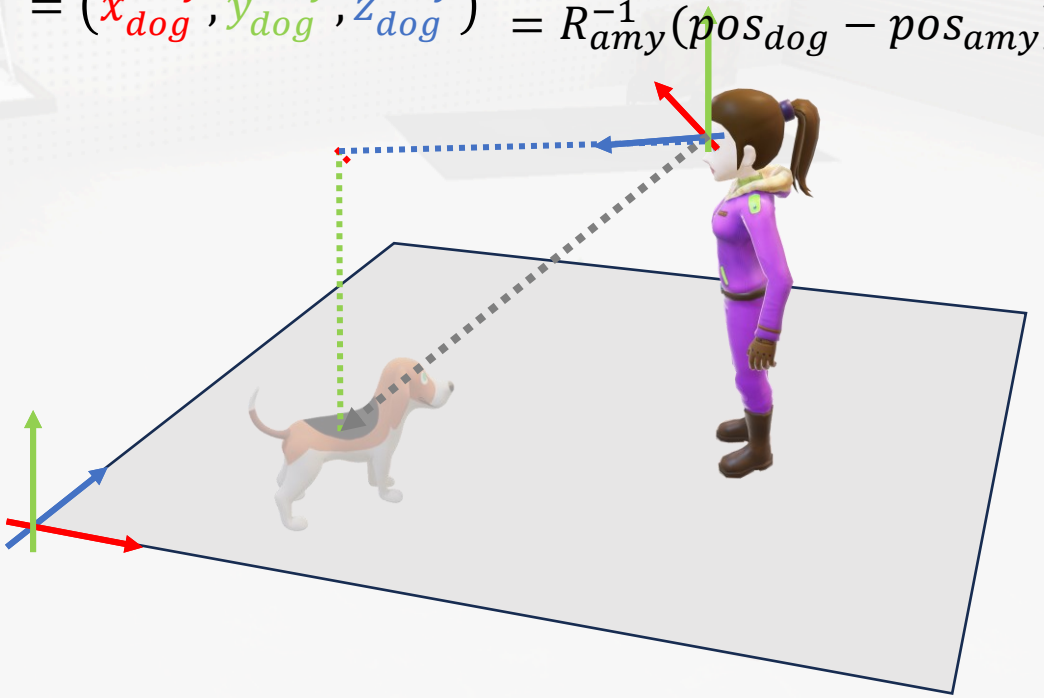
Spatial reference frames

world space vs local space(s)

$$pos_{dog}^{amy} = (x_{dog}^{amy}, y_{dog}^{amy}, z_{dog}^{amy}) = R_{amy}^{-1}(pos_{dog} - pos_{amy})$$



R_{amy}:

$$pos_{dog} = R_{amy}(pos_{dog}^{amy}) + pos_{amy}$$

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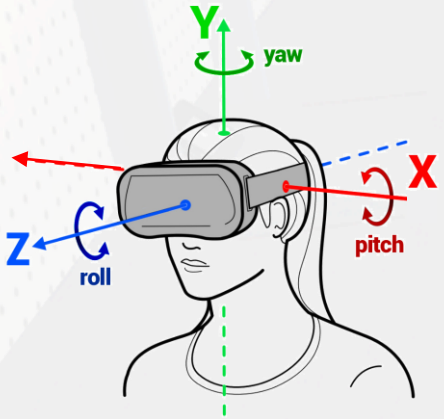
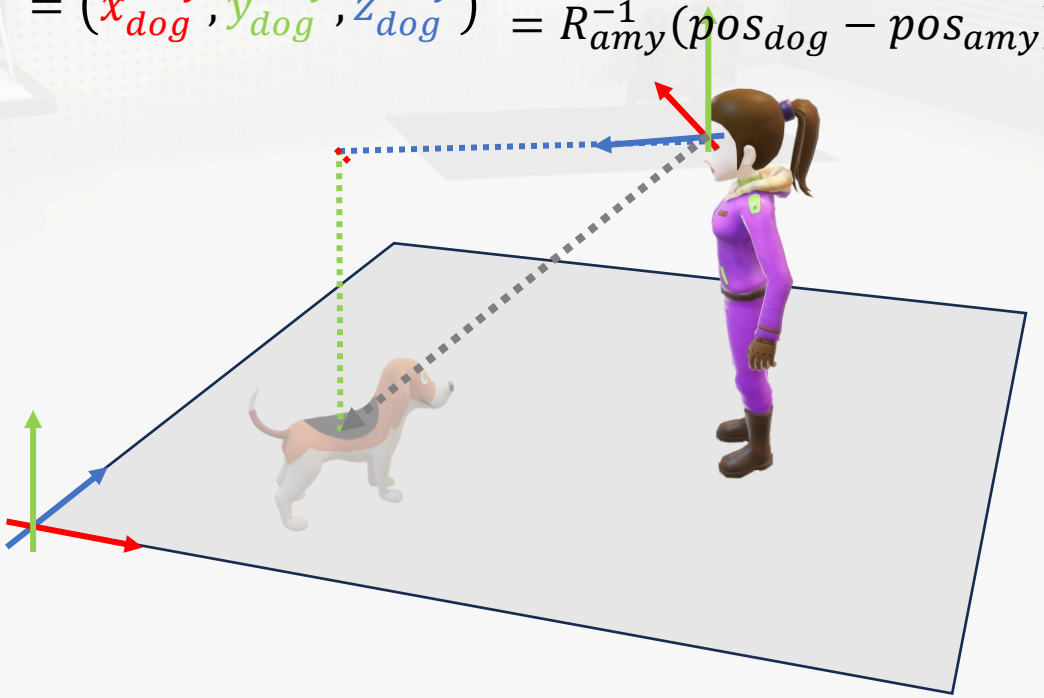
Spatial reference frames

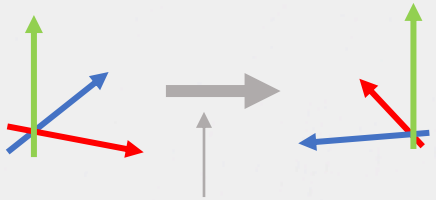
world space vs local space(s)

$$pos_{dog}^{amy} = (x_{dog}^{amy}, y_{dog}^{amy}, z_{dog}^{amy}) = R_{amy}^{-1}(pos_{dog} - pos_{amy})$$





R_{amy}:



Rotation via **matrix multiplication** or **quaternion conjugation**

$$pos_{dog} = R_{amy}(pos_{dog}^{amy}) + pos_{amy}$$

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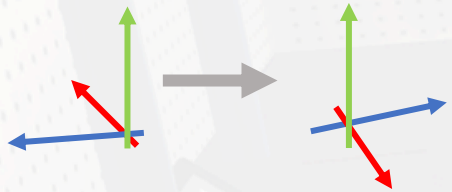
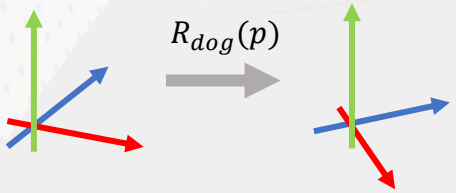
Spatial reference frames

world space vs local space(s)

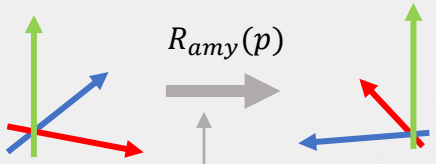
R_{dog}^{amy}:



R_{dog}:

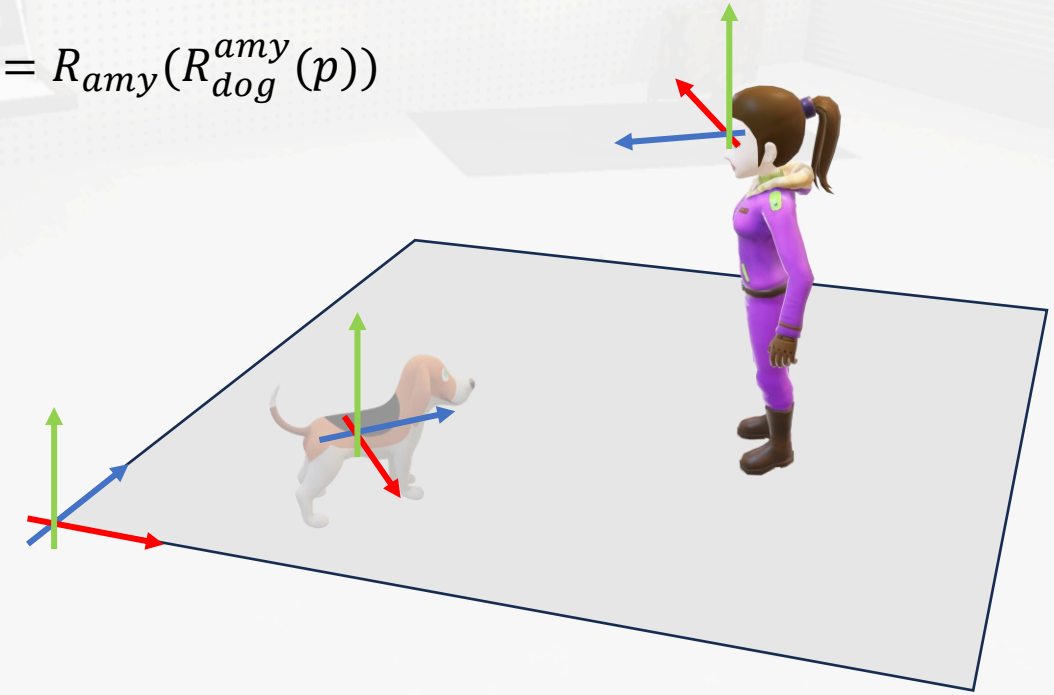


R_{amy}:



Rotation via **matrix multiplication** or **quaternion conjugation**

$$R_{dog}(p) = R_{amy}(R_{dog}^{amy}(p))$$



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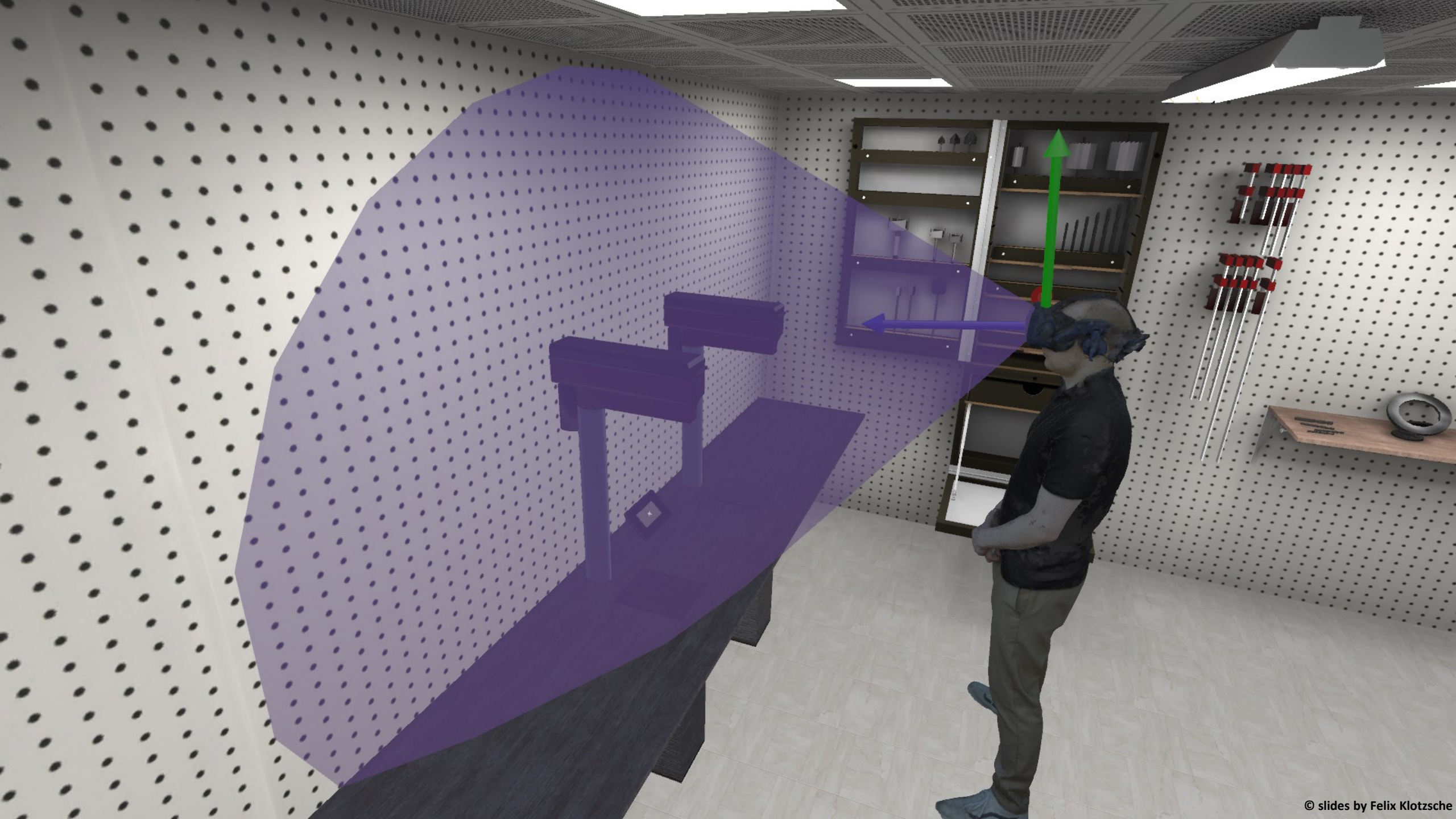

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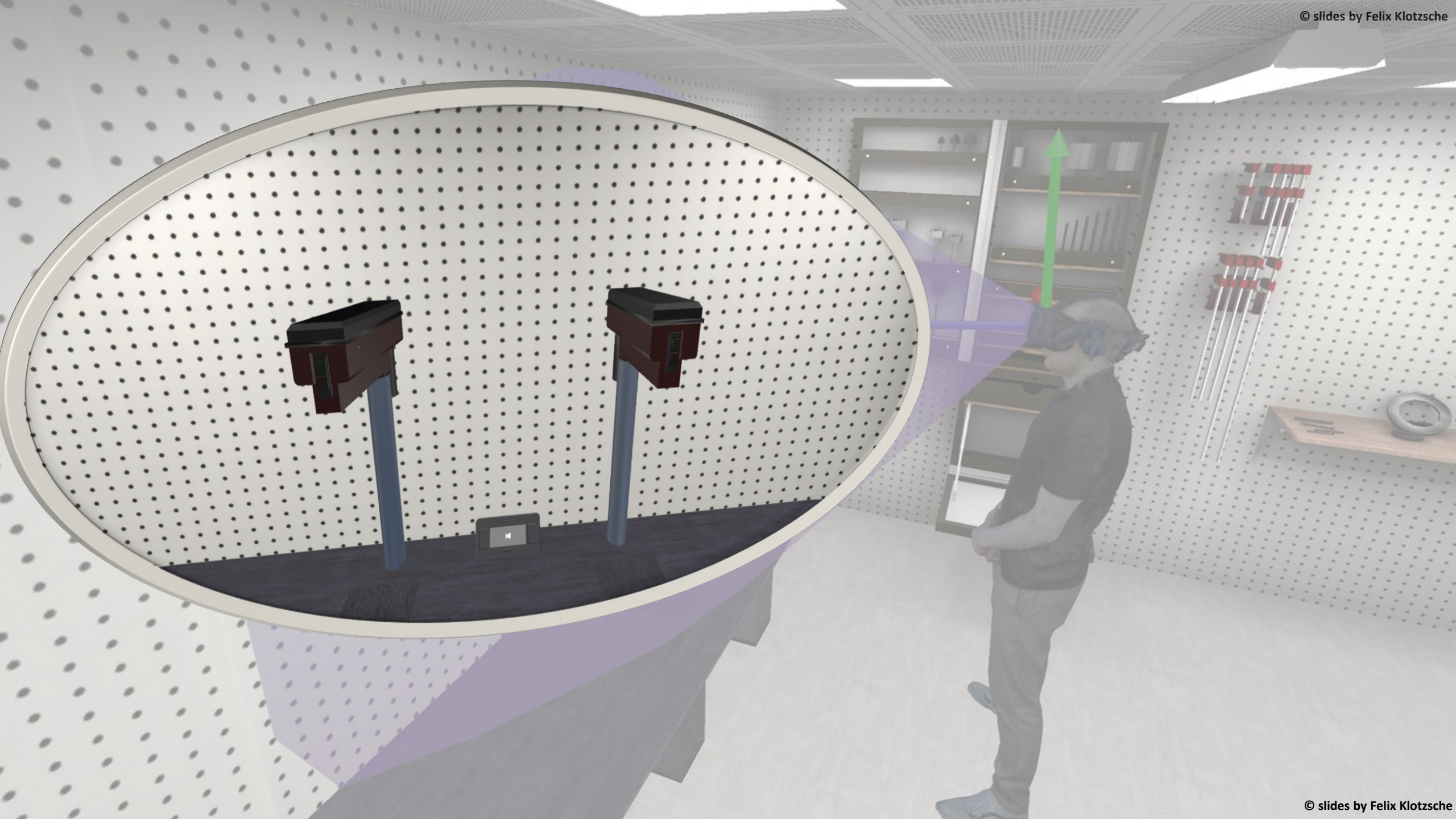

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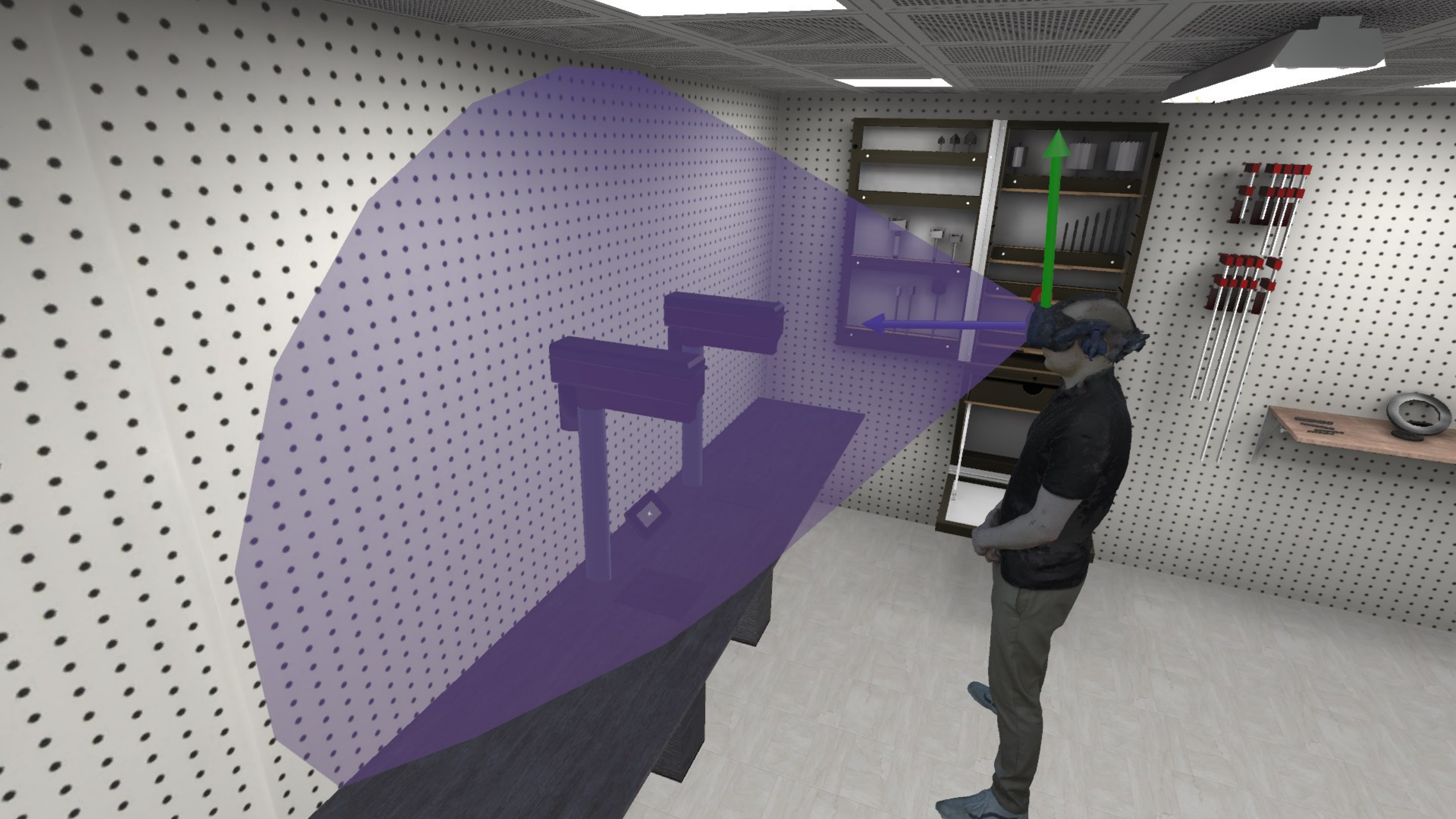

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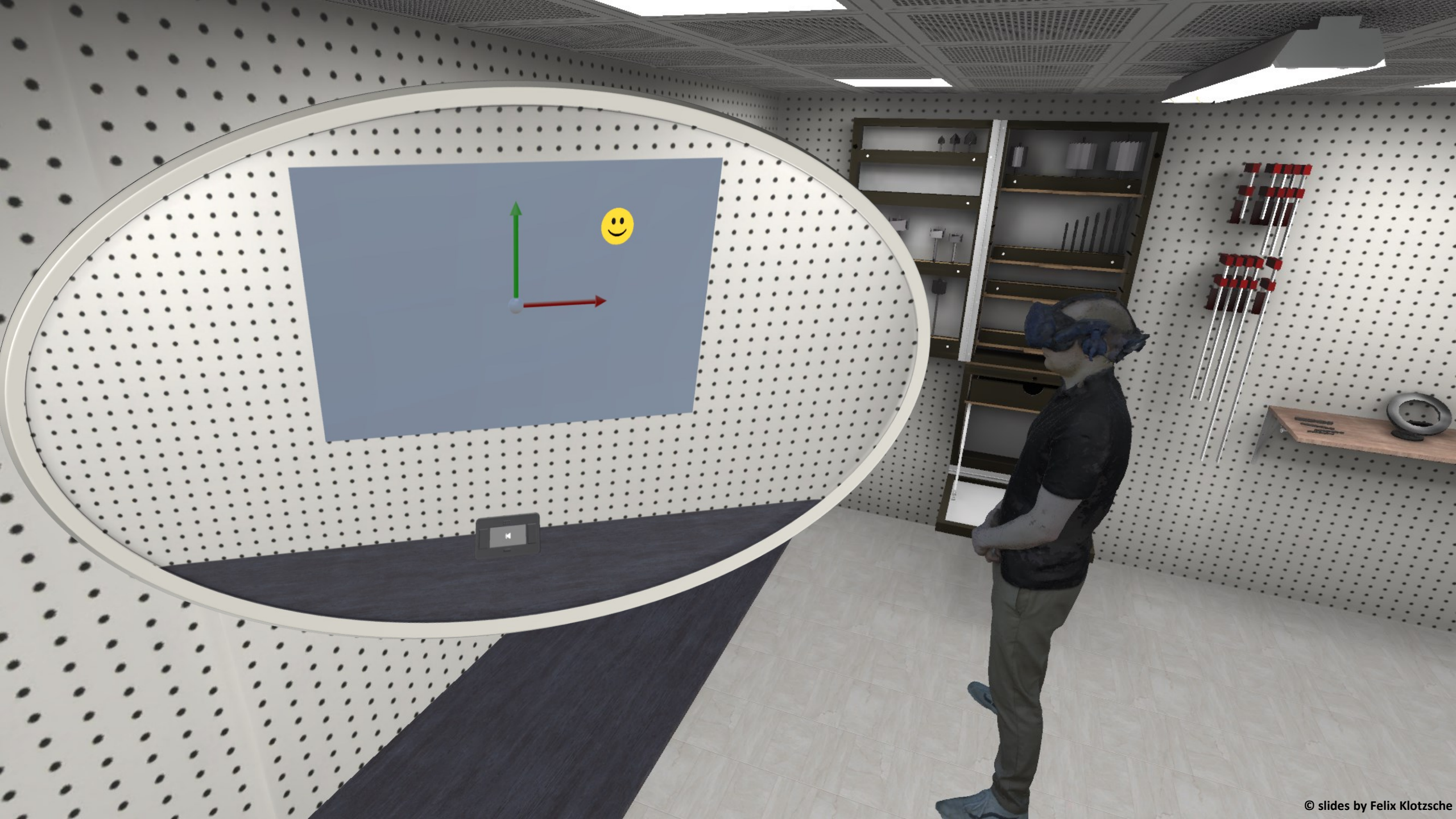

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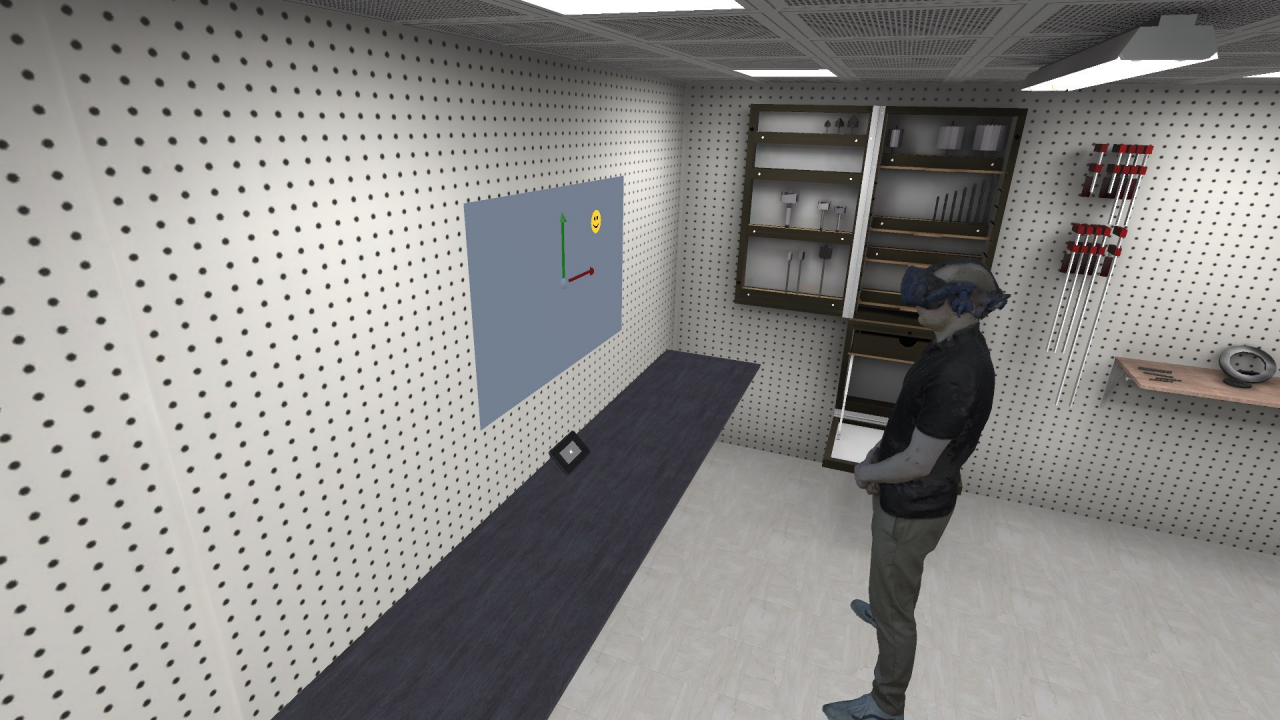


$$\boldsymbol{pos_{stim}^{emil}} = R_{emil}^{-1}(pos_{stim} - pos_{emil})$$

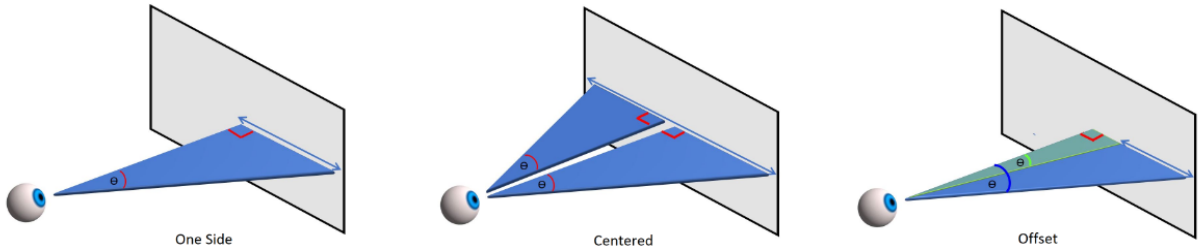
$$pos_{stim} = R_{board}\left(pos_{stim}^{board}\right) + pos_{board}$$

$$\boldsymbol{pos_{stim}^{emil}} = R_{emil}^{-1}\left(R_{board}\left(pos_{stim}^{board}\right) + pos_{board} - pos_{emil}\right)$$

$$= R_{emil}^{-1}\left(R_{board}\left(pos_{stim}^{board}\right) + R_{emil}^{-1}(pos_{board} - pos_{emil})\right)$$

Visual Angle Calculation

Calculating the amplitude of this angle involves some very basic maths – specifically some right-sided triangle trigonometry. You were probably taught this stuff in school – I remember thinking it could never possibly be useful in real life… As you can see in the images below (which switch to the horizontal axis), calculating the visual angle involves doing the sums for one or two right triangles, depending on exactly what it is you want to know.



assuming $\boldsymbol{R_{board}} = \boldsymbol{R_{emil}}$:

$$= pos_{stim}^{board} + R_{emil}^{-1}(pos_{board} - pos_{emil})$$

$$= \boldsymbol{pos_{stim}^{board}} + \boldsymbol{pos_{board}^{emil}}$$

© Sam Hutton, https://www.sr-research.com/eye-tracking-blog/background/visual-angle/

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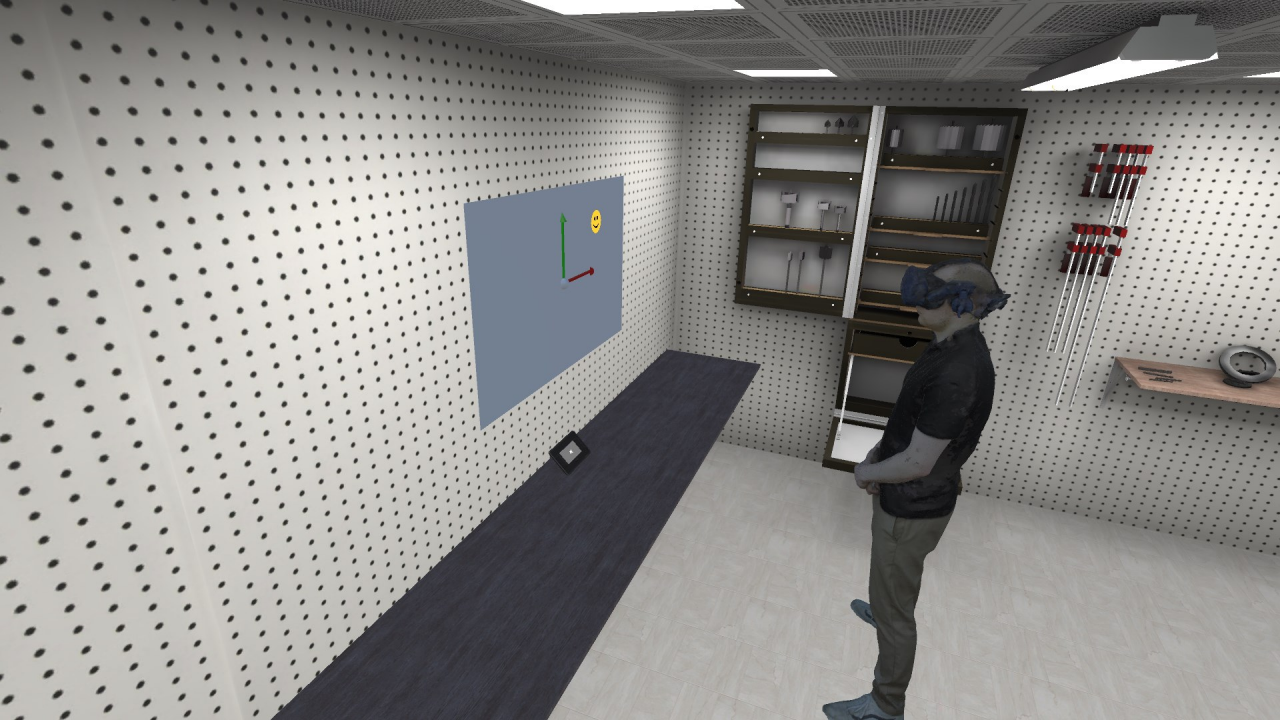
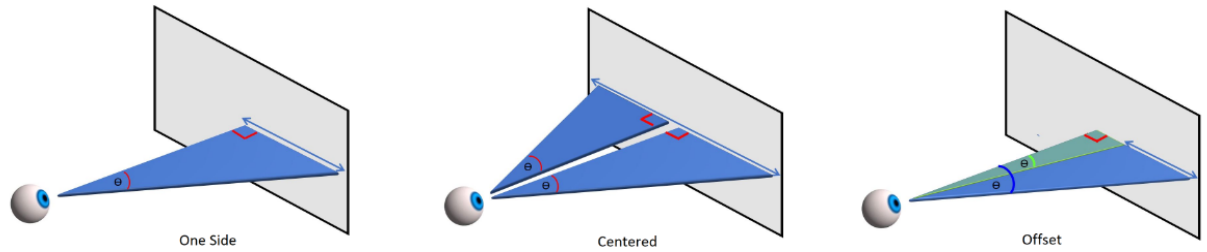


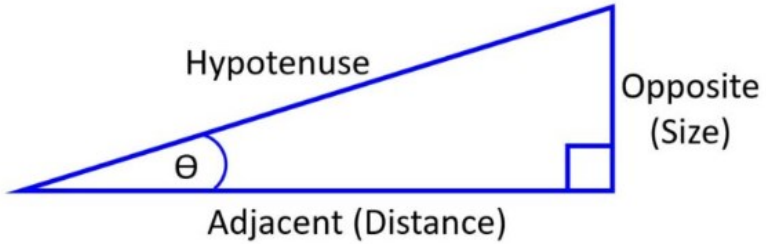
Local (head) space:

$$\boldsymbol{pos_{stim}^{emil} = pos_{stim}^{board} + pos_{board}^{emil}}$$ **(translation only!)**

$$pos_{stim}^{board} = (0.1, 0.2, 0)^t$$
$$pos_{board}^{emil} = (0, 0, 1.5)^t$$

$$pos_{stim}^{emil} = (0.1, 0.2, 1.5)^t$$





We can now apply simple trigonometry to figure out the position of a stimulus in the (2D) visual field (*vpos[x,y]*).

$$vpos[x] = \text{atan}\left(\frac{pos_{stim}^{emil}[x]}{pos_{stim}^{emil}[z]}\right)$$

$$vpos[y] = \text{atan}\left(\frac{pos_{stim}^{emil}[y]}{pos_{stim}^{emil}[z]}\right)$$

© Sam Hutton, https://www.sr-research.com/eye-tracking-blog/background/visual-angle/

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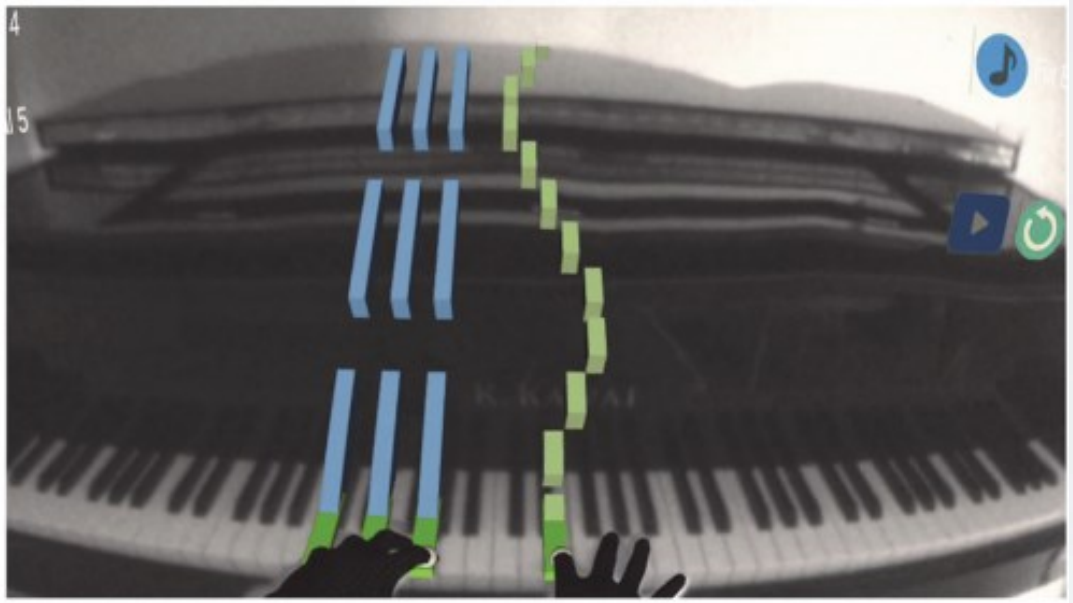
Excursus: coordinates in VR vs in actual visual field

Is the assumption justified that dimensions in virtual space translate 1:1 to the retinal image?

Answer 1 (observational):

it works! (e.g., alignment of digital assets and real objects)



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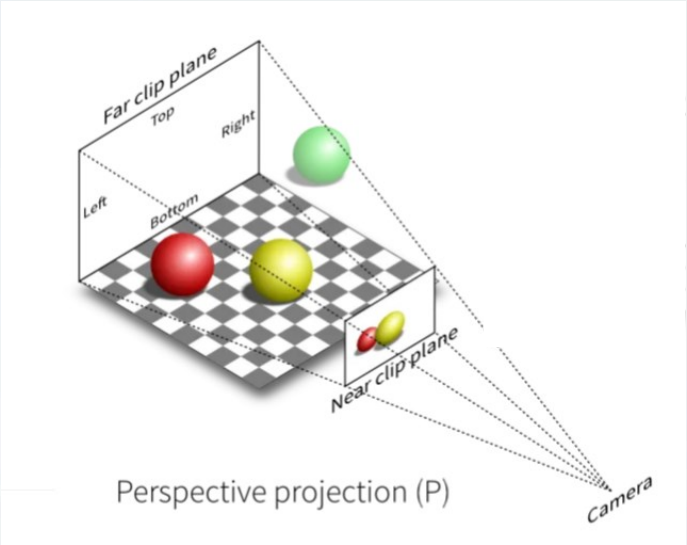
Excursus: coordinates in VR vs in actual visual field

Is the assumption justified that dimensions in virtual space translate 1:1 to the retinal image?

Answer 2 (numbers):

in the end, in VR headset the participant is also looking at a 2D display, so (theoretically) we should be able to determine the actual viewing angle



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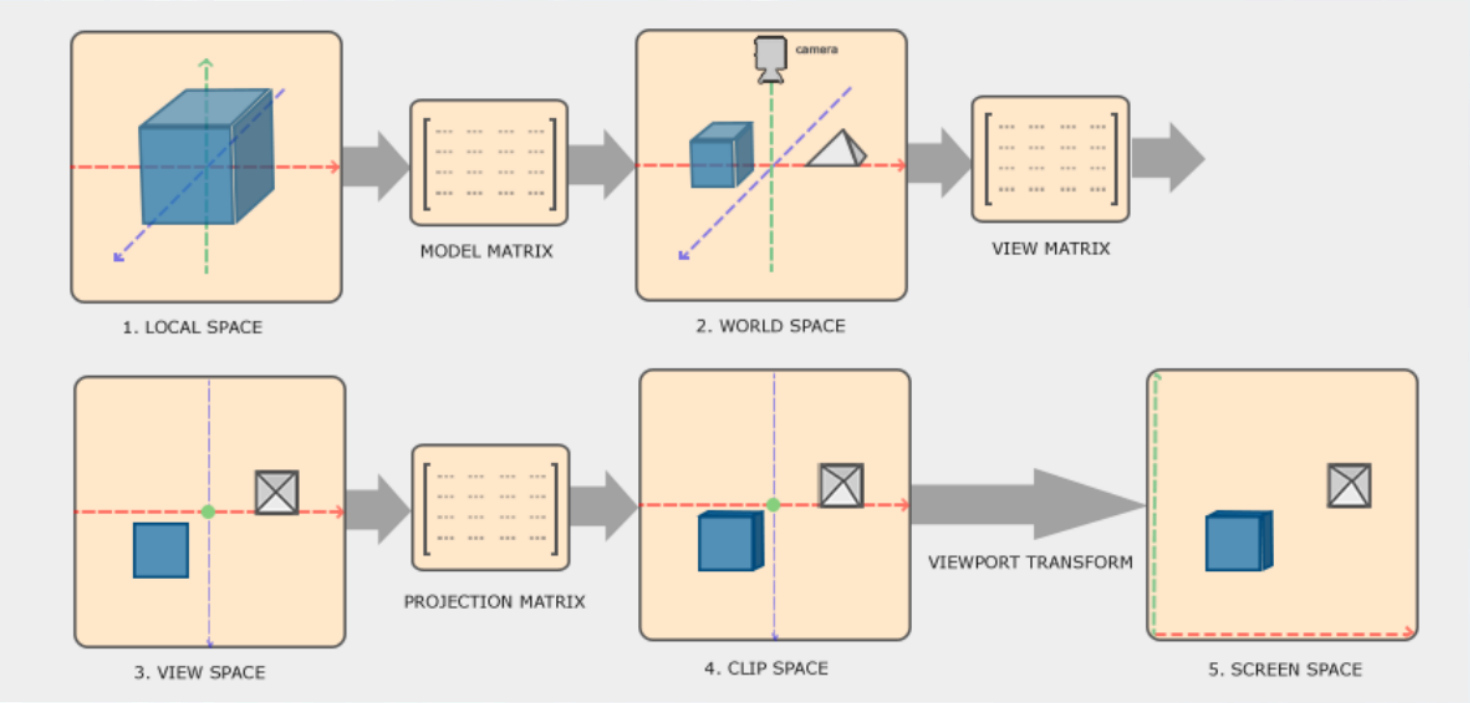
From 3D space to screen space

In theory



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From 3D space to screen space

In practice

… we query Unity to transform a point's coordinates (in world space) to screen space coordinates:

```
Vector3 stimulusPosScreenSpace = VrCam.WorldToScreenPoint(stimulusPosWorldSpace)
```

which returns **(x,y) coordinates in pixel space** (and z in world space).

We can now put this into relation to the extent of the display!

```
int screenWidth = XRSettings.eyeTextureWidth;
int screenHeight = XRSettings.eyeTextureHeight;

Debug.Log($"Relative position x-axis: {stimulusPosScreenSpace.x / screenWidth}");
Debug.Log($"Relative position y-axis: {stimulusPosScreenSpace.y / screenHeight}");
```

Tested (HTC Vive Pro Eye) with a stimulus presented centrally in the visual field: $pos_{stim}^{emil} = (0, 0, 1)^t$

```
Vector3 stimPosLocal = new Vector3(0, 0, 1);
Vector3 stimPosWorld = VrCam.transform.TransformPoint(stimPosLocal);
Debug.Log($"Rel. position x axis: {VrCam.WorldToScreenPoint(stimPosWorld).x / screenWidth}");
Debug.Log($"Rel. position y axis: {VrCam.WorldToScreenPoint(stimPosWorld).y / screenHeight}");
```

```
[02:34:05] vvvv
```

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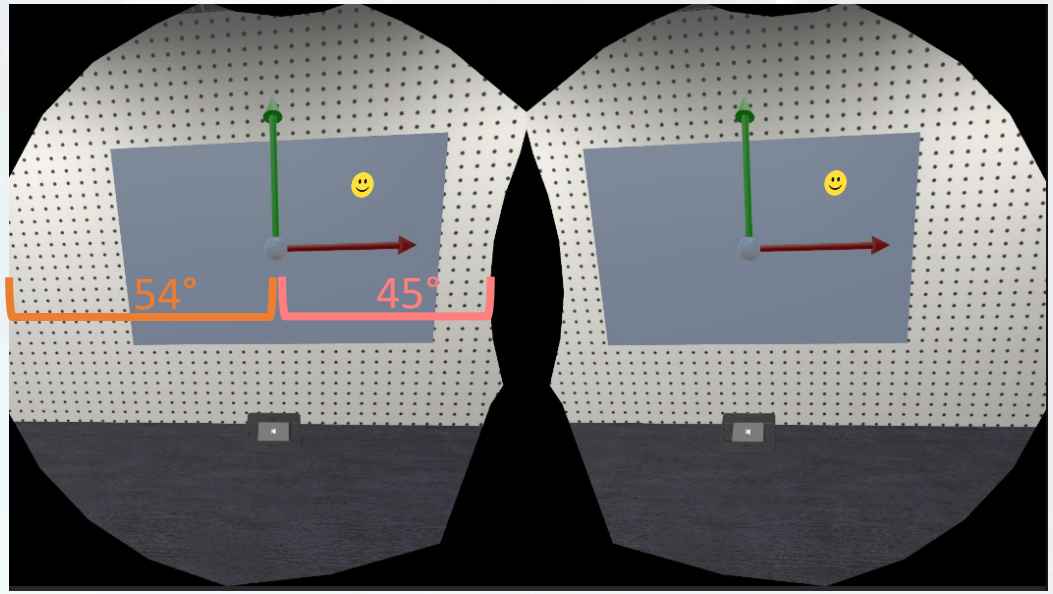
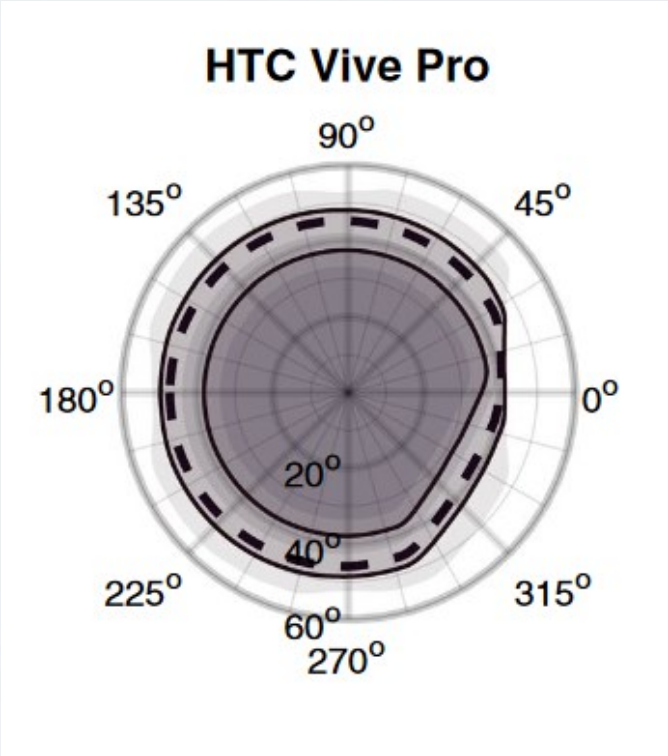
From 3D space to screen space

In practice





Sauer et al., 2022, *Virtual Reality*
https://link.springer.com/article/10.1007/s10055-021-00619-x

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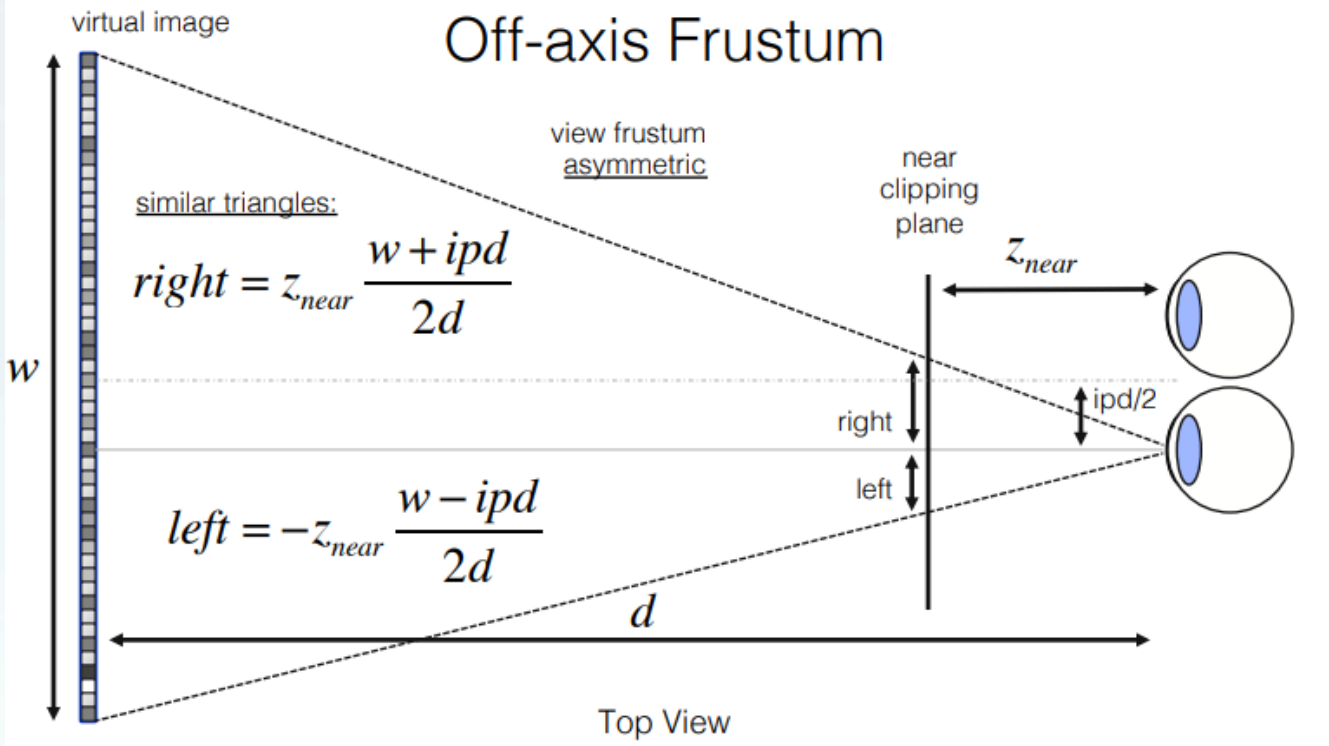
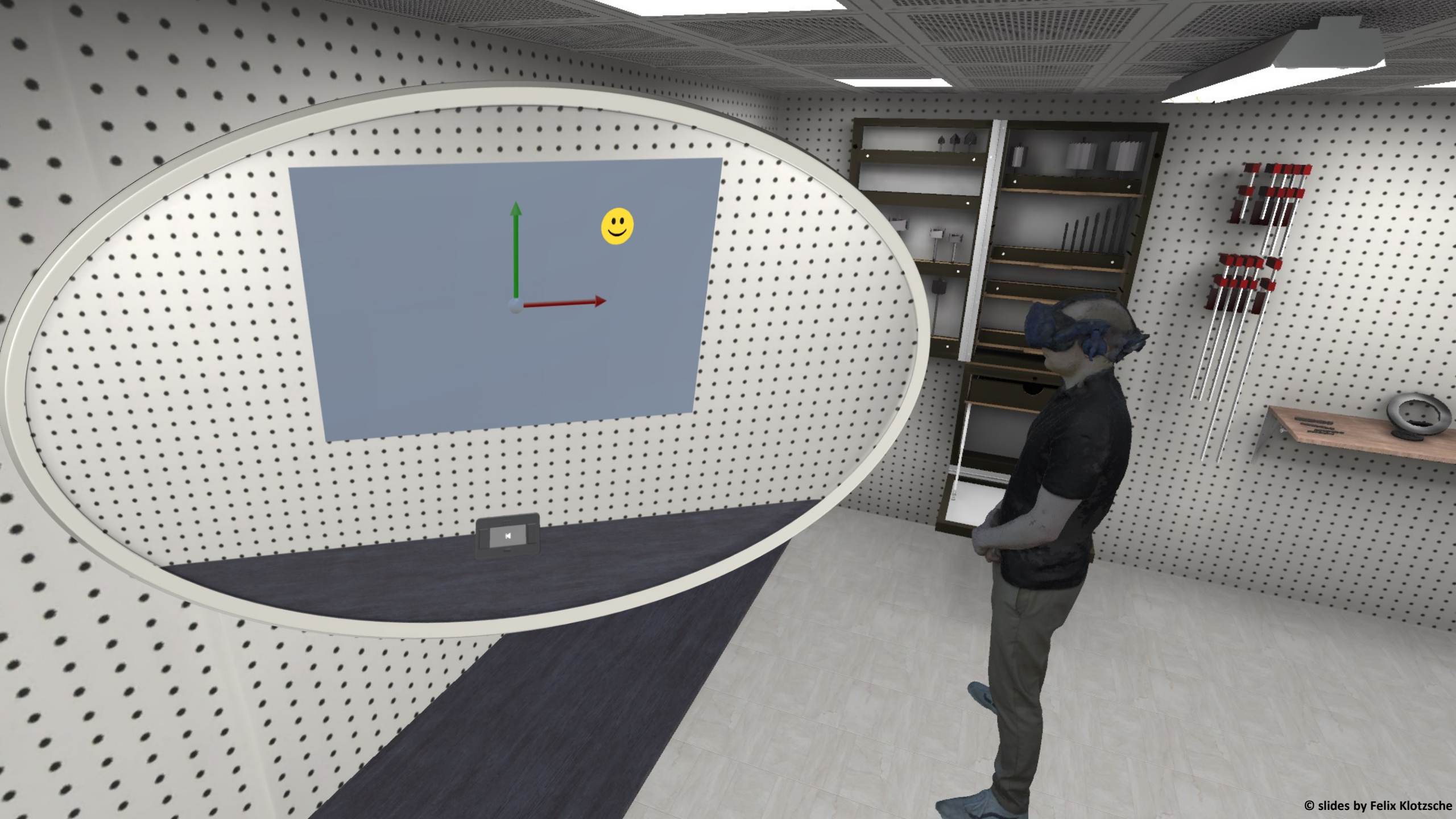
From 3D space to screen space

More theory



© Wetzstein, Stanford EE267, *Virtual Reality,* Lecture 6
https://stanford.edu/class/ee267/lectures/lecture6.pdf

Stanford EE267: Virtual Reality
https://stanford.edu/class/ee267/



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To get the local coordinates (head space) of the apple:

$$pos_{apple}^{emil} = R_{emil}^{-1}\left(pos_{apple} - pos_{emil}\right)$$

which gives us a 3D vector in the same reference frame as Emil
⇒ calculate viewing angles via trigonometry.

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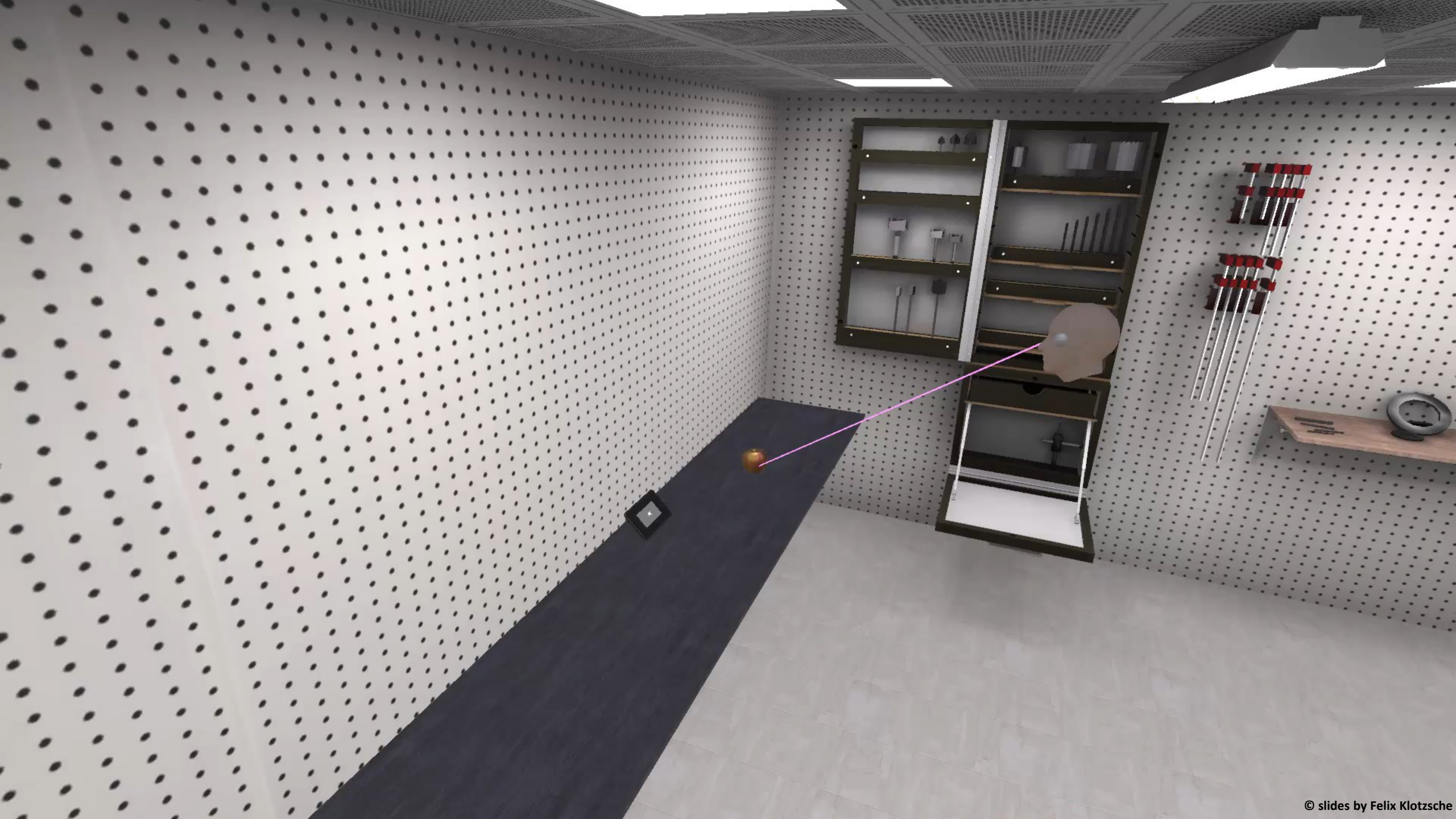

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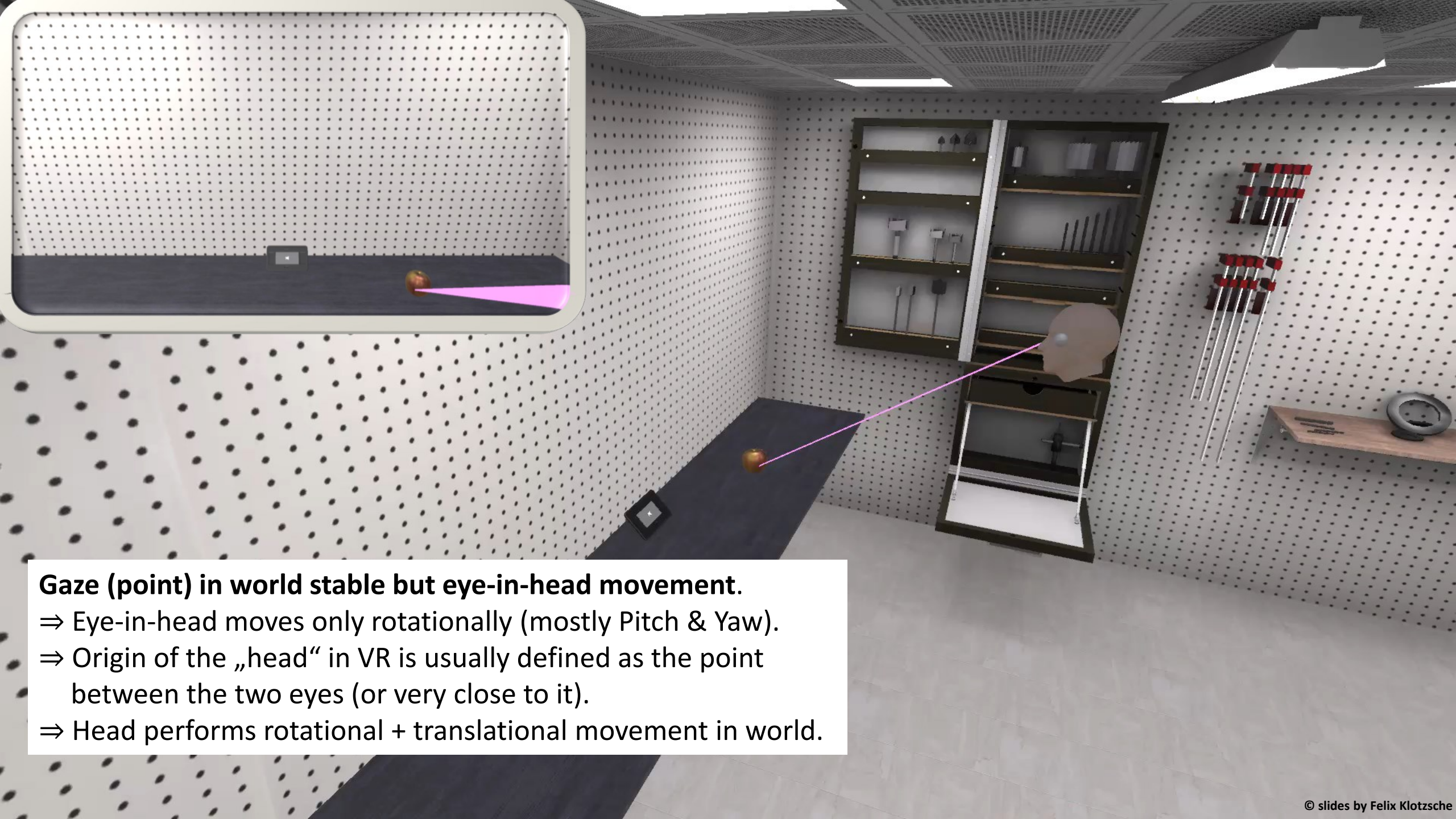

Gaze (point) in world stable but eye-in-head movement.

⇒ Eye-in-head moves only rotationally (mostly Pitch & Yaw).

⇒ Origin of the „head“ in VR is usually defined as the point between the two eyes (or very close to it).

⇒ Head performs rotational + translational movement in world.

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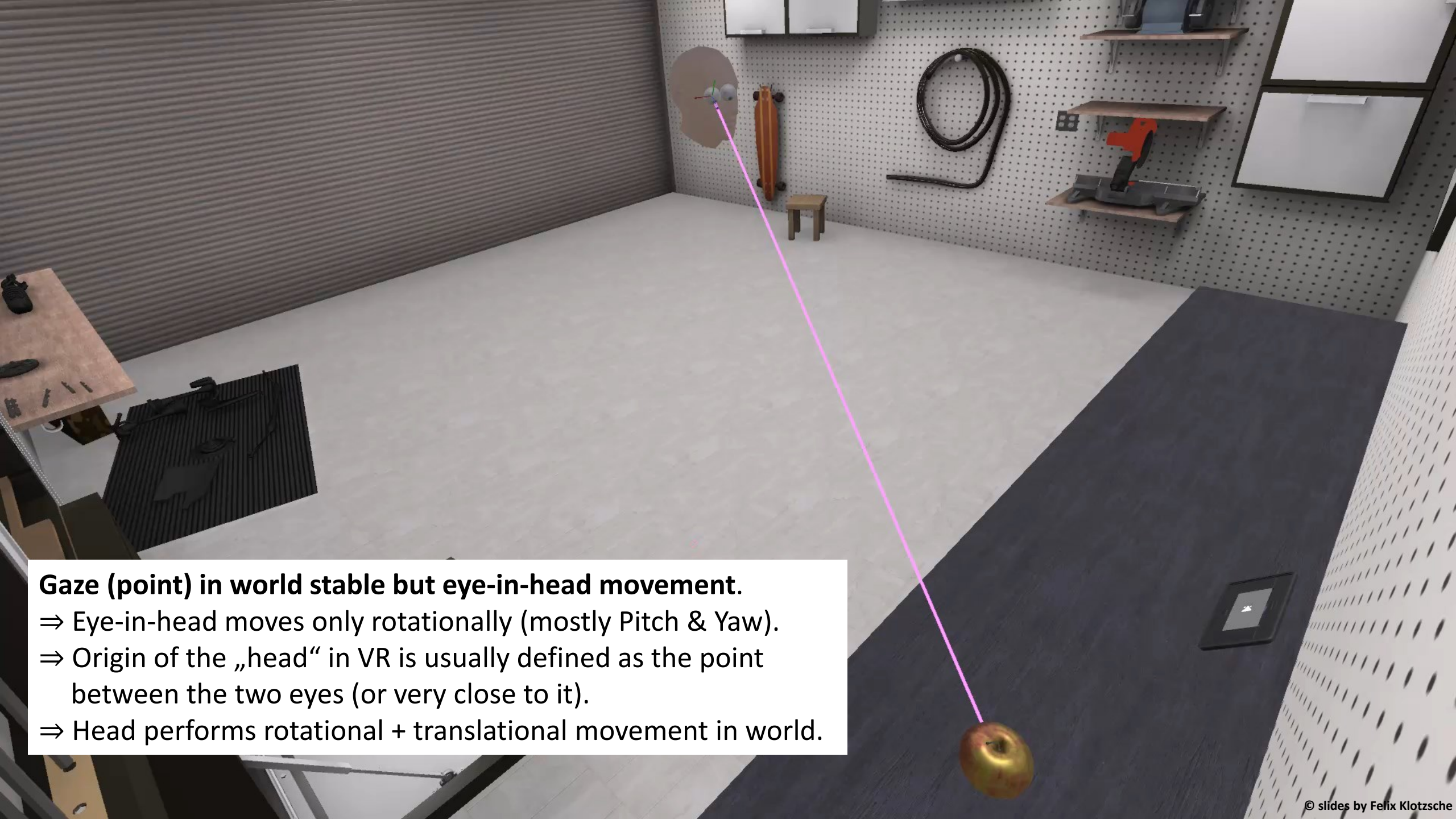

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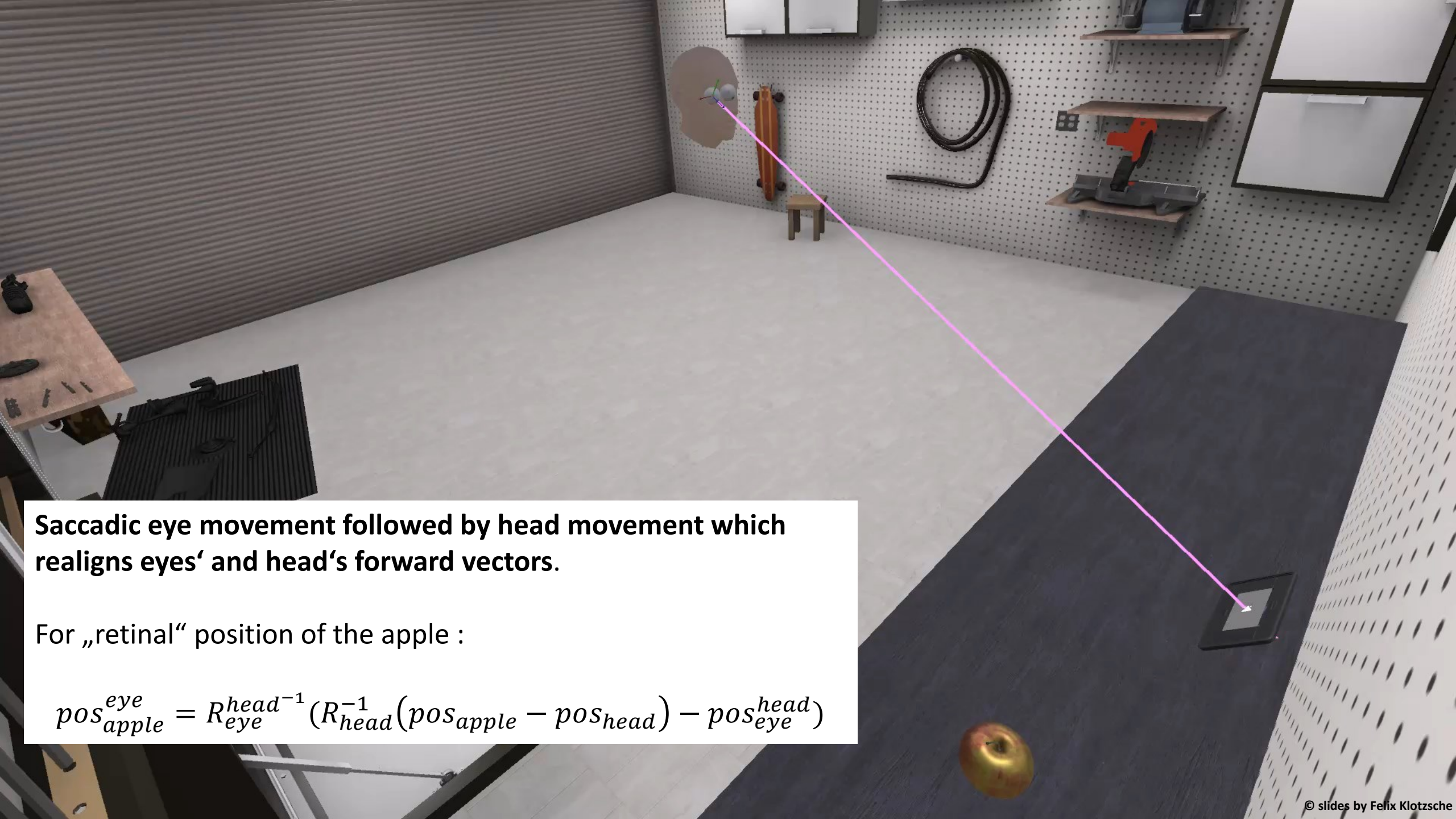

Saccadic eye movement followed by head movement which realigns eyes‘ and head‘s forward vectors.

For „retinal“ position of the apple :

$$pos_{apple}^{eye} = R_{eye}^{head^{-1}}(R_{head}^{-1}(pos_{apple} - pos_{head}) - pos_{eye}^{head})$$

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Eye-tracking in VR — Logfiles

- "Pose":
  - 6D: position (x, y, z) & rotation in Euler angles: ("pitch", "yaw", "roll")
  - 7D: position (x, y, z) & rotation as quaternion (w, *i*x, *j*y, *k*z)

- Useful variables:
  - Eye-in-head (eye position+rotation local to the head)
  - Head-in-world
  - Relevant stimulus positions (esp. when dynamic)
  - Position data of gaze ray hit point (intersection with collider)
    - as position in world space (3 dim)
    - as length of the gaze ray (1 dim)
    - can also be calculated post-hoc (if scene is deterministic enough)

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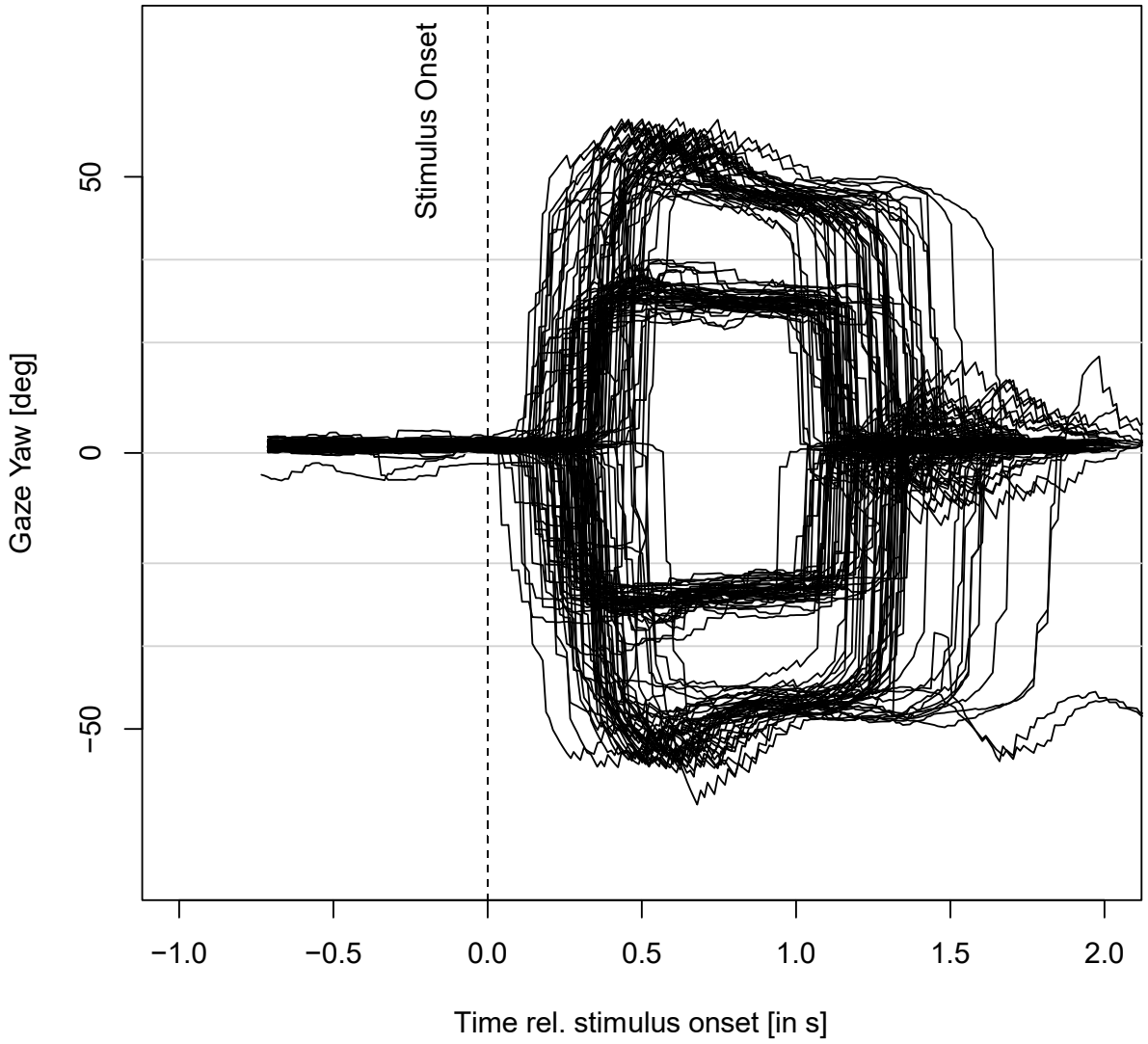
Eye movements in VR



- Gaze traces for two eccentricities locked to stimulus onset
- Potential gaze targets on the left and right side.

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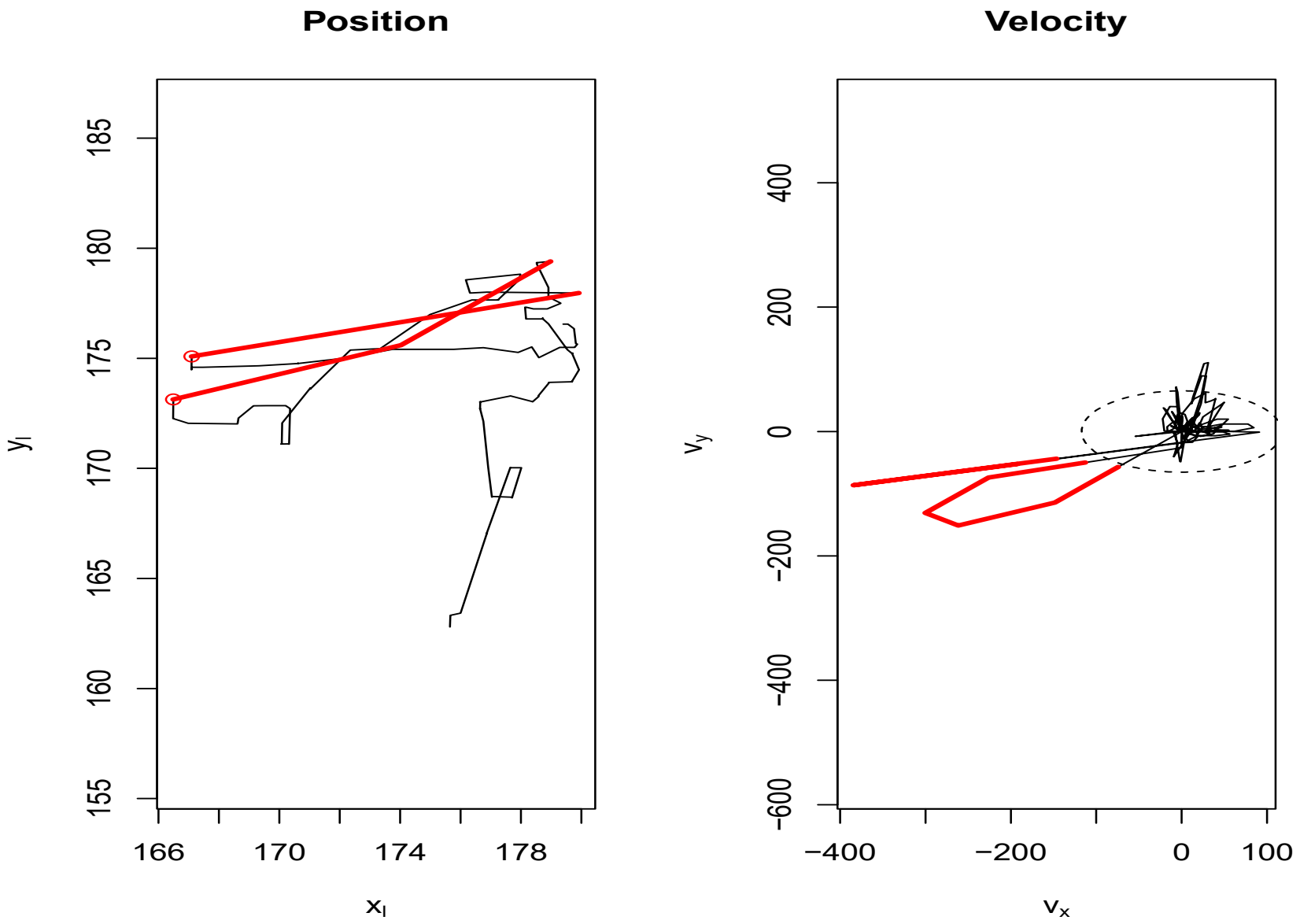
Eye in head position and velcocity space



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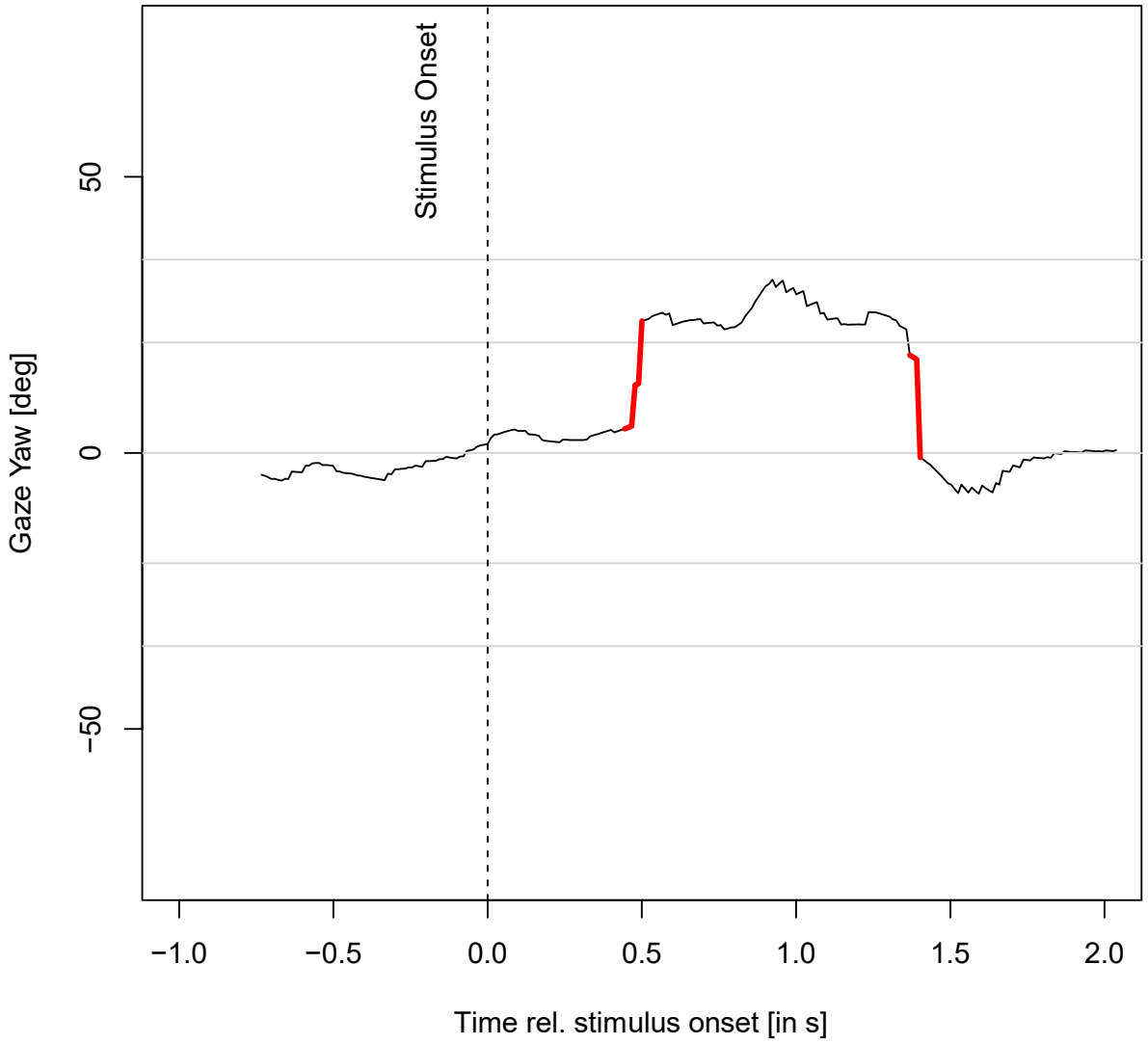
Eye movements in VR



- Gaze trace
- Saccade detection in eye in head coordinates.

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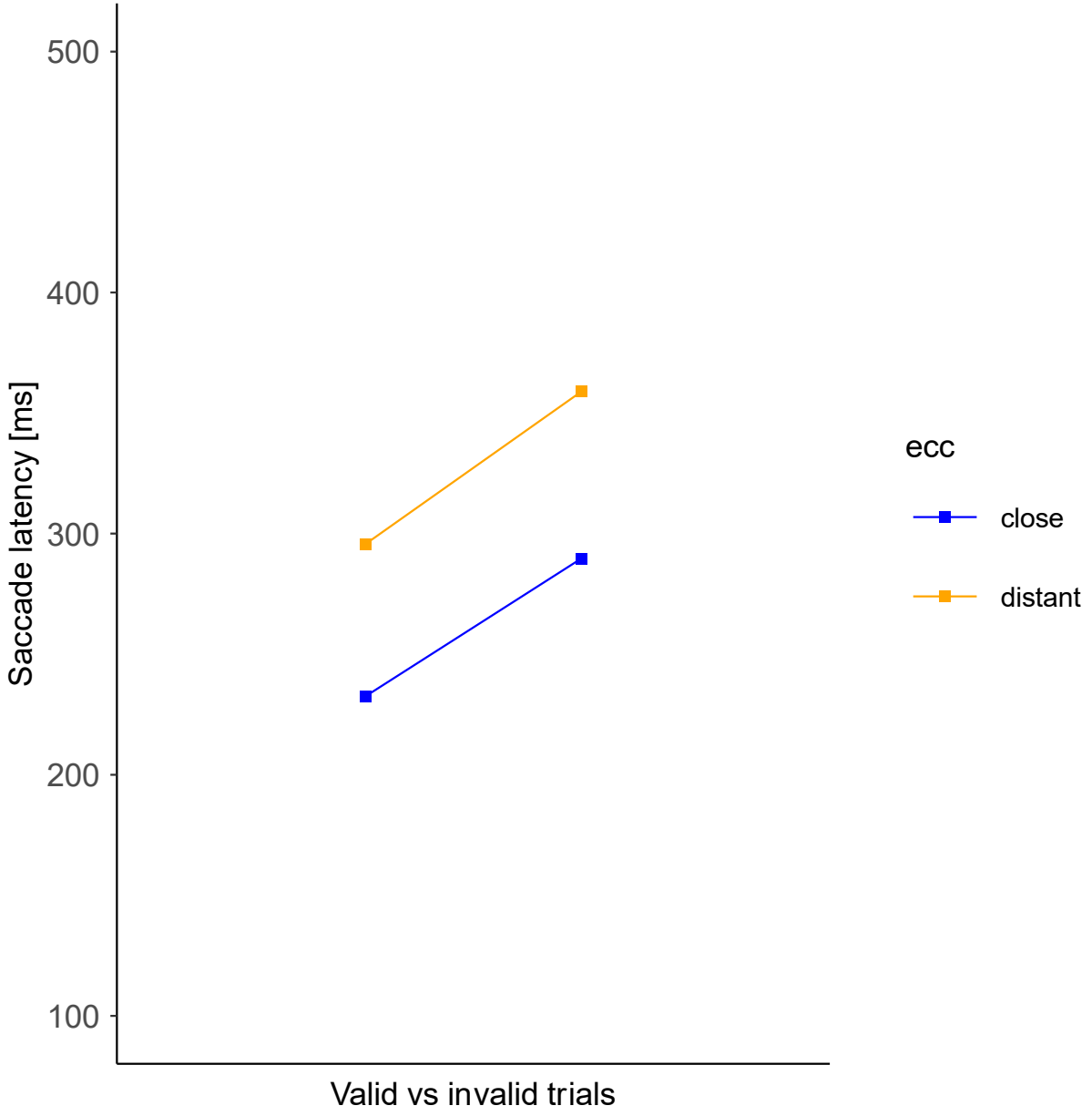
Eye movements in VR



- Analysis is based on 160 trials
- Endogenous cue
- Two eccentricities

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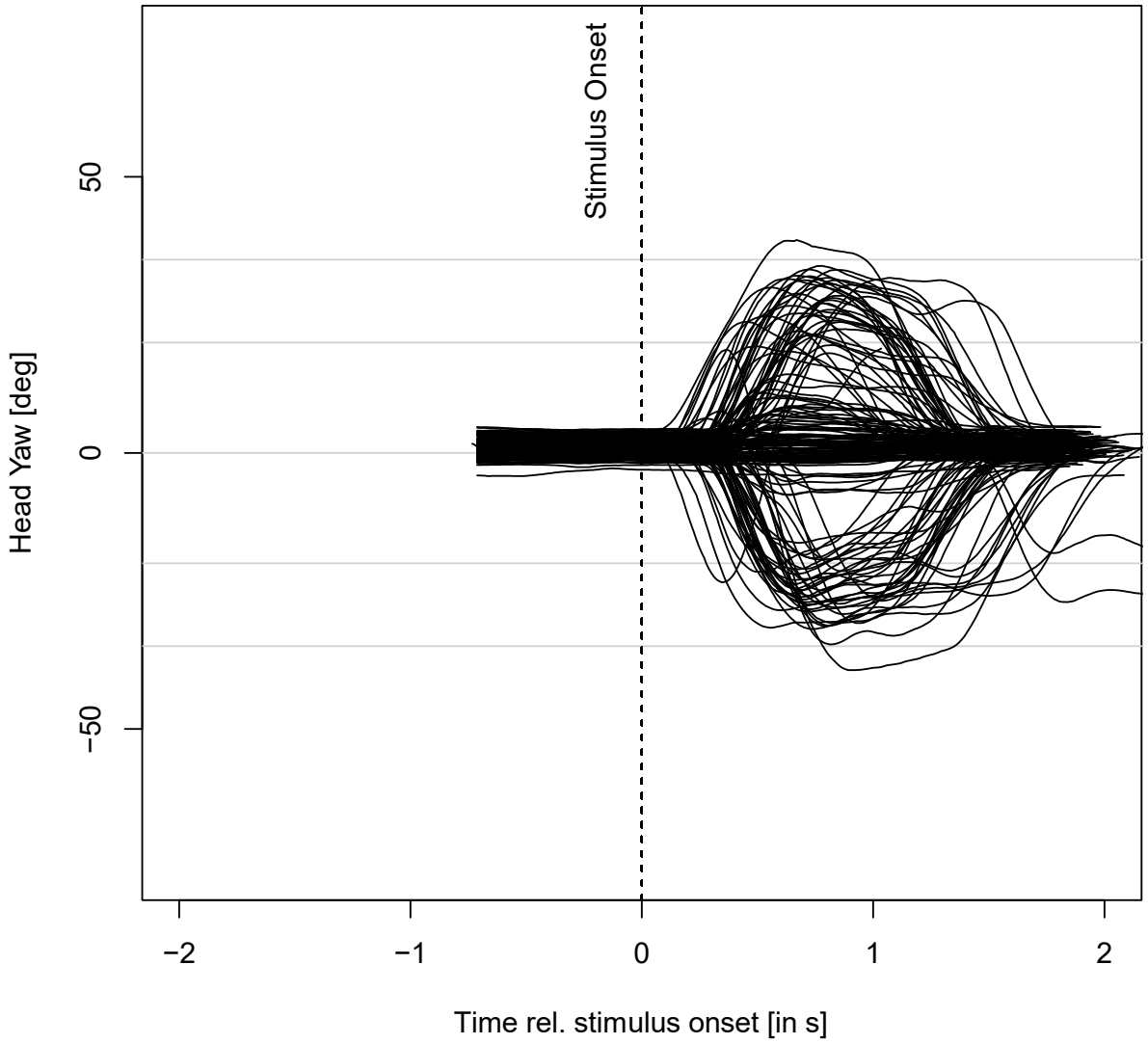
Eye movements in VR



- Head movements

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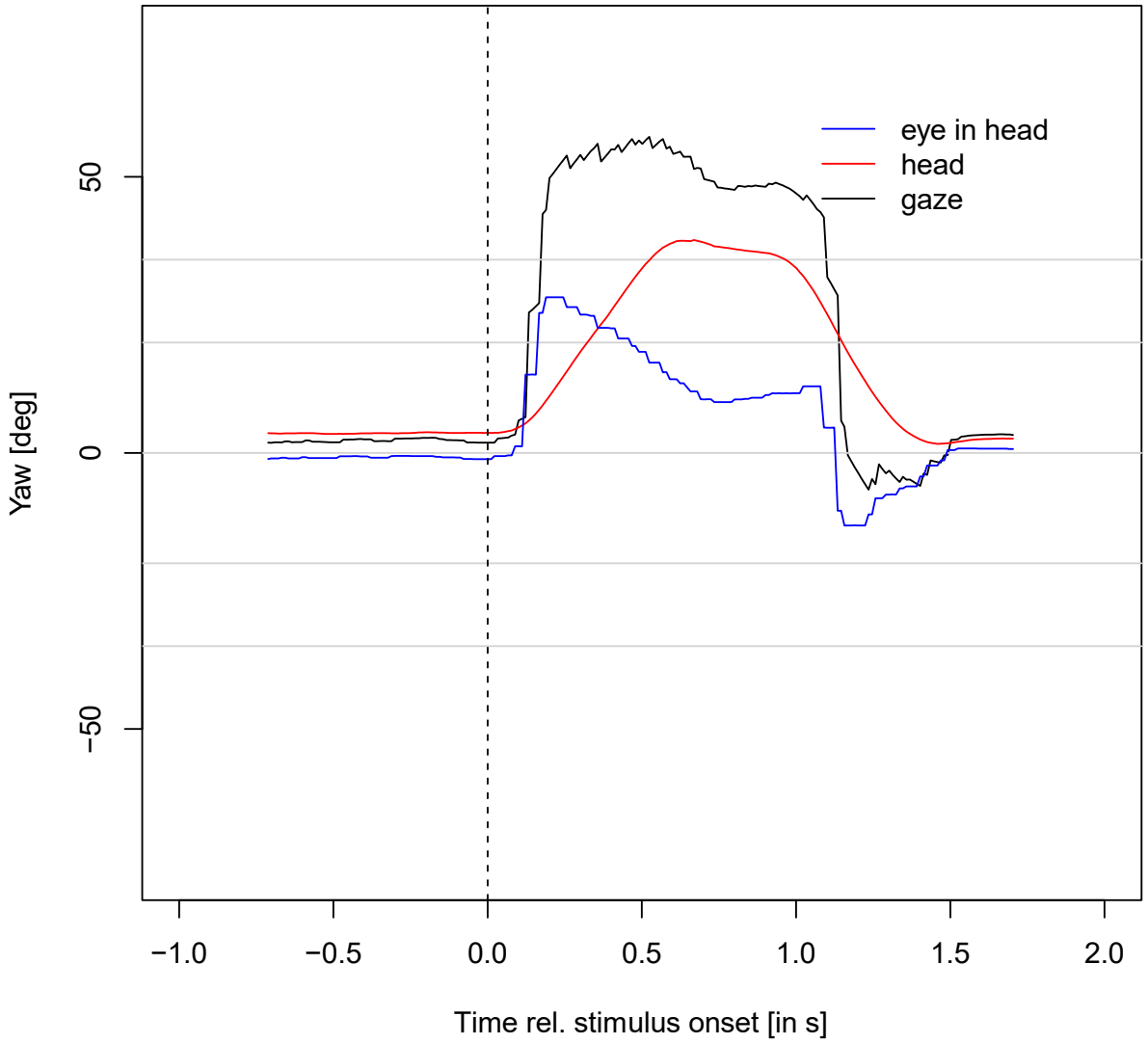
Eye movements in VR



- Gaze position, head position and eye in head position.

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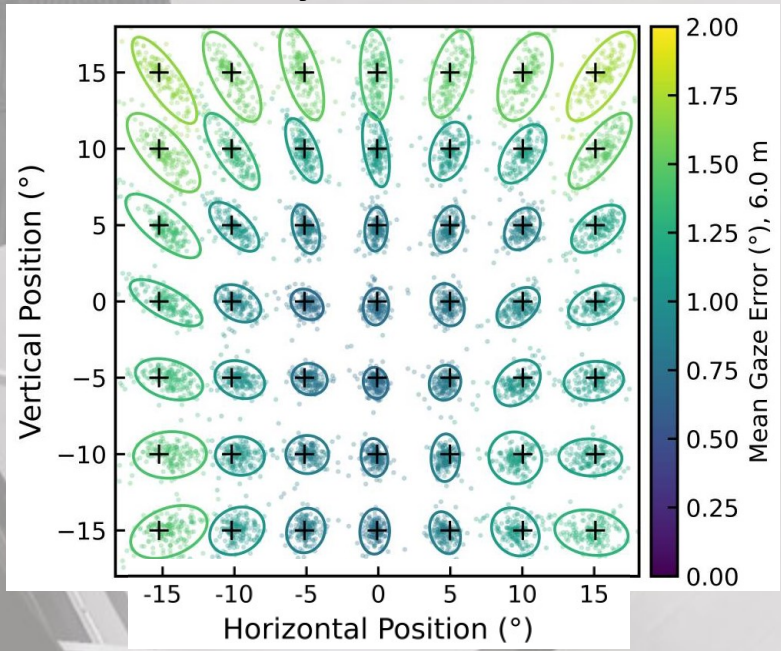
Eye-tracking in VR — Challenges

- Rather low (at worst variable) sampling rates
- Mostly preprocessed data (no access to eye camera images)

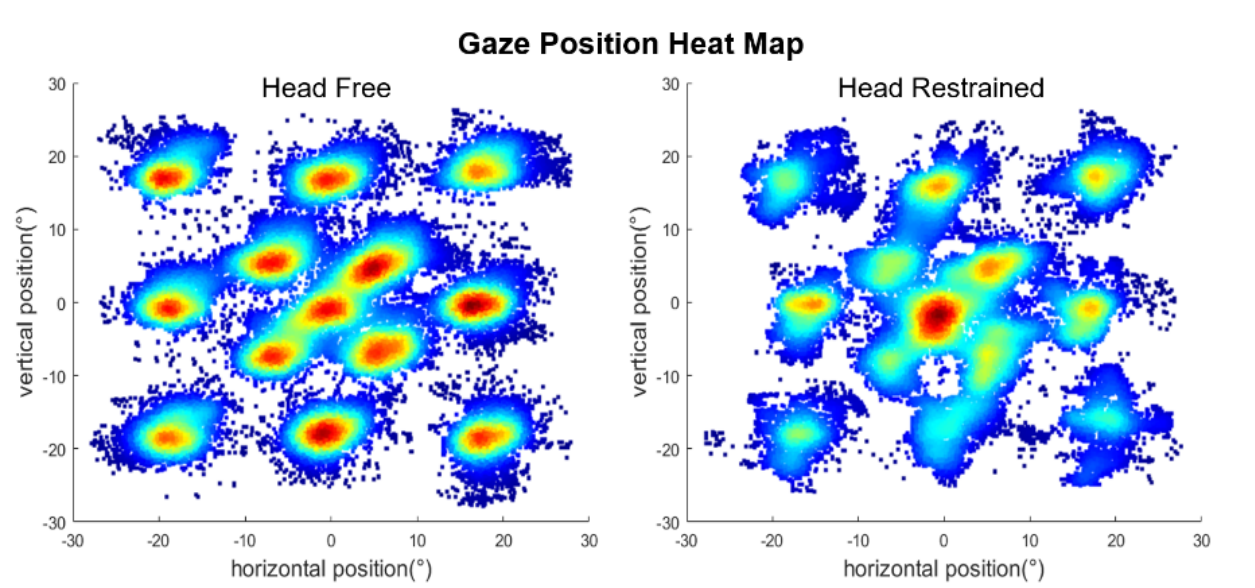
  E.g., Quest Pro: data from the two eyes is clearly not independent, fixed “vergence”
- Precision and accuracy varies across the visual field

HTC Vive Pro Eye



Schuetz et al., 2022, *J Eye Mov Res,*
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10136368/

Quest Pro



Wei et al., *ACM IMX 2023,*
https://dl.acm.org/doi/10.1145/3573381.3596467

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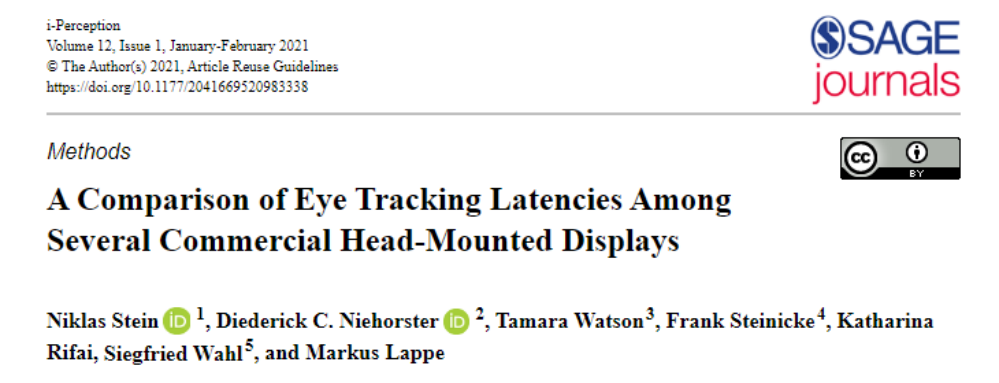
Eye-tracking in VR — Challenges

- ❑ Rather low (at worst variable) sampling rates
- ❑ Mostly preprocessed data (no access to eye camera images)

  E.g., Quest Pro: data from the two eyes is clearly not independent, fixed “vergence”
- ❑ Precision and accuracy varies across the visual field
- ❑ Latency between actual movement and availability of the according data samples


i-Perception
Volume 12, Issue 1, January-February 2021
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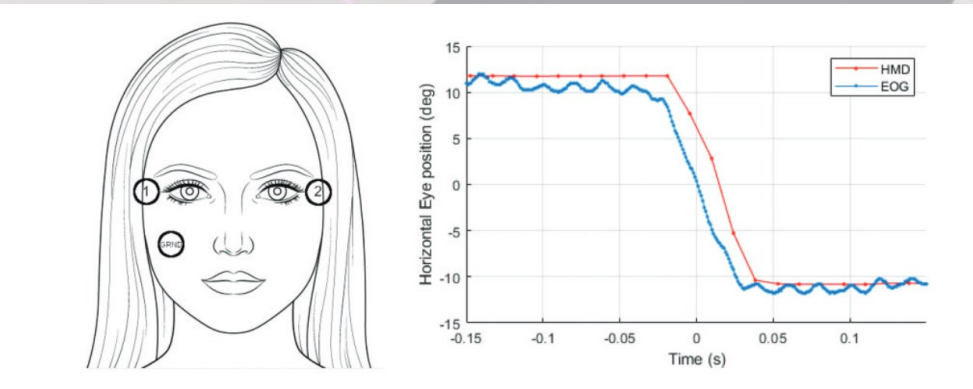
https://doi.org/10.1177/2041669520983338

SAGE journals

Methods

A Comparison of Eye Tracking Latencies Among Several Commercial Head-Mounted Displays

Niklas Stein [1], Diederick C. Niehorster [2], Tamara Watson[3], Frank Steinicke[4], Katharina Rifai, Siegfried Wahl[5], and Markus Lappe



Stein et al., 2021, iPerception
https://pubmed.ncbi.nlm.nih.gov/33628410/

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Hand-on part: preparation

- ❑ Download Unity Hub + Unity (LTS 2022.3.12f)
- ❑ Clone the repository:
  https://github.com/eioe/workshop_vrcogsci
- ❑ Wait for Part II.

For questions, comments, collabs, …
please do not hesitate to get in touch:

klotzsche@cbs.mpg.de

Timings

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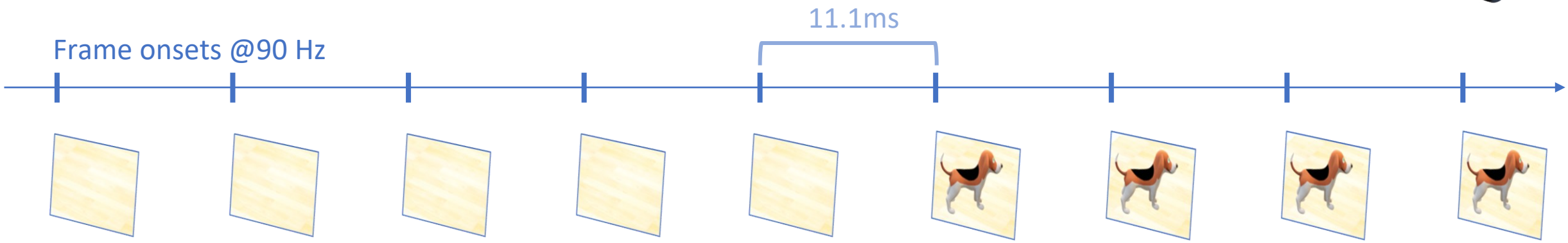
Timings



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Timings

Time in Unity

Time.time returns time (in s) since the start of the application **at the beginning of each frame** (VSync) and **stays constant throughout the frame**

Time.realtimeSinceStartup(AsDouble) returns **continuous** time since start of application (allows to get precise timings *within* one frame)

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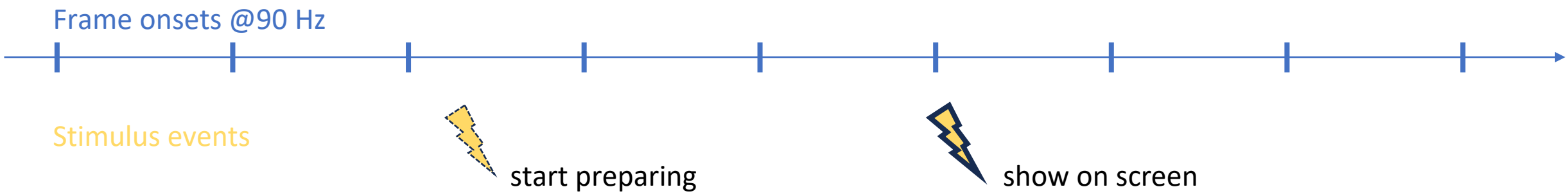

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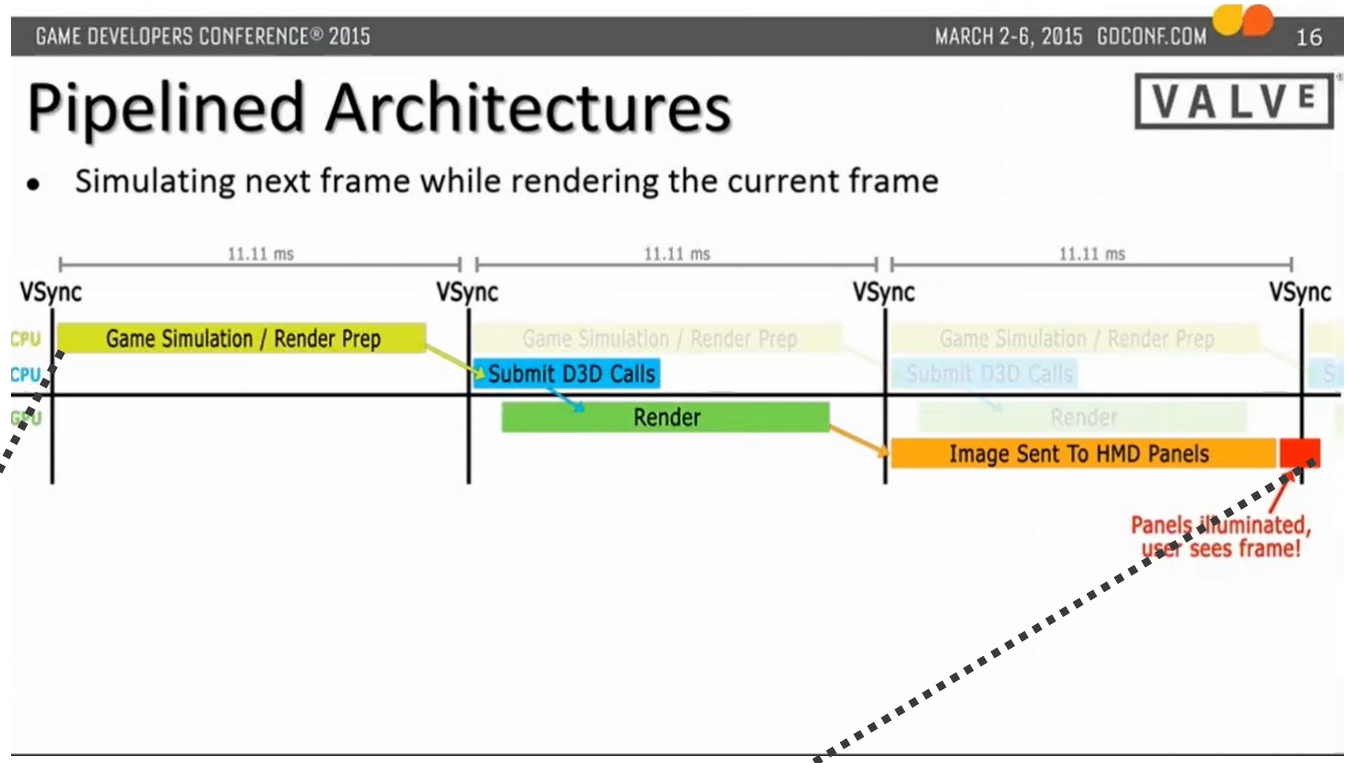

Frame onsets @90 Hz

Stimulus events

start preparing

show on screen

Alex Vlachos (Valve): https://www.gdcvault.com/play/1021771/Advanced-VR

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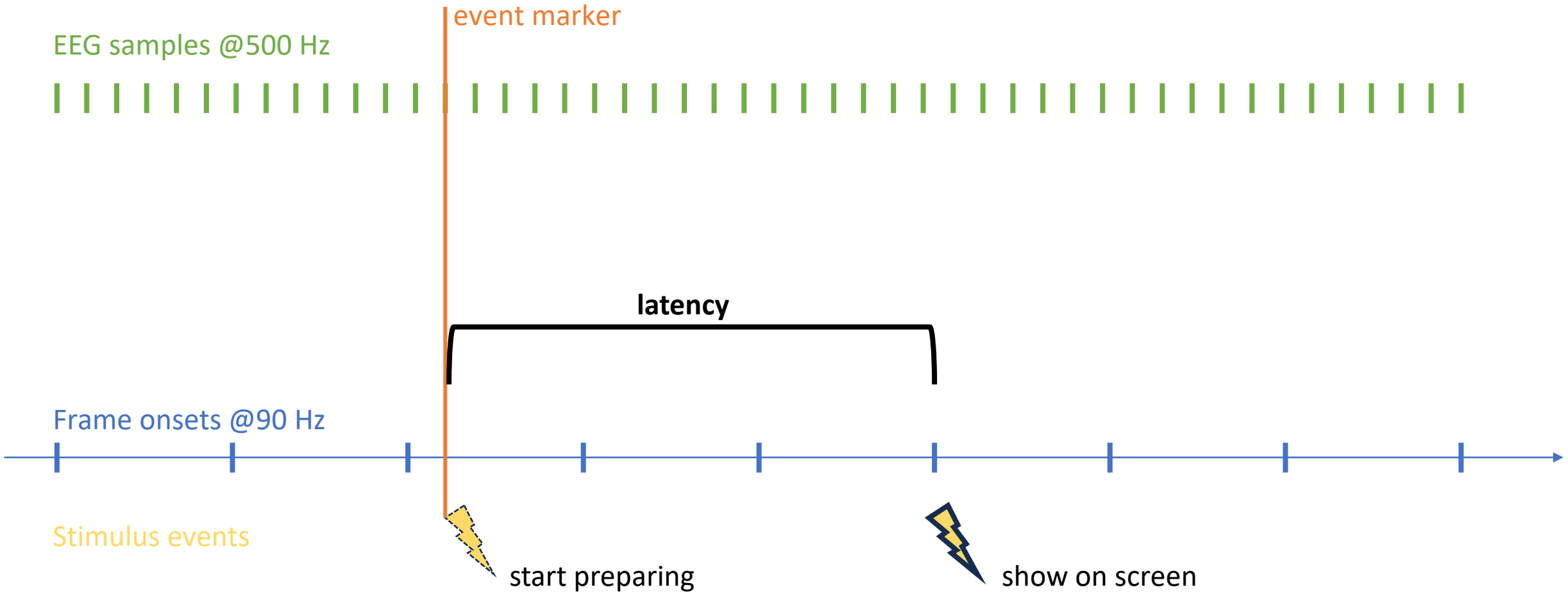

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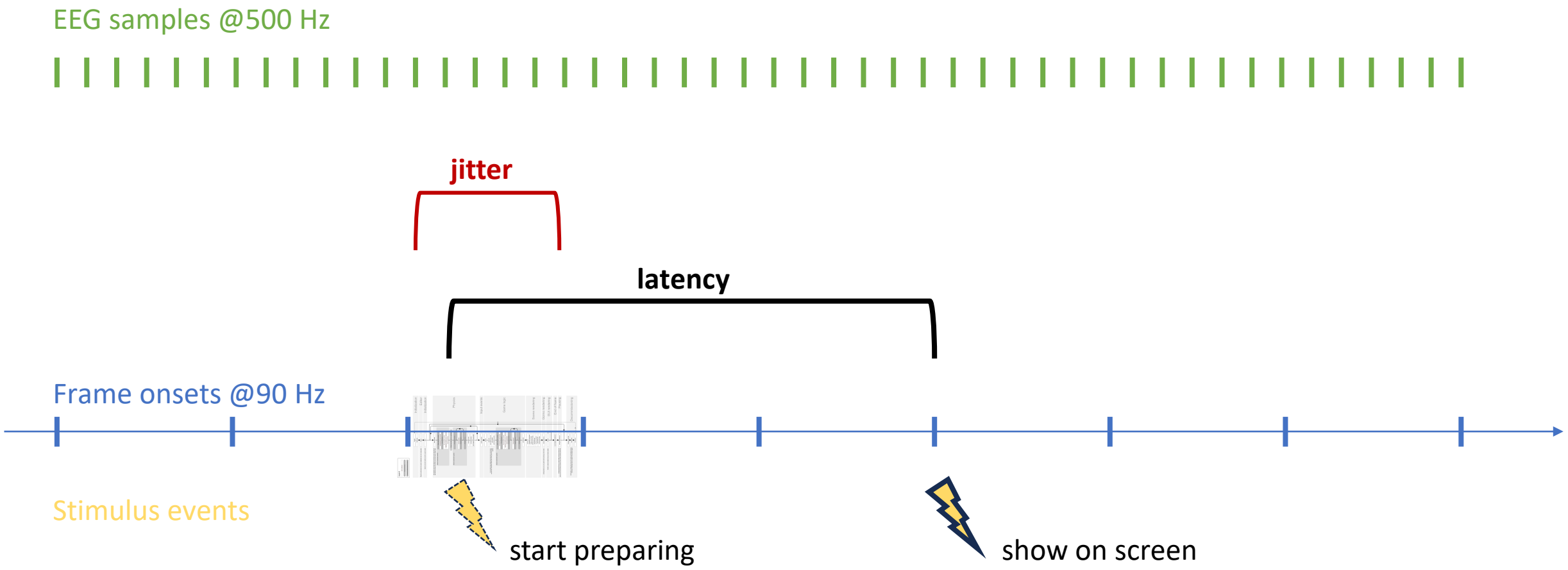

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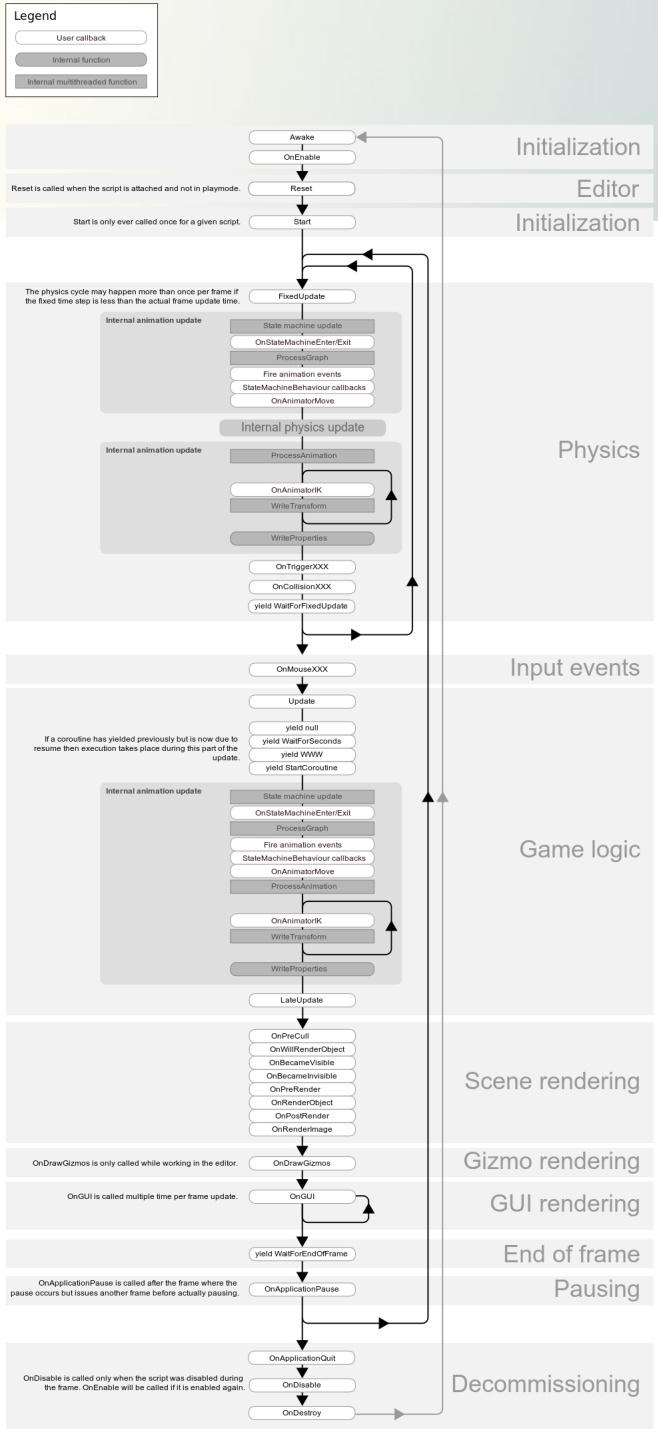

1 frame (~11.1 ms)

https://docs.unity3d.com/Manual/ExecutionOrder.html

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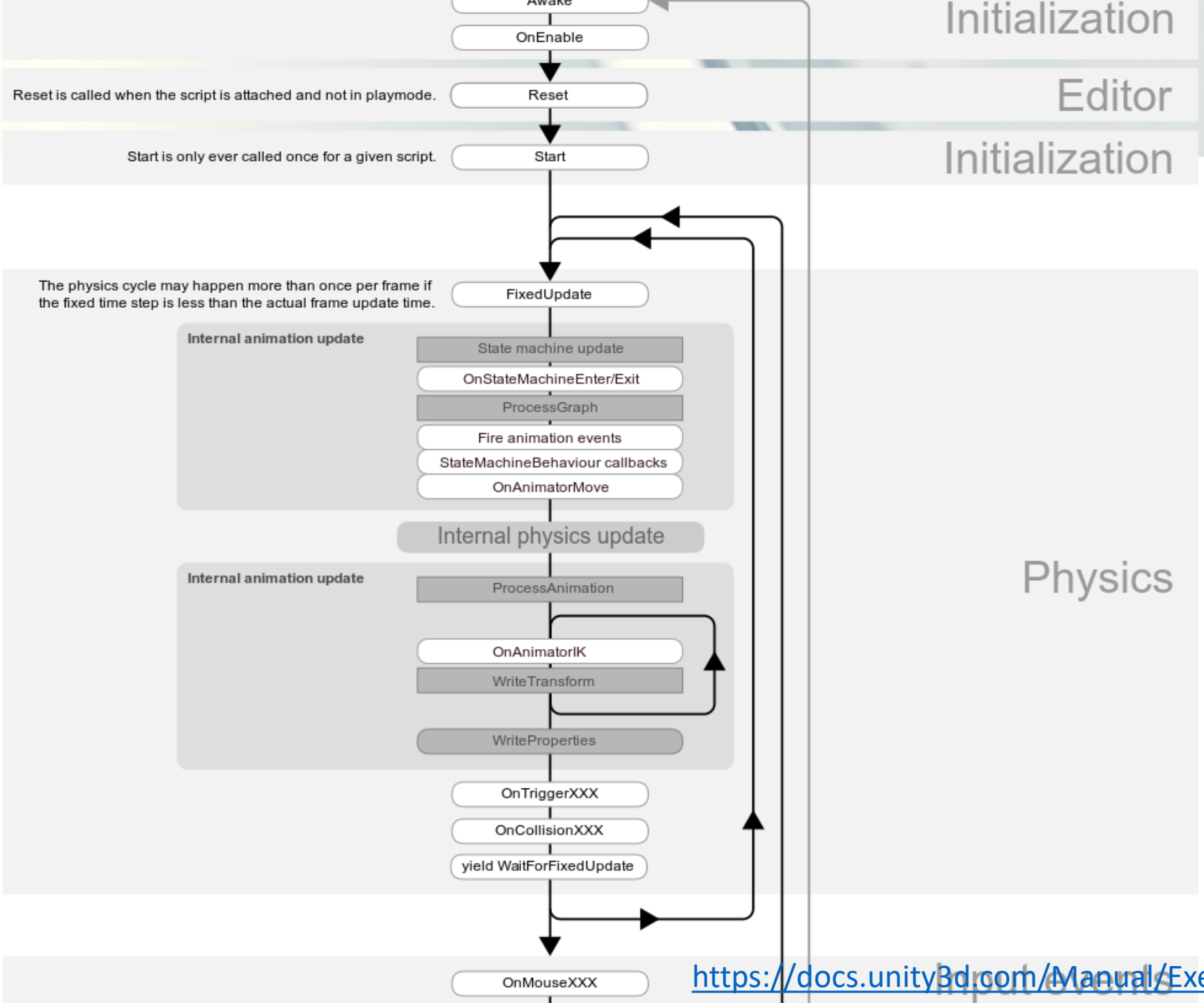

https://docs.unity3d.com/Manual/ExecutionOrder.html

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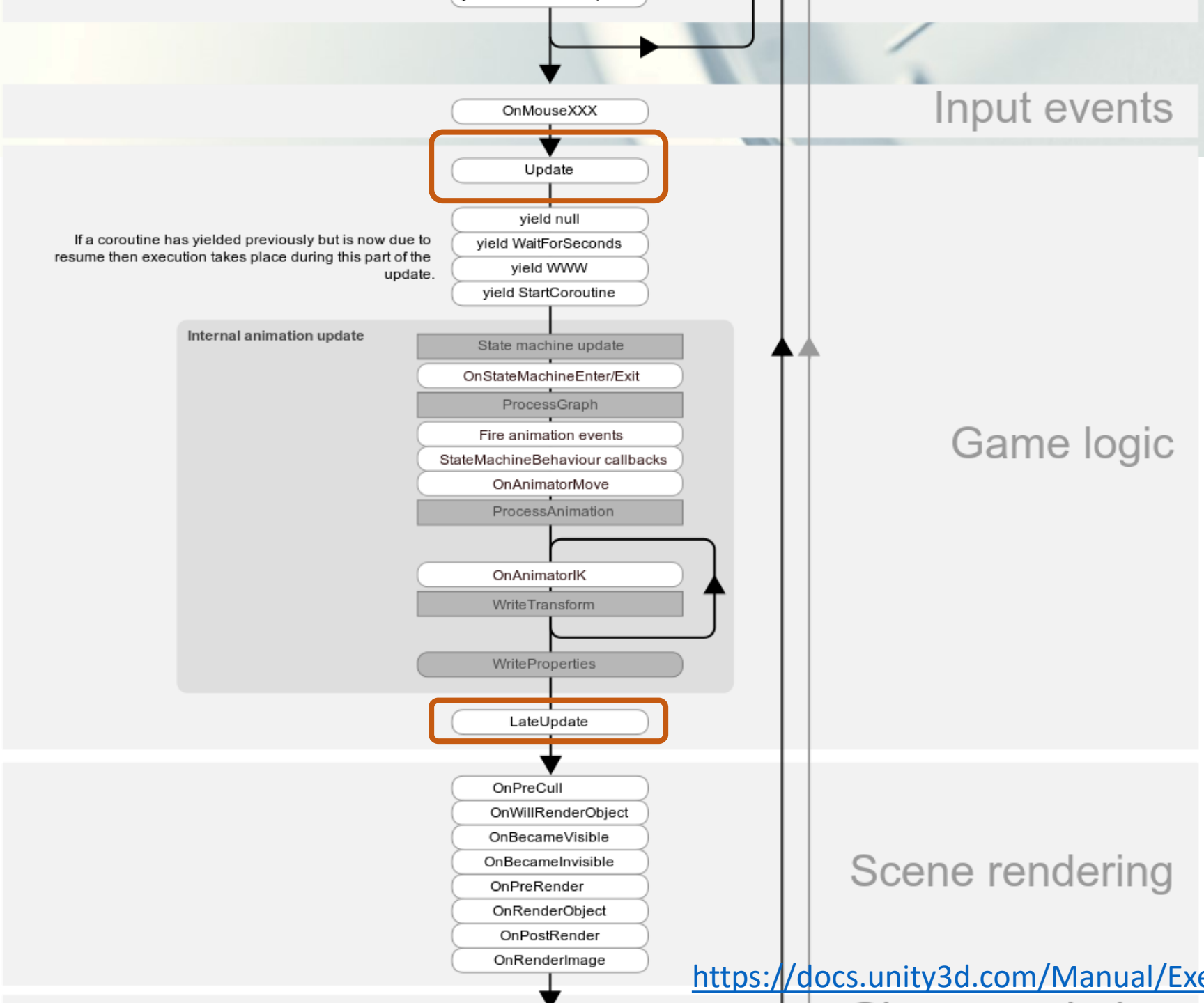

https://docs.unity3d.com/Manual/ExecutionOrder.html

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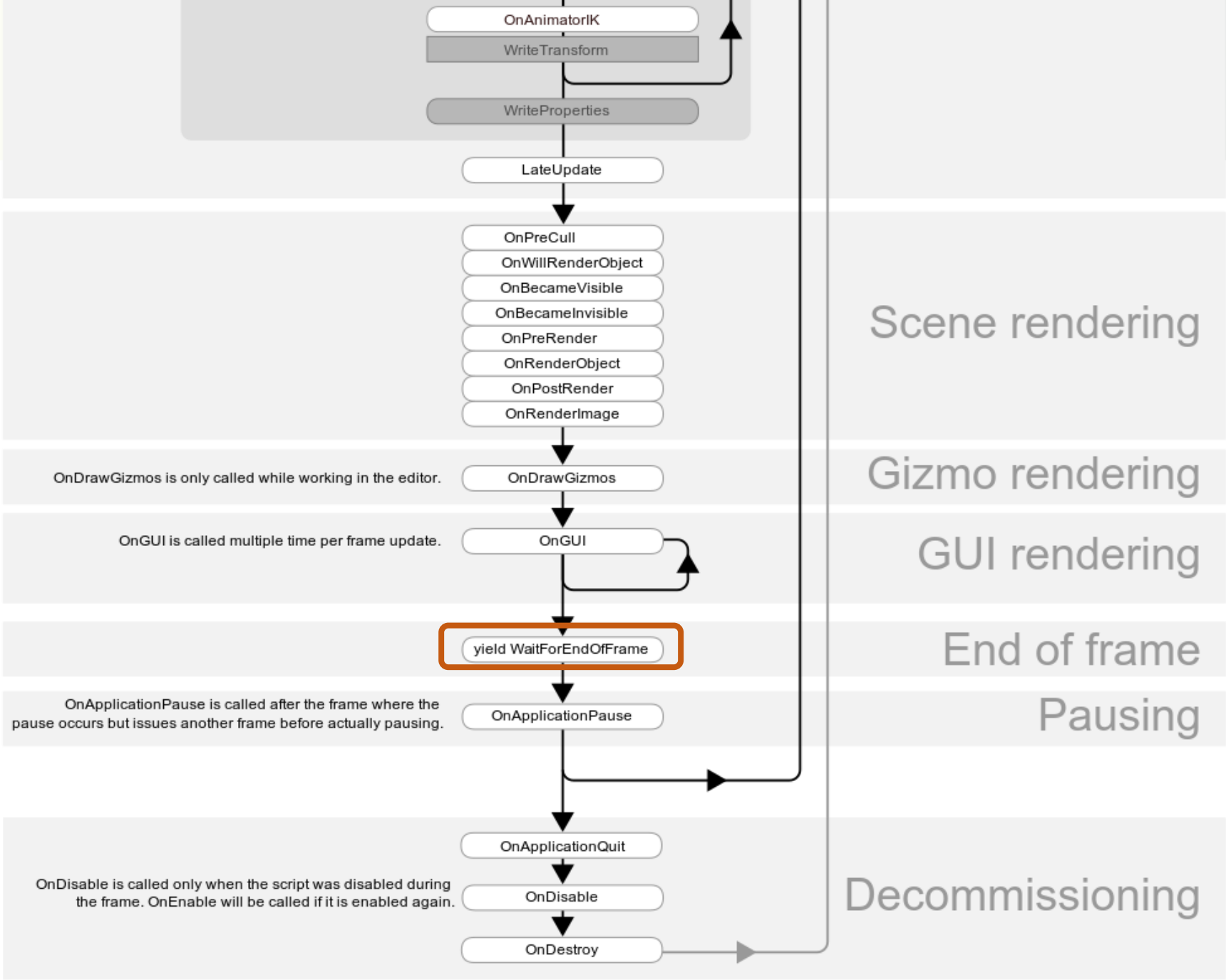

https://docs.unity3d.com/Manual/ExecutionOrder.html

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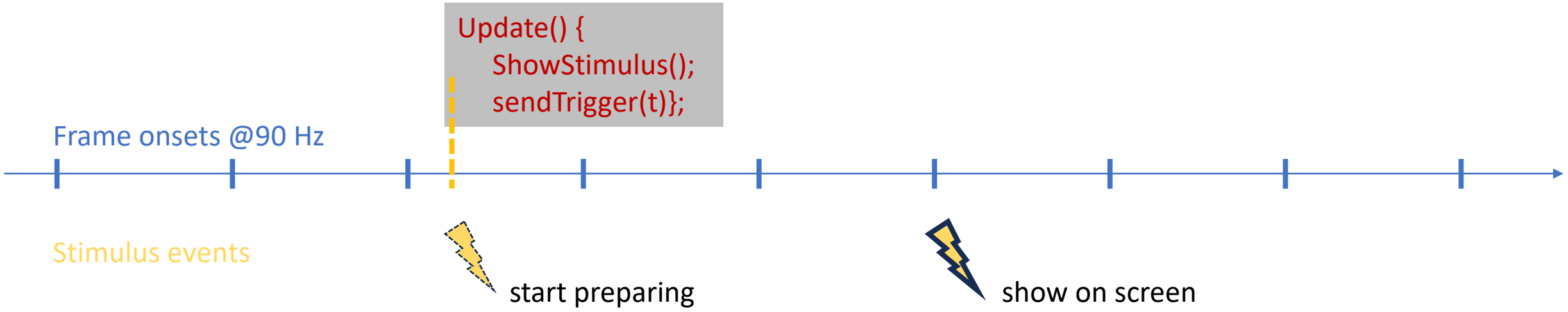
When to send triggers?

- **current frame:**
  Update() → when we execute our game/experimental logic
  (e.g., ShowStimulus())

natural choice, BUT: many (variable) things are executed during Update() and we cannot easily control their order. This will introduce jitter.



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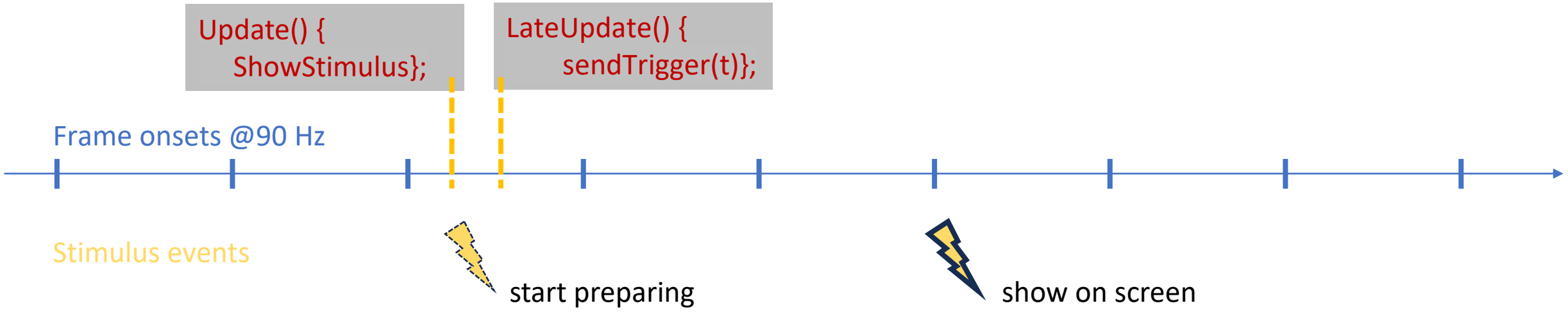
When to send triggers?

- **current frame:**
  LateUpdate() → after (almost) all game/experimental logic is done

Afterwards, still the entire rendering pipeline is called for this frame. Its execution time will vary from frame to frame → **jitter**.



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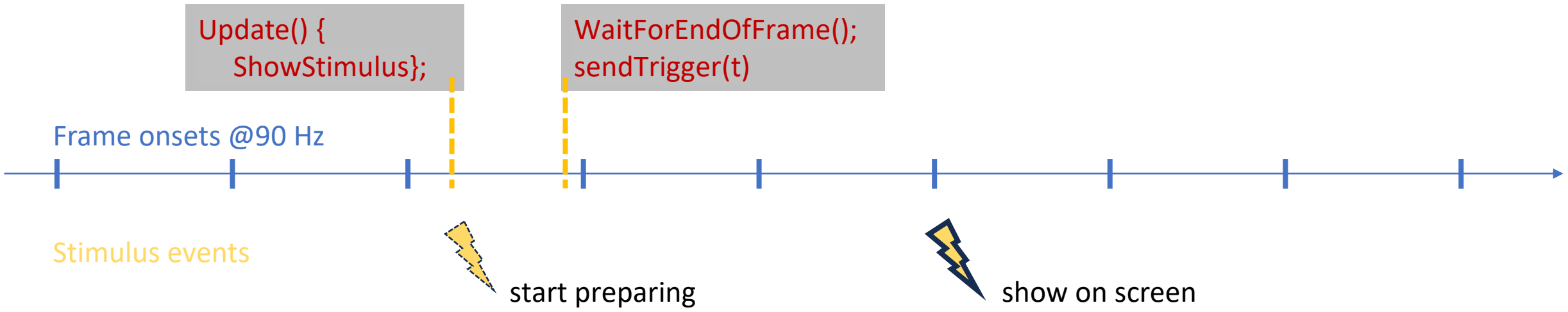
When to send triggers?

- **current frame:**
  WaitForEndOfFrame() → latest point Unity handles the frame
  (all logic and GPU calls have been executed).

⚠ latency due to frames in back buffer, etc. remains!



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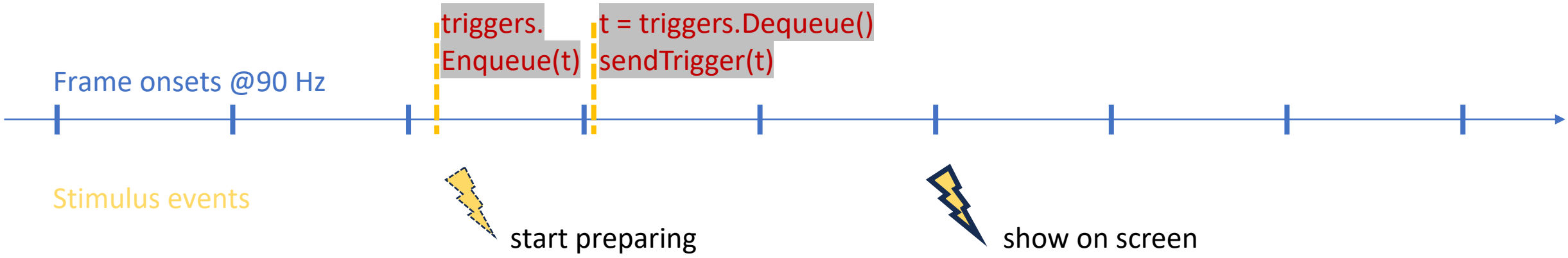
When to send triggers?

- **following frame:**
  send trigger at the very beginning of the **next frame**



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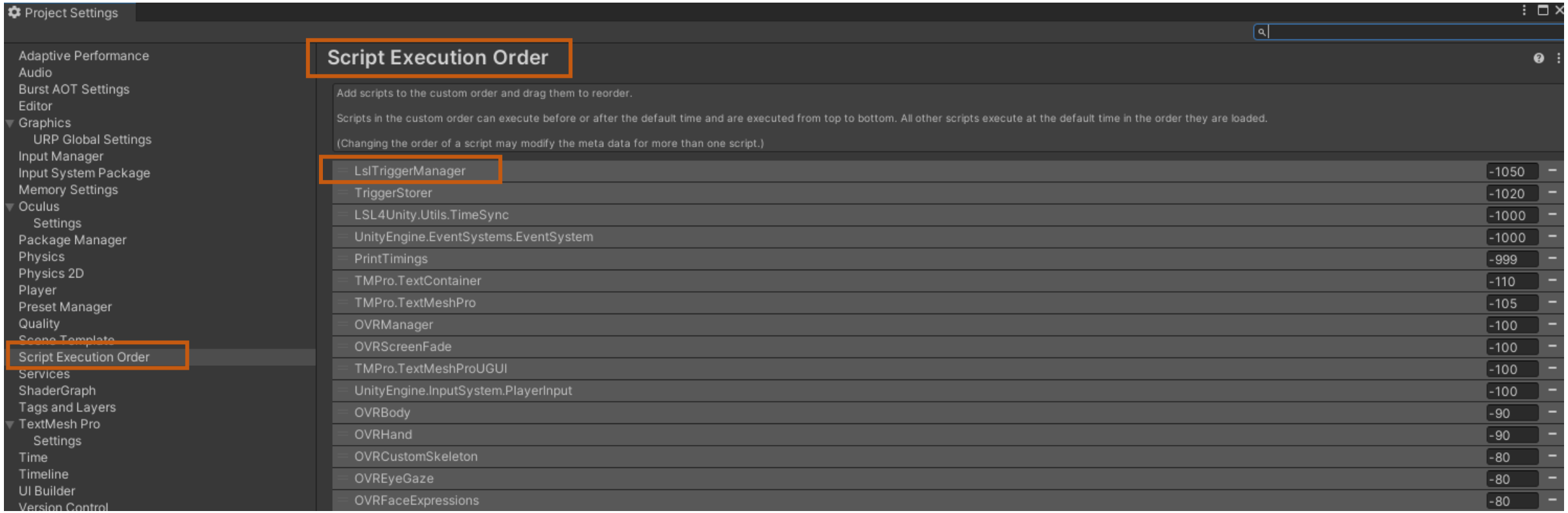

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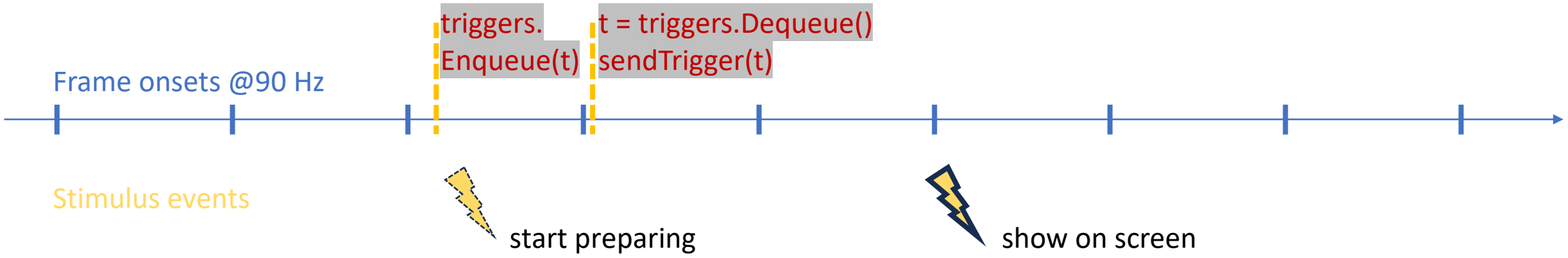
When to send triggers?

- **following frame:**
  send trigger at the very beginning of the next frame

⚠ (reduced) latency due to frames in back buffer, etc. remains!



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Oculus Quest Pro
https://komete-xr.com/de/products/meta-quest-pro

Test setup:

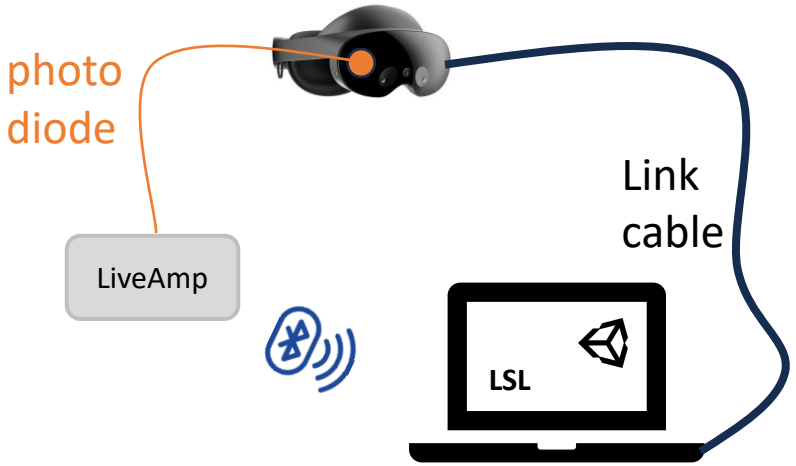
- Quest Pro in Link Mode (wired)
- Photodiode on lens of the HMD connected to BrainProducts LiveAmp
- Unity: alternating color in front of the camera (10 Hz)
- LSL triggers sent at various times within the frame loop

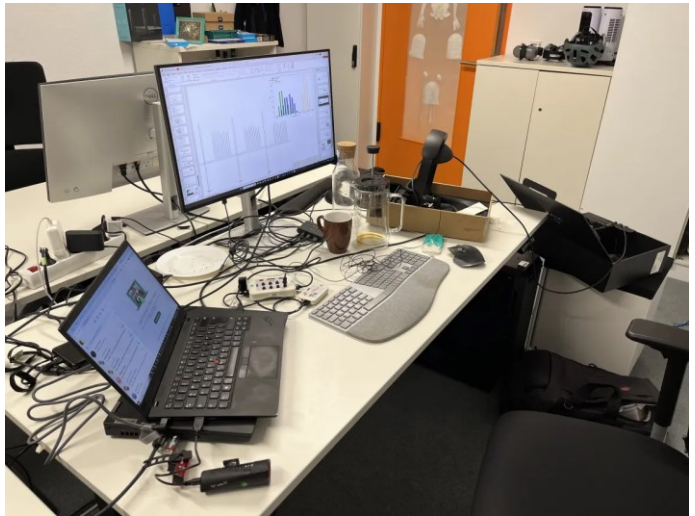
  Update: when executing the game logic

  EndOfFrame: at the end of the same frame (after rendering)

  <next frame>: as early as possible in Update() of the next frame
- To simulate variance of CPU load:

  randomly injecting Sleep() for [0;5]ms during Update()





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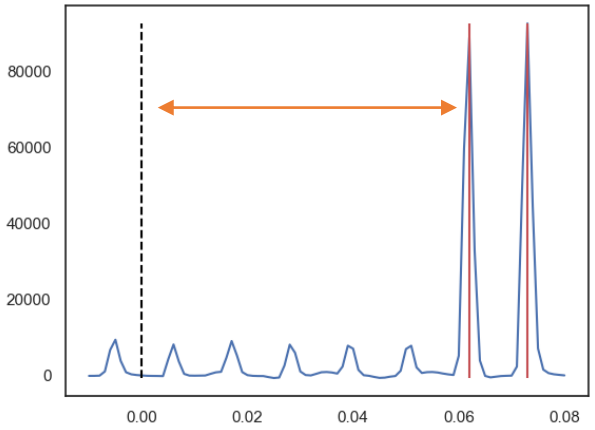
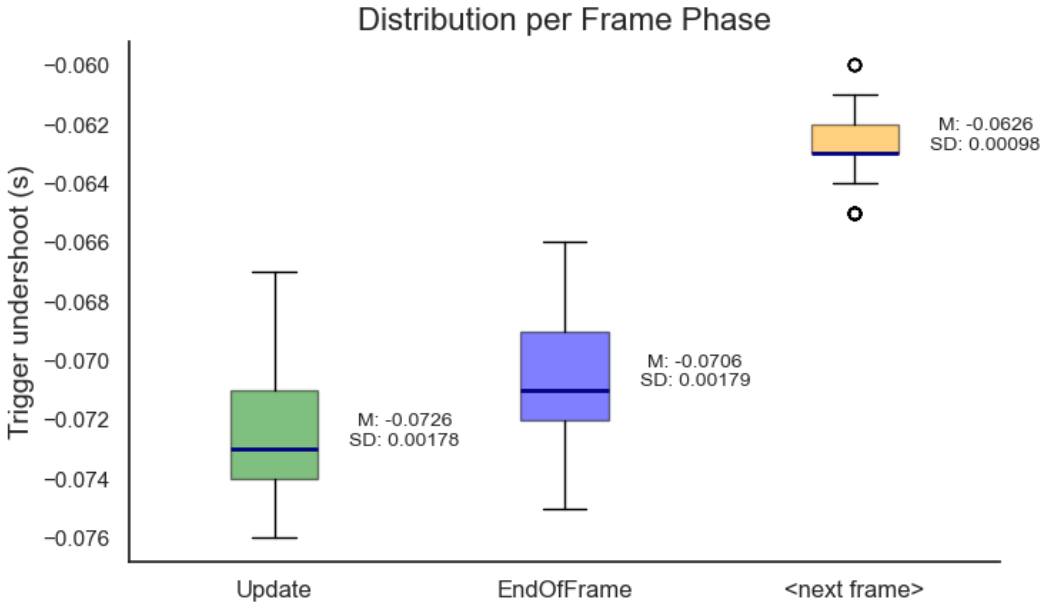
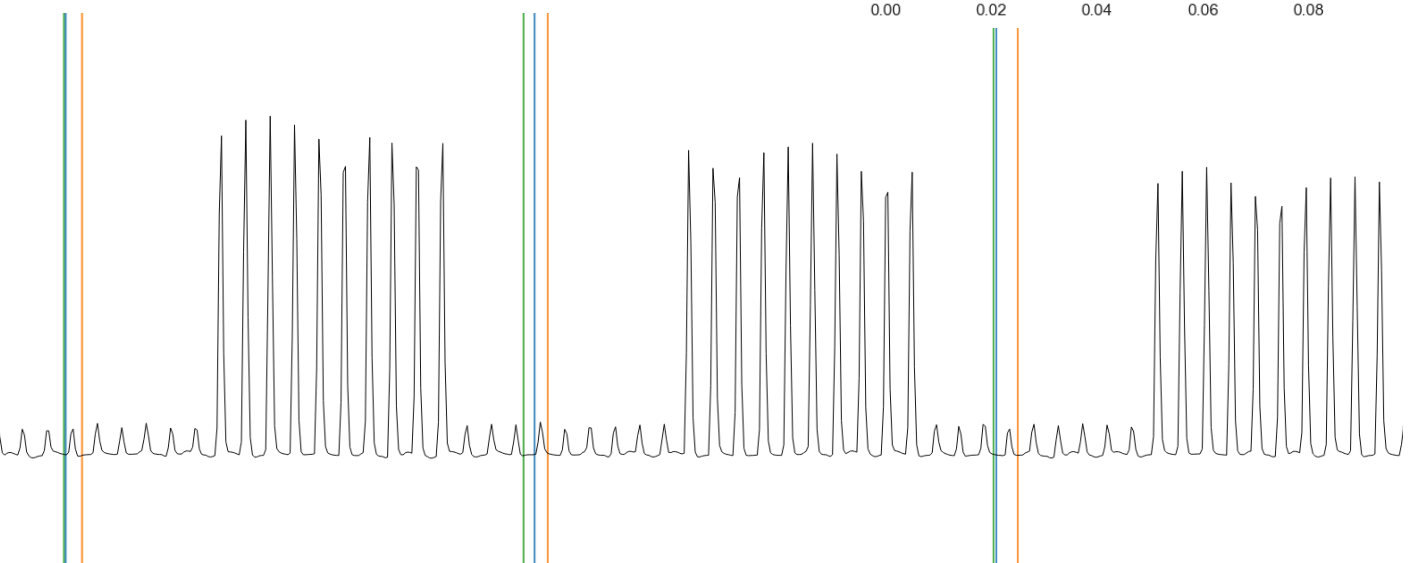
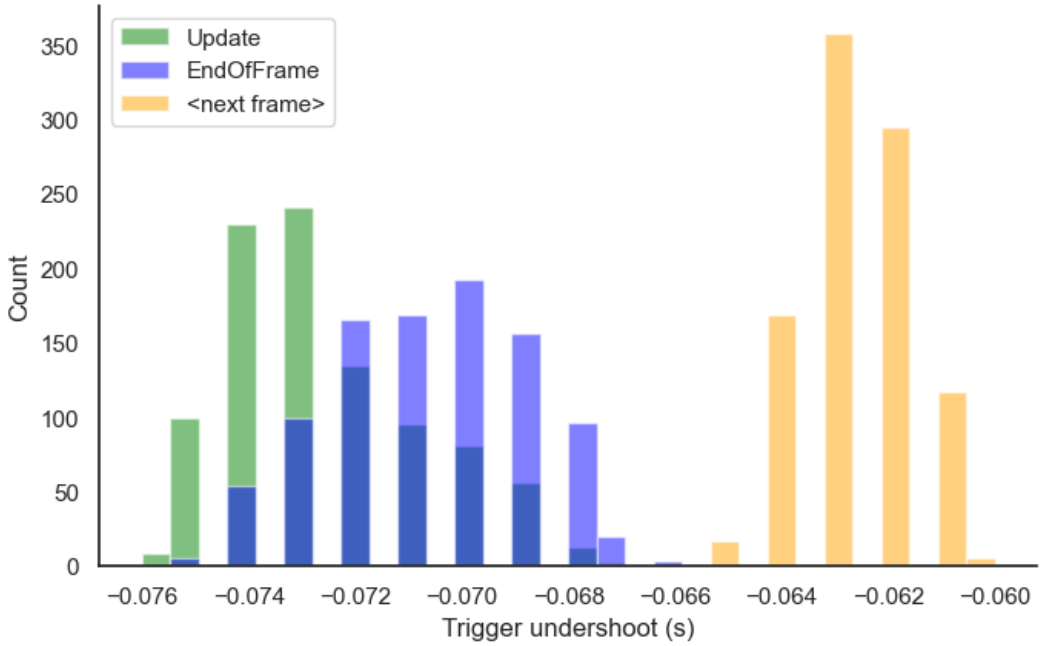
Oculus Quest Pro
https://komete-xr.com/de/products/meta-quest-pro









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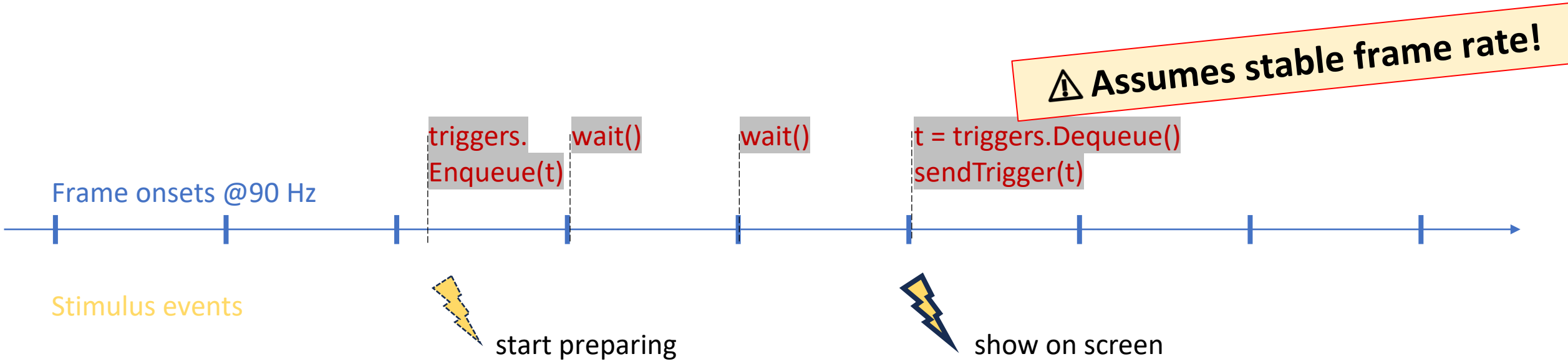
When to send triggers?

- **following frame — delayed:**
  find out (measure) the number of frames in the back buffer, etc.
  queue the trigger and send it at the very beginning of the predicted vsync which will flash your frame of interest



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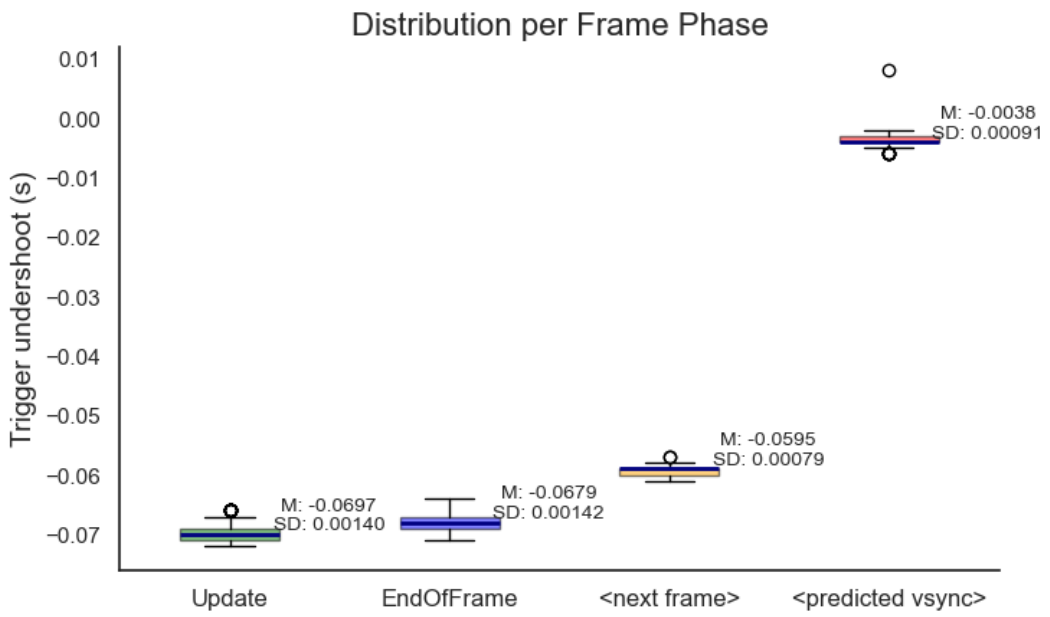
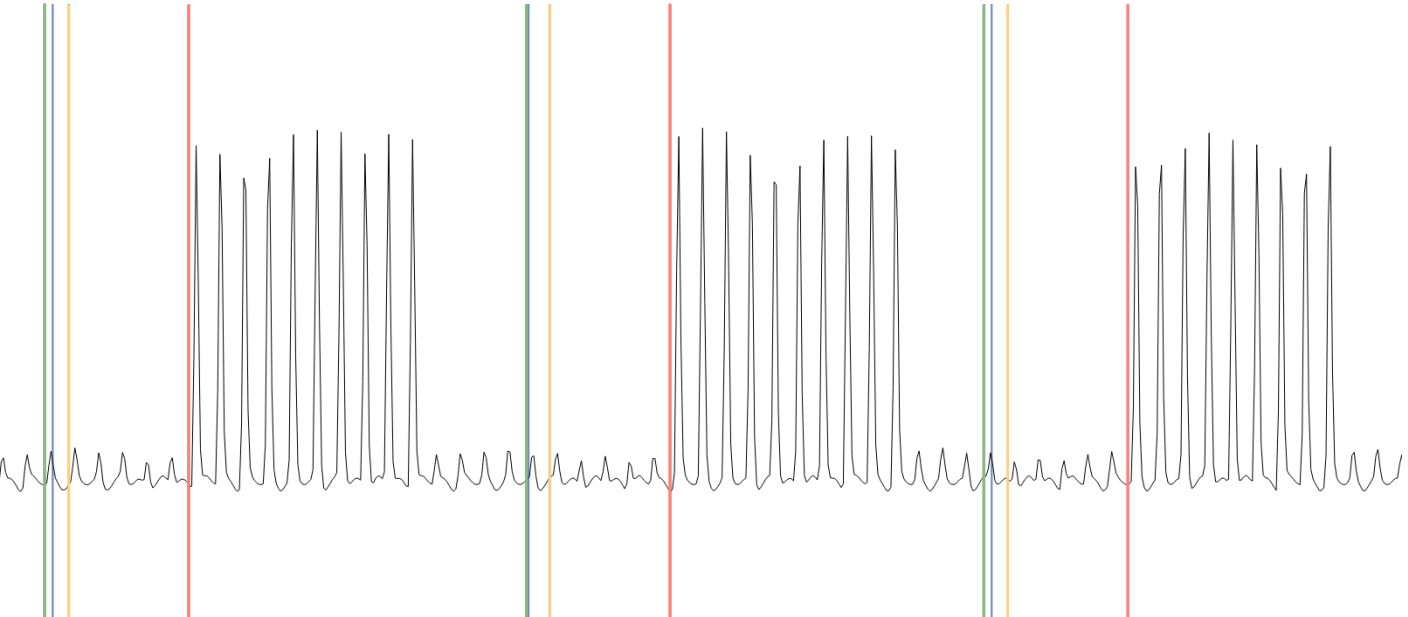
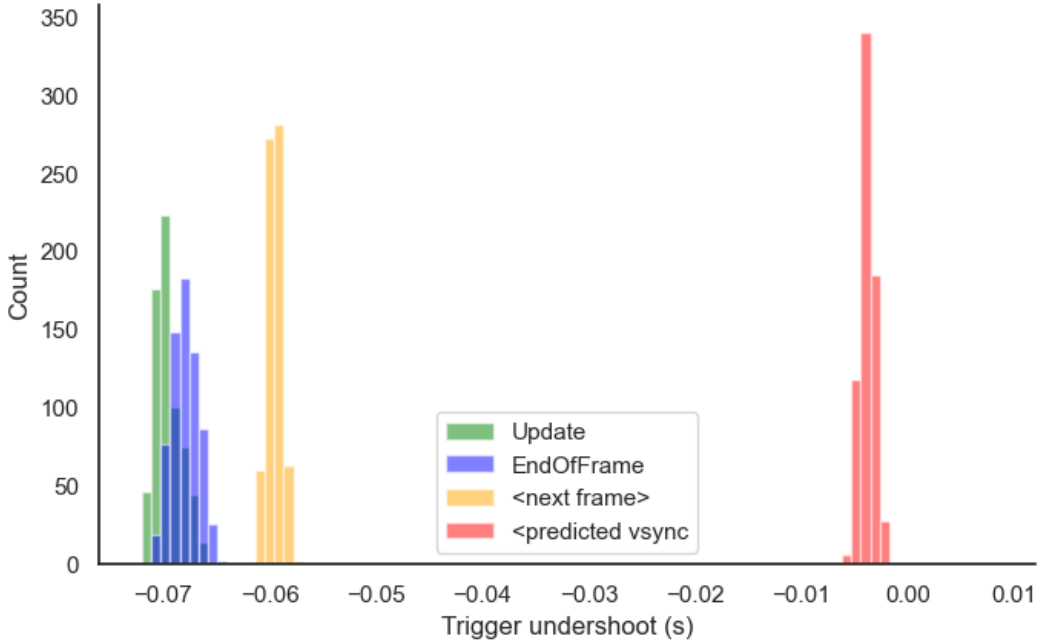
Oculus Quest Pro
https://komete-xr.com/de/products/meta-quest-pro

⚠ Assumes stable frame rate!







Data synchronization

EEG samples @500 Hz

Frame onsets @90 Hz

Stimulus events

start preparing

show on screen

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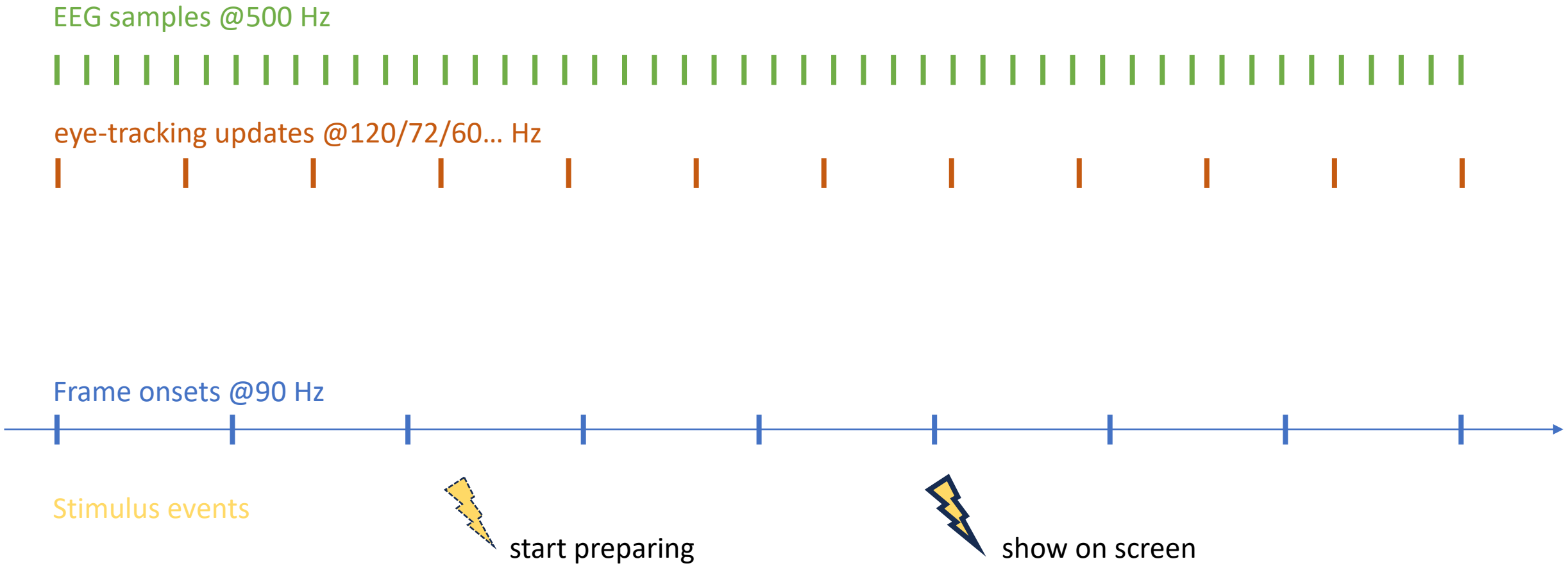
Data synchronization



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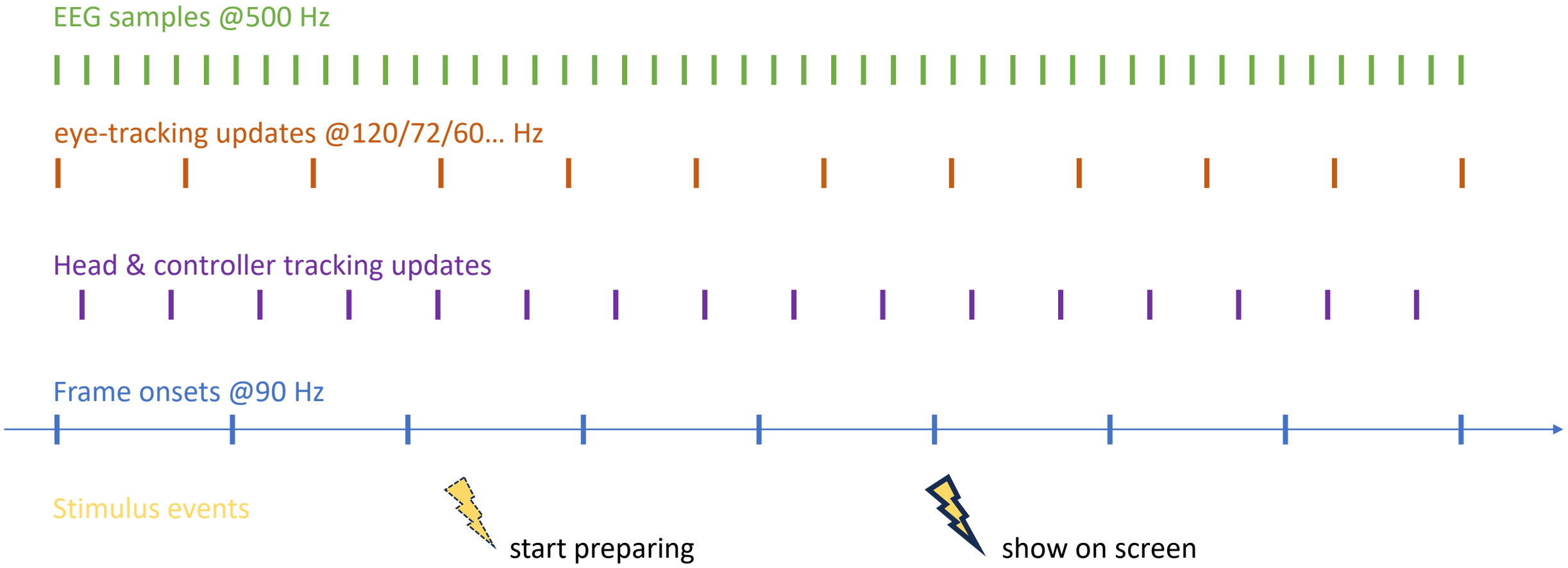
Data synchronization



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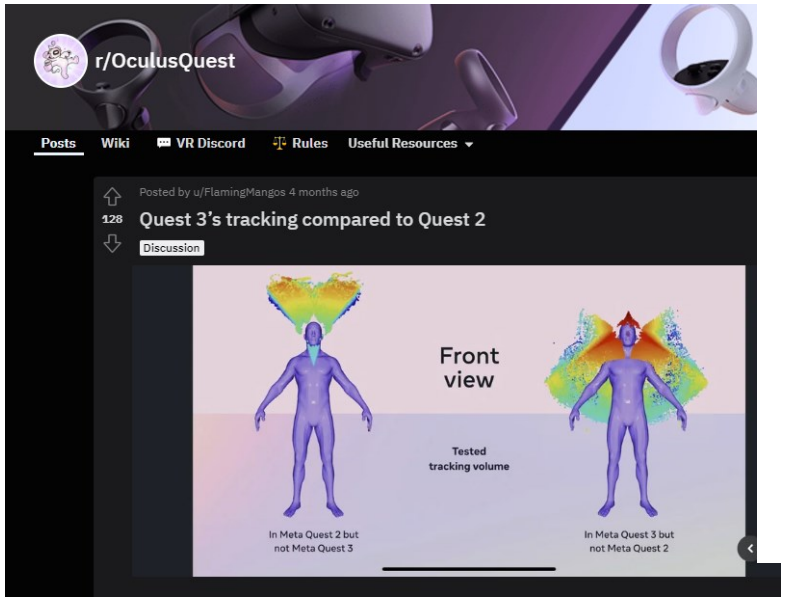
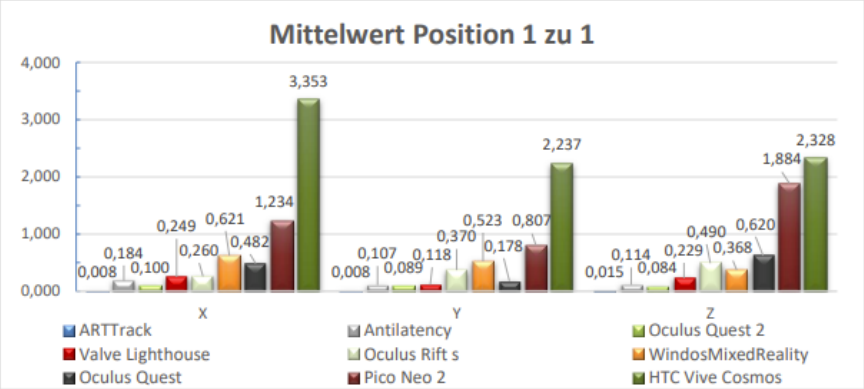
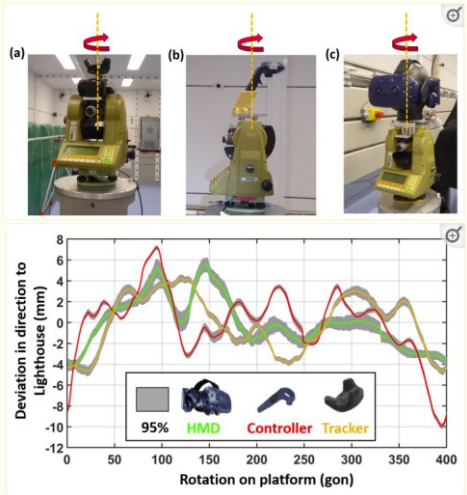


Mittelwert aller Abweichungen

Die folgende Abbildung stellt die durchschnittliche absolute Abweichung zu ihrem Mittelwert dar. Es fällt auf, dass mit Ausnahme eines Trackingsystems die Werte an Position 1 (s. Abbildung 09) nicht zu stark voneinander abweichen und unter 0,50 mm liegen.



https://www.vdc-fellbach.de/fileadmin/user_upload/Applikationszentrum_VAR_-_Bericht__04_2_-_AP2_-_Werkstattbericht__02_-_Messung_VR-Tracking-Praezision_-_Update.pdf



https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7956487/

i-Perception

Impact Factor: **1.9** / 5-Year Impact Factor: **1.6**

JOURNAL HOMEPAGE

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The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research

Diederick C. Niehorster, Li Li, and Markus Lappe View all authors and affiliations

All Articles | https://doi.org/10.1177/2041669517708205

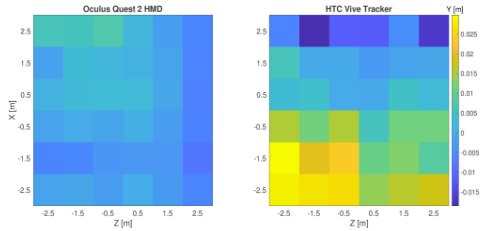

Figure 4: Sample mean errors in the tracked object height of the Oculus Quest 2 HMD and the HTC Vive Tracker.

https://dl.acm.org/doi/fullHtml/10.1145/3463914.3463921#BibPLXBIB0001

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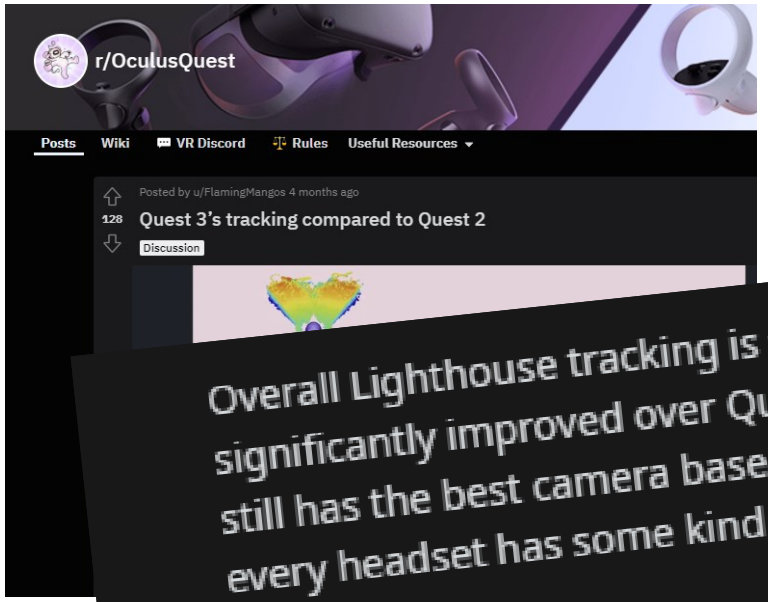
Head & controller tracking



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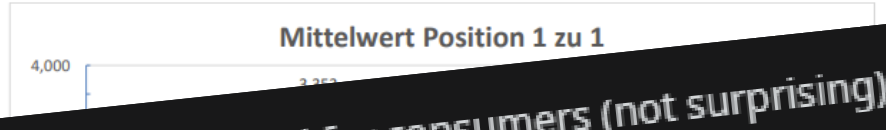

956487/

Overall Lighthouse tracking is still the gold standard for consumers (not surprising). Quest 2 tracking is significantly improved over Quest 1, both in tracking volume and even more so tracking quality. Rift S still has the best camera based inside-out tracking volume. WMR has mostly good tracking quality but every headset has some kind of significant downside. Vive Cosmos is garbage.

5 Comments Share Save ...

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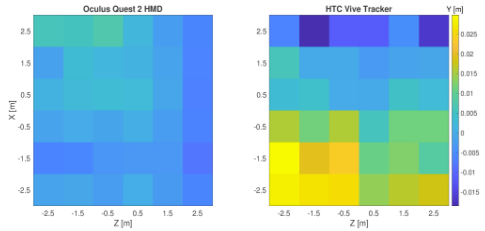

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Data synchronization

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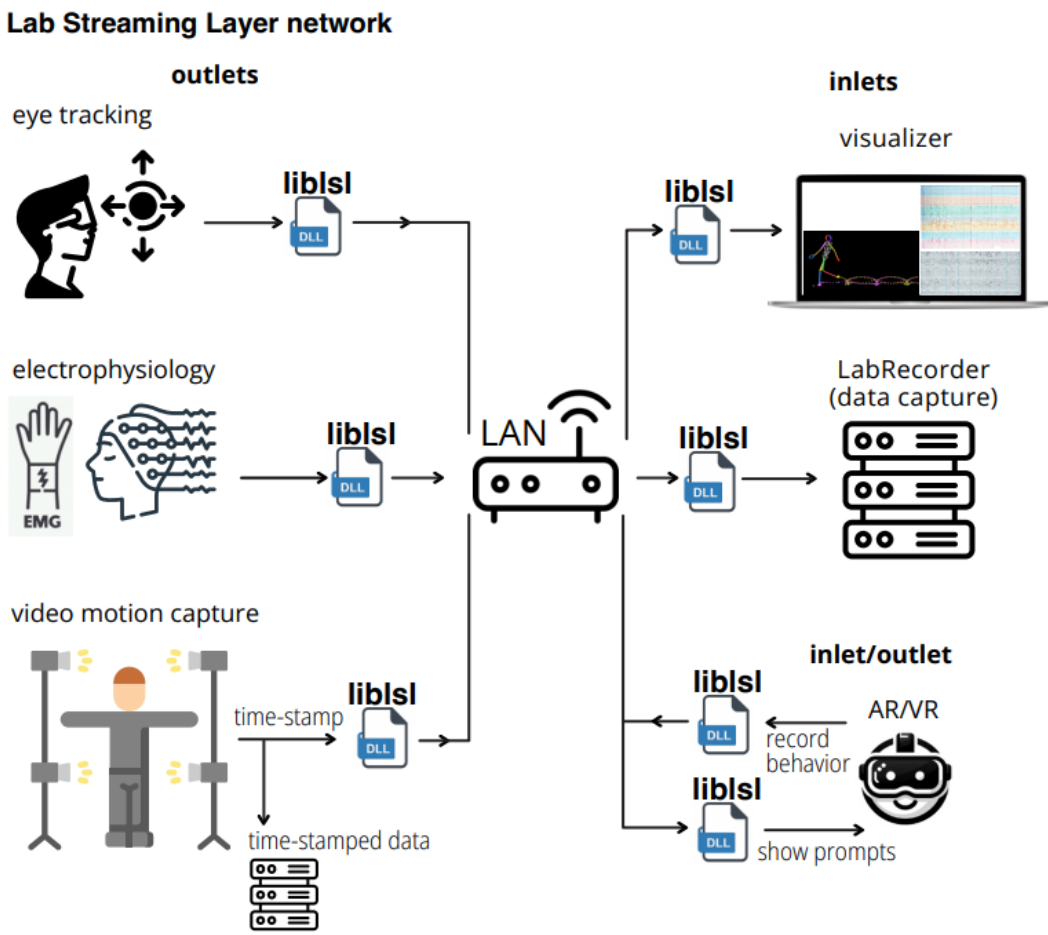
doi: https://doi.org/10.1101/2024.02.13.580071

https://www.biorxiv.org/content/10.1101/2024.02.13.580071v1



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For questions, comments, collabs, … please do not hesitate to get in touch:

klotzsche@cbs.mpg.de

Time for a break!

We'll see you later.

Thank you …

for the invite!

Prof. Dr. Dejan Draschkow
Department of Experimental Psychology
University of Oxford

for VR support!

Jeroen de Mooij
https://thefirstfloor.nl/

MAX PLANCK INSTITUTE
FOR HUMAN COGNITIVE AND BRAIN SCIENCES

Mind Body Emotion

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