Eye Tracking

Applications, Recording, Analytics, Interaction

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Acknowledgements

Funding

U.S. National Science Foundation

Donations

Collaborations

SWPS, Universität Tübingen

Collaborators



SWPS University of Social Sciences and Humanities

Krzysztof & Iza Krejtz

Justyna Garnier

Universität Tübingen

Nina Gehrer

Objectives

The tutorial is based on four objectives: a survey of the field followed by hands-on examples of gaze recording, analytics and gaze interaction. The goals are for attendees to learn about classic eye-tracking research as well as current directions and open problems, and then to learn about basic and advanced eye movement analysis and interaction techniques.

For 2023, the tutorial will include new PsychoPy demonstration code with which attendees will be able to record their own data provided they have access to an eye tracker supported by PsychoPy, i.e., Tobii, Gazepoint, SR Research, or simulate gaze data with the mouse (also an available PsychoPy option).

Abstract

The tutorial starts with an overview of eye-tracking applications, distinguishing eye movement analysis from synthesis in virtual reality, games, and other venues including mobile eye tracking. The focus is on five forms of applications: diagnostic (off-line measurement), active (selection, look to shoot), passive (foveated rendering, a.k.a. gaze-contingent displays), assistive (translation), and expressive (gaze synthesis). The tutorial then covers details of a Python-based gaze analytics pipeline developed and used by Prof. Duchowski and others. The gaze analytics pipeline consists of Python scripts for extraction of raw eye movement data, analysis and event detection via velocity-based filtering, collation of events for statistical evaluation, analysis and visualization of results using R. The tutorial covers basic eye movement analytics, e.g., fixation count and dwell time within AOIs, as well as advanced analysis using ambient/focal attention modeling and gaze transition entropy. Newer analytical tools and techniques such as microsaccade detection and the pupillary activity will be covered, time permitting. The tutorial concludes with an overview and demo of how to build an interactive Python application.

Taget Audience

The intended audience should largely be composed of novice attendees who may have heard something about eye tracking and would like to learn more about what is involved.

Seasoned veterans, are also welcome, they may benefit from the section on experimental design.

Finally, time permitting, anyone interested in developing a basic eye-tracking application will benefit from an overview of a Python application designed to obtain gaze information in real-time from a commodity eye tracker.

Agenda & Table of Contents

- 80 min: Gaze Applications
  - 20 min: Active
  - 20 min: Passive
  - 20 min: Expressive
  - 20 min: Diagnostic
- 100 min: Gaze Analytics
  - 50 min: Experimental Design & Analytics Pipeline
  - 50 min: Gaze Metrics & Statistics
- 50 min: Gaze Recording
- 30 min: Gaze Interaction
  - 10 min: Instrumentation
  - 10 min: Socket Communication
  - 10 min: Real-time Gaze Signal Analysis

Biosketch

Dr. Duchowski is a professor of Computer Science at Clemson University. He received his baccalaureate (1990) from Simon Fraser University, Canada, and doctorate (1997) from Texas A&M University, USA, both in Computer Science. His research and teaching interests include visual attention and perception, computer vision, and computer graphics. He is a noted research leader in the field of eye tracking, having produced a corpus of related papers and a monograph on eye tracking methodology, and has delivered courses and seminars on the subject at international conferences. He maintains Clemson's eye tracking laboratory and teaches a regular course on eye tracking methodology attracting students from a variety of disciplines across campus.

Biosketch

- Professor of Computer Science
  - *Gastprofessor* 2016 ETH Zürich
  - PhD 1997 Texas A&M
  - BSc 1990 Simon Fraser

- Visual Computing division at Clemson
  - computer graphics, computer vision, eye tracking

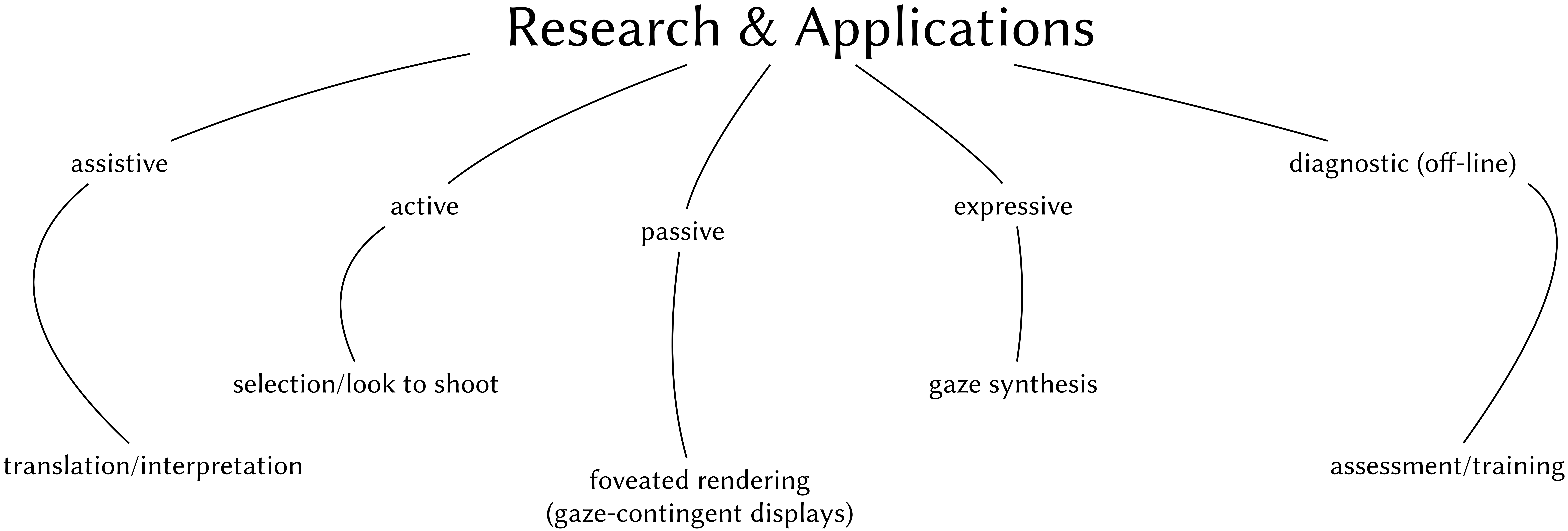
- Founded ETRA, CHI `alt.chi`, and SIGGRAPH *Groovy Graphics Assignments*

Eye Tracking

Research & Applications

Andrew T. Duchowski *duchowski@clemson.edu*

Eye Tracking



Intro: binocular eye tracking in VR

- Recent entrants: ~$600
  - Facebook (bought Eye Tribe, owns Oculus)
  - Google (bought Eyefluence)
  - Apple (bought SMI)
  - FOVE
  - Samsung or HTC Vive (using SMI)
  - HTC Vive (using Pupil Labs)

Intro: binocular eye tracking in VR

- Earlier technology: ~$60,000
  - VR Research HMD
  - ISCAN eye tracker
  - 2 IR LEDs per eye
  - half-silvered mirrors

Duchowski, et al. (ETRA 2002)

Who is left today?




- Wearables
  - Ergoneers (Dikablis), Pupil Labs, Tübingen (EyeRecToo), Tobii (Glasses2)

- Desktop
  - SR Research (Eyelink), Gazepoint (GP3), Tobii (various)



Affordable to facilitate classroom instruction

- Clemson's eye tracking classroom houses 20 Gazepoint GP3 trackers

Emergent Technology

- AR
  - Microsoft's HoloLens 2
- Pupil Labs Invisible

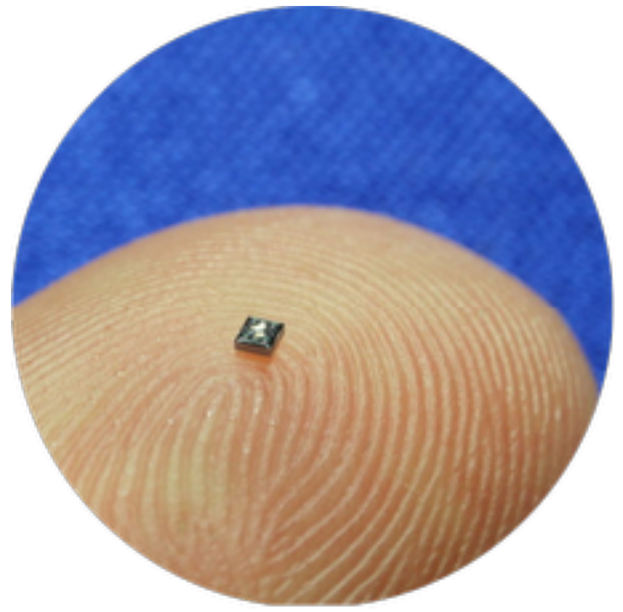
Emergent Technology

- AR
  - Meta Oculus Pro

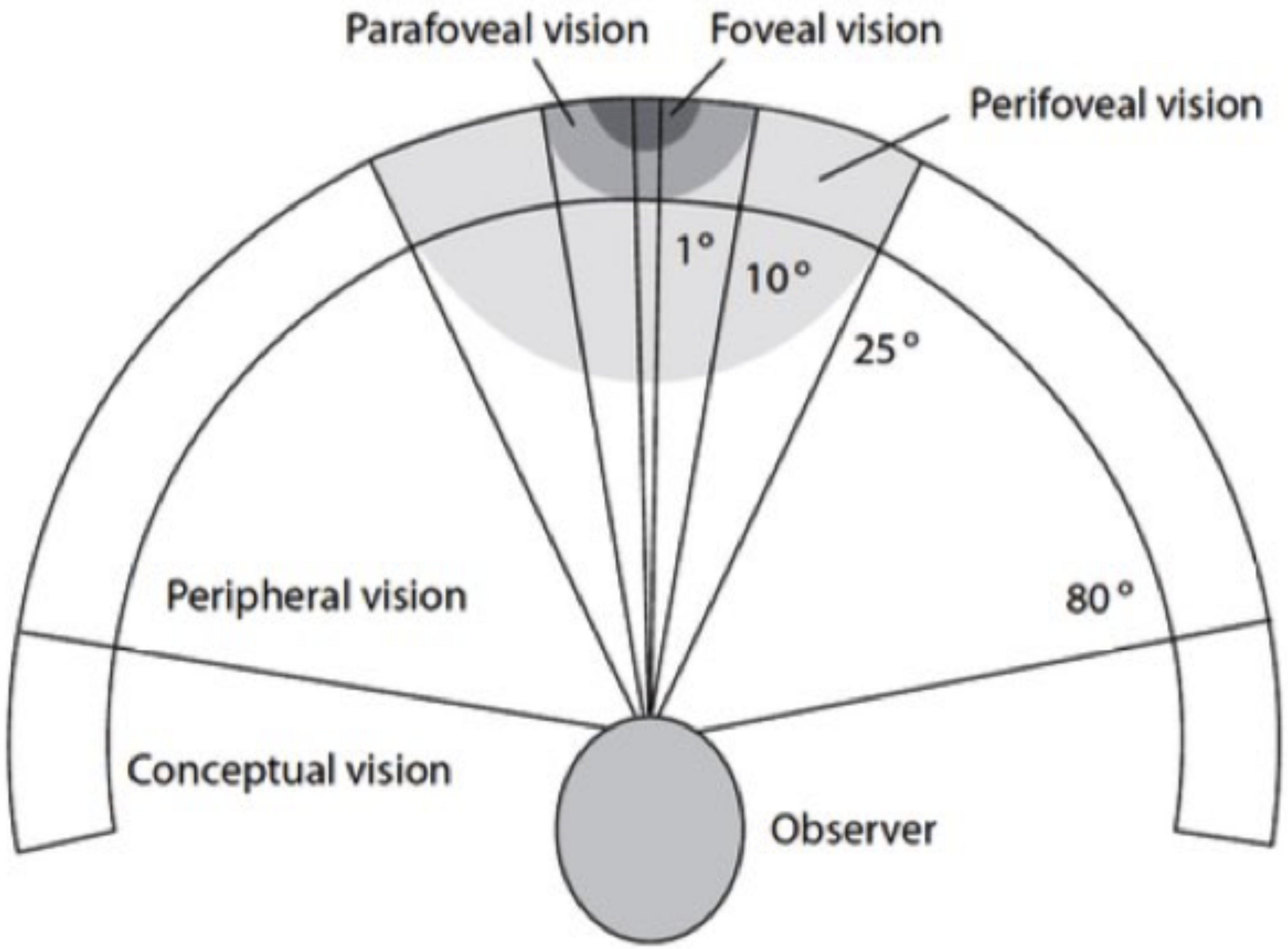
Reliability of Eye Trackers

RealEye AdHawk microsystems Inseye

- Web-based: limited accuracy but ok (see our ETRA 2022 paper)
- Video-based: accurate, sampling rate determines *event detection*
  - 300 Hz needed for microsaccades
- New technologies: MEMS, photosensors
- Fixational drift:
  - something else entirely, more gaze dynamics than anything
  - current fixational algorithms would ignore this (wronlgy)



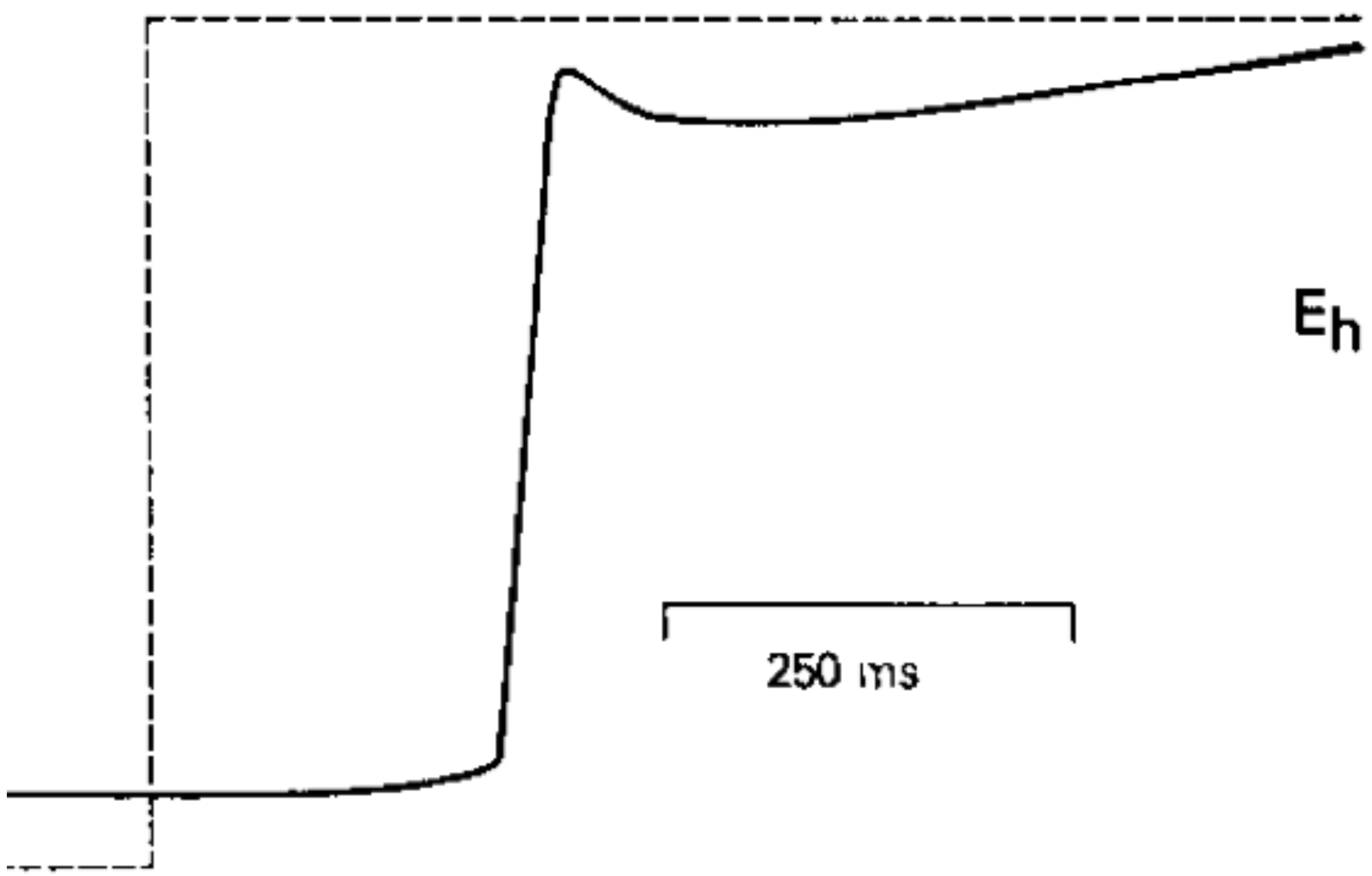
The basics



Schematic representation of the human visual field.

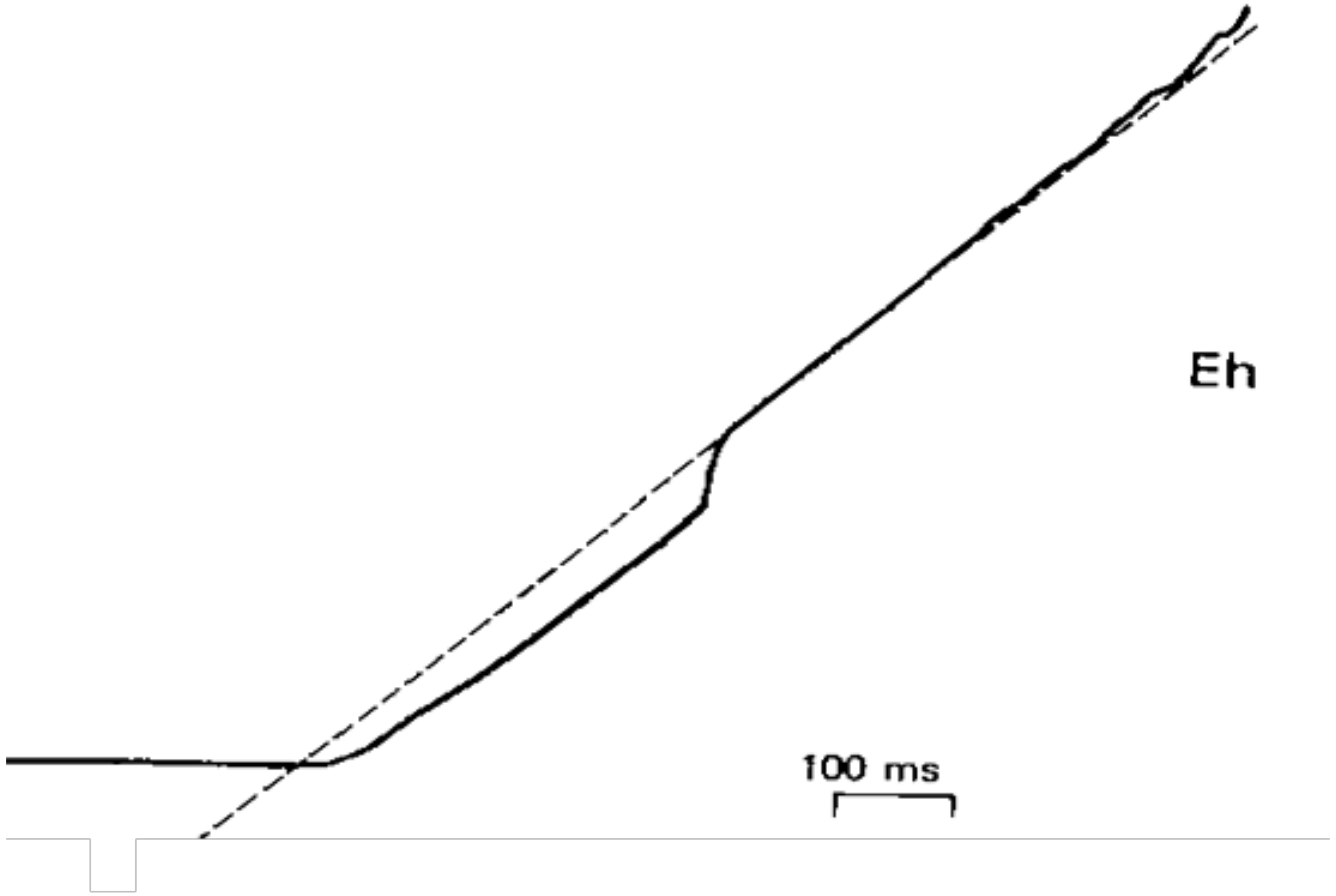
From Sundstedt, V., Gazing at Games, SIGGRAPH 2010 course notes.
Adapted from MacEvoy, B. The Visual Field. http://www.handprint.com

Saccades



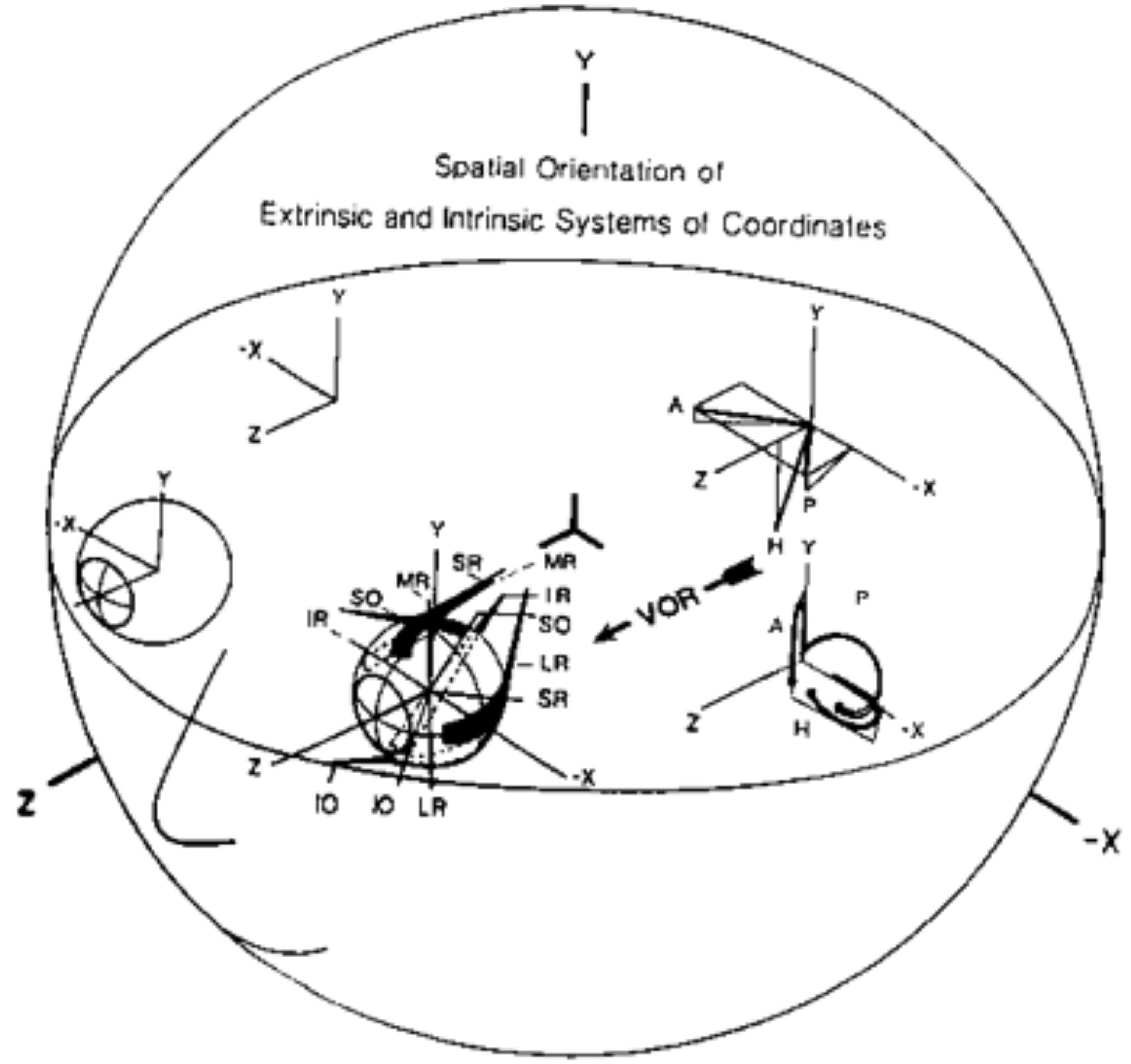
- Used to shift gaze
  - < 1 deg to > 45 deg
  - 500 deg/s

Smooth pursuits



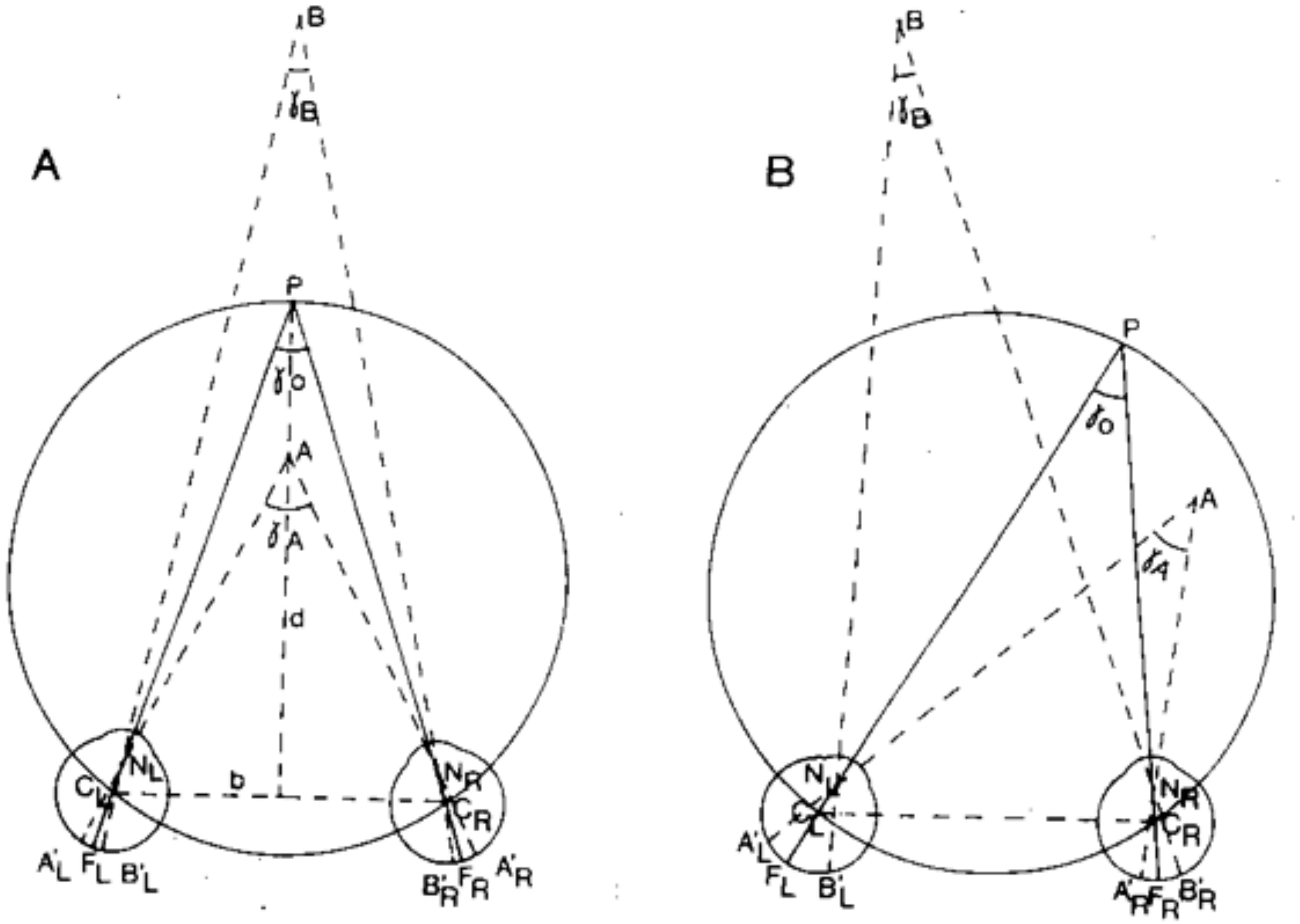
- Used to track object in motion

Vestibular Ocular Response



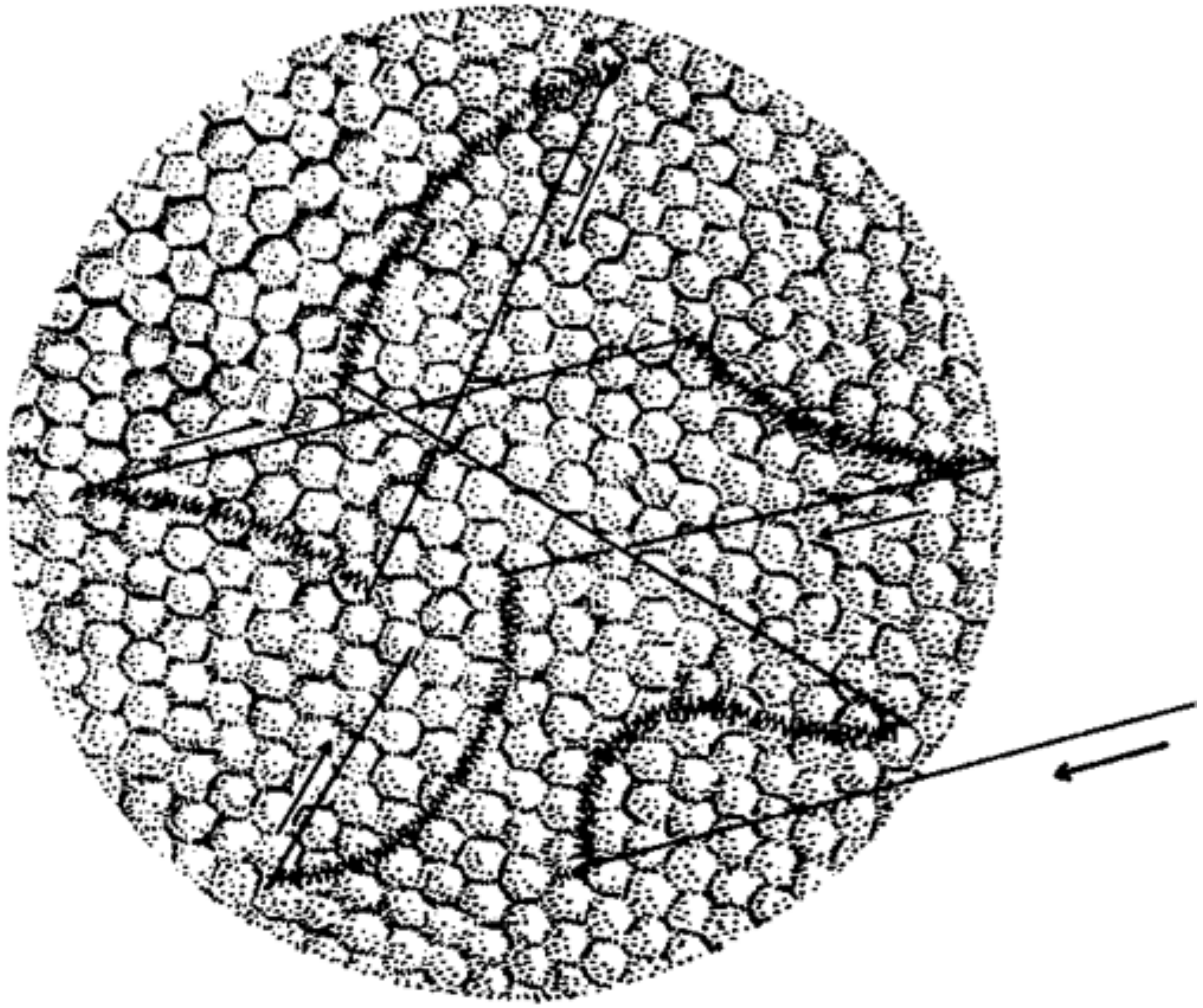
- Used to counter-rotate eyes when head turns

Vergence



- Used for depth perception (arm's length)

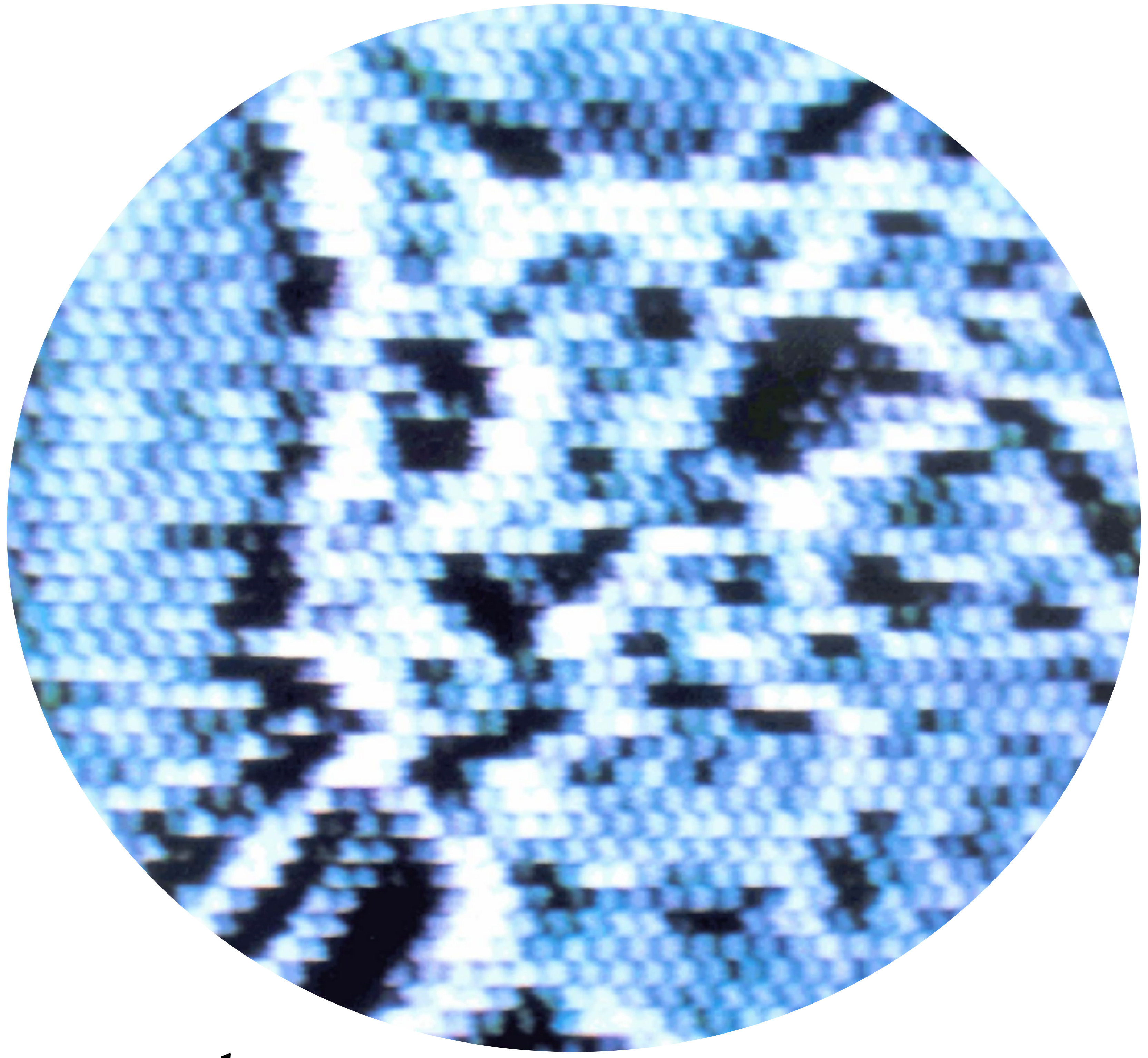
Fixations



from Pritchard (1961)

- Used to stabilıze gaze
  - characterized by tremor, drift, and microsaccades
  - 90% viewing time spent in fixations

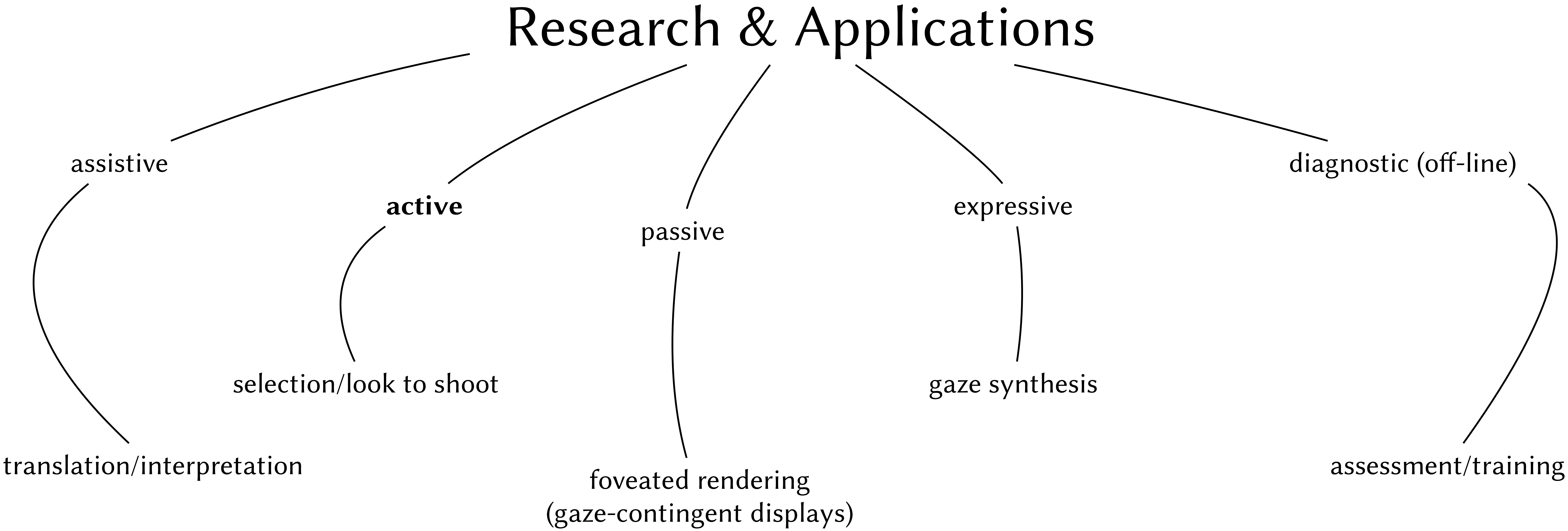
Fixations



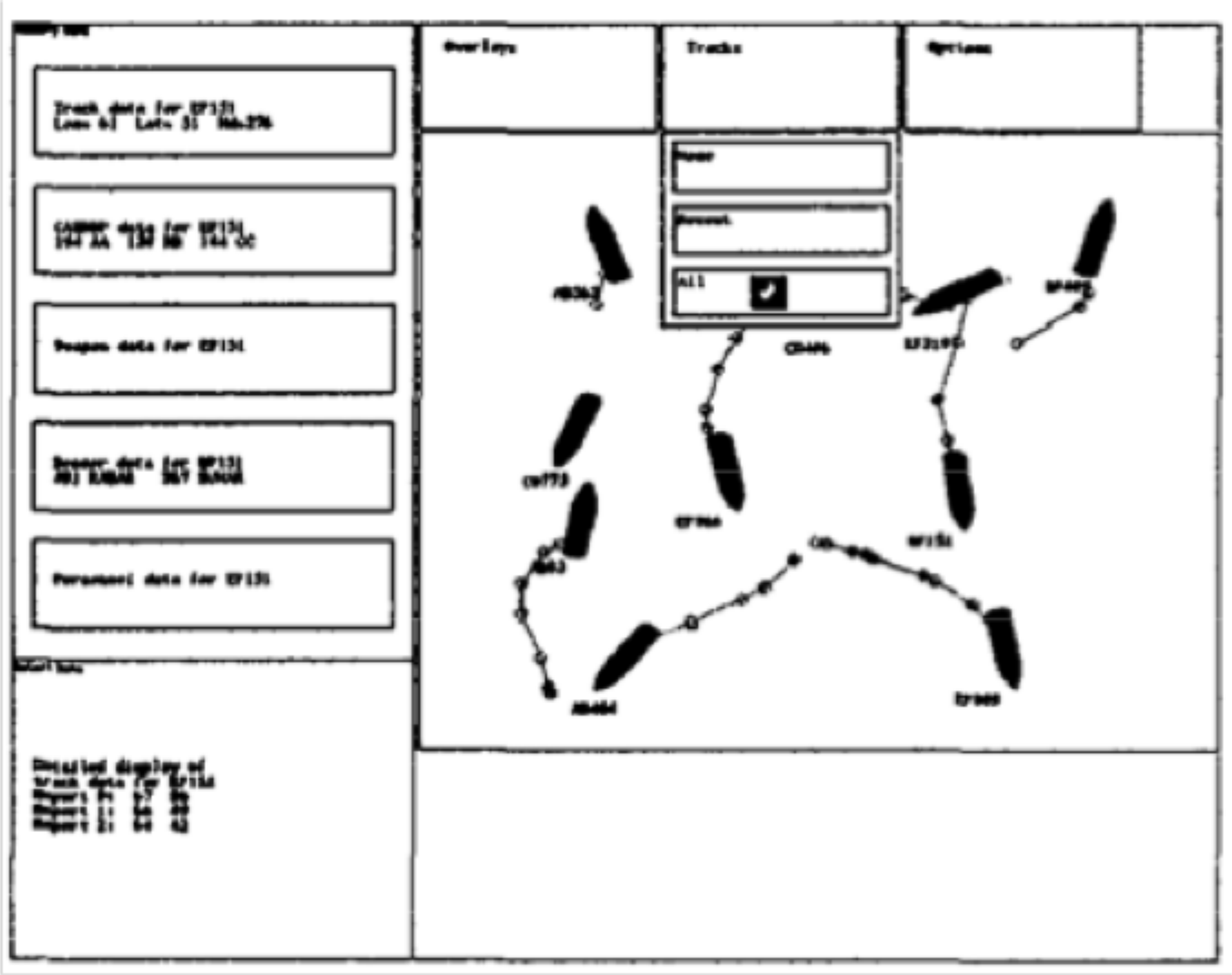
Mahowald and Mead
(Scientific American, 1991)

- Silicon sees a cat
  - time-derivative silicon retina (see youtube vid)
  - image fades when no movement

Eye Tracking



Classic gaze-based selection



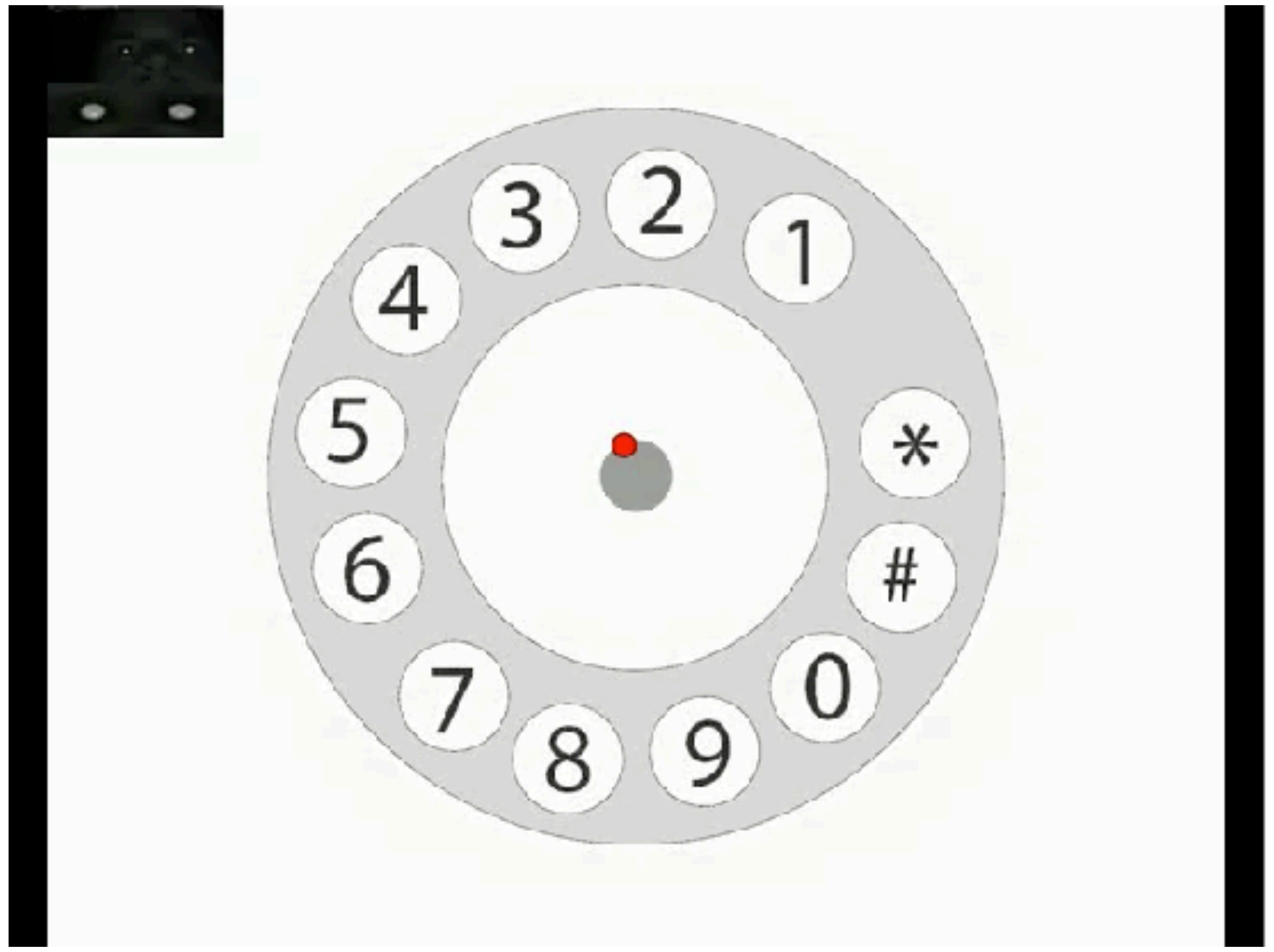
- Key problem: Midas Touch
  - solution: dwell time

Jacob (CHI 1990)

Gaze-based PIN selection

4444cccccc**999999999**cccccccc7777**6666**cccccc**11111111**ccccc**000000000**cccccccccccc##

dwell-time



boundary-crossing gestures

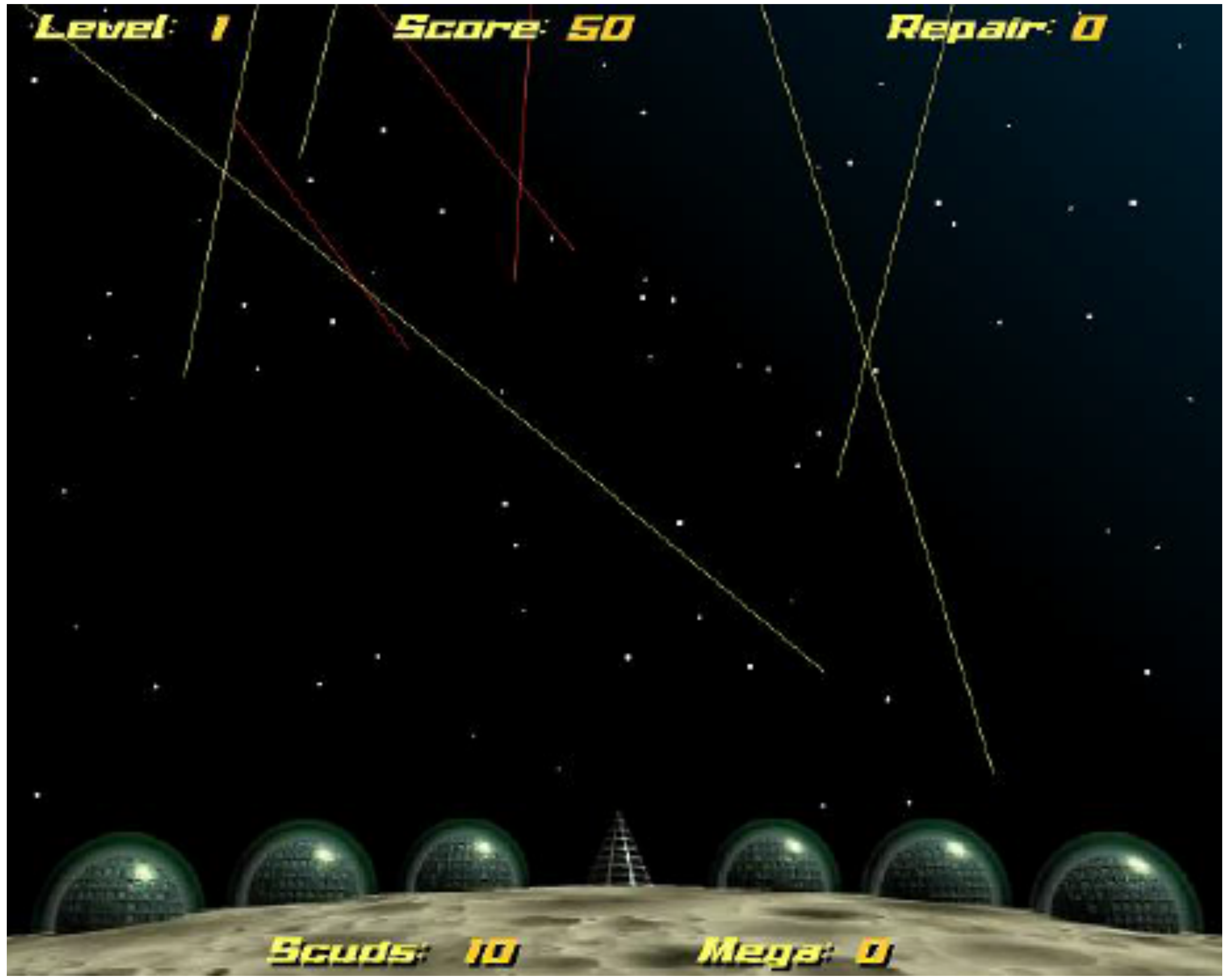
Best and Duchowski (ETRA 2016)

Gaze-based selection in gameplay

- Gaze-based viewpoint orientation

Smith and Graham (ACE 2006)

Gaze-based selection in gameplay



- Eye-based pointing

Smith and Graham (ACE 2006)

Tobii integrated eye tracker

* Note: I don't get paid by Tobii

Summary: Active gaze

Gaze interaction in the post-WIMP world:
SIGCHI 2013 workshop

Bob Jacob, Raimund Dachselt, Andreas Bulling, me, Sophie Stellmach, Veronica Sundstedt

- Outstanding problems:
  - Midas Touch ever present
  - multi-modality gaining popularity
  - gaze gestures also popular
  - new interaction techniques always welcome

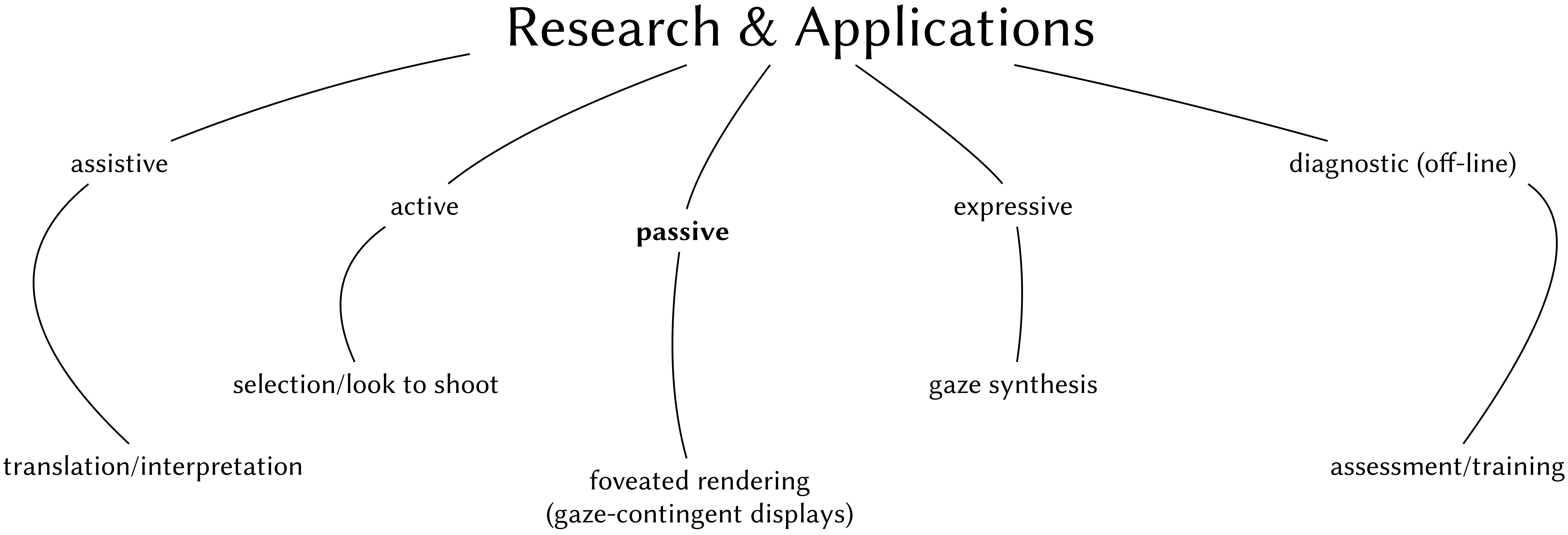
Summary: Active gaze

Ubiquitous Gaze Sensing and Interaction:
Dagstuhl 2018 seminar 18252

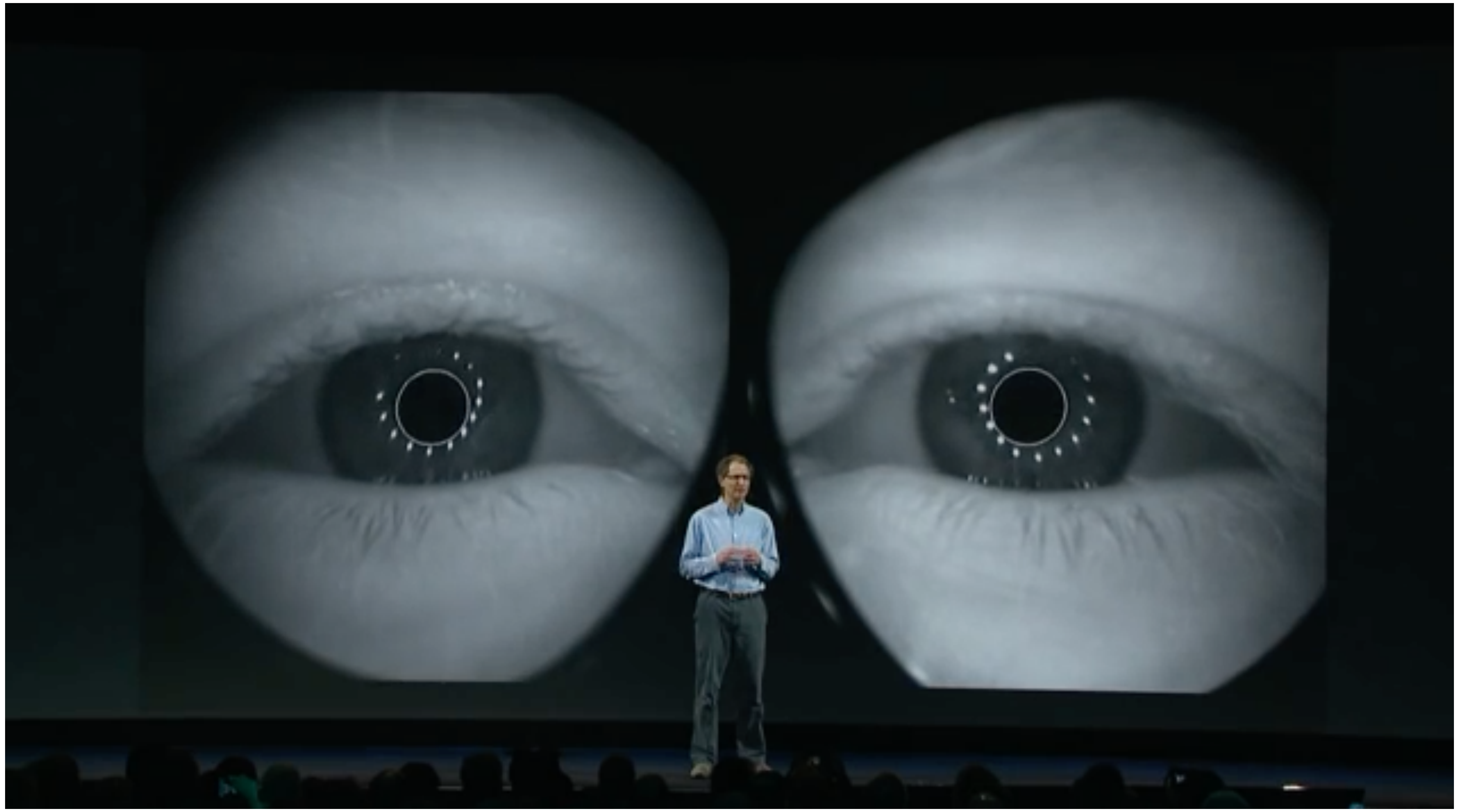
L. L. Chuang, A. T. Duchowski, P. Qvarfodt, D. Weiskopf

- Challenges:
  - privacy
  - gaze + X
  - recommendation & guidance
  - intent & prediction
- Scenarios:
  - mobility
  - healthcare
  - play & learn
  - everyday use

Eye Tracking



Foveated rendering for gaze-tracked VR



- Michael Abrash of Oculus Research:
  - foveated rendering core VR technology in 5 years
  - “great eye tracking is central to the future of VR”

Abrash keynote (Oculus Connect 3, Oct. 2016)

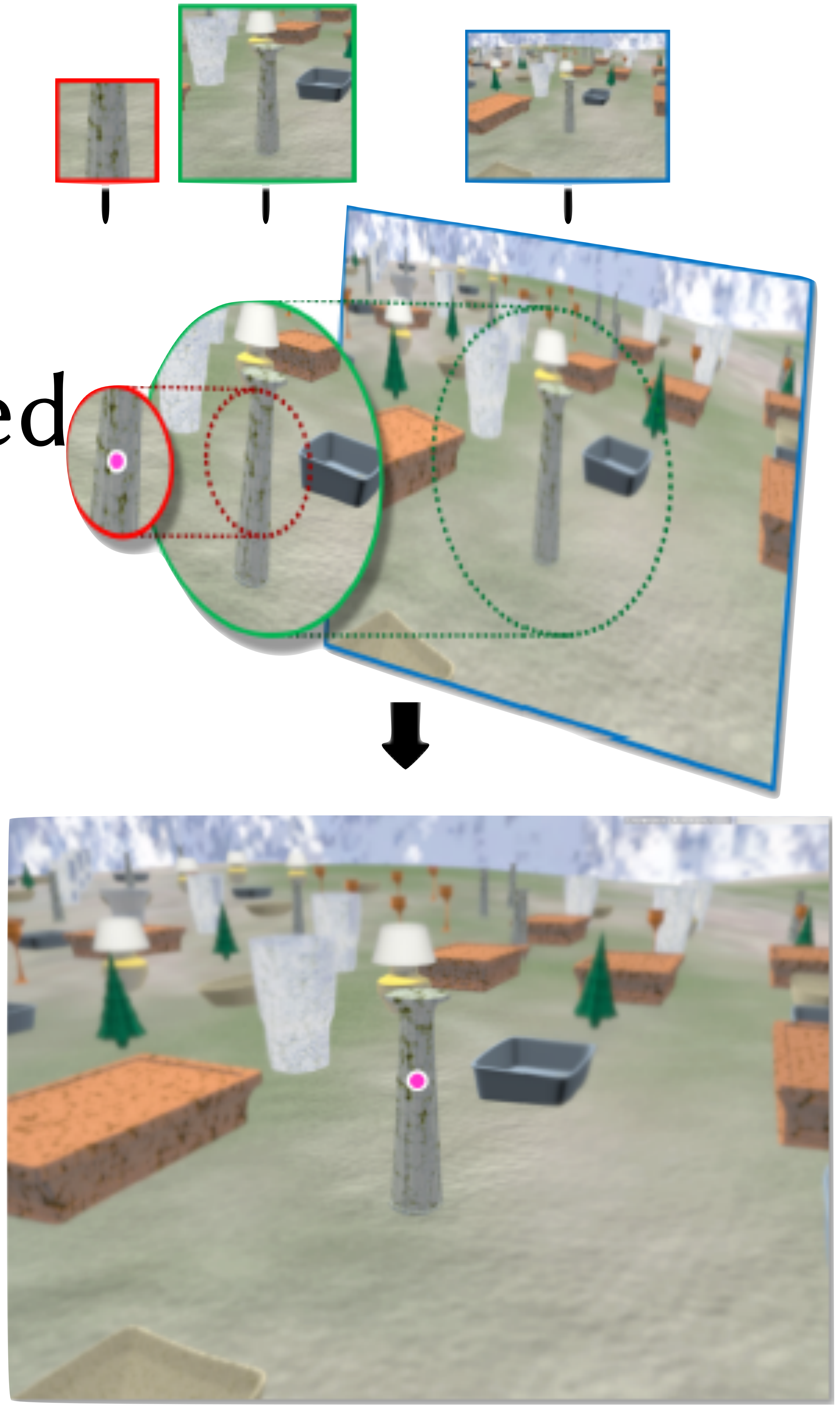
Foveated rendering for gaze-tracked VR

- Perceptually-based foveated VR from NVIDIA

Patney et al. (SIGGRAPH Asia 2016)

Foveated 3D graphics

- Rendering speedup
  - 100 times speedup predicted
  - at 70 deg field of view
  - three layers:
    - foveal
    - middle
    - outer



Guenter et al. (SIGGRAPH Asia 2012)

Simulation of arbitrary visual fields

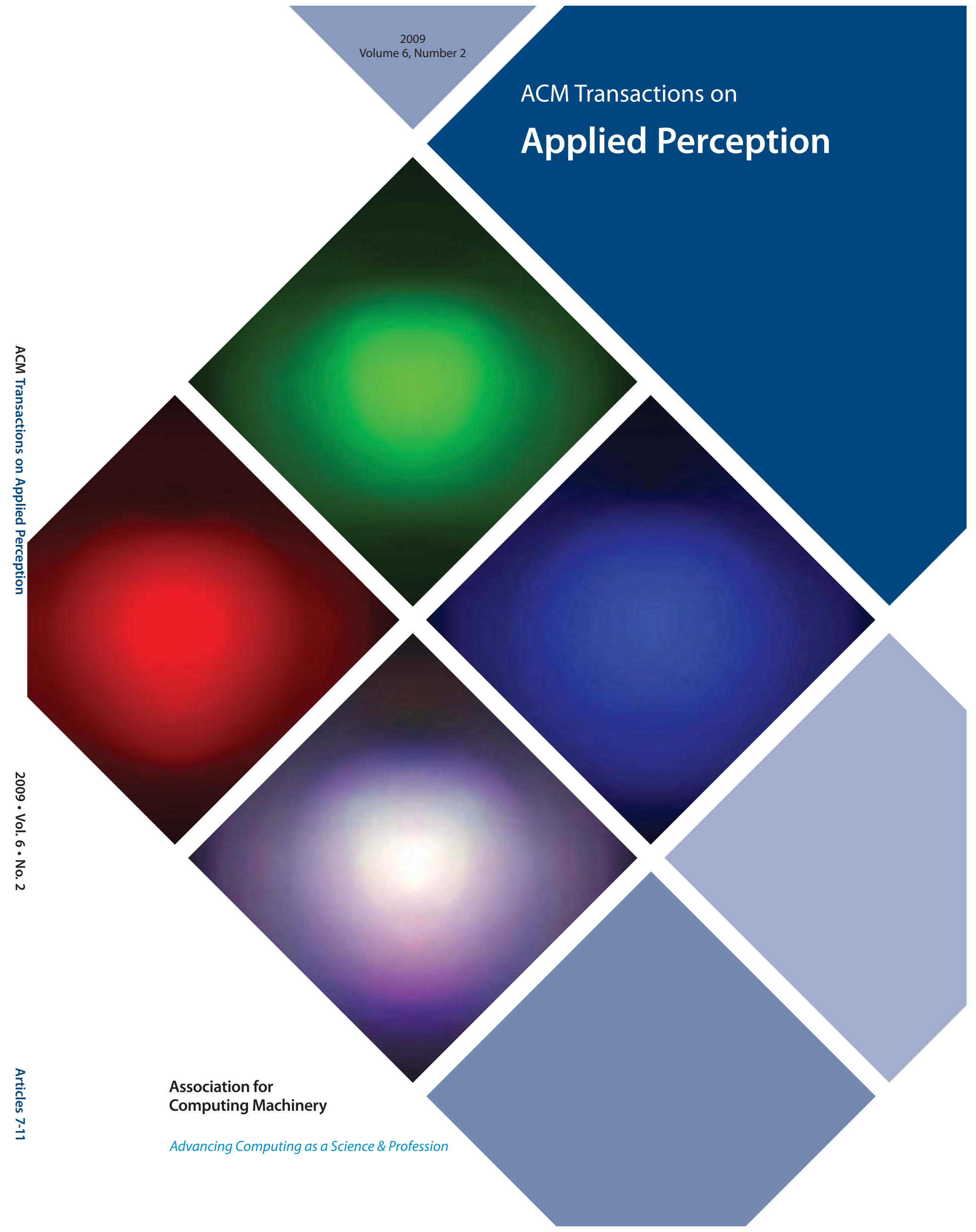
Geisler and Perry (2002)

- Gaze-contingent rendering can simulate glaucoma
- Arbitrary visual field in general simulates scotoma

Simulation of arbitrary visual fields

Duchowski and Eaddy
(EG short papers, 2009)

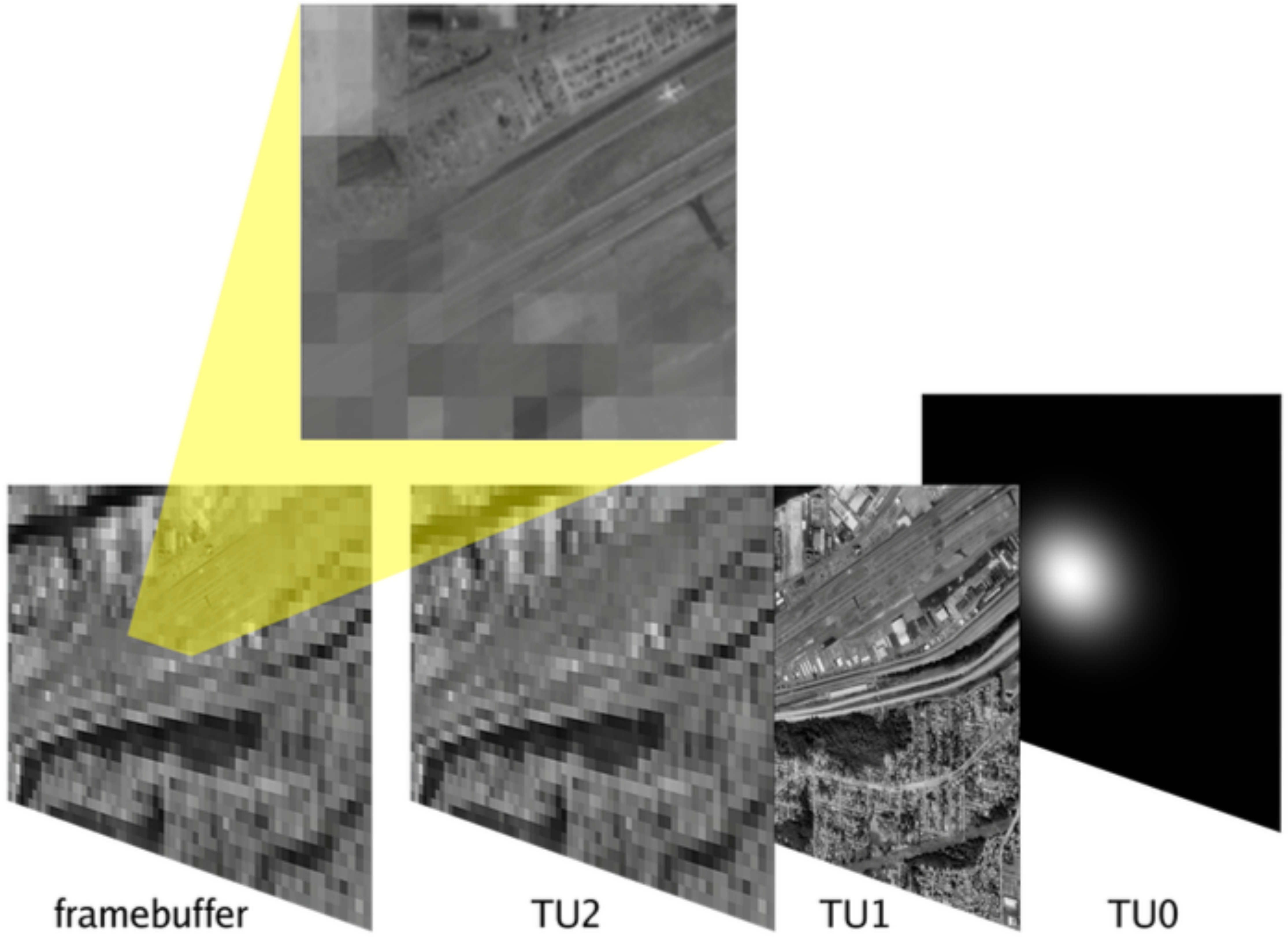
Duchowski and Çöltekin
(TOMCCA, 2007)



Duchowski et al.
(TAP, 2009)

- Simulating scotoma
- Spatiochromatic degradation

Simulation of arbitrary visual fields



Duchowski (ETRA 2004)

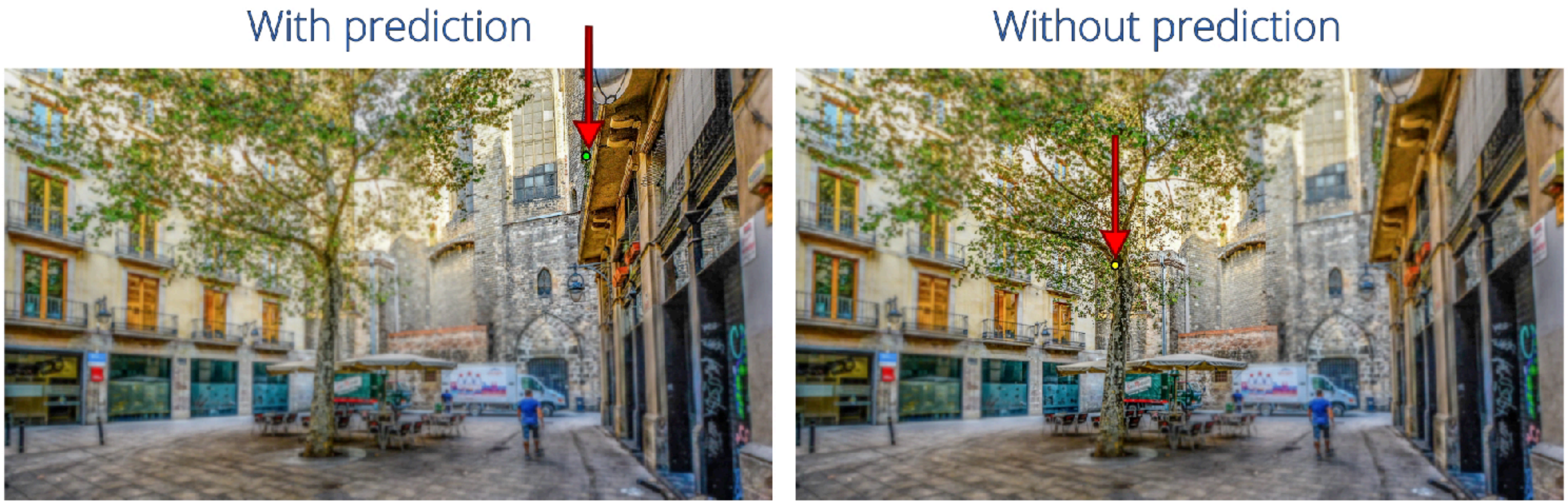
- Pixel-based approach using Mip-mapping
- GLSL shaders make this fairly easy

Saccade prediction

Saccade Onset

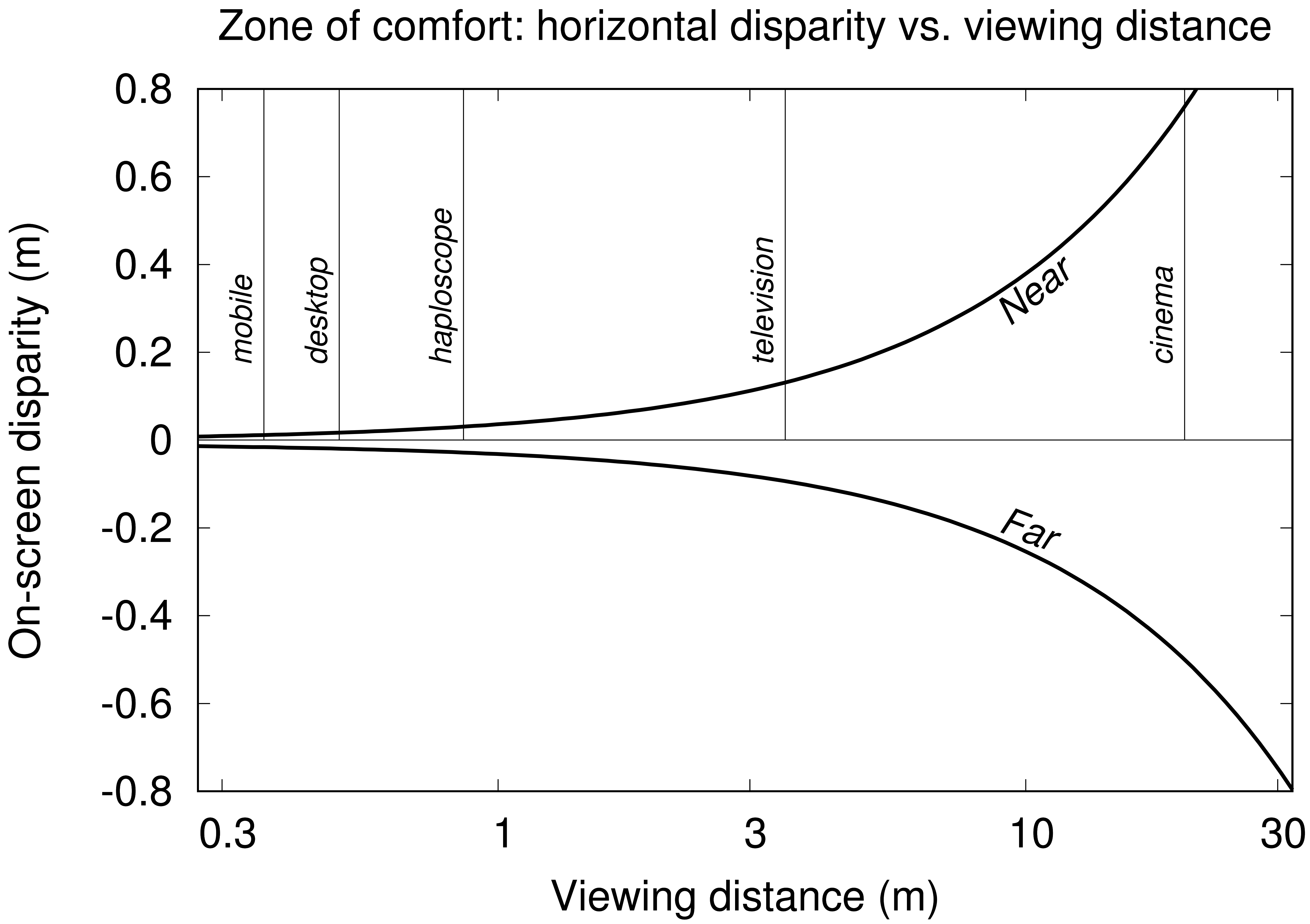
Arabadzhiyska et al. (SIGGRAPH 2017)

Saccade prediction



Arabadzhiyska et al. (SIGGRAPH 2017)

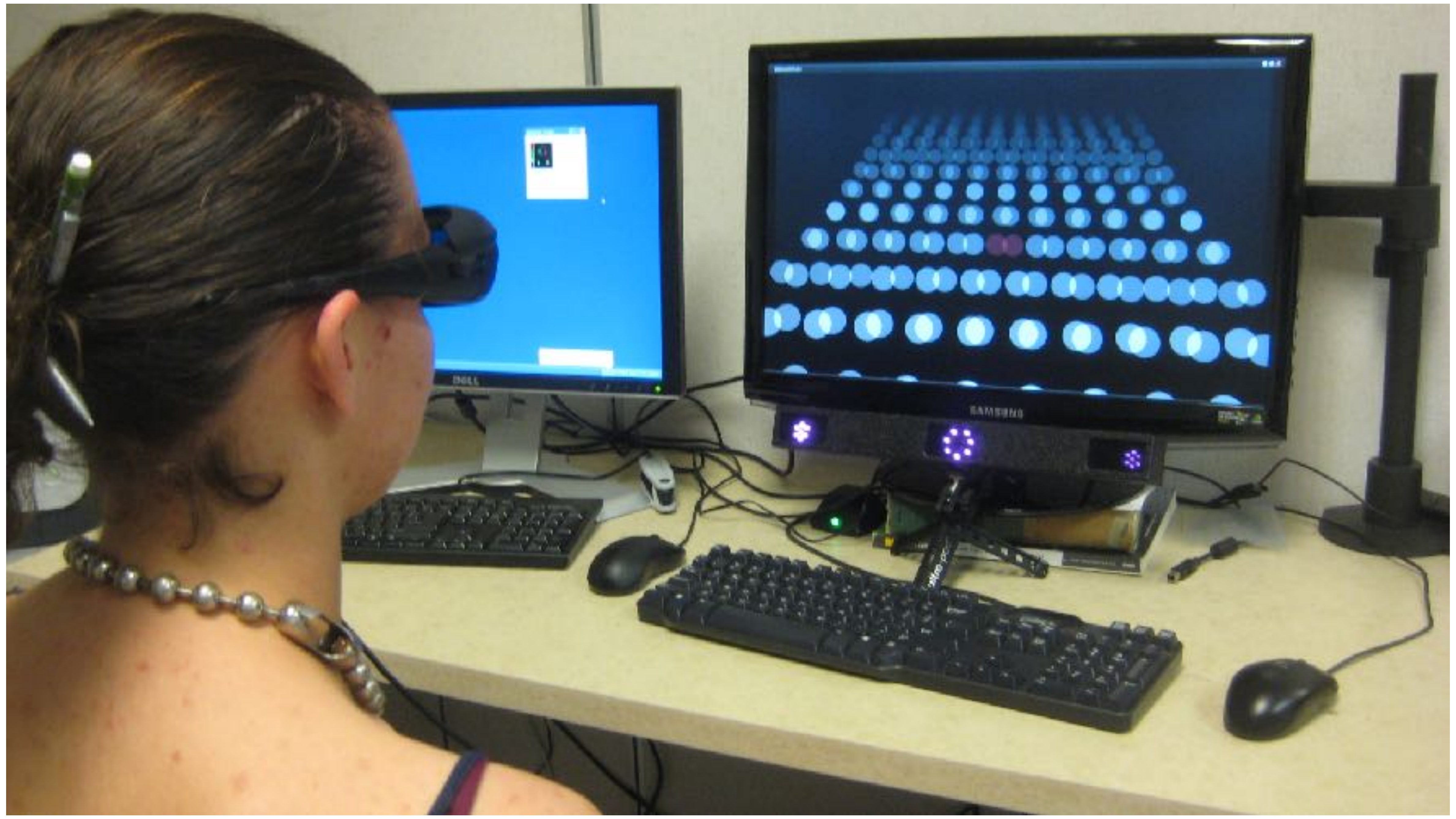
Stereo zone of comfort

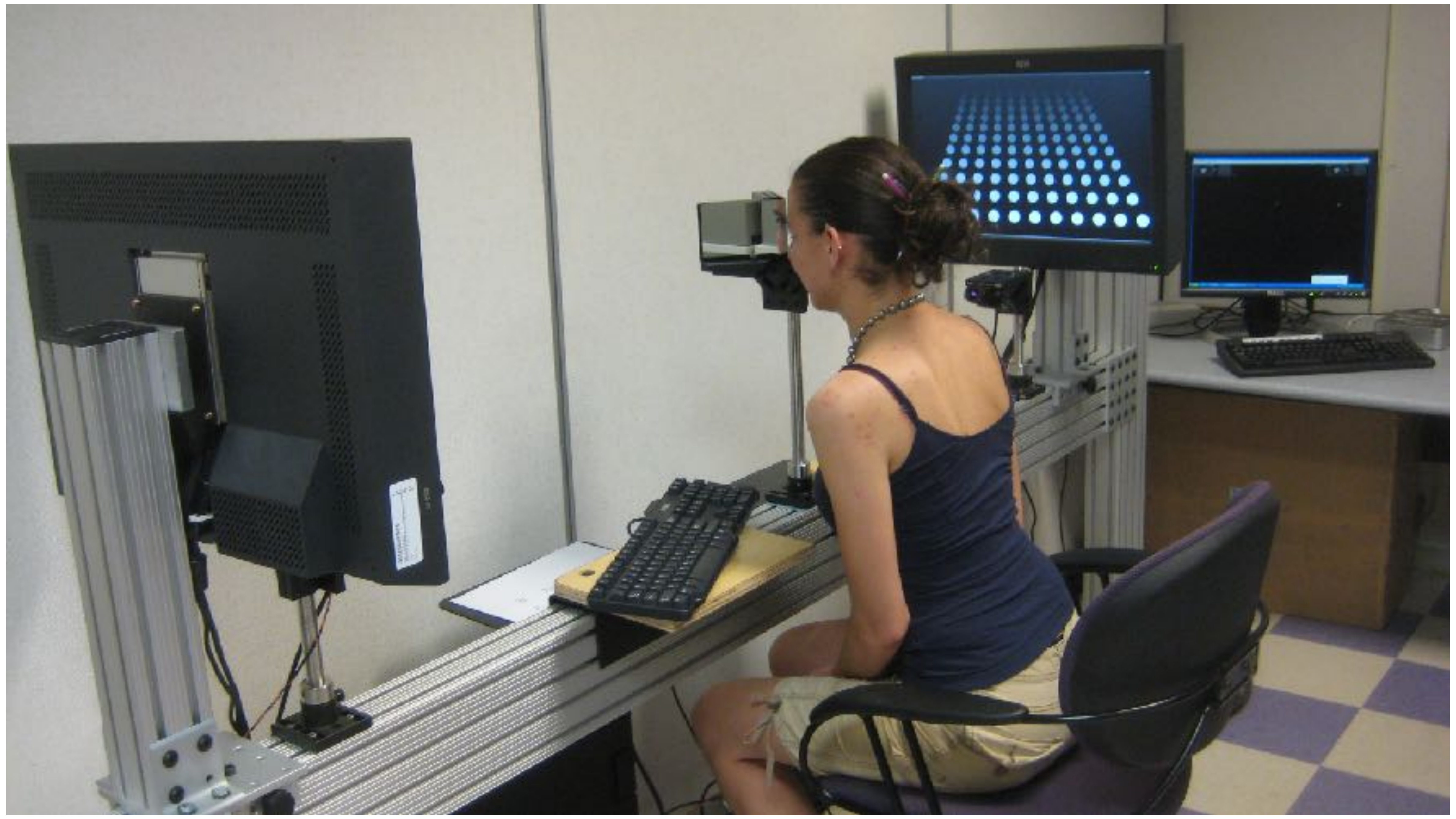


Shibata et al. (2011)

- Accommodation-vergence conflict

Stereo zone of comfort





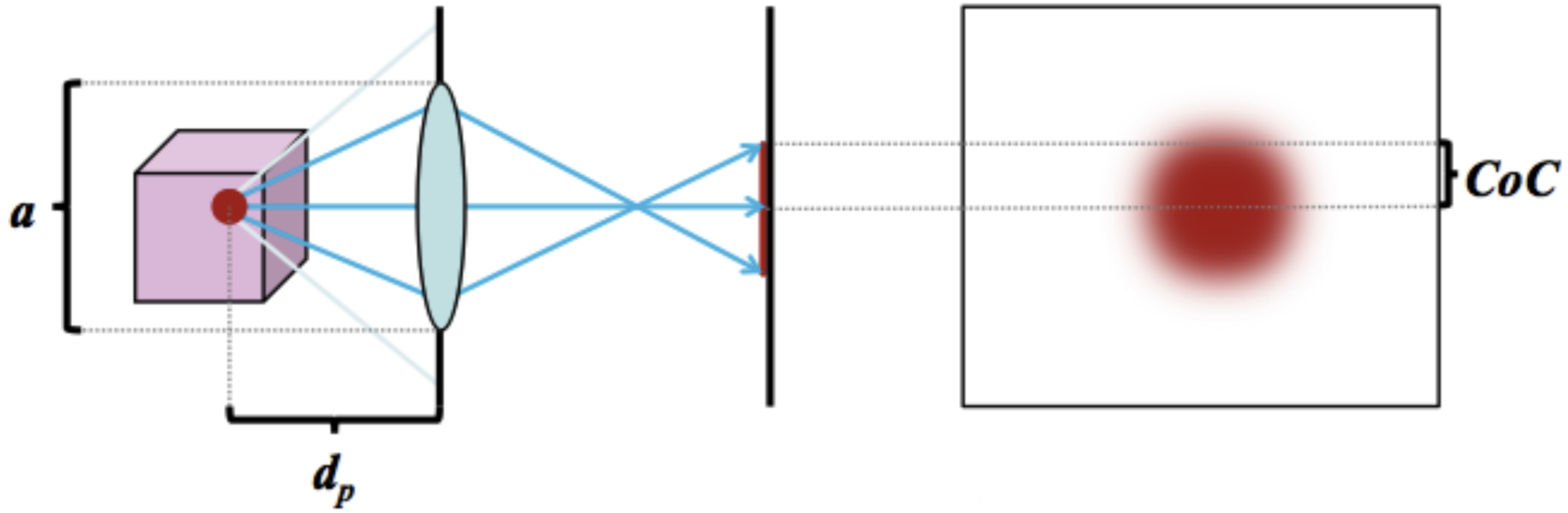
- Desktop and Wheatstone haploscope stereo displays

Seamless disparity remapping

- Remapping disparity at gaze location
  - e.g., if disparity range is narrow

Kellnhofer et al. (SIGGRAPH 2016)

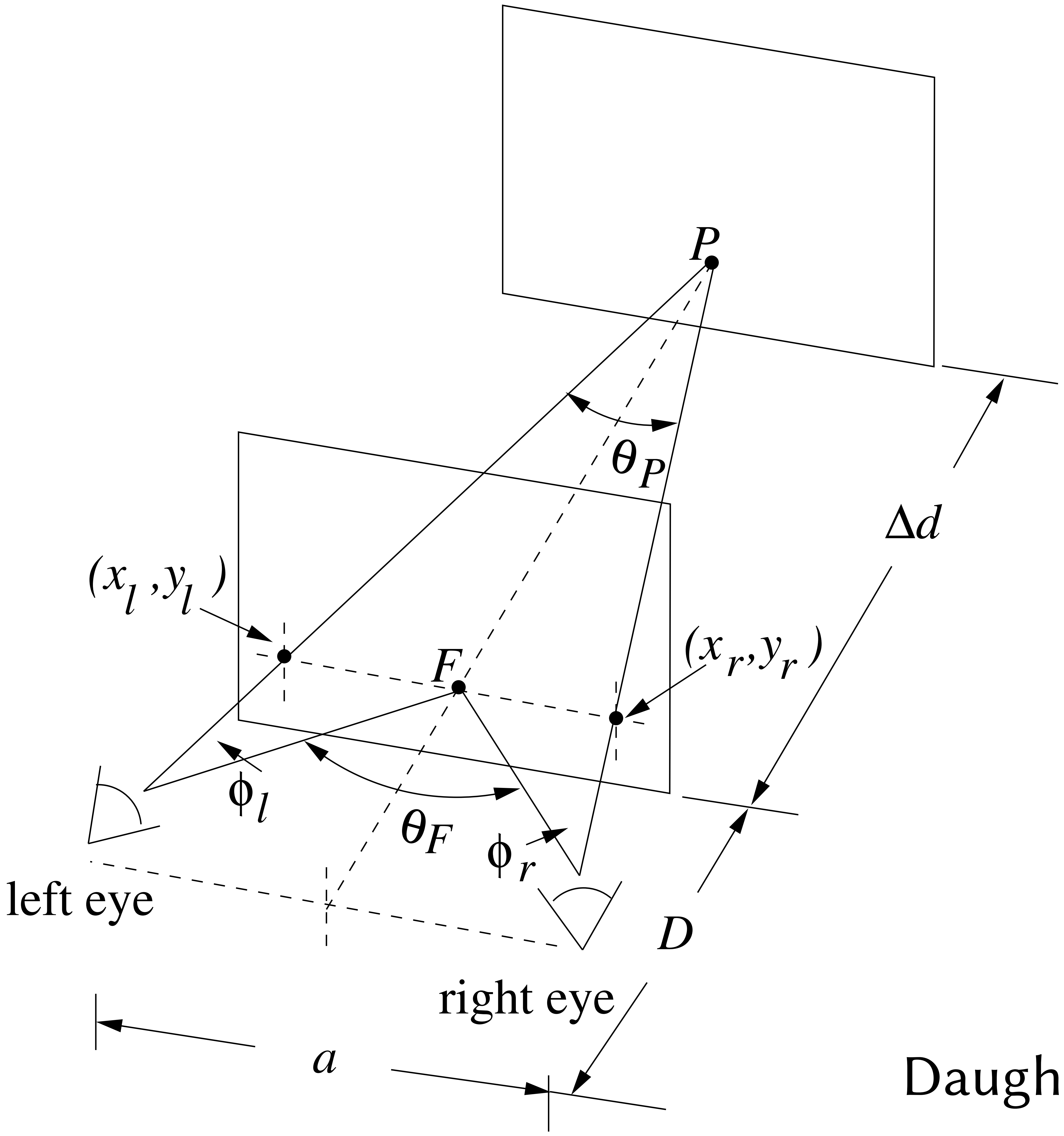
Gaze-contingent DOF



$$\text{CoC} = a \cdot \left|\frac{f}{d_0 - f}\right| \cdot \left|1 - \frac{d_0}{d_p}\right|$$

- Compute DOF following Mantiuk et al. (2011)
  - Circle of Confusion (CoC) determines peripheral blur
  - implement on GPU as per Riguer et al. (2004)
  - substitute depth value (d_0) by gaze depth z

Computing gaze depth

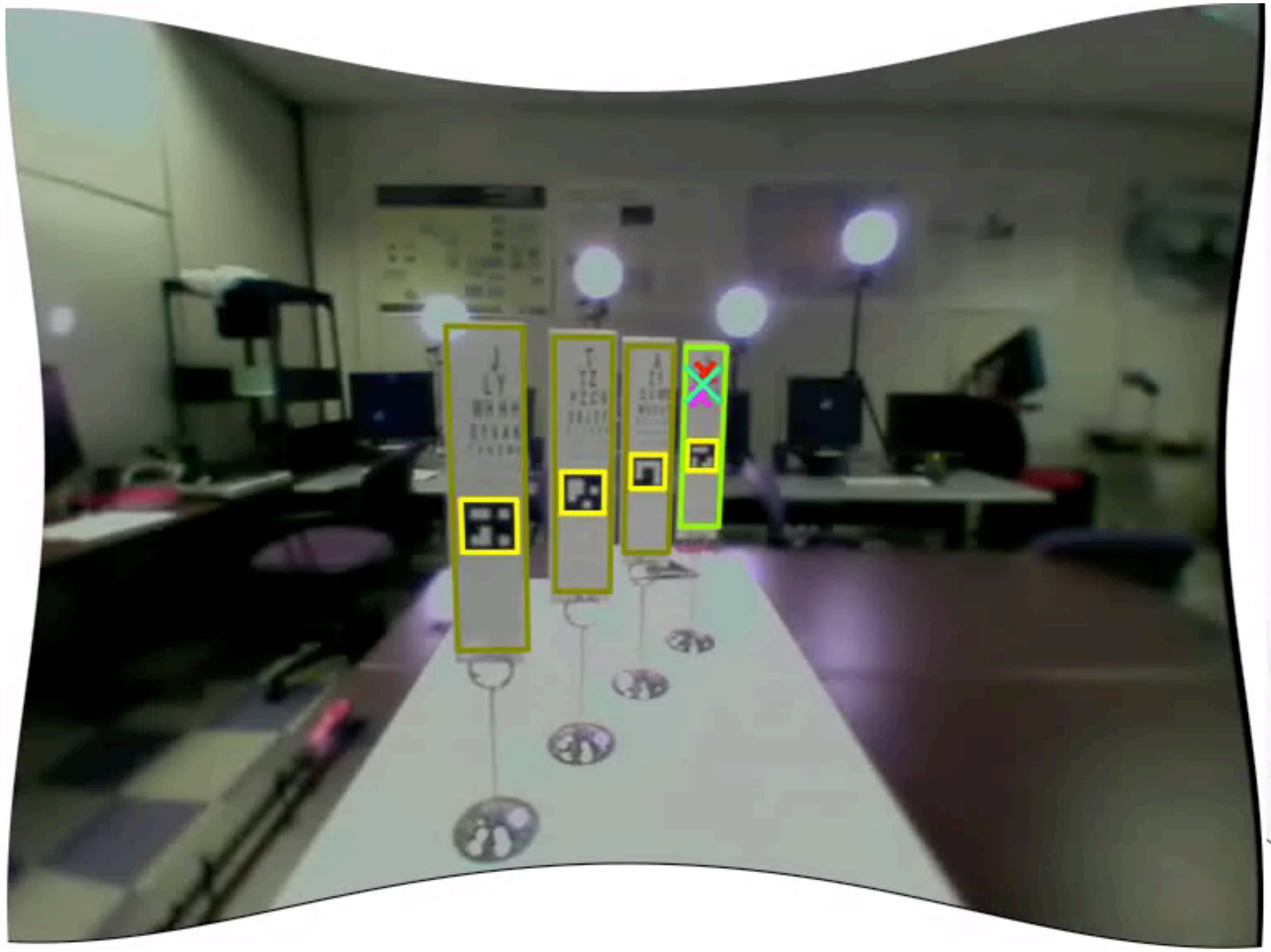


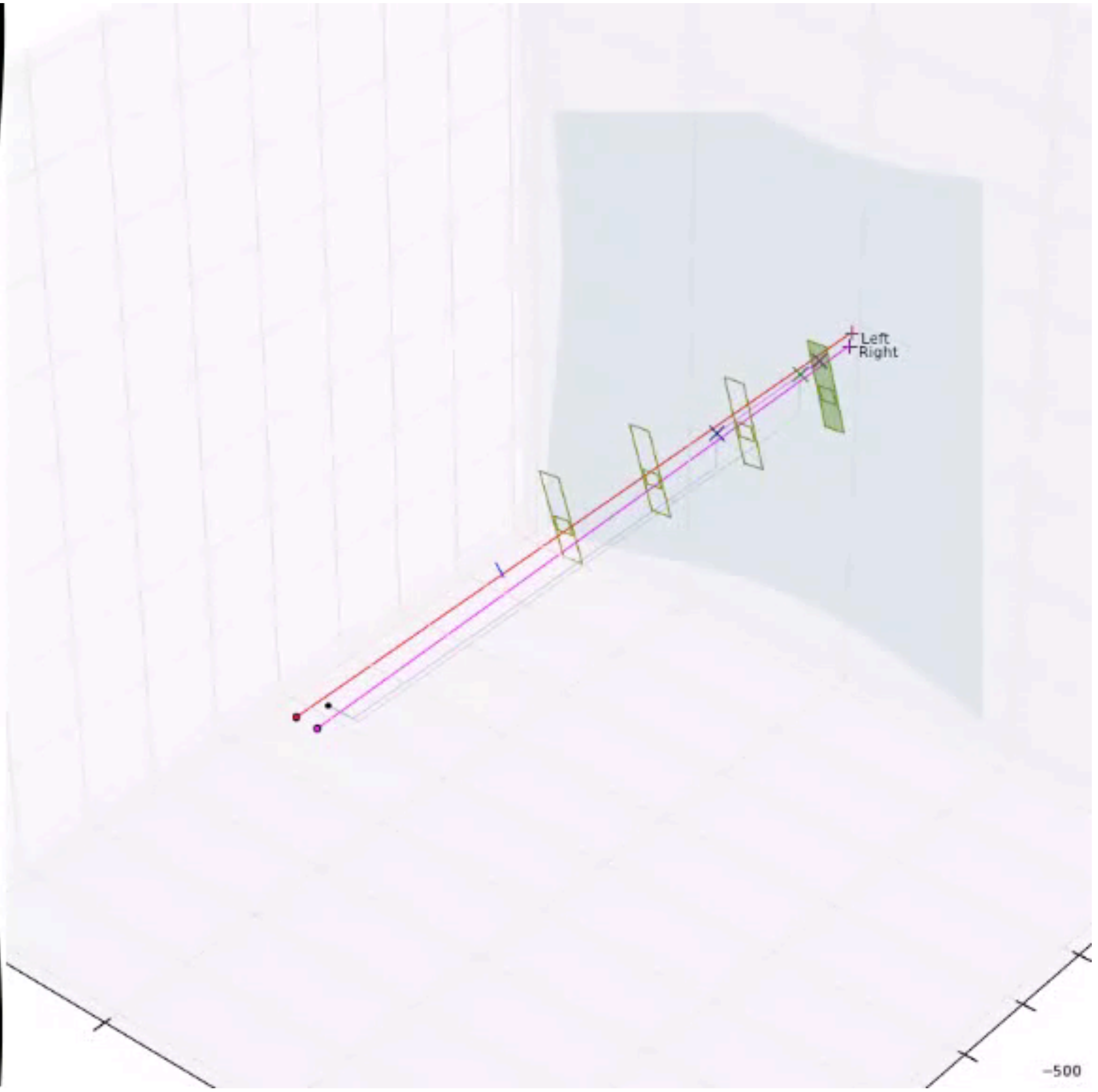
$$\Delta x = x_r - x_l$$

$$z = \frac{\Delta x D}{\Delta x - a}$$

Daugherty et al. (ETRA 2010)

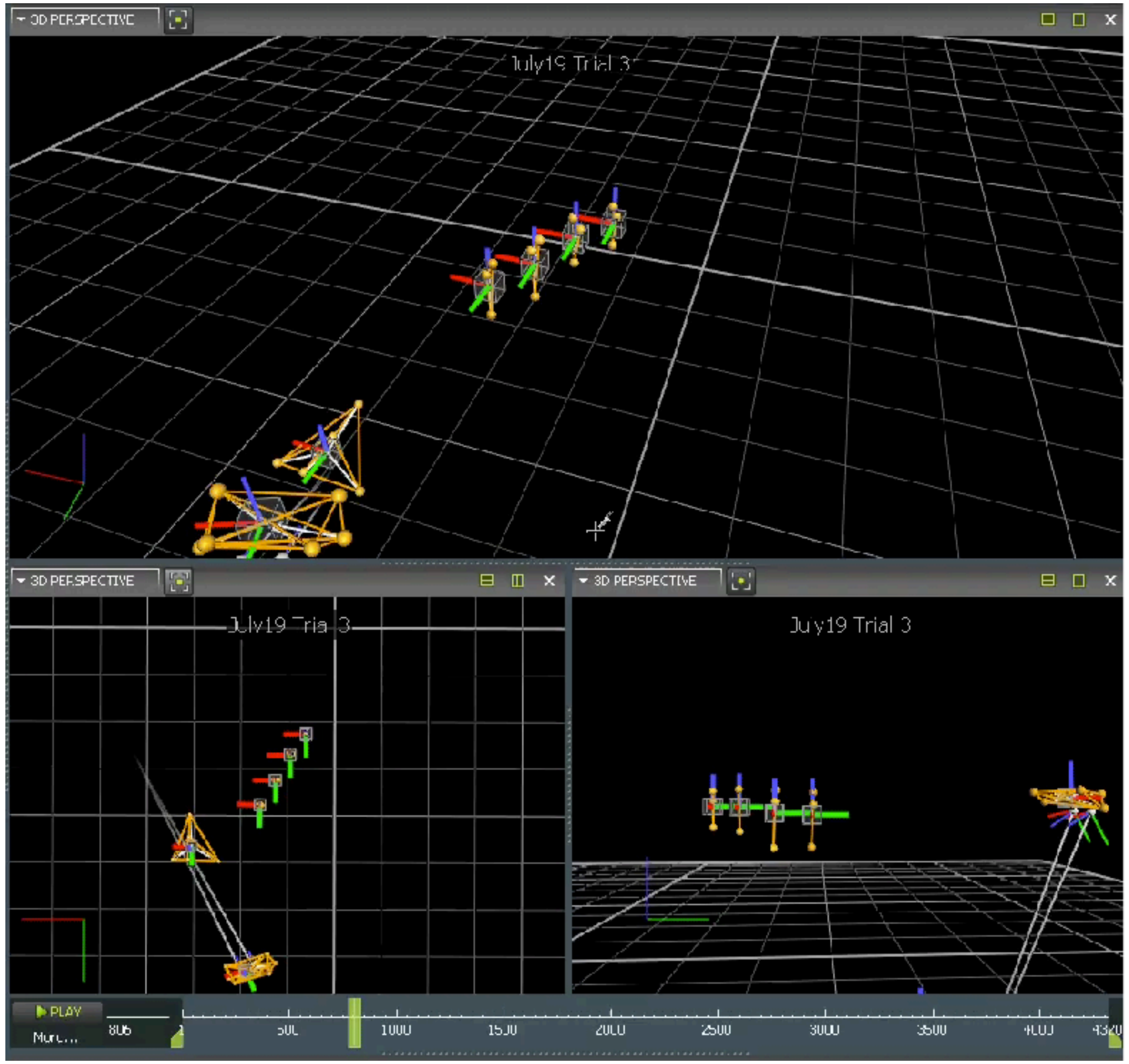
Computing gaze depth





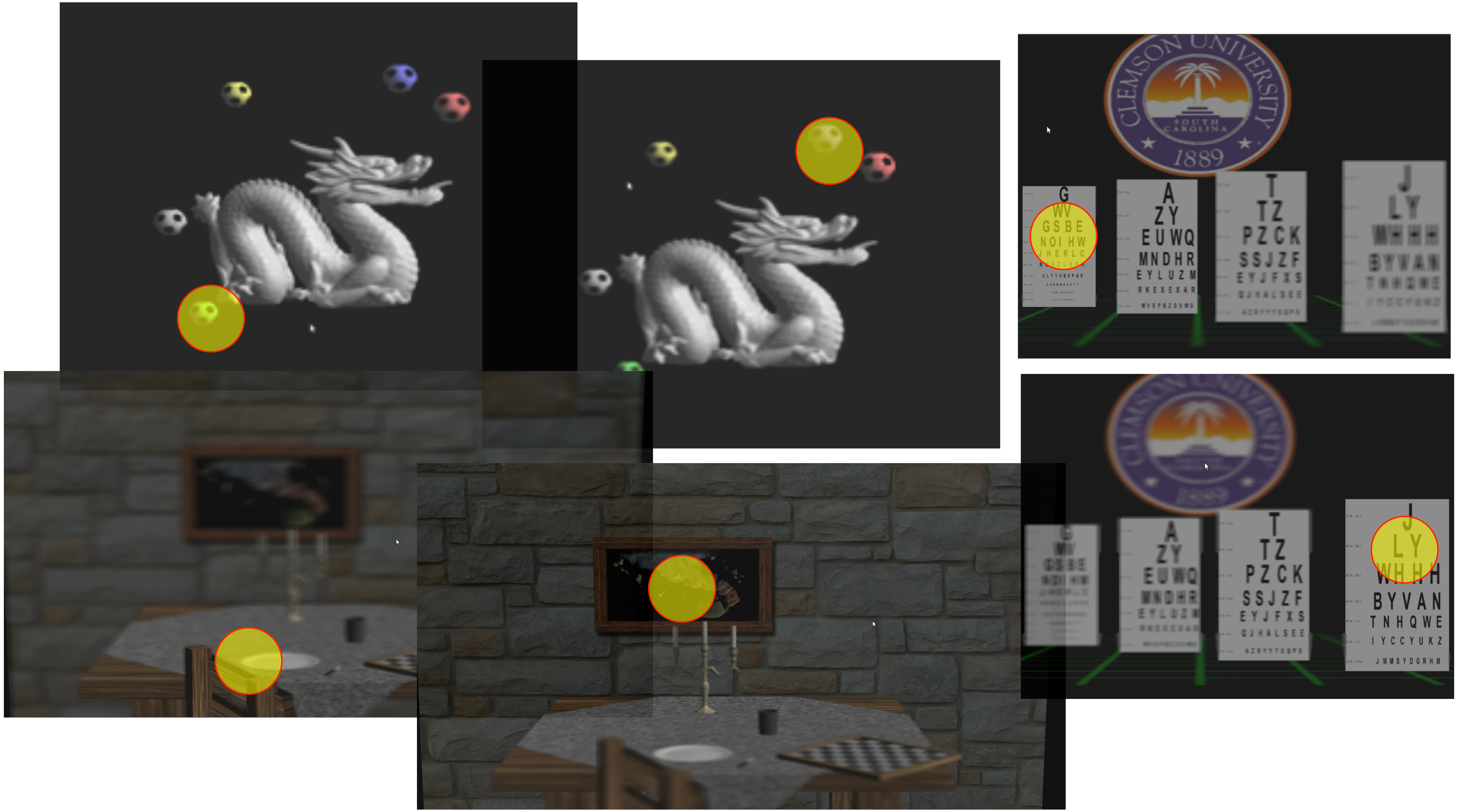
Duchowski et al. (ETRA 2014)

Computing gaze depth

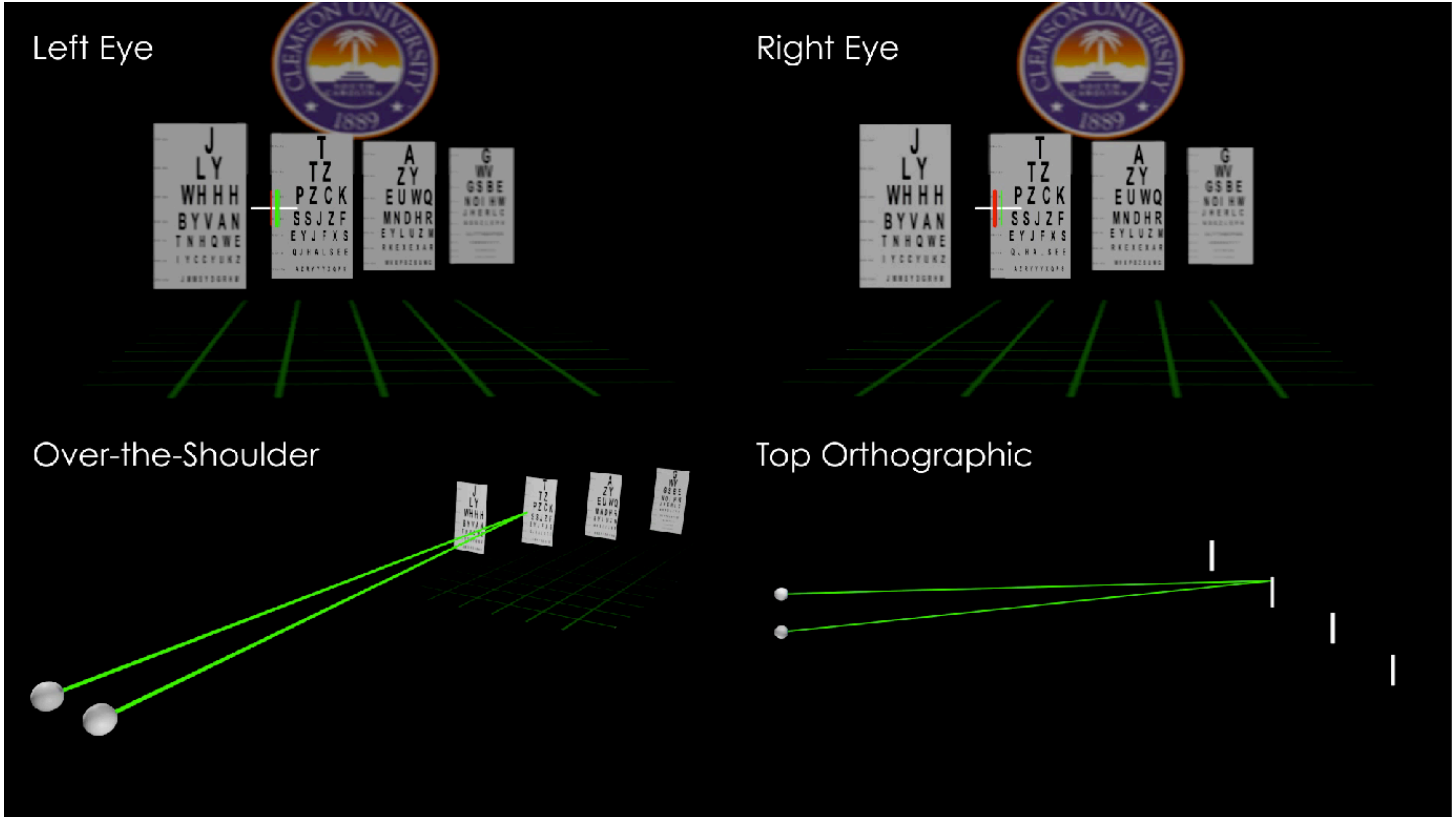


Duchowski et al. (ETRA 2014)

Render for comfort, not speed

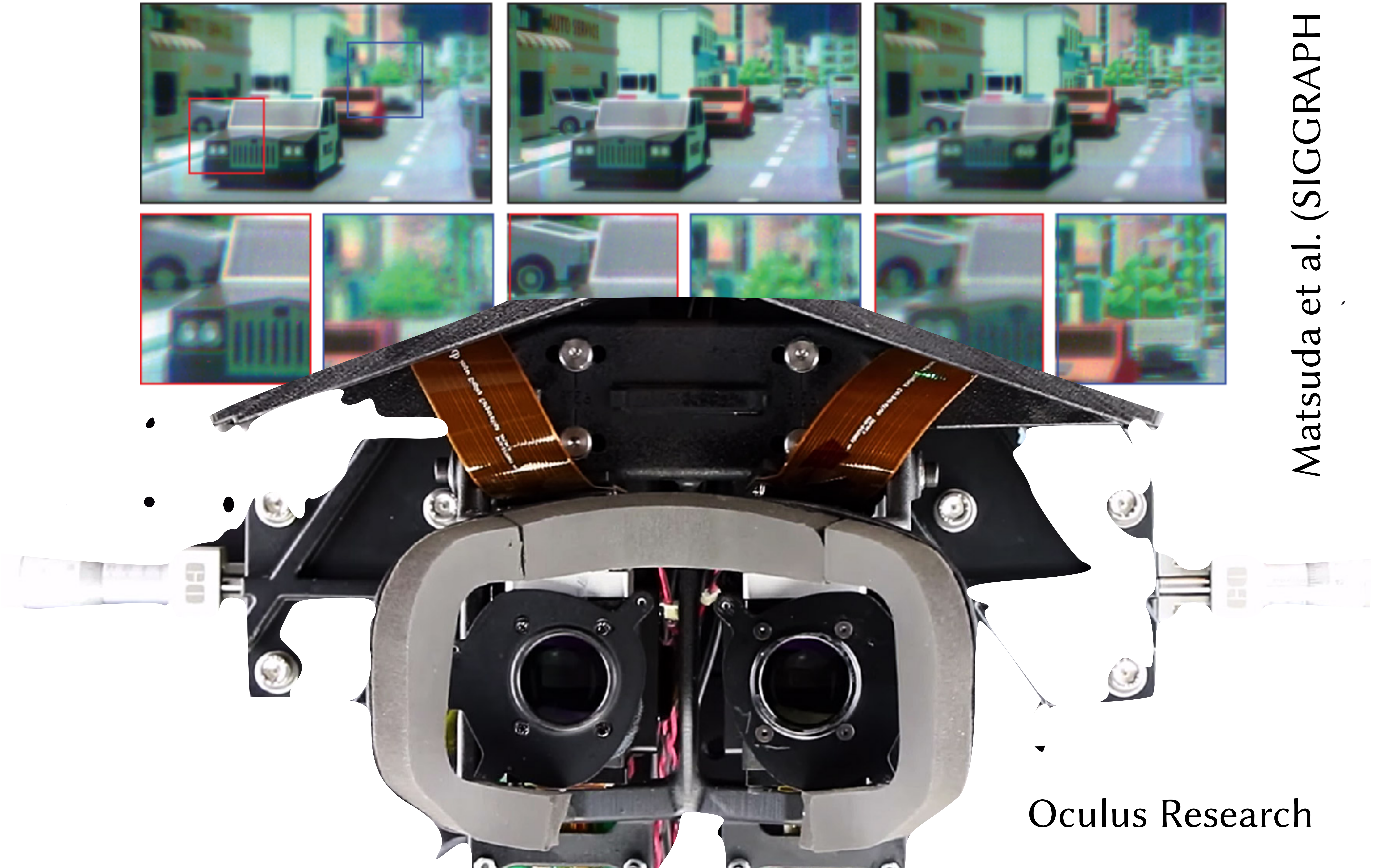


Gaze-contingent DOF



Duchowski et al. (SAP 2014)

Focal surface displays



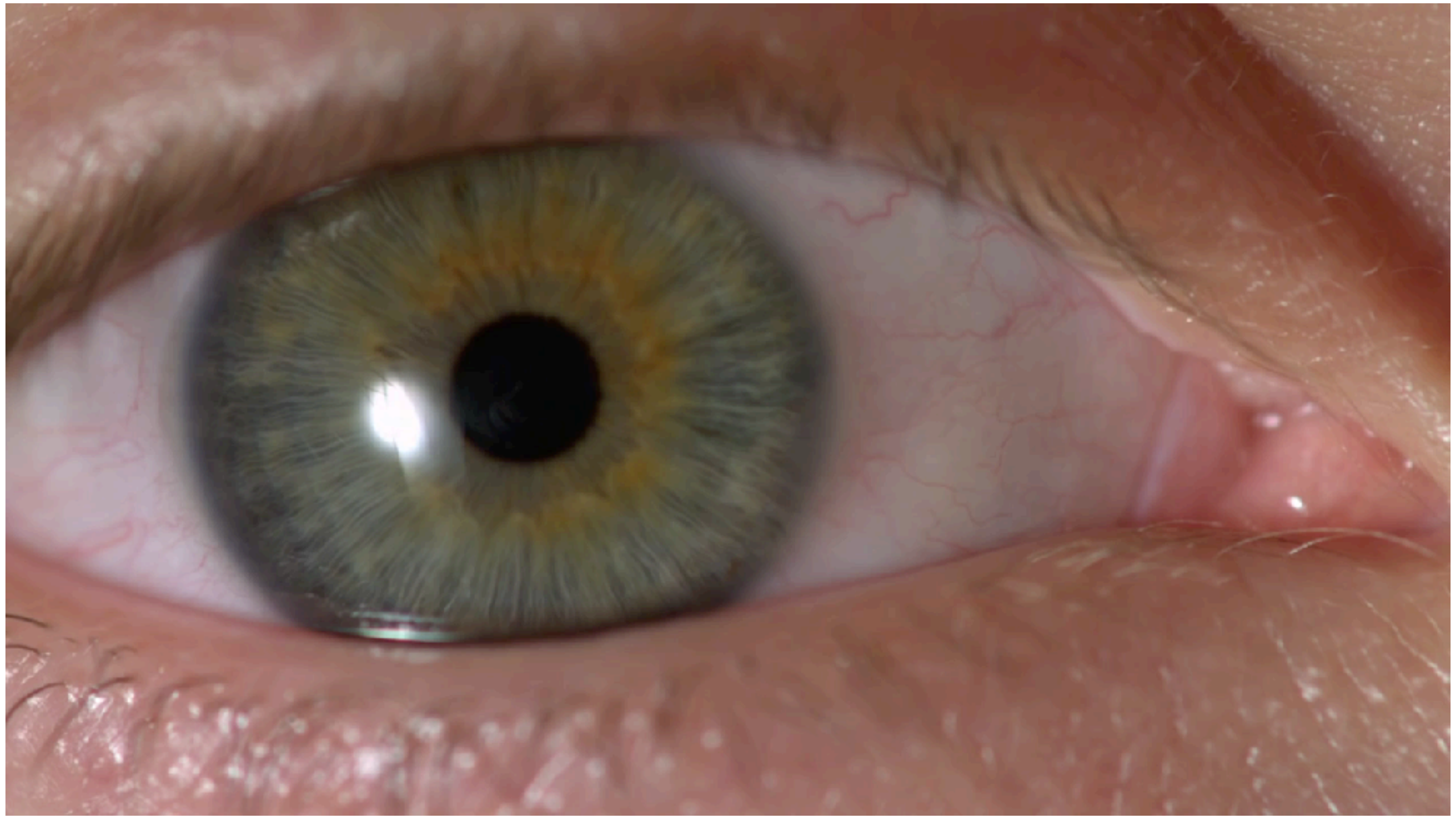
Matsuda et al. (SIGGRAPH 2017)

Oculus Research

Focal surface displays

SIGGRAPH 2018

Summary: Passive gaze

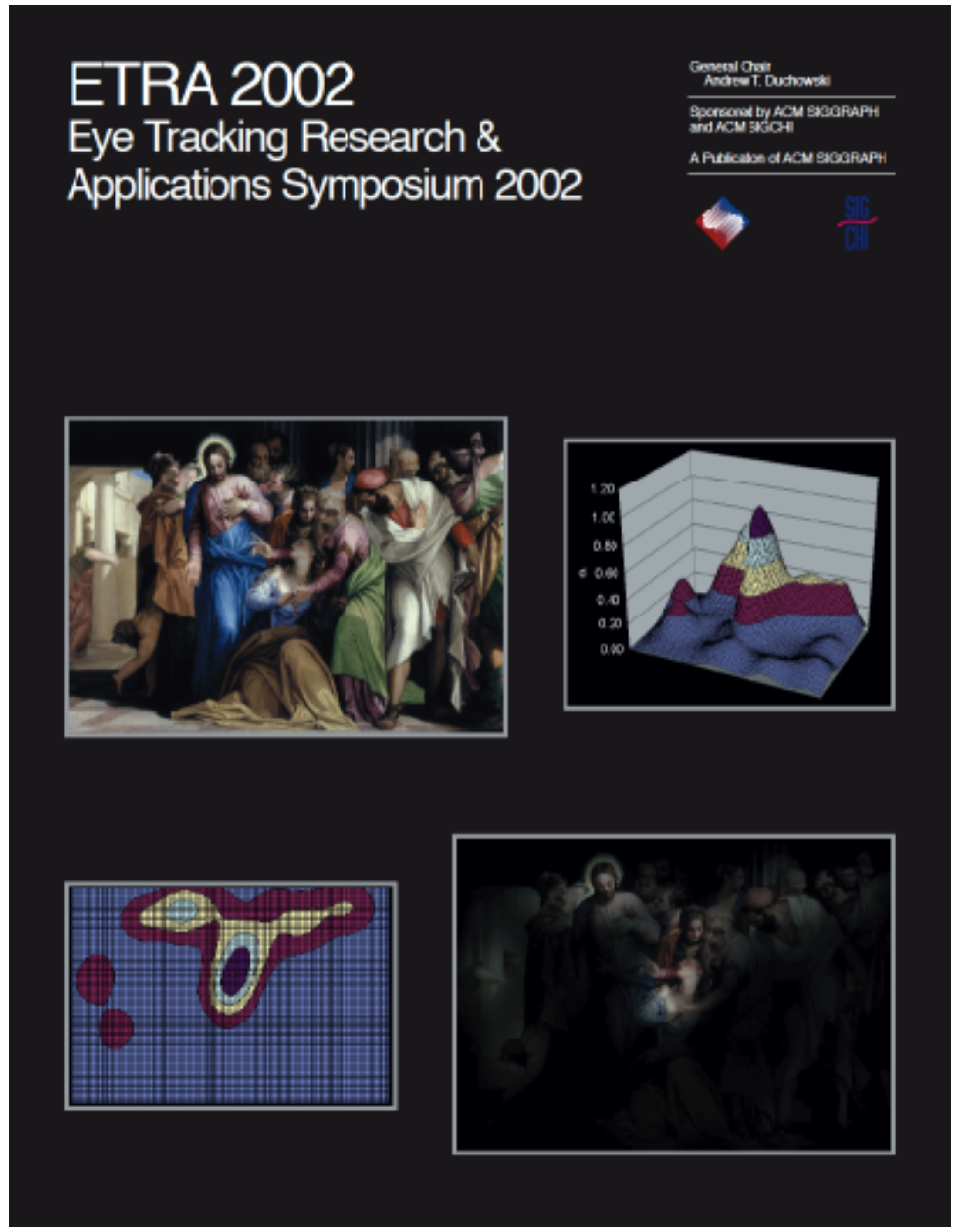


The Slow Mo Guys: shot with Phantom Flex @ 1000 fps

- Outstanding problems:
  - eye is not rigid (like a bag of jello)
  - need lots of IR illuminators (in VR, according to Oculus)
  - latency, latency, latency (e.g., saccade prediction)

For more information...

- Various sources, incl. proceedings
  - SIGGRAPH, ETRA, ETVIS, etc.



For more information...

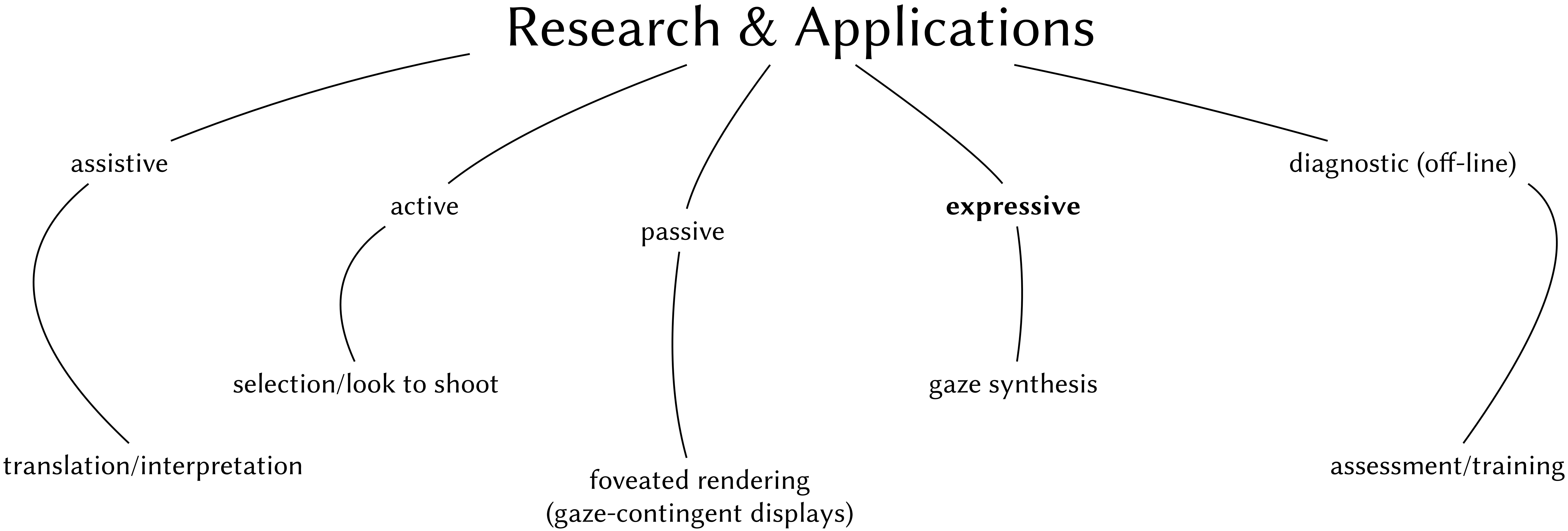
- Michael Abrash's blog is also a good read


VR's Grand Challenge: Michael Abrash on the Future of Human Interaction

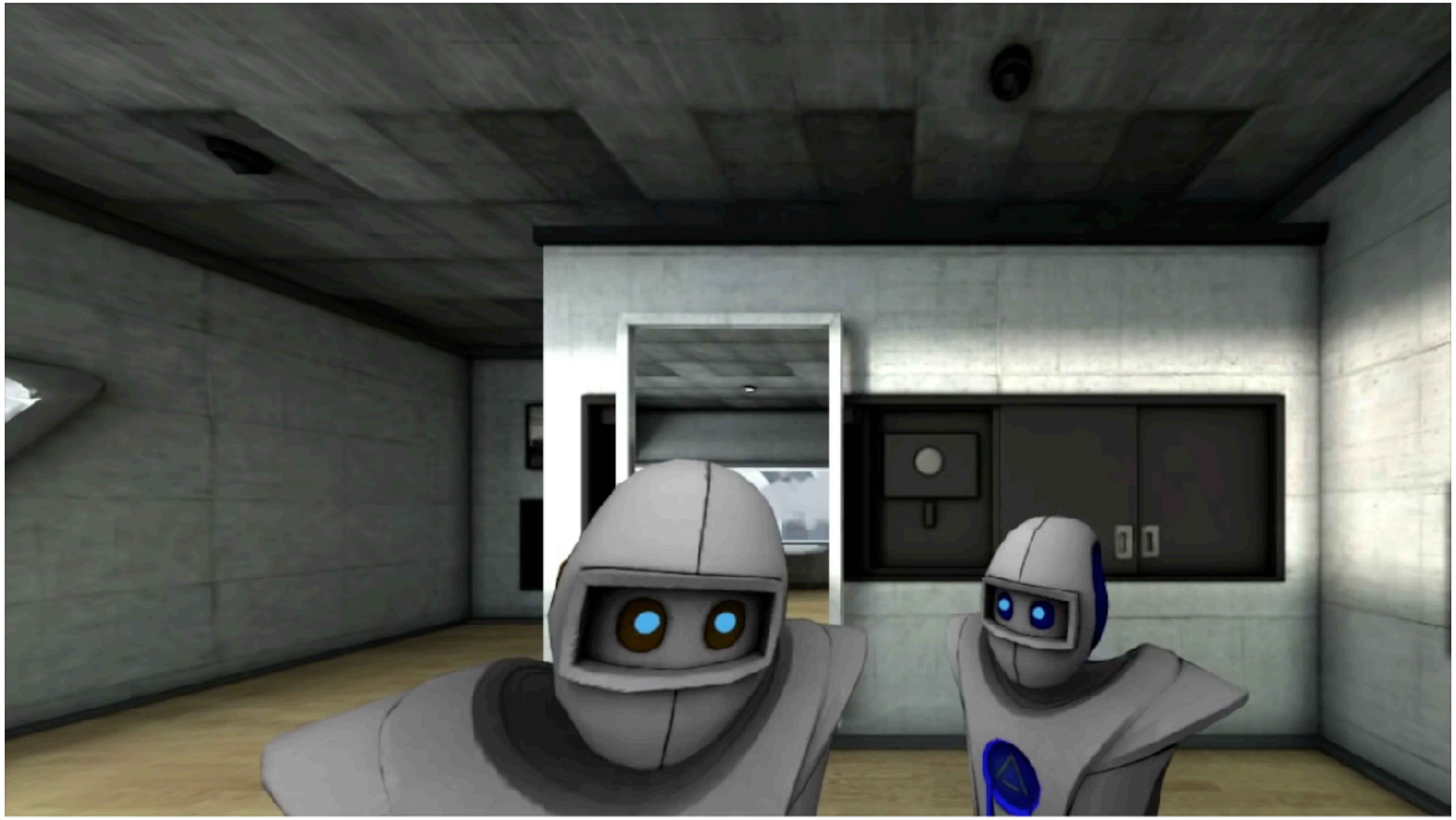
Oculus Blog | Posted by Michael Abrash | July 24, 2017 | Share

https://www.oculus.com/blog/vrs-grand-challenge-michael-abrash-on-the-future-of-human-interaction/

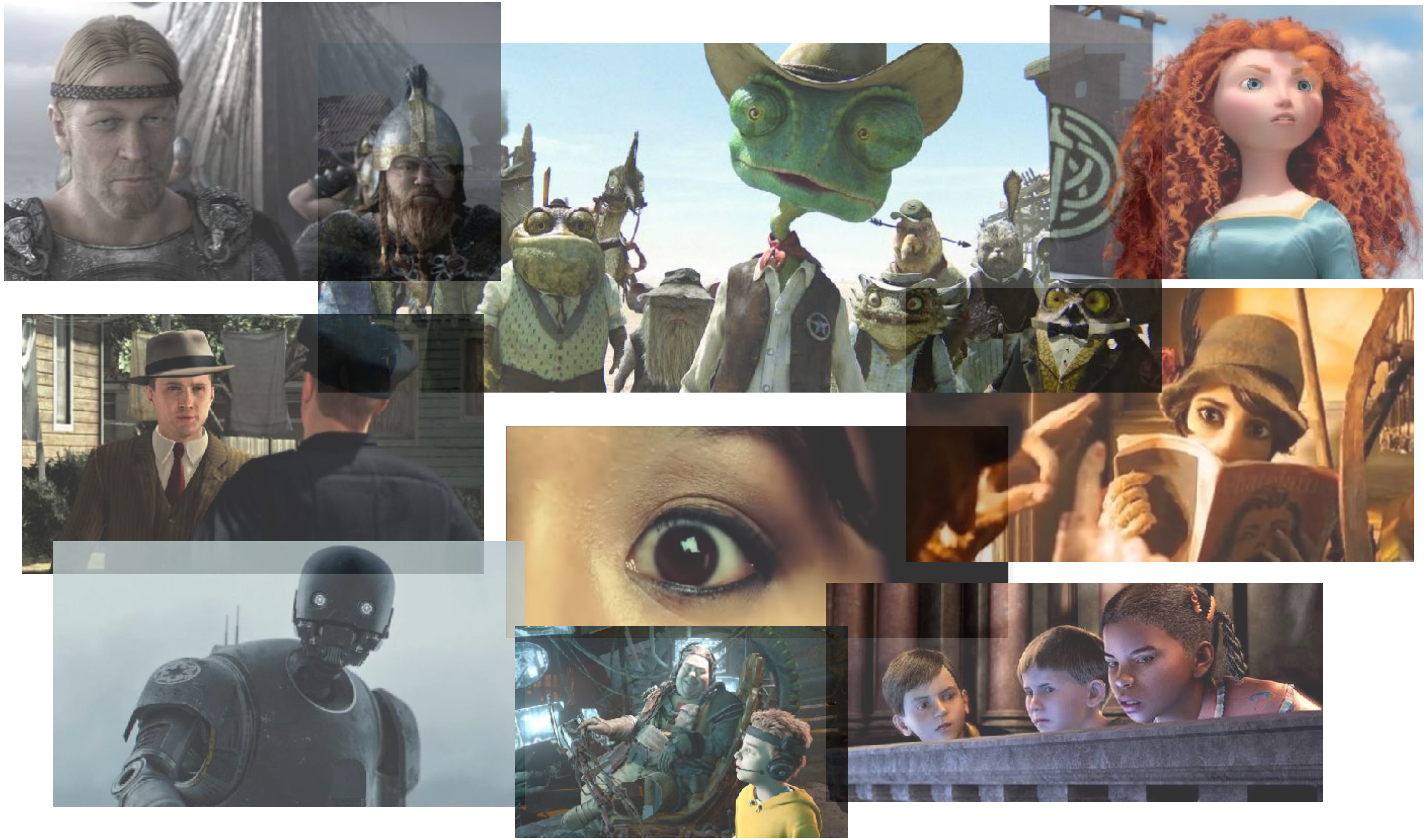
Eye Tracking



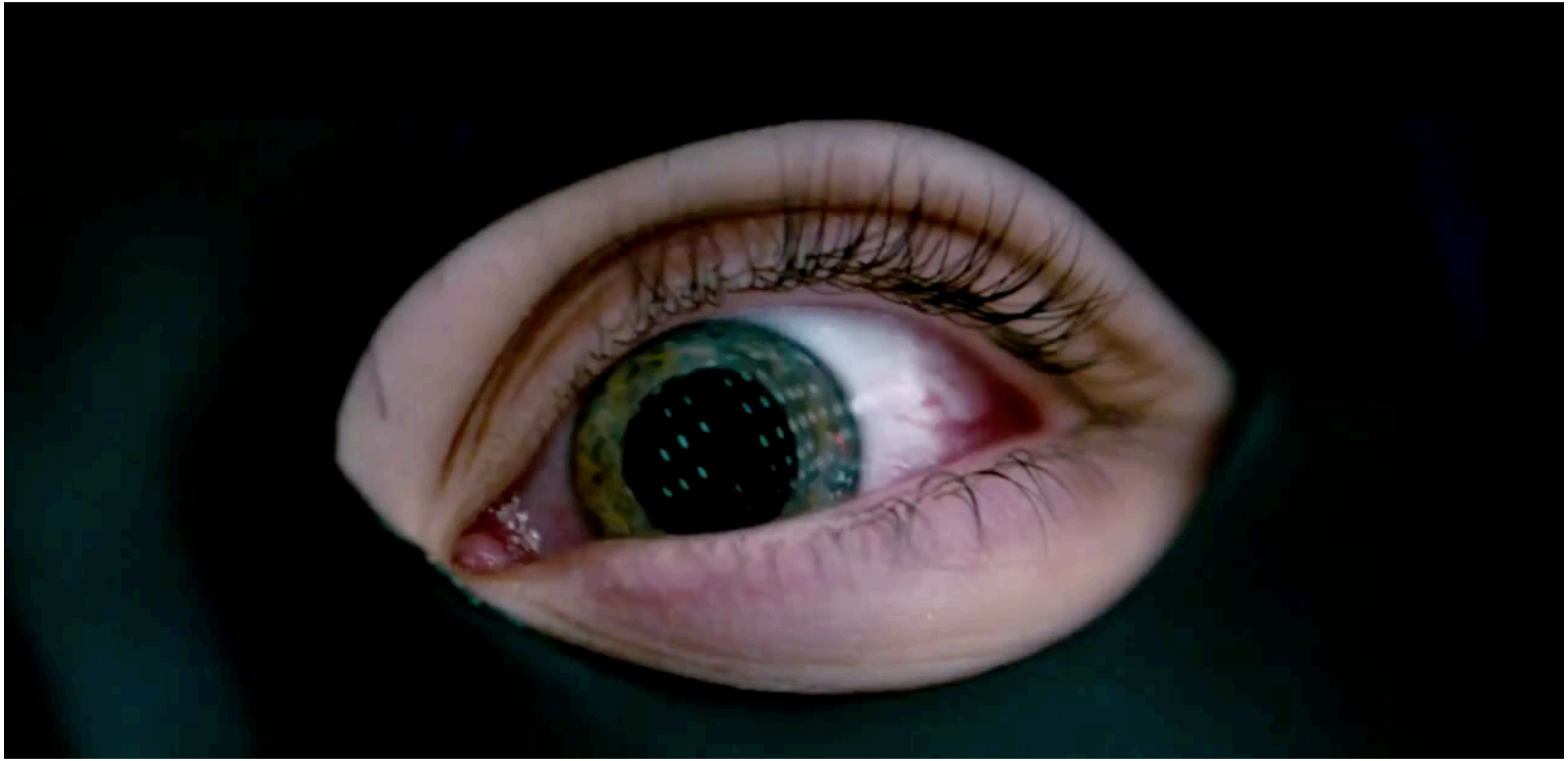
Eye motion in VR



Motivation

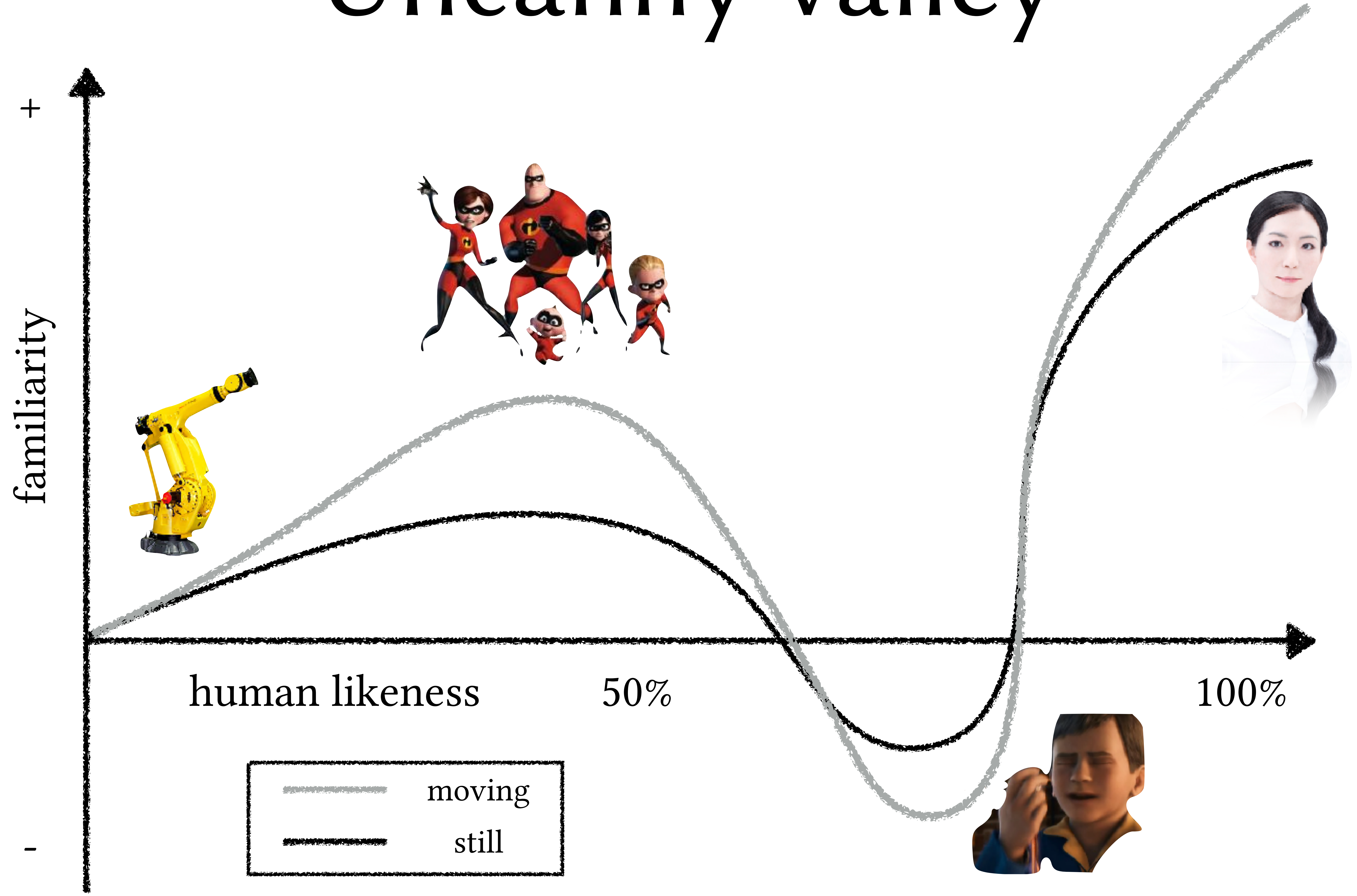


Motivation



Jeff Wadlow's *Kick-Ass 2* (2013) © Universal

Uncanny valley



Motion in games

- Team Bondi's *L.A. Noire* Non-Player Characters:
  - eye motions are key to player deciding if NPC is lying

Gaze and trust

- Gaze affects perceived trust (Normoyle et al., 2013)

Bidirectional gaze simulation

- Stochastic model promotes gaze coordination (Andrist, 2017)

Avatar realism

- Garau et al. (2003)
  - found strong interaction between character realism and gaze
  - a more realistic character requires more elaborate gaze

Self-avatar realism

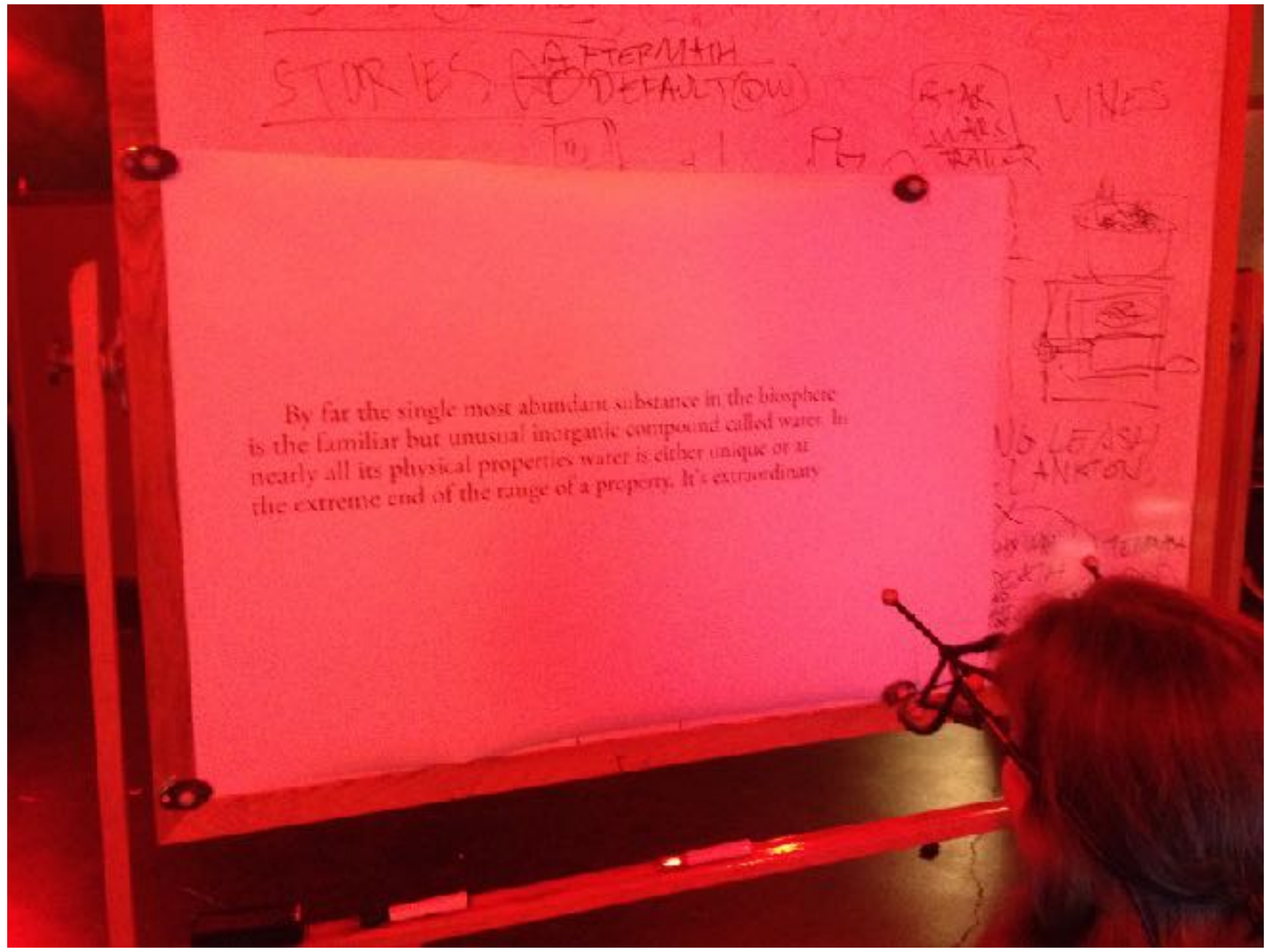
- Borland et al. (2013)
  - avatar’s rotating eyes promoted eye contact vs. fixed gaze
  - increases self-identification with the avatar

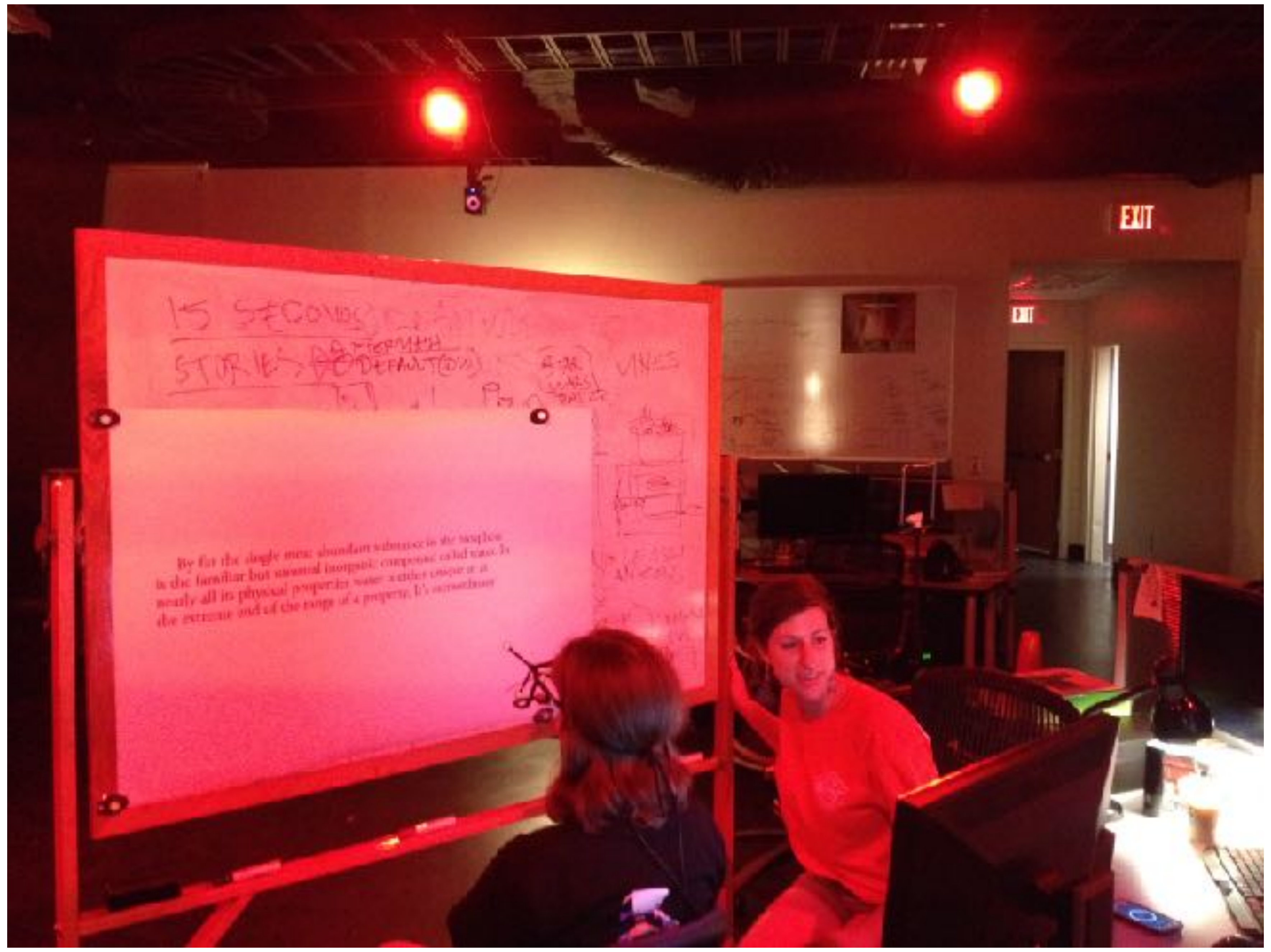
All you need is an eye tracker

* Note: I still don't get paid by Tobii

All you need is an eye tracker

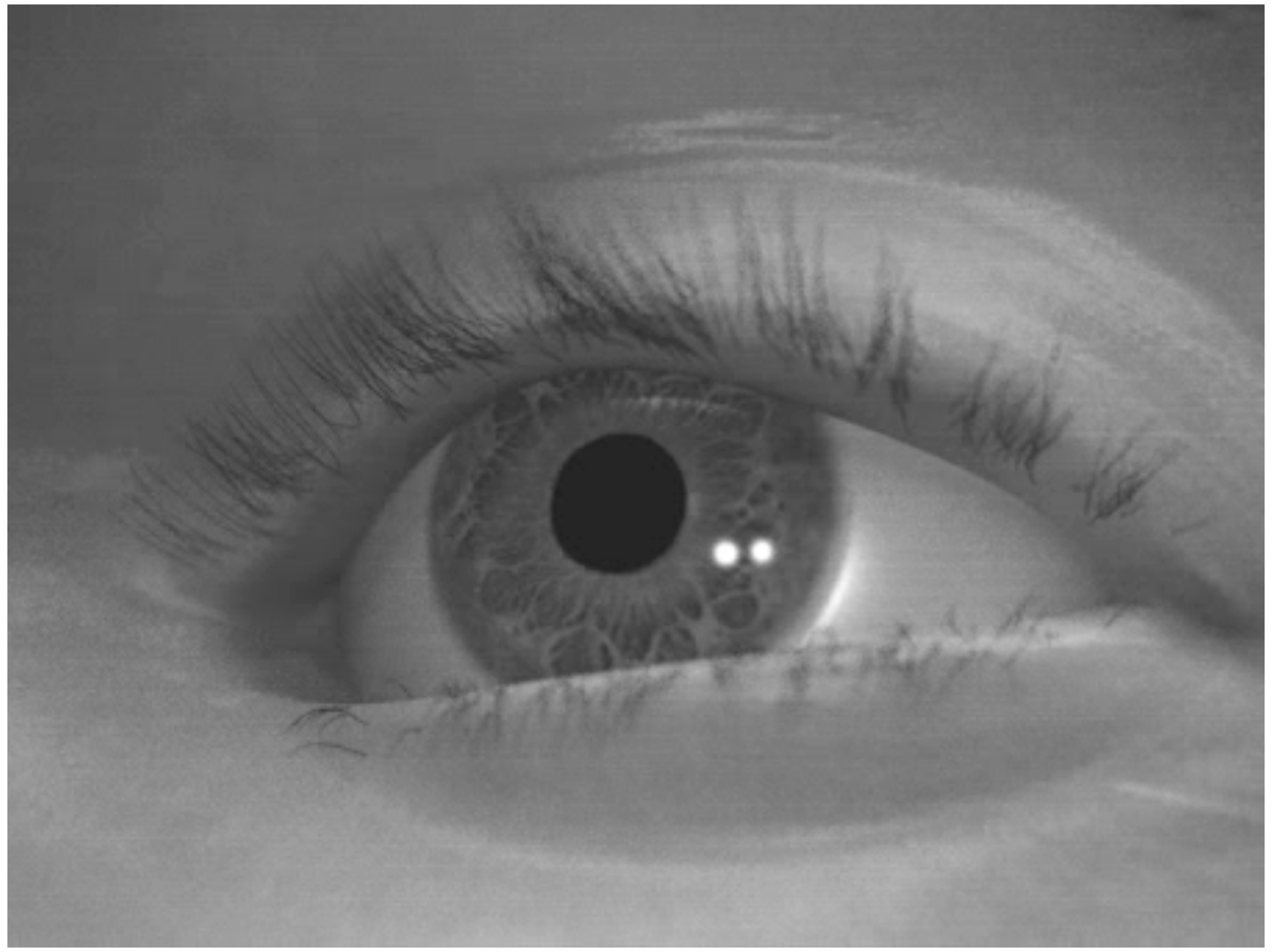
- Not always easy to use, noisy
- They don't always provide reference video
  - hence signal attenuation vs. reference not always possible



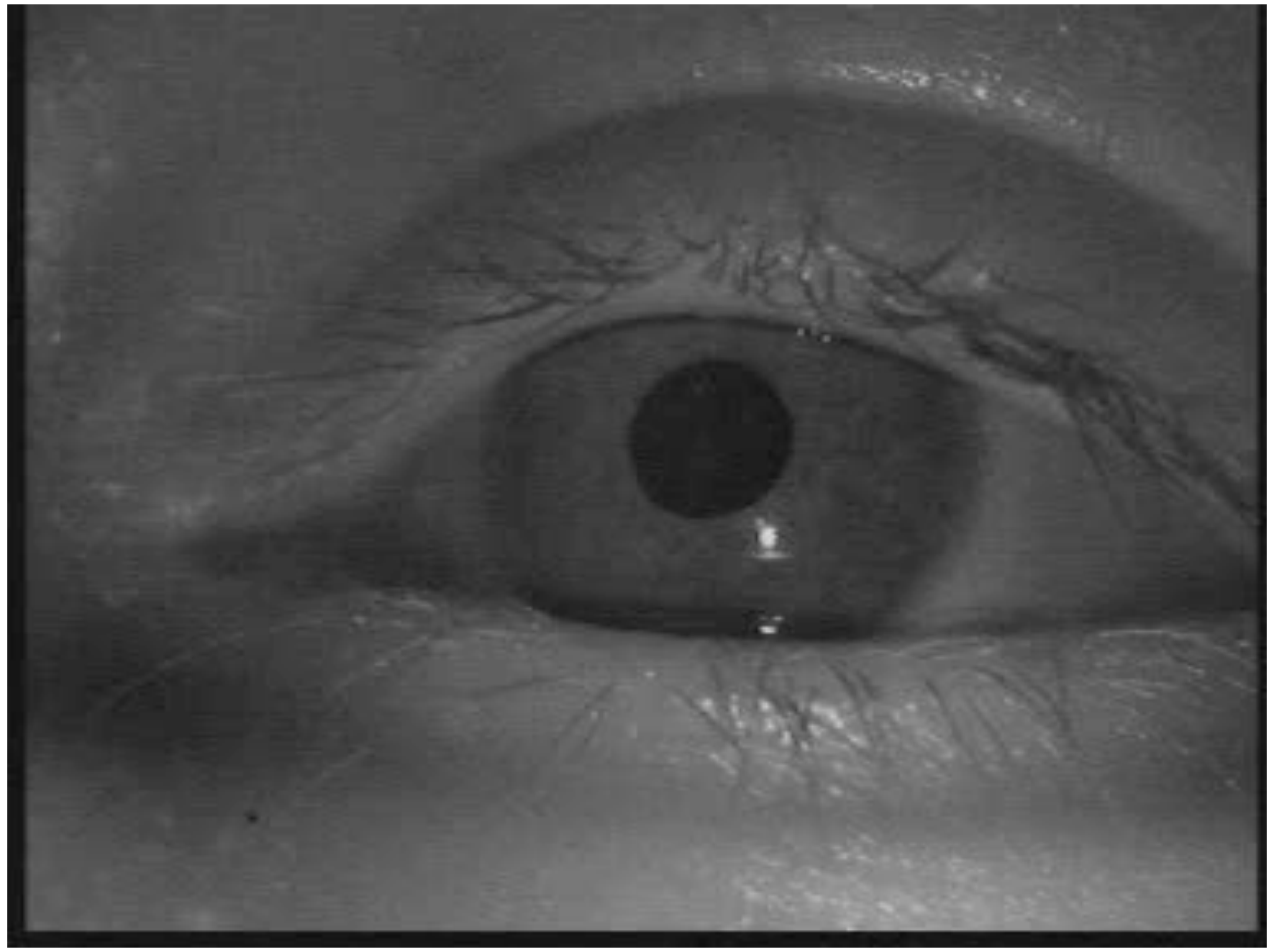


Motion capture

- Automatic generation of realistic eye motion
- Why not just use real data?
  - humans or eye trackers not always available



cleaned data



eye tracker camera

Synthesizing eye movements

- Lee et al.'s (2002) *Eyes Alive*
  - top-down approach modeling the saccadic ***main sequence***

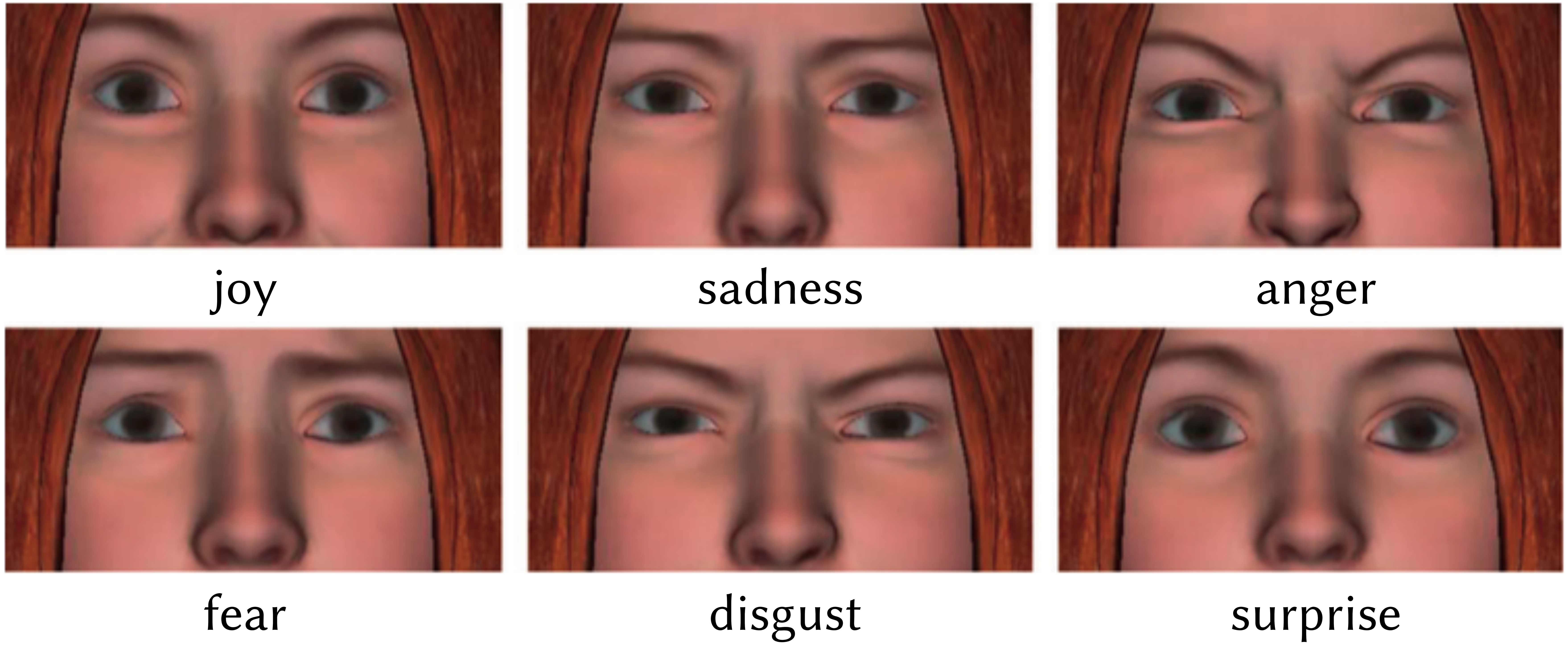
$$\Delta t = 2.2\theta + 21$$

- We approach simulation bottom-up
  - start with a signal processing perspective

Coupling eye & head movements

- Yeo et al.'s (2012) Eyecatch
  - saccades, smooth pursuits
  - head coupling
  - no microsaccades

Emotional expressivity



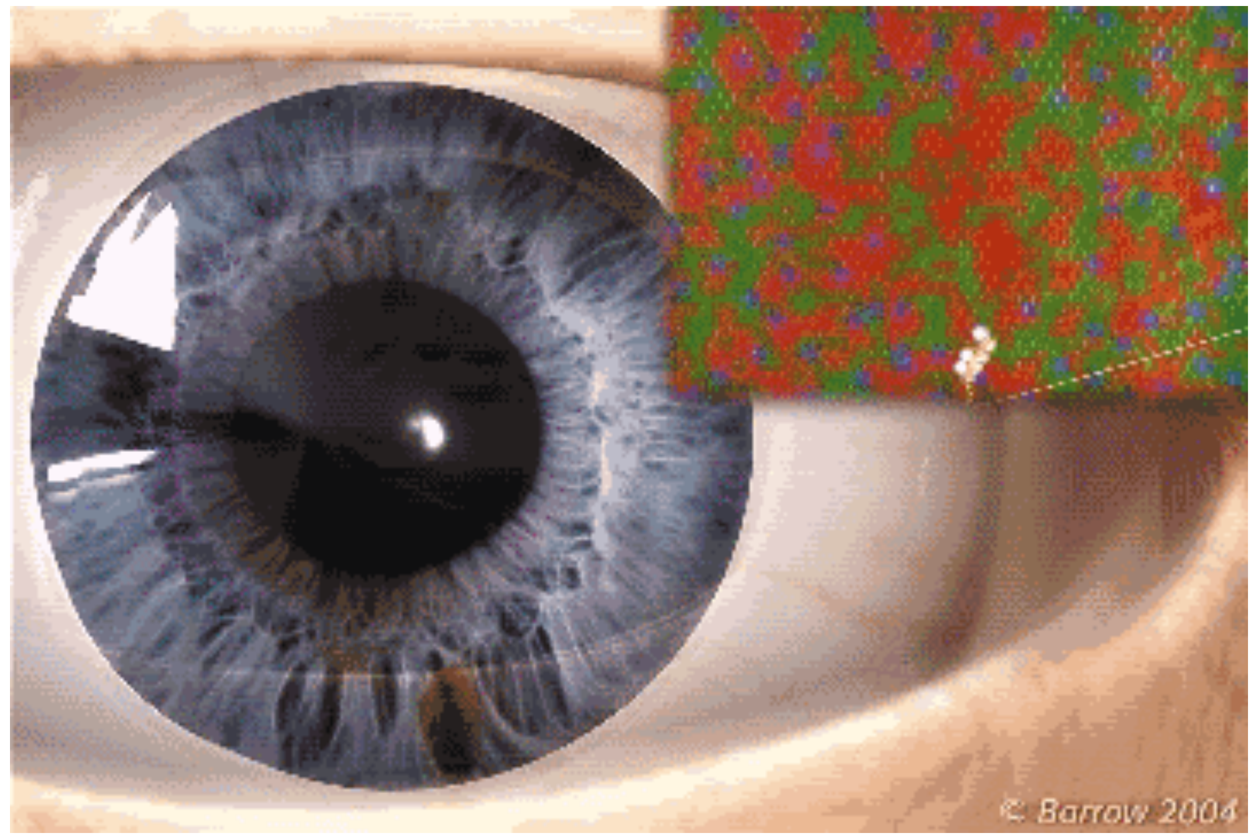
- Li and Mao (2012):
  - saccades, blink rate, pupil diameter
  - matching Facial Action Coding System and Geneva Emotion Wheel

Probabilistic eye movements

- Lance and Marsella (2008)
  - combined eye movements with head rotations
  - "Any **jitter**...destroys communication and believability"
    - (quoting Disney animators Thomas and Johnston)

How about microsaccadic jitter?

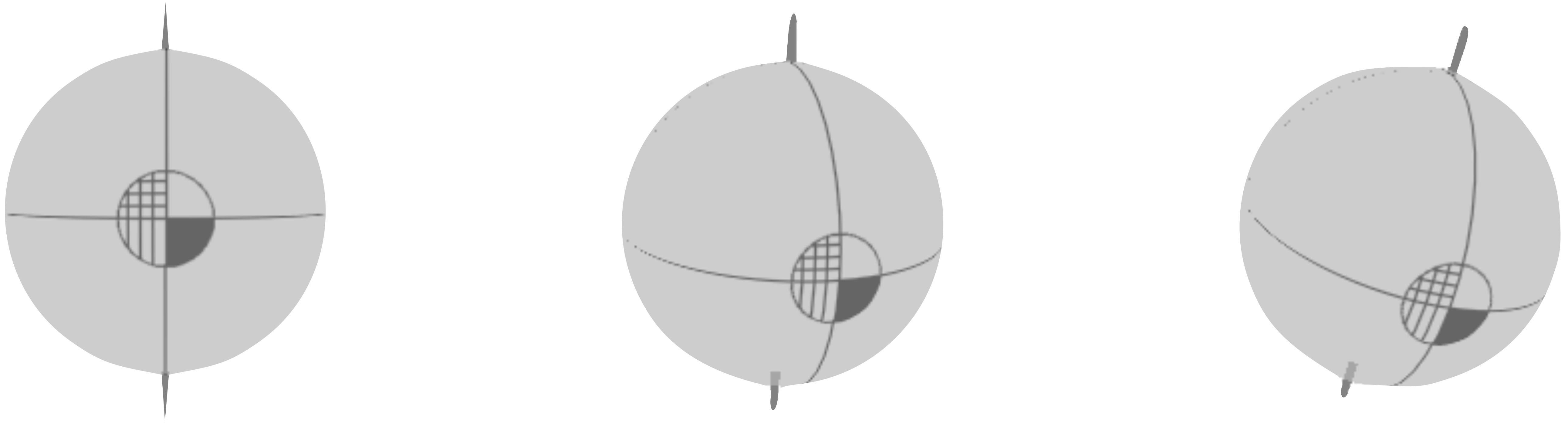
- When we look at something:
  - our eyes are never perfectly still



from Martinez-Conde Laboratory

- When others look at us:
  - perceptual system is sensitive to and amplifies small fluctuations

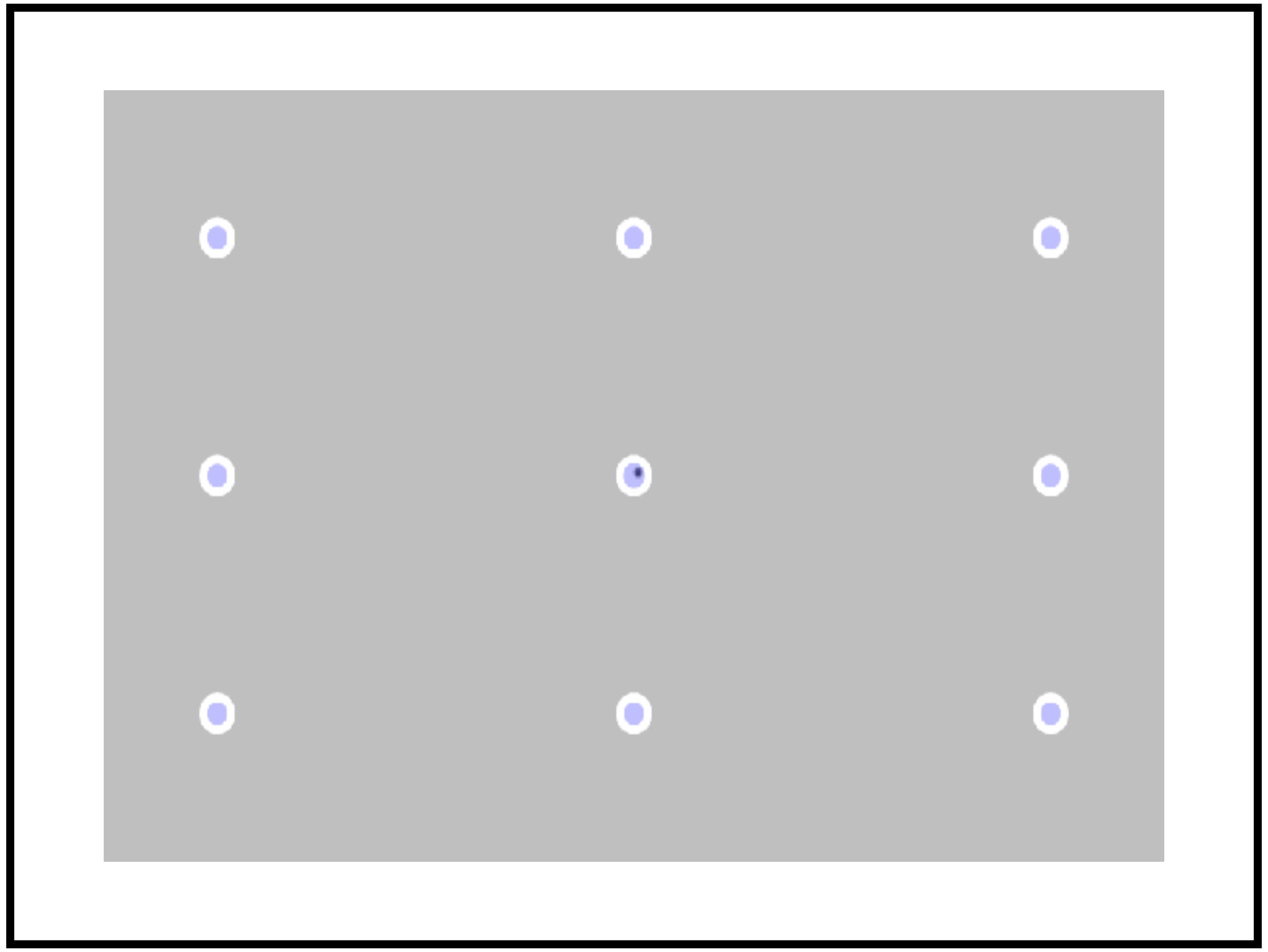
Eye movement simulation



Duchowski and Jörg (2015)

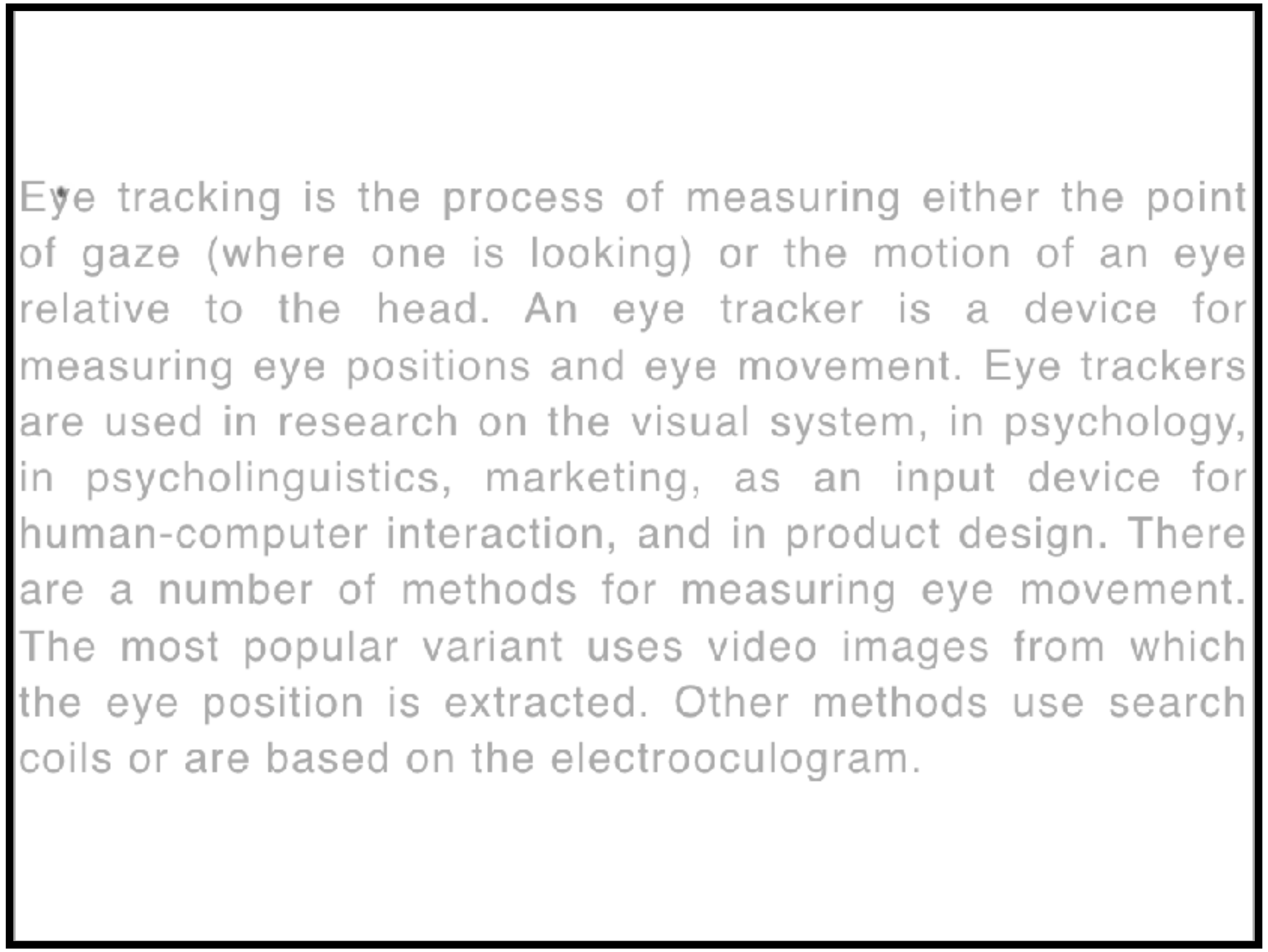
- Not modeling musculature or gimbaled movement
  - sophisticated models of extraocular muscles do exist
- Sufficient to model look point

Look point simulation

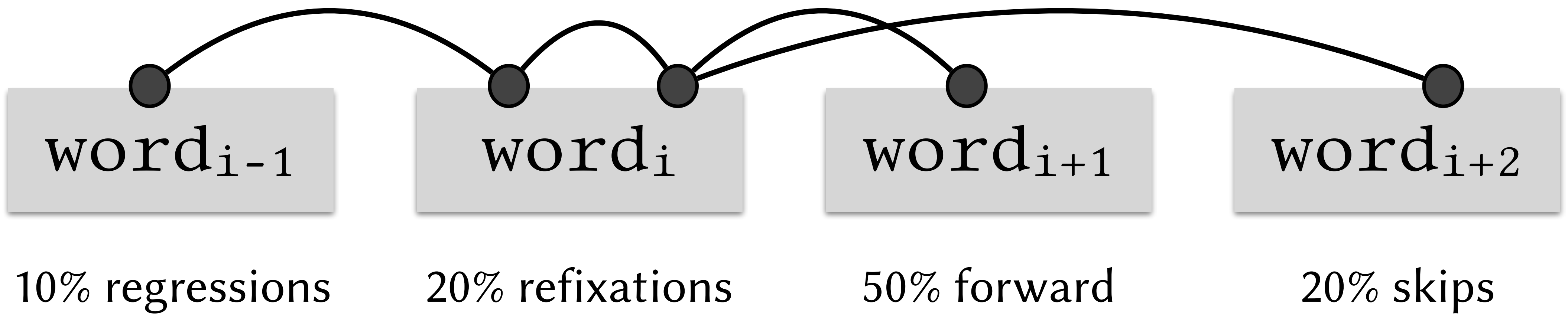


* Note: no GPU required!

Look point simulation



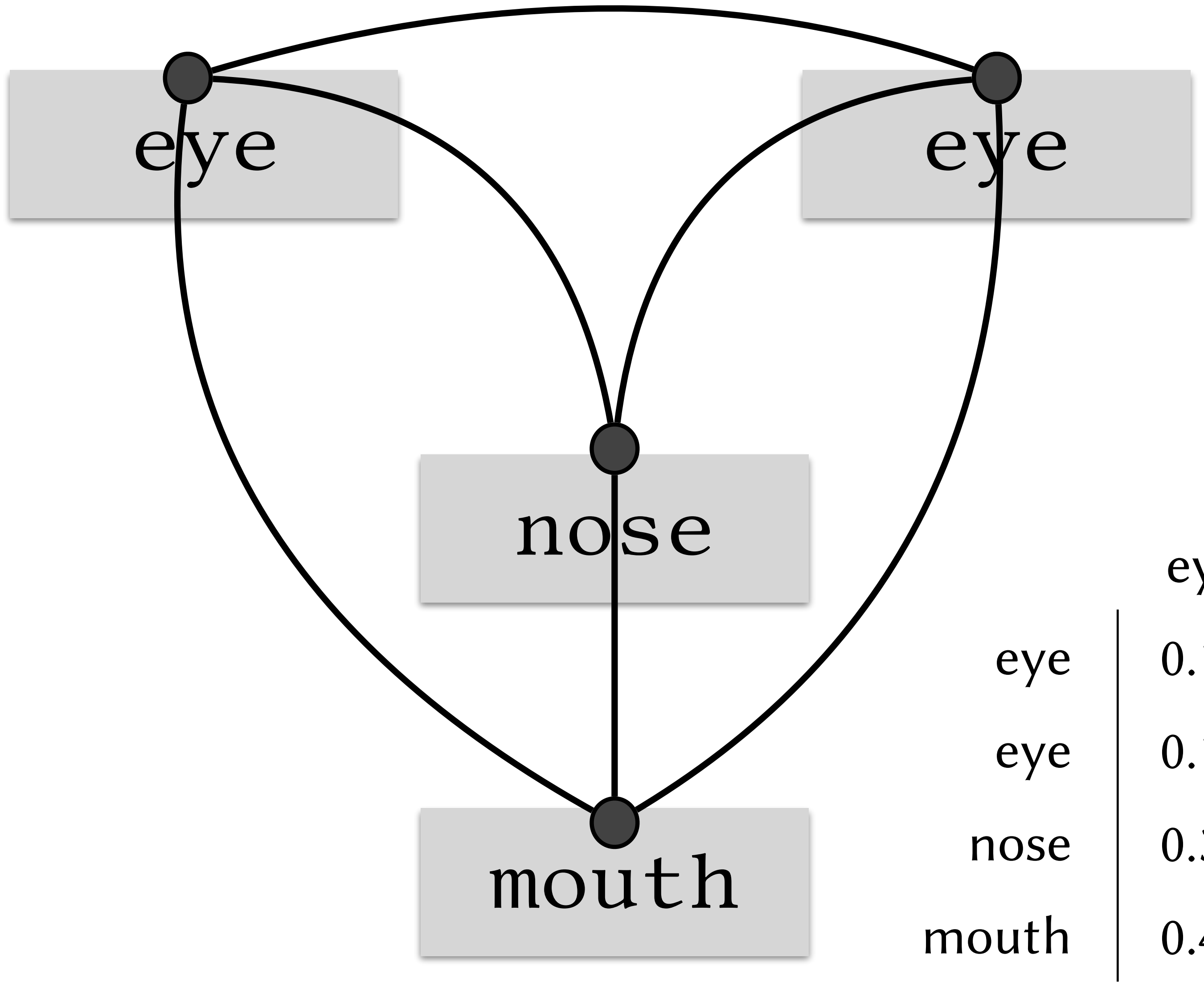
Eye tracking is the process of measuring either the point of gaze (where one is looking) or the motion of an eye relative to the head. An eye tracker is a device for measuring eye positions and eye movement. Eye trackers are used in research on the visual system, in psychology, in psycholinguistics, marketing, as an input device for human-computer interaction, and in product design. There are a number of methods for measuring eye movement. The most popular variant uses video images from which the eye position is extracted. Other methods use search coils or are based on the electrooculogram.



Rayner (1998)

* Note: no GPU required!

Look point simulation



	eye	eye	nose	mouth
eye	0.15	0.15	0.15	0.15
eye	0.15	0.15	0.15	0.15
nose	0.30	0.30	0.30	0.30
mouth	0.40	0.40	0.40	0.40

Normoyle et al. (2013)

* Note: no GPU required!

Stochastic modeling

- Saccade duration via main sequence:

$$\Delta t = 2.2\mathcal{N}(\theta, \sigma = 10^\circ) + 21 + \mathcal{N}(0, 0.01)$$

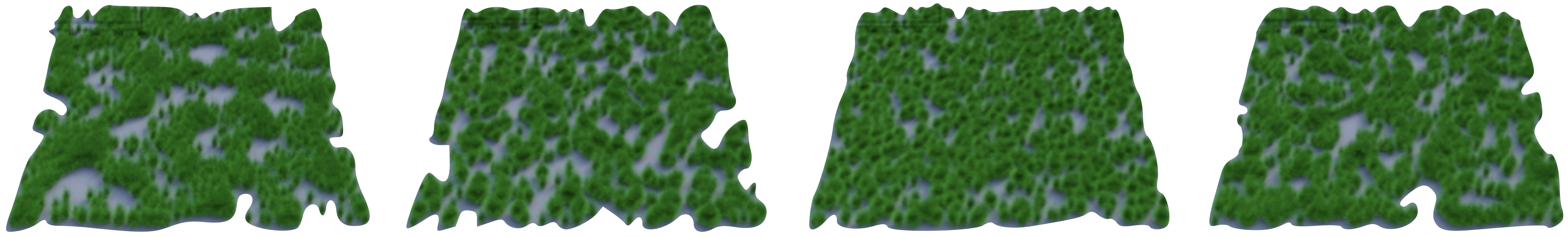
- Fixation duration (ms): $\mathcal{N}(250, 50)$ or data-driven
- Microsaccadic jitter at fixation:

$$\mathbf{p}_{t+h} = \mathbf{p}_t + \mathcal{P}(\alpha, \omega_0)$$

  - where $\mathcal{P}(\alpha, \omega_0)$ is a pink noise filter with two parameters:
  - $1/f^\alpha$ describes power spectral distribution
  - ω_0 is the filter's unity gain frequency

Kretjtz et al. (2017)

Why $1/f^\alpha$ pink noise?

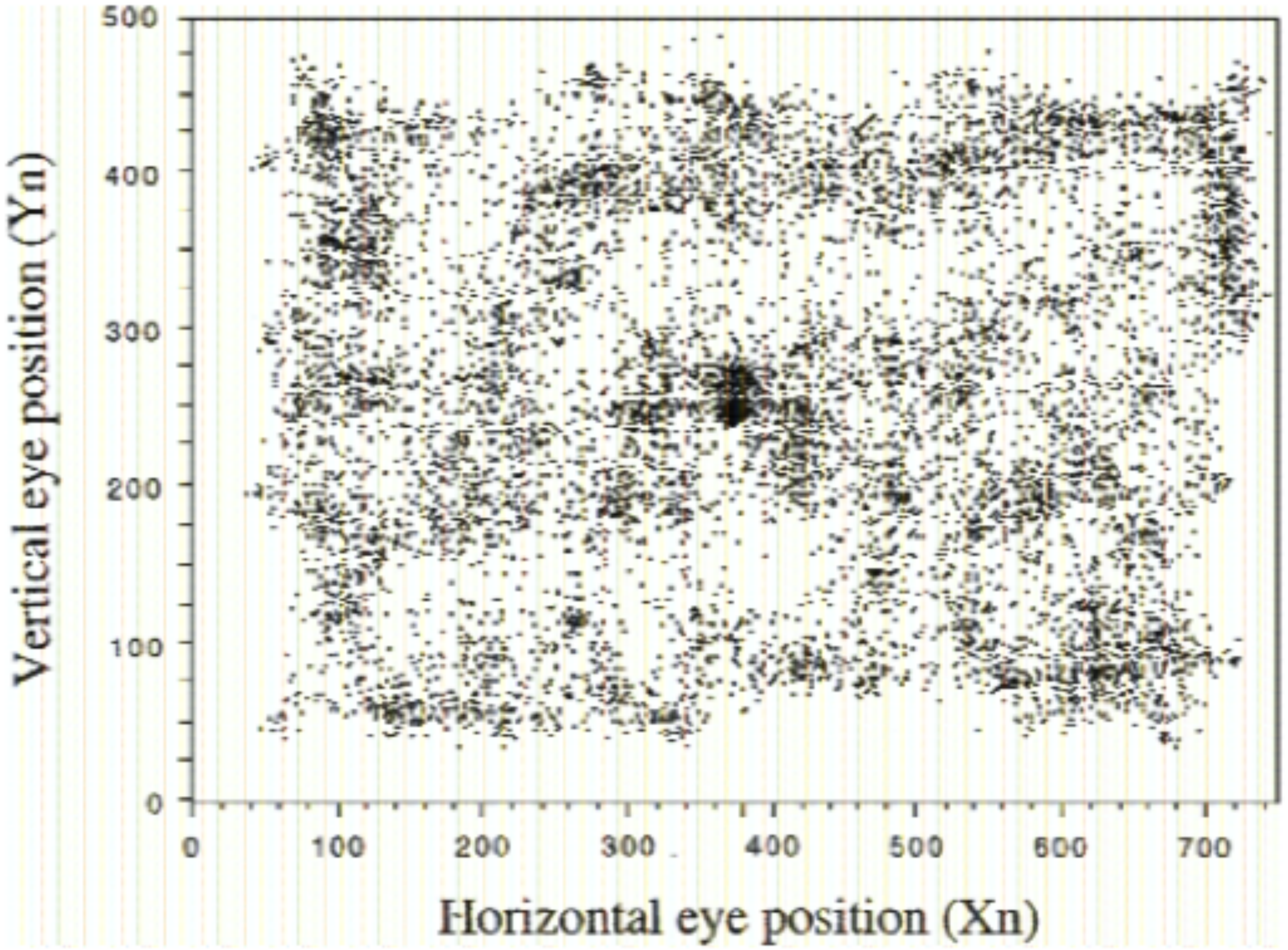


Zhou et al. (2012)

- Good for modeling physical/biological distributions
  - e.g., plants (Ostling et al., 2000) and galaxies (Landy, 1999)
  - behavior of biosystems in general (Szendro et al., 2001)

- Also good for modeling microsaccadic jitter
  - fixation error & neural noise combine to trigger microsaccades
  - can be approximated by $1/f^\alpha$ noise (Yang et al., 2009)

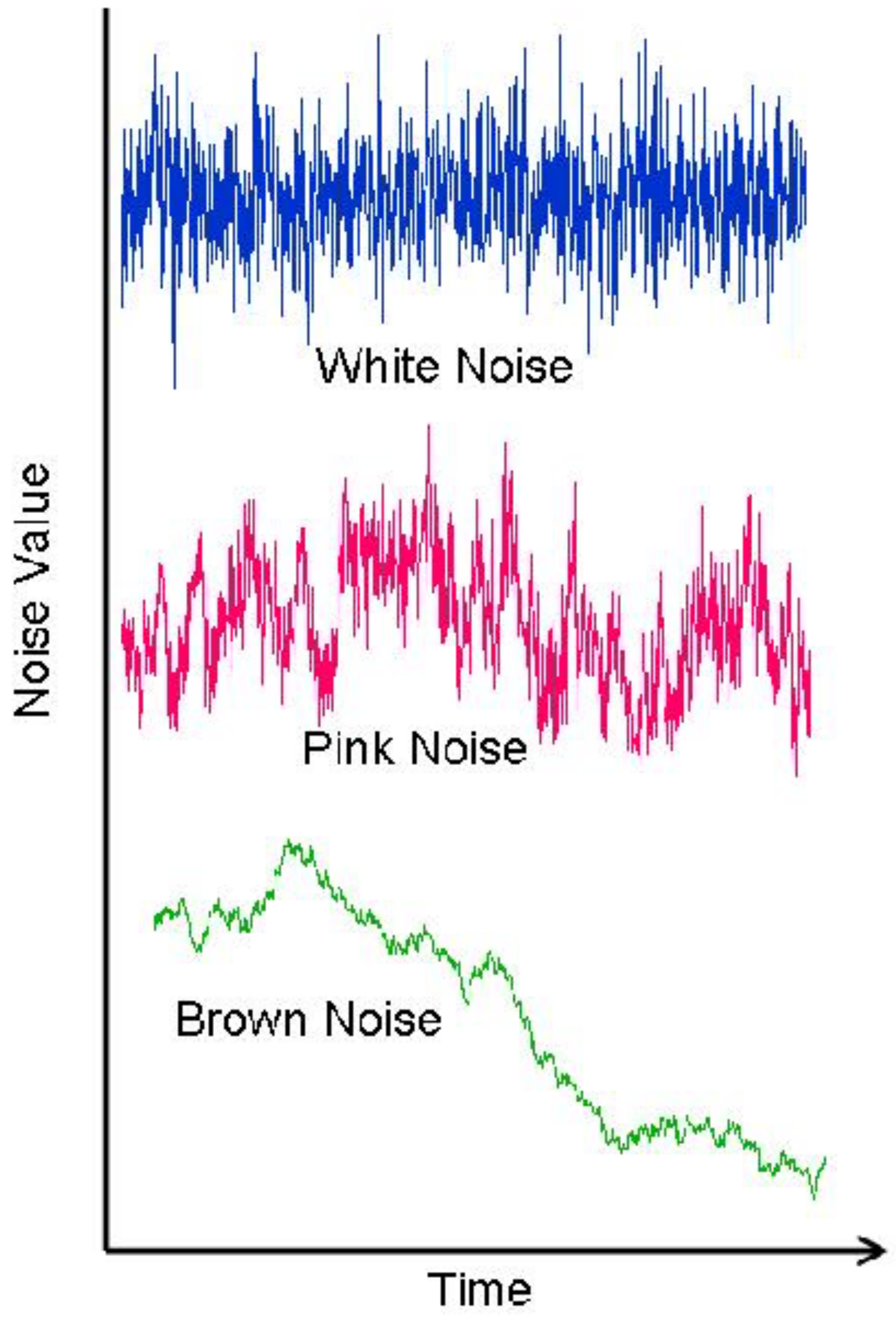
Why $1/f^{\alpha}$ pink noise?

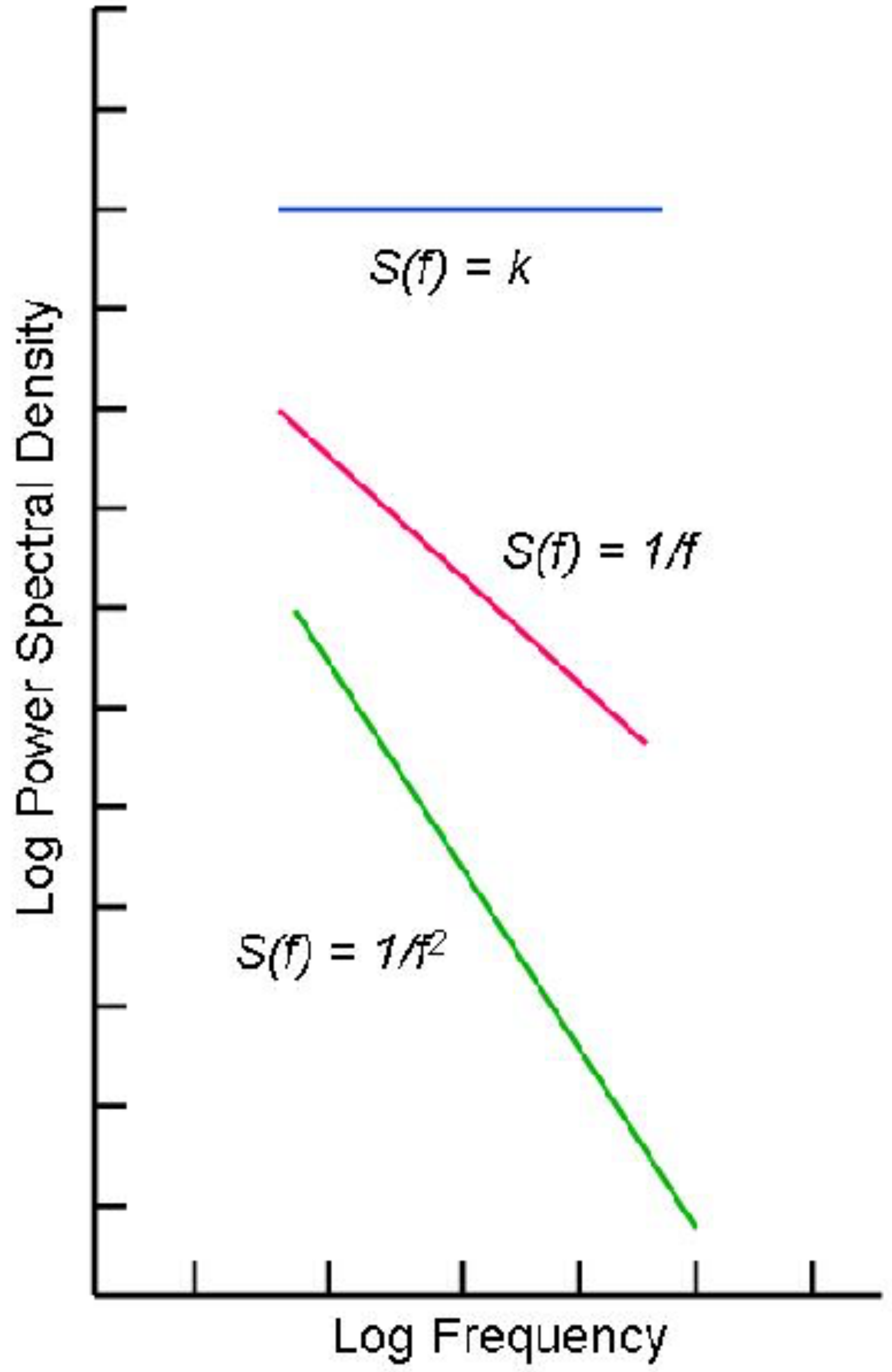


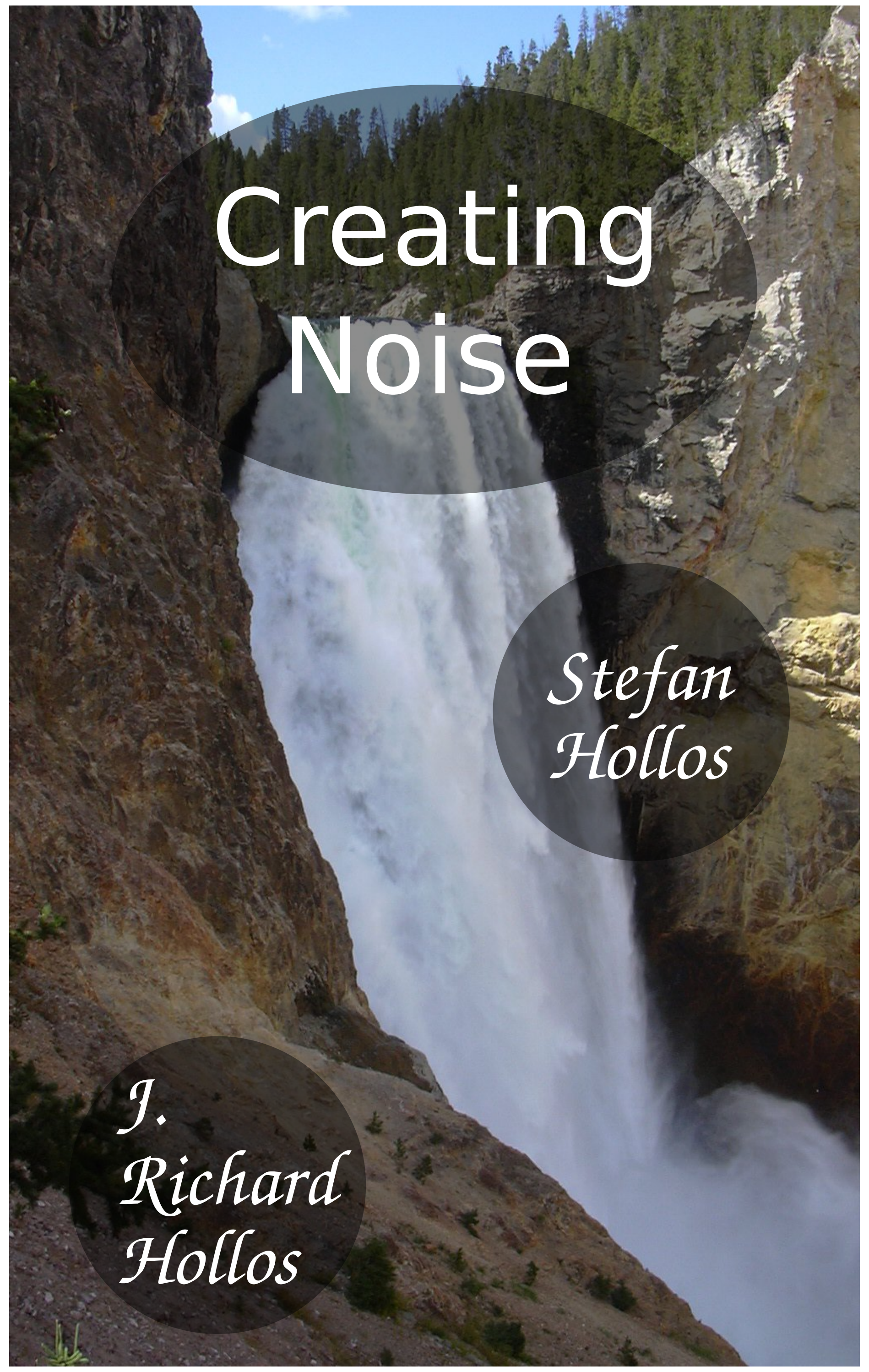
Gaze position during visual search
Aks et al. (2012)

- $1/f^{\alpha}$ neuronal noise accomplishes tradeoff:
  - memory inherent in $1/f^{\alpha}$ system serves as priming effect
  - sensitivity to small fluctuations (Usher et al., 1995)

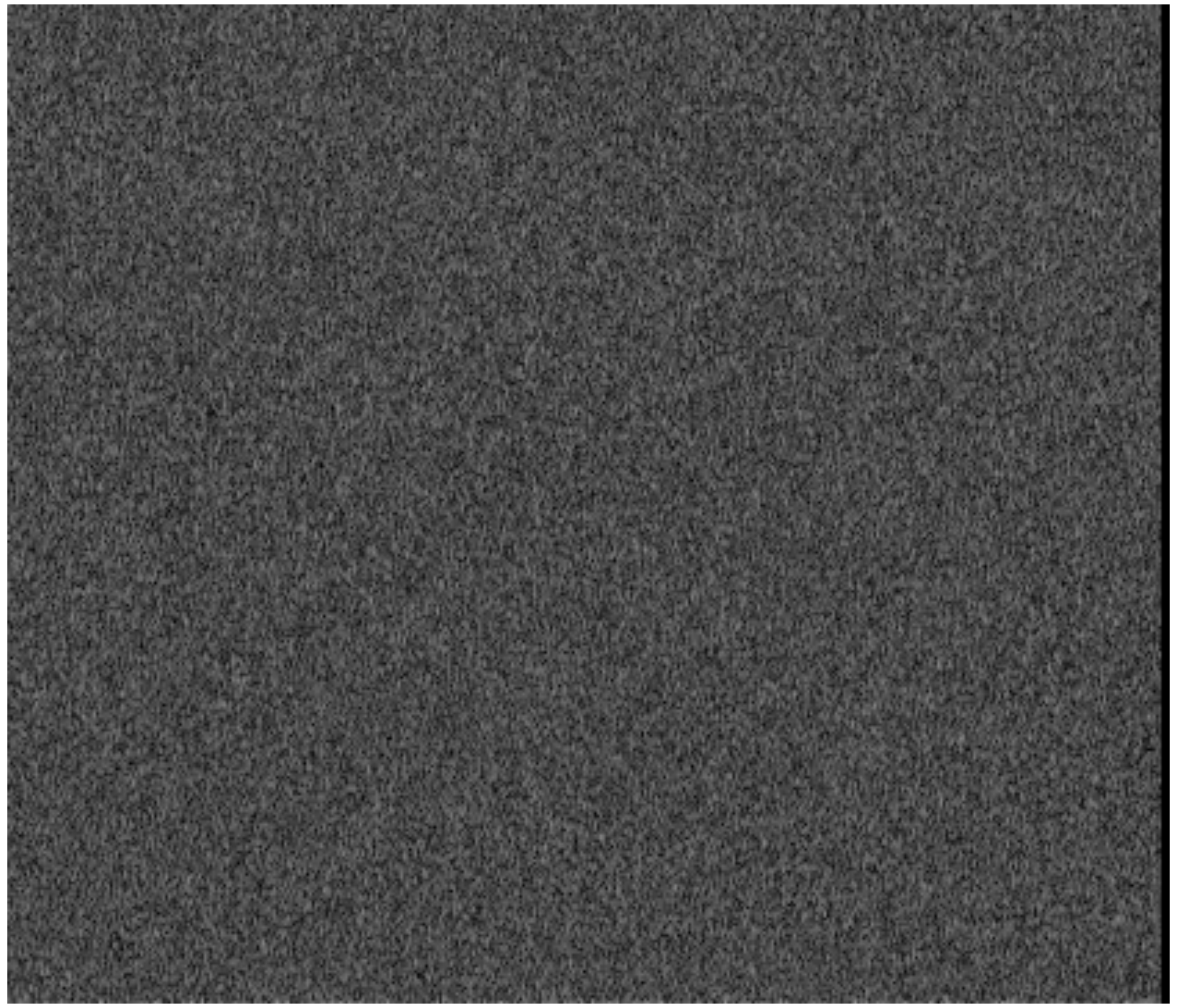
Pink noise


White Noise
Pink Noise
Brown Noise
Noise Value
Time

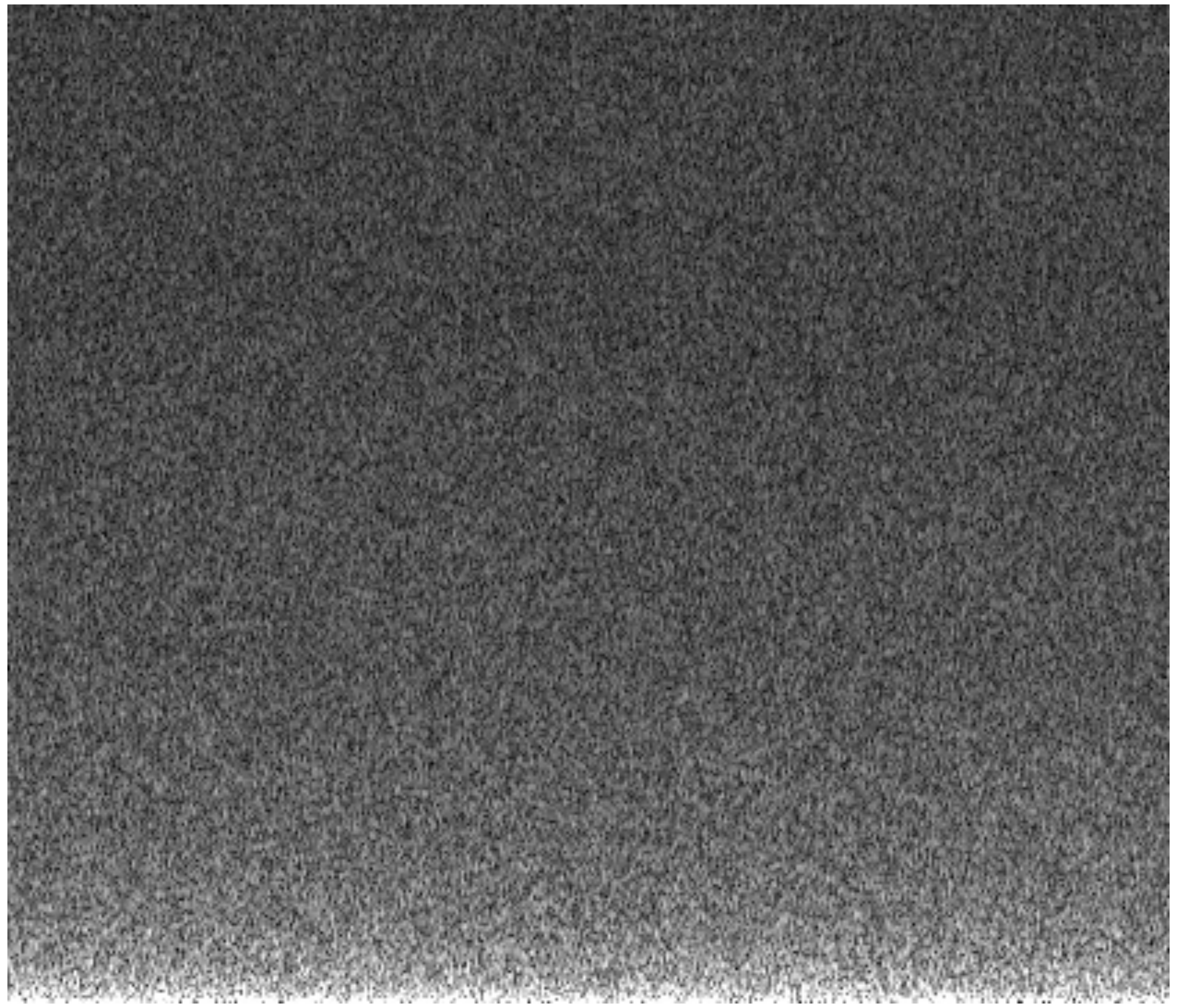

S(f) = k
S(f) = 1/f
S(f) = 1/f2
Log Power Spectral Density
Log Frequency


Creating Noise
Stefan Hollos
J. Richard Hollos

Pink noise

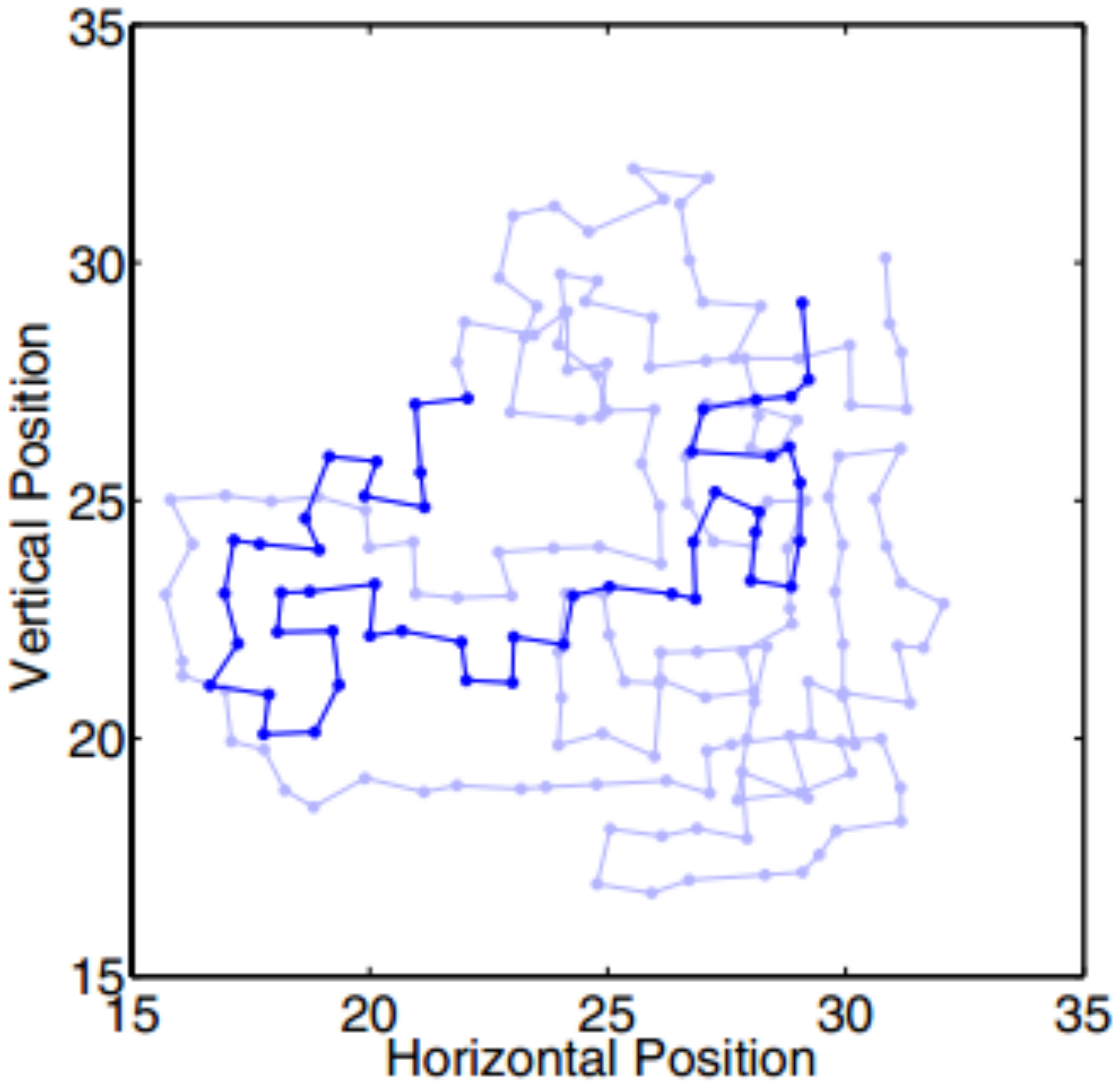


white noise

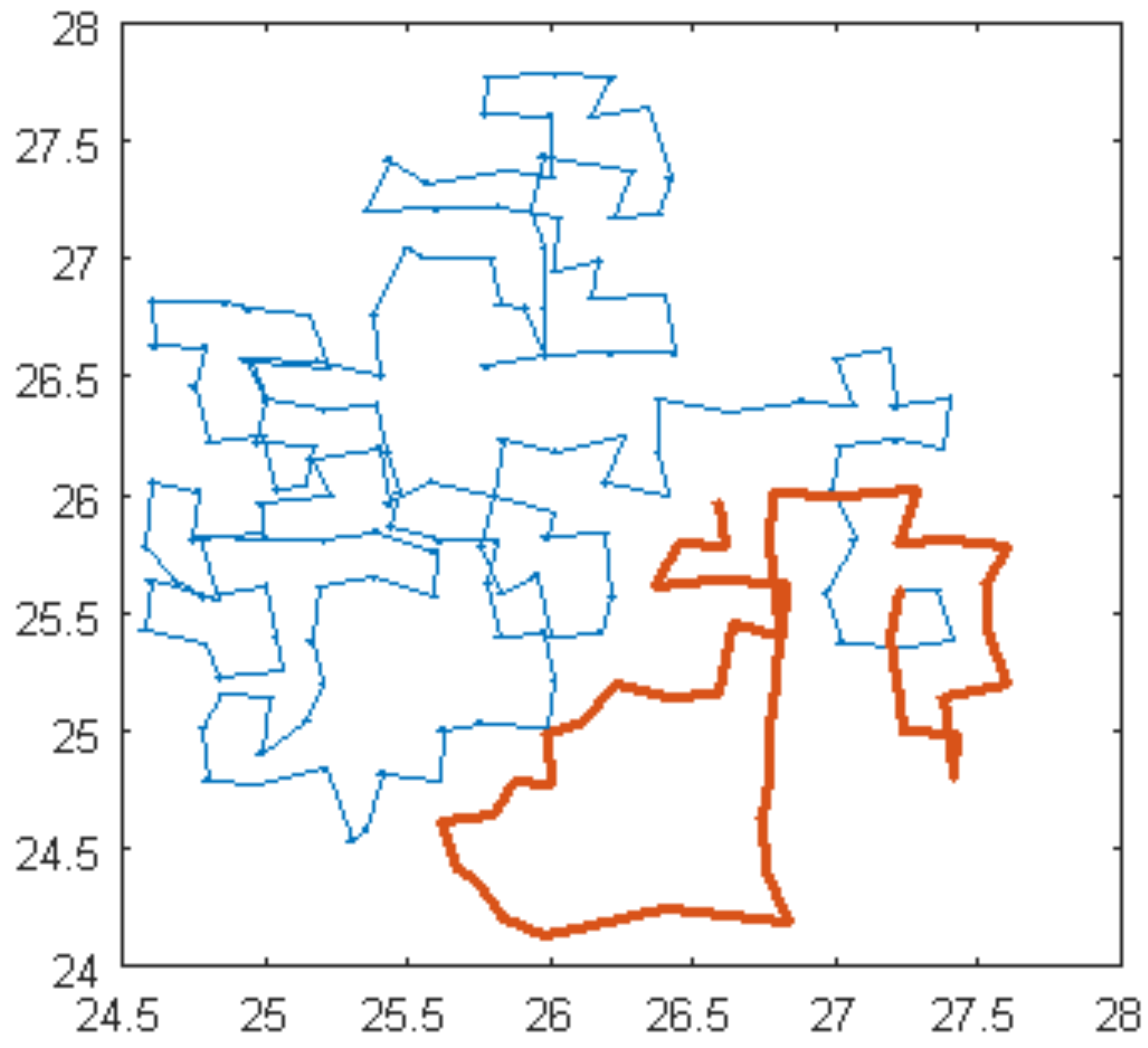


pink noise

Alternative approaches



Engbert 2012



ours (just starting out)

- Self-avoiding random walk

Alternative approaches

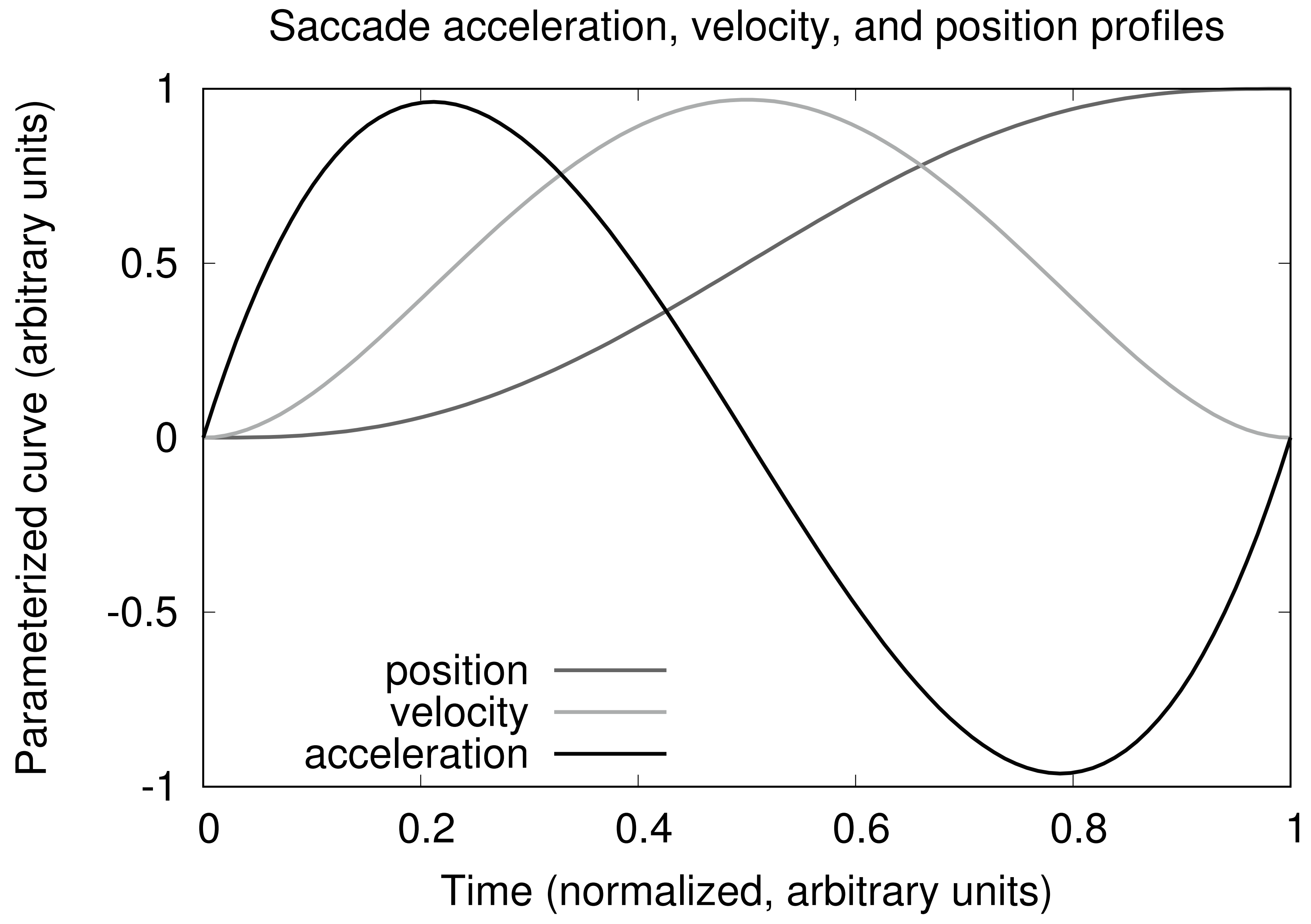
Stochastic modeling

- Saccade movement: $\mathbf{p}_t = \mathbf{P}_{i-1} + h(s)\mathbf{P}_i$
  - use force-time function (similar to limb movement)
  - assume symmetric-impulse model (Abrams et al., 1989)
  - combine two Hermite blending functions for $\ddot{h}(s)$

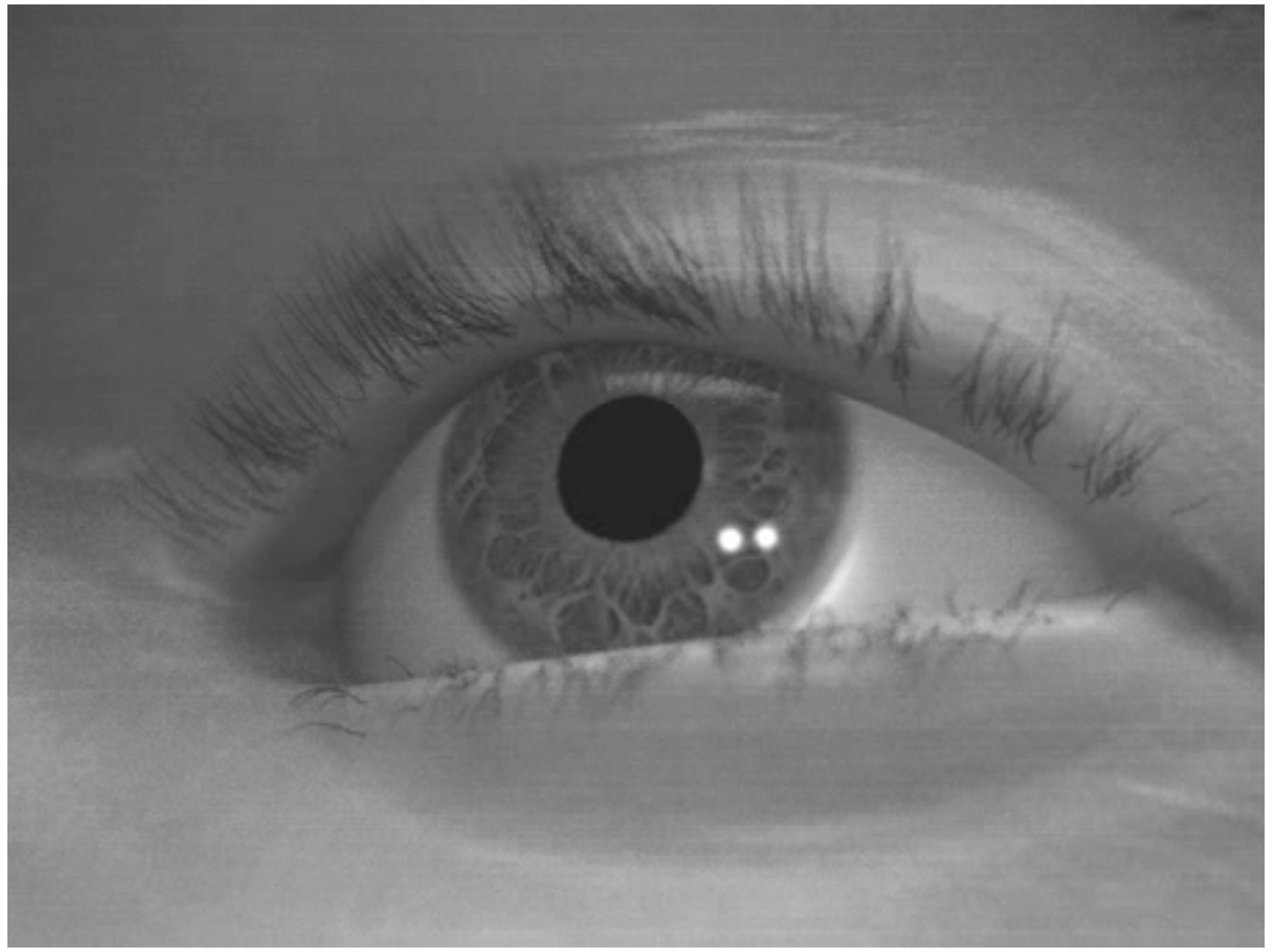
$$\ddot{h}(s) = 2s^3 - 3s^2 + s$$

$$\dot{h}(s) = \frac{1}{2}s^4 - s^3 + \frac{1}{2}s^2$$

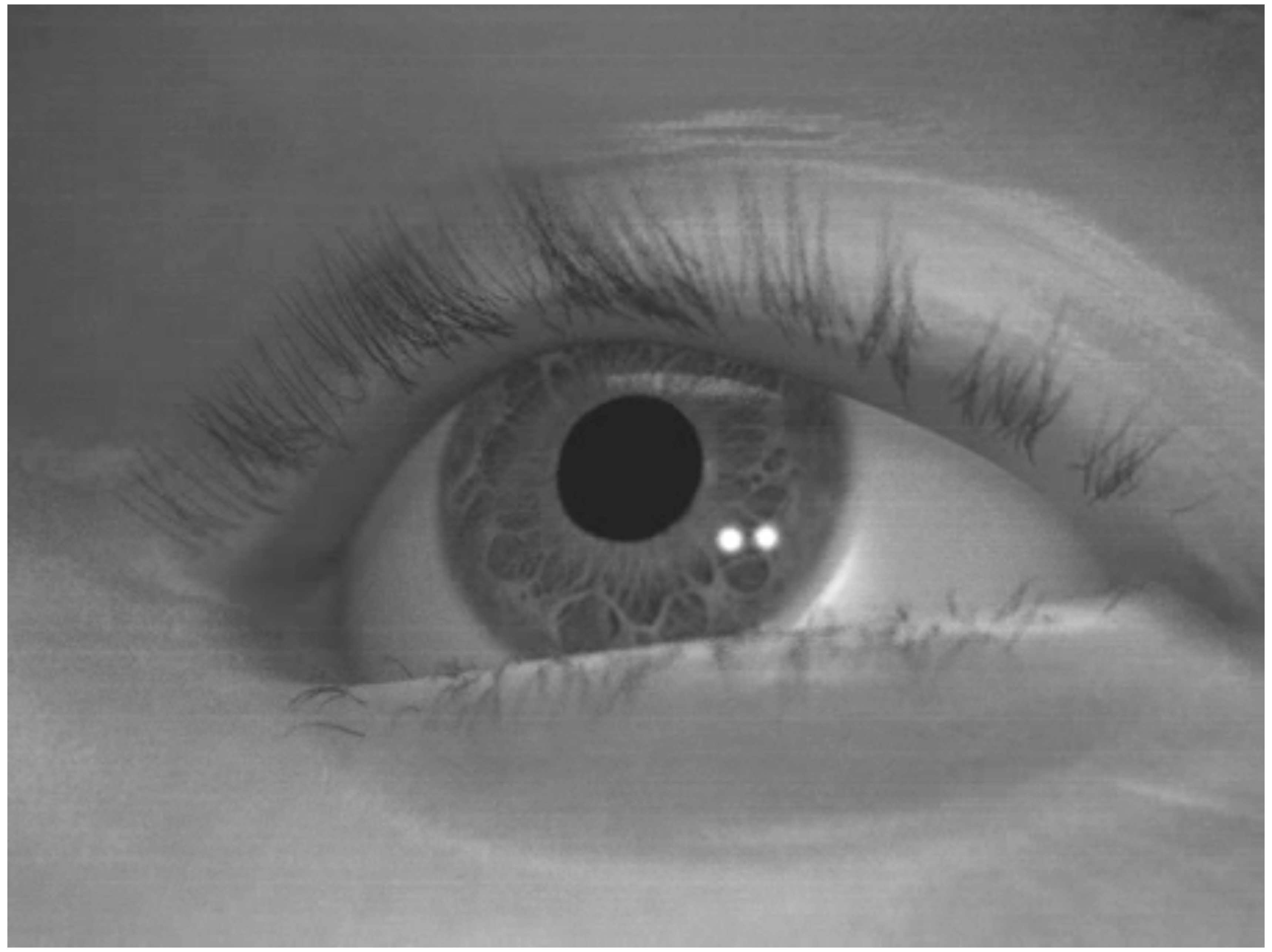
$$h(s) = \frac{1}{10}s^5 - \frac{1}{4}s^4 + \frac{1}{6}s^3$$



Microsaccadic jitter

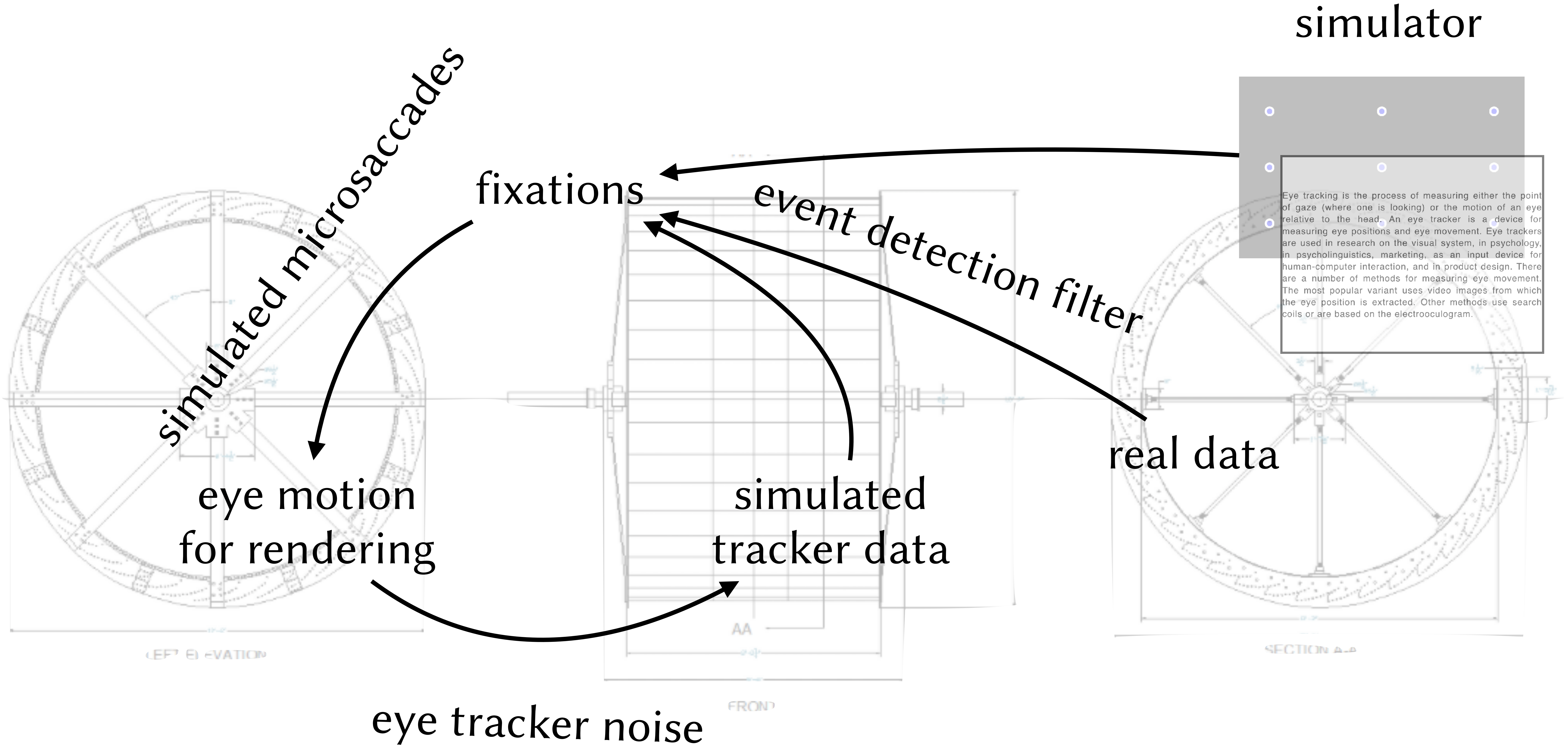


no microsaccadic jitter



(too much?) microsaccadic jitter

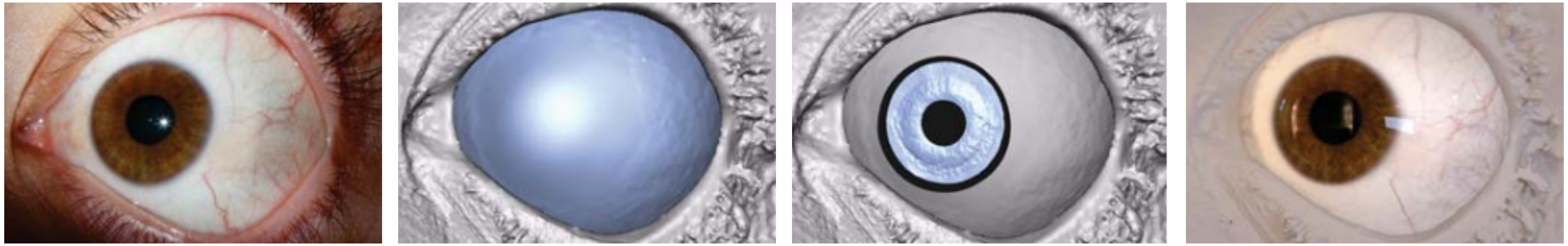
Gaze-guided gristmill



Eye movement synthesis

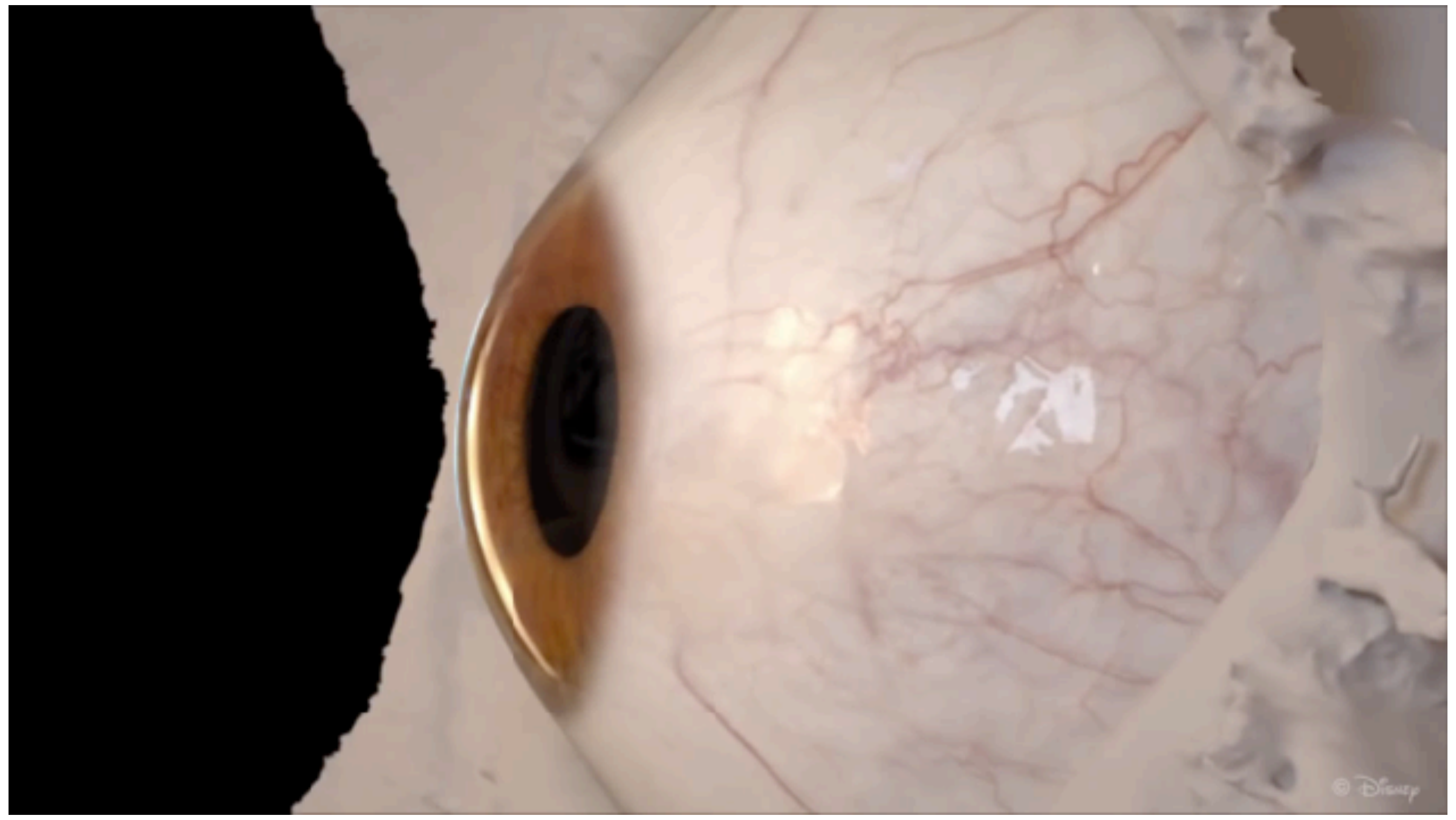
Jörg et al. (SAP 2018)

Summary: Expressive eyes

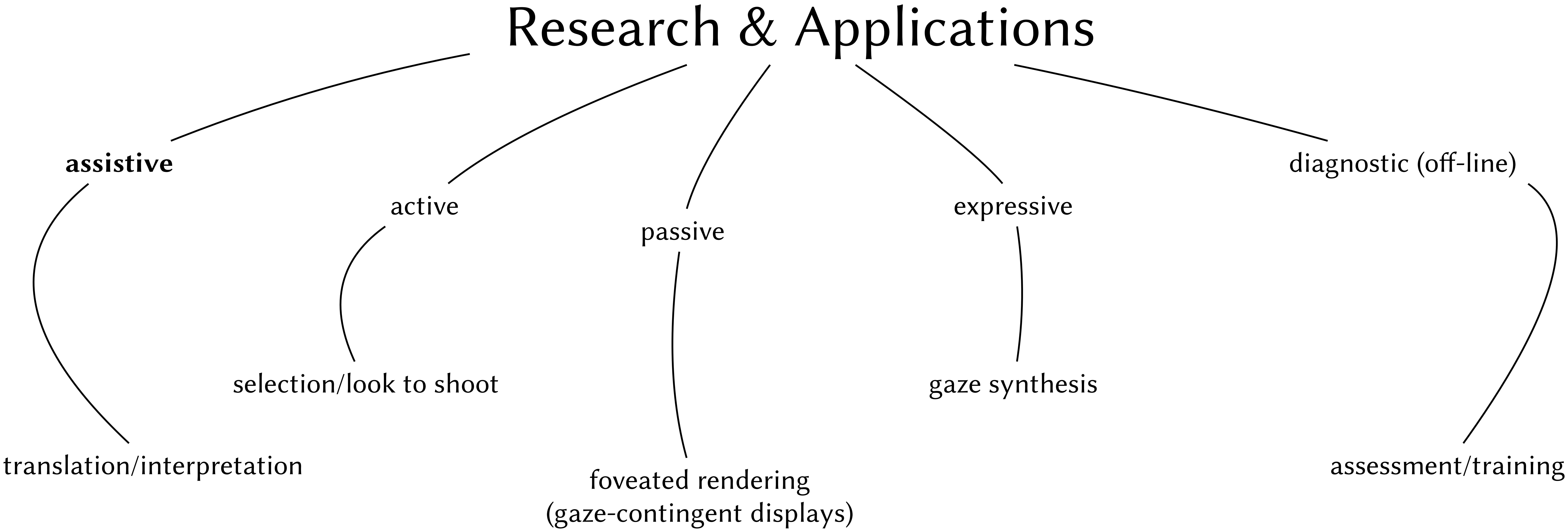


Bérard et al. (SIGGRAPH Asia 2014)

- Outstanding problems:
  - need more expressive eyes (based on experiments)
  - periocular skin animation (eyelids, etc.)
  - caruncle



Eye Tracking



Motivation: accessible 360 video in VR

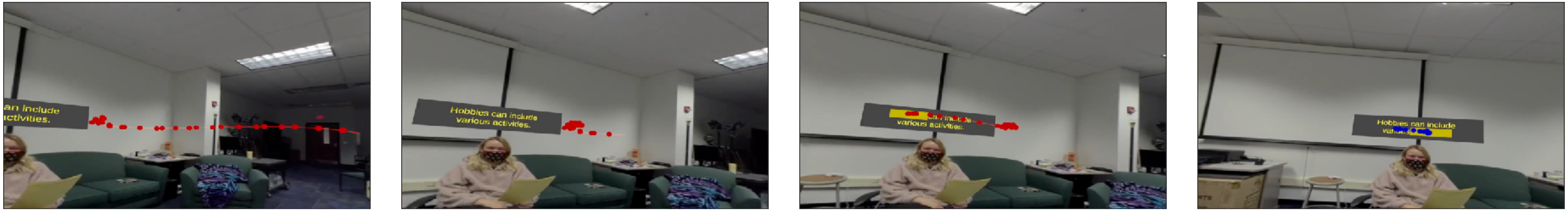
- Predominant subtitling methods might not work well in VR
- Fixed, head-locked subs may not indicate location of speaker
- For example, person below in pic is *not* speaking

Background

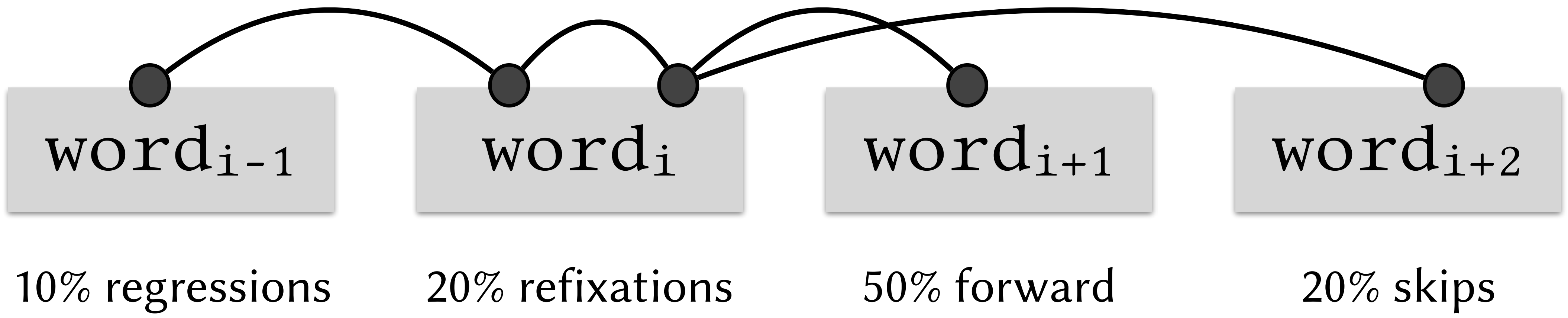
- Various subtitling schemes have been tried by the BBC
  - evenly spaced, fixed below eye line
  - head-locked, always visible, fixed within view
  - head-locked with lag
  - appearing in front, then fixed
- Results somewhat inconclusive
  - various rendering options available
  - newer methods are needed to evalute them

Hughes et al. (2015)

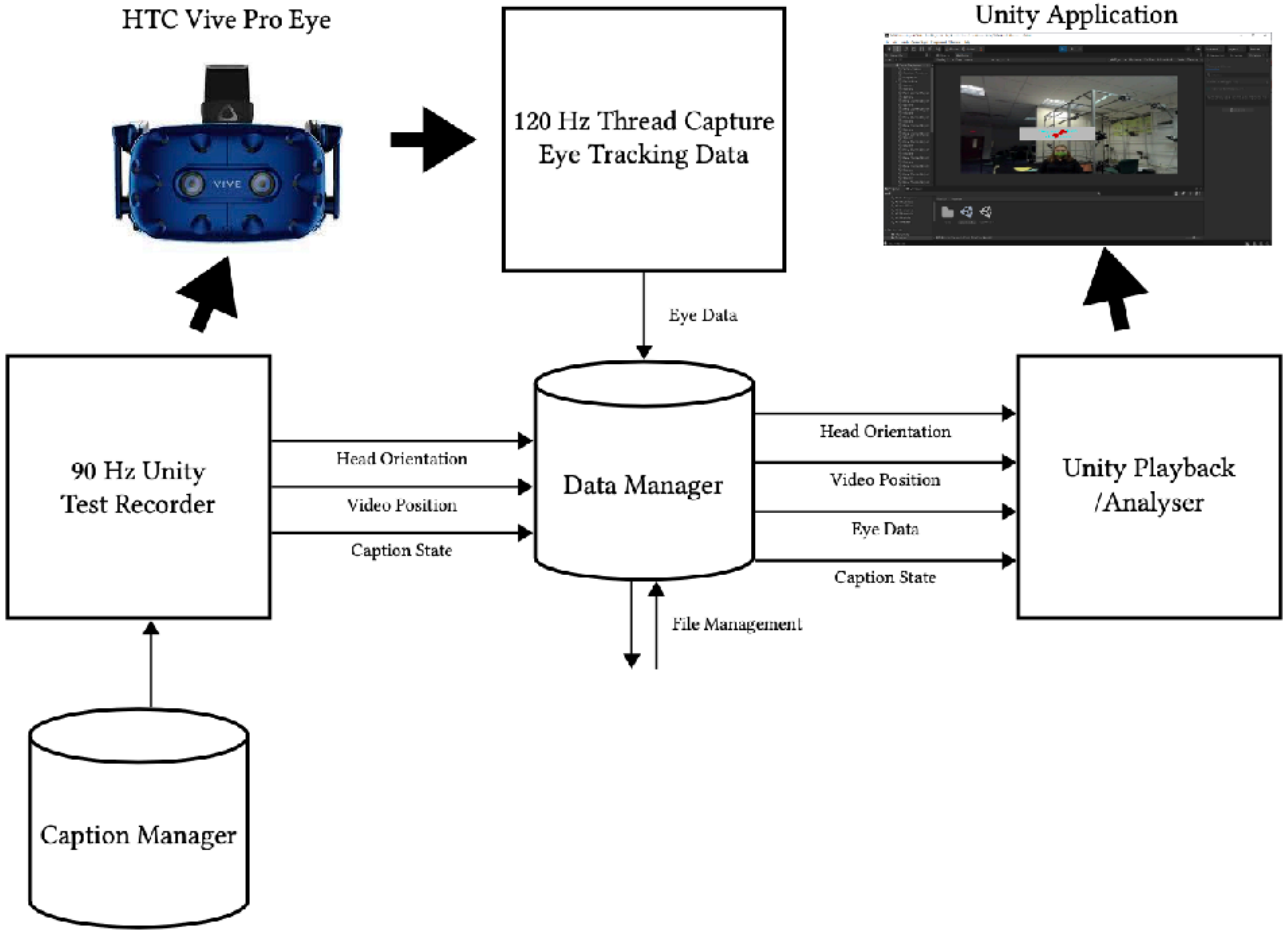
Objective: measure eye movements in VR



- Eye-tracking methodology is needed to test subtitling methods
- Methodology affords objective comparisons, not just subjective
- Metrics could lead to novel models of reading

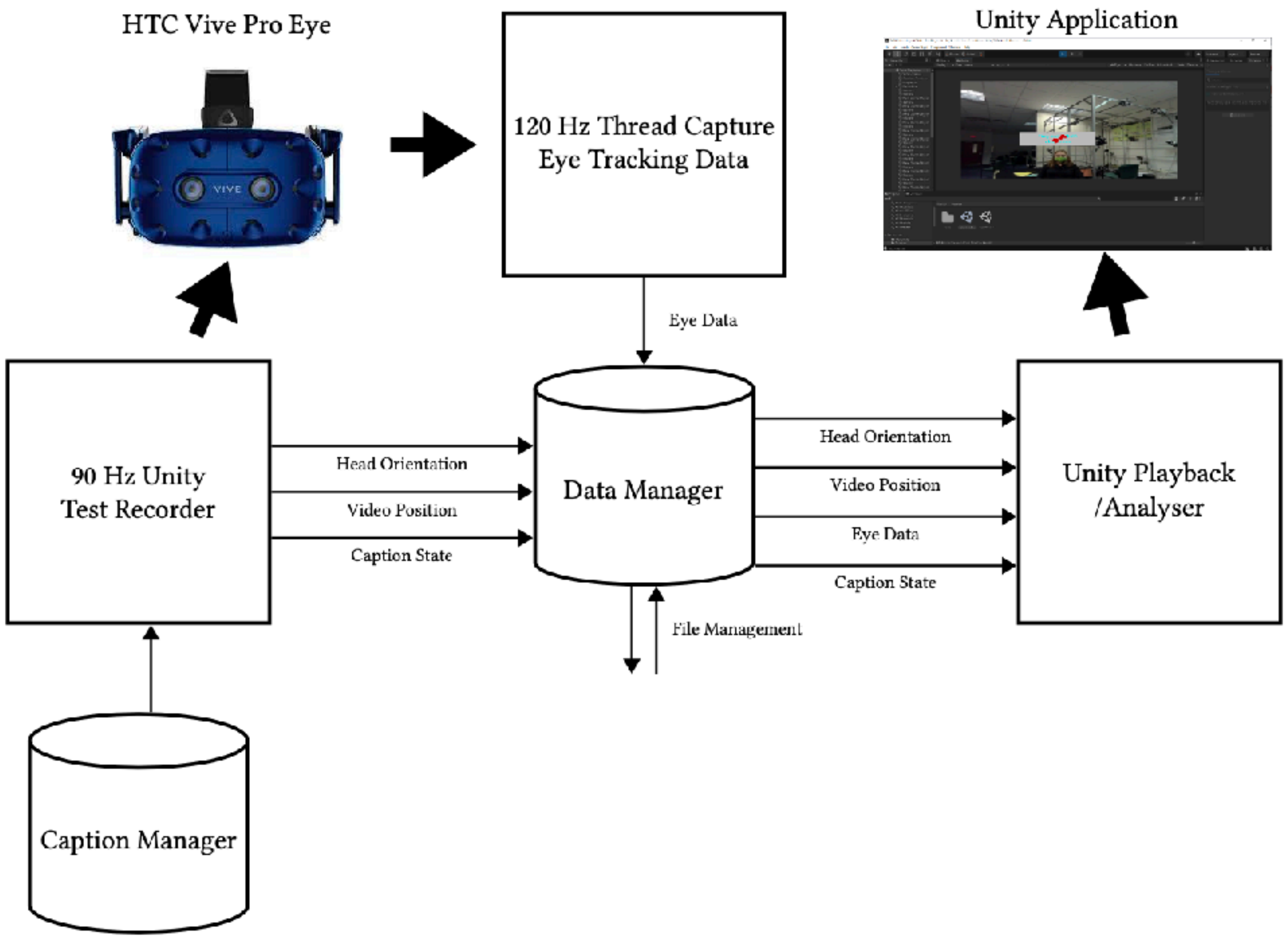


Live Web Testing Framework



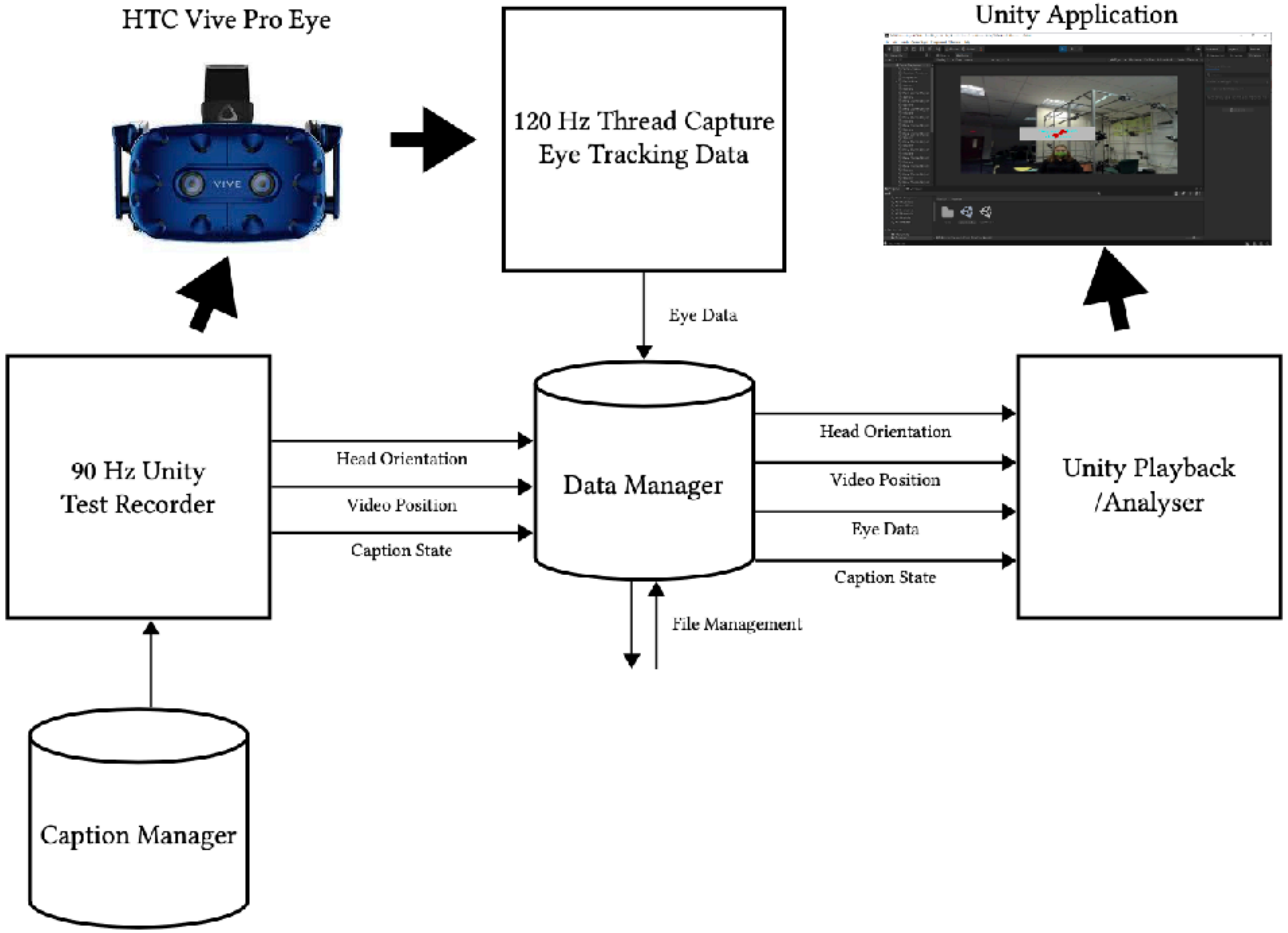
- Web-based subtitle testing framework ported to VR (Unity 3D)

Live Web Testing Framework



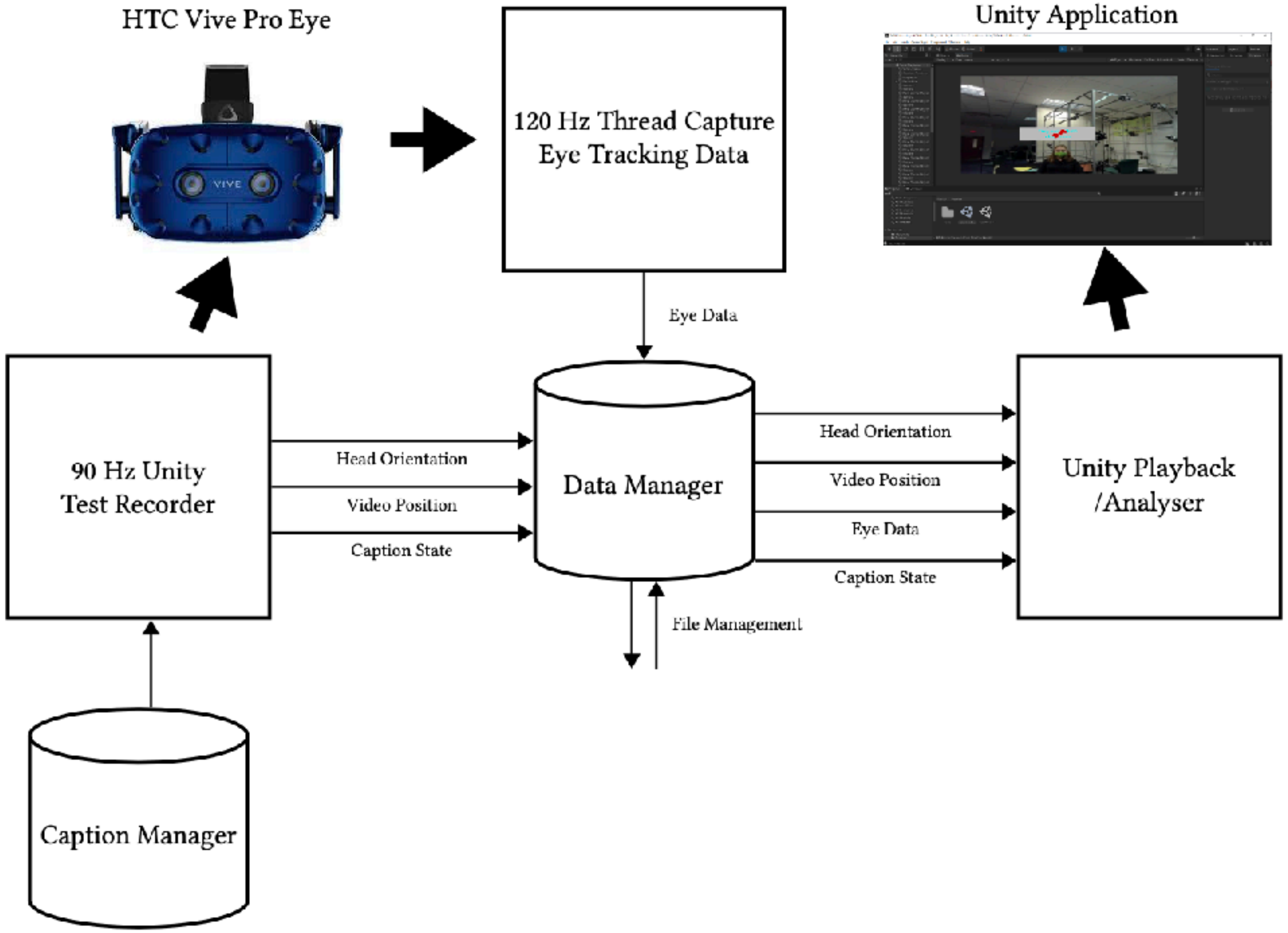
- 3 components: video, fake camera, and subtitle containers

Live Web Testing Framework



- Allows various subtitle rendering styles, various parameters

Live Web Testing Framework



- Allows recording and playback of gaze, subtitles, 360 video

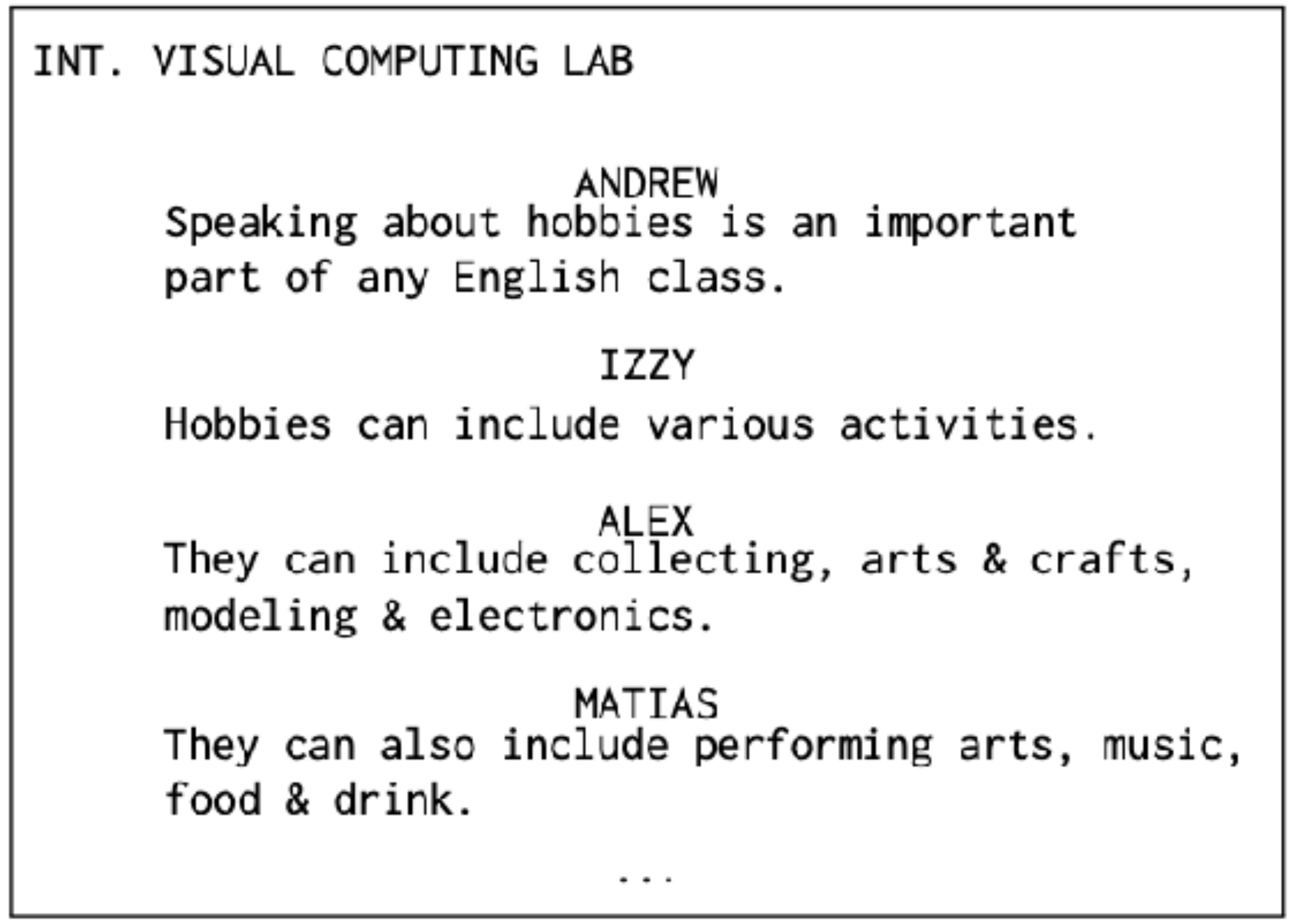
Live Web Testing Framework

- Allows recording and playback of gaze, subtitles, 360 video

Objective: controlled empirical testing in VR

- Need to control 360 video stimulus, e.g., render / record video
- Either fully synthetic or principal photography
- Stimulus is scripted and directed like a short film
  - e.g., position actors / speakers at specific locations

Methodology: stimulus generation



INT. VISUAL COMPUTING LAB

ANDREW
Speaking about hobbies is an important part of any English class.

IZZY
Hobbies can include various activities.

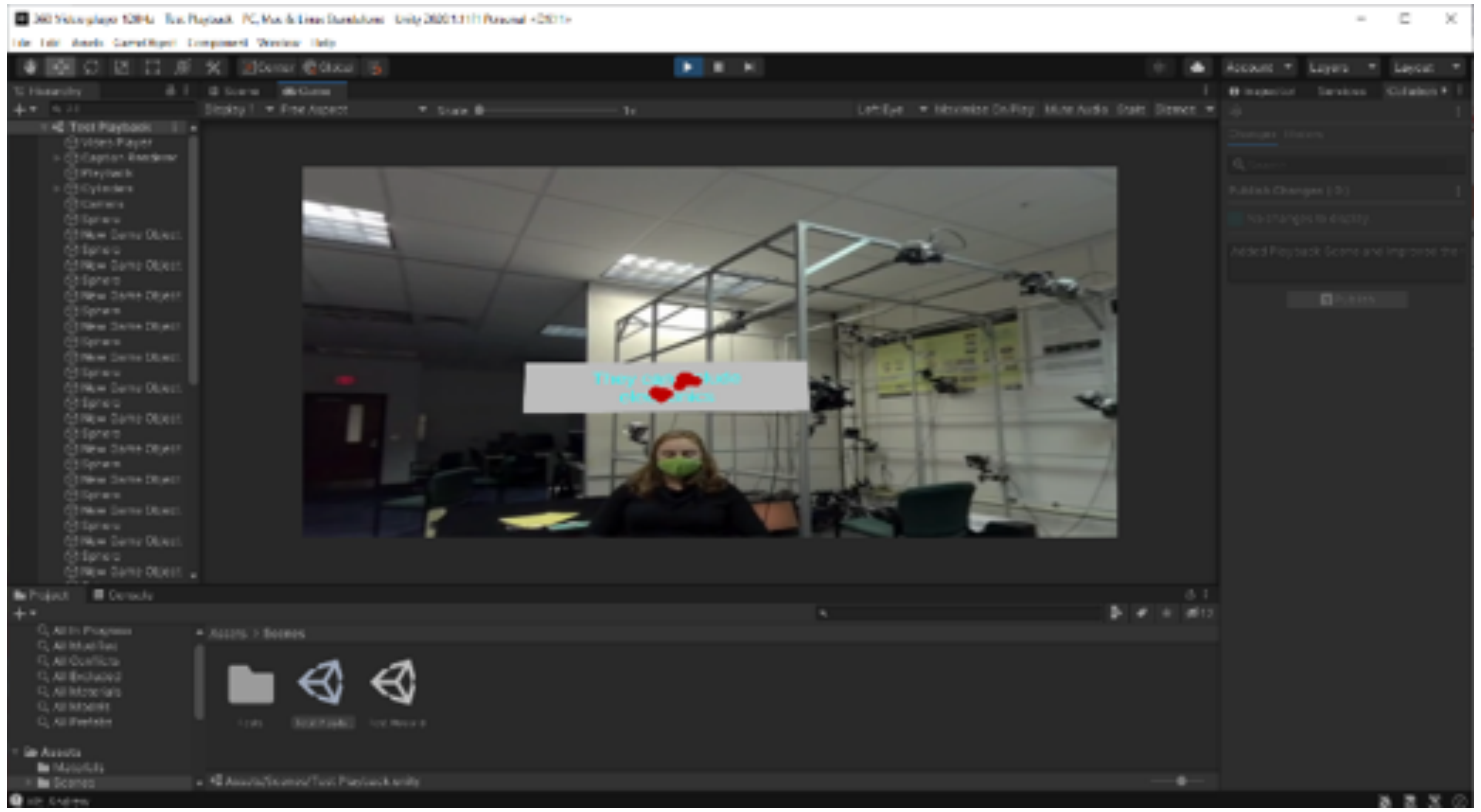
ALEX
They can include collecting, arts & crafts, modeling & electronics.

MATIAS
They can also include performing arts, music, food & drink.

...

- Script controls what is spoken and when (subtitle consistency)
- Principle photography recorded in 360 directly (Vuze 360 camera)

Methodology: apparatus



- 360 video projected in VR via Unity 3D
- Playback and gaze recording via HTC Vive Pro Eye
- Gaze sampling at 120 Hz in own thread, display at 90 Hz

Methodology: experimental design

- Experimental design is key to meaningful studies & results
- Ecological validity
  - push / pull between “in the wild” reality and “in the lab” control
  - controlled experiments are needed to establish baseline observations
- Preliminary study design: $2 \times 2 \times 2$ design with indep. variables:
  - stage (360 vs. 180)
  - masks (on vs. off)
  - object (human vs. abstract [cylinder])
- Idea is to compare how well subtitles are read (e.g., WPMs)

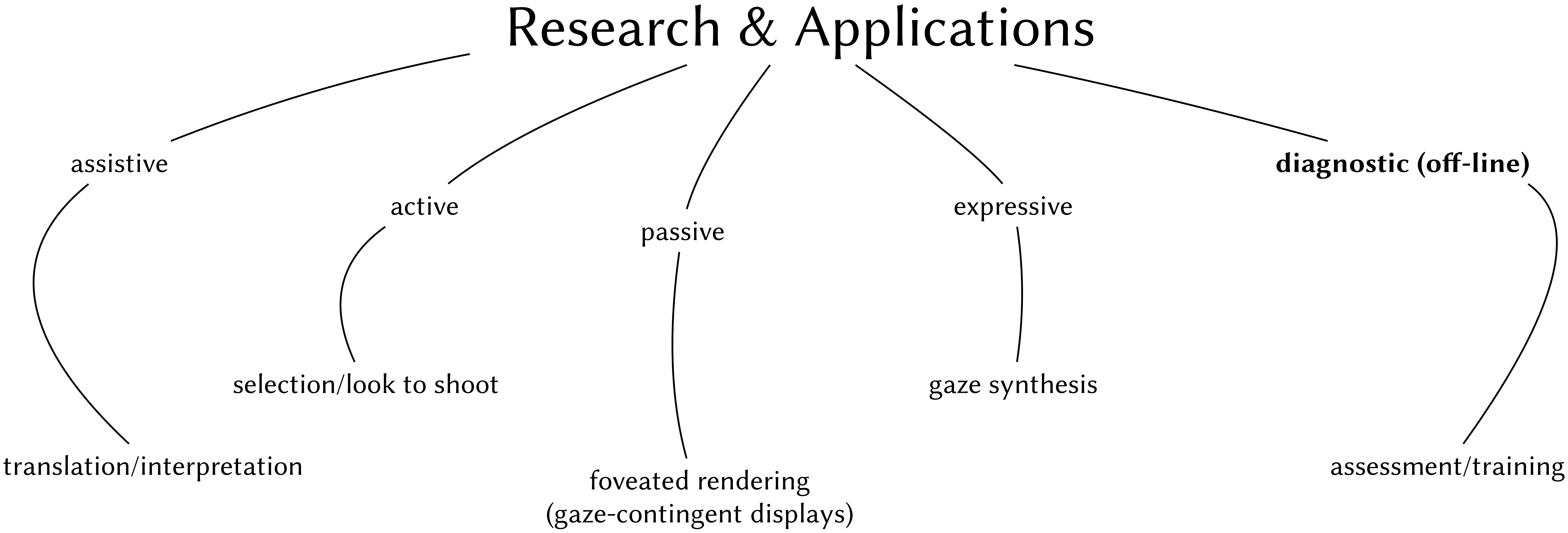
Methodology: gaze metrics

- Gaze signal can be analyzed in real-time or during playback
- Analysis relies on detecting fixations using velocity-based filter
- Further statistics rely on counting fixations in subtitles

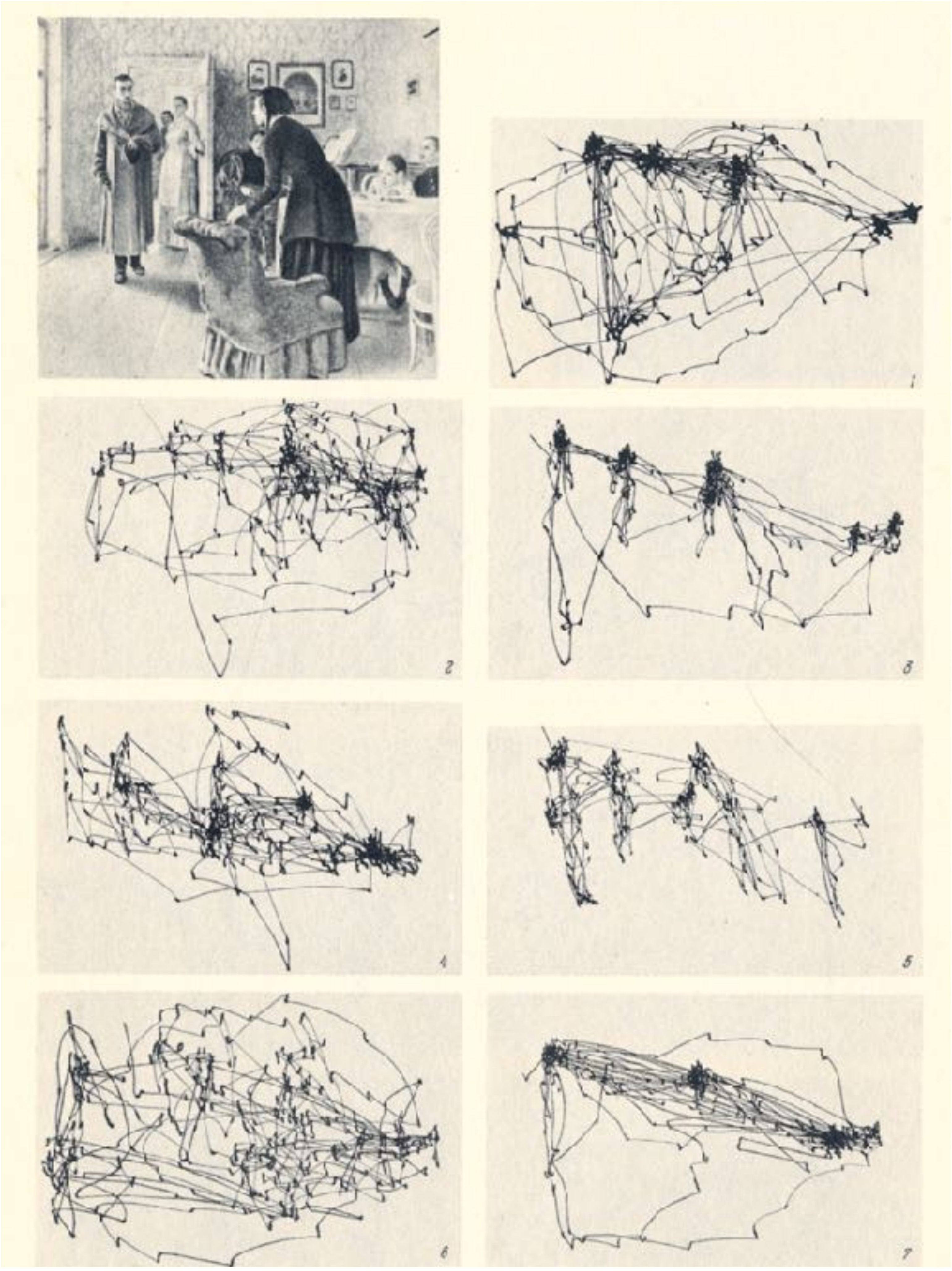
Conclusion

- Architecture is ready for eye-tracked testing
- Next steps: conduct experiments in a controlled manner
- Analyze and report results

Eye Tracking



Task dependency

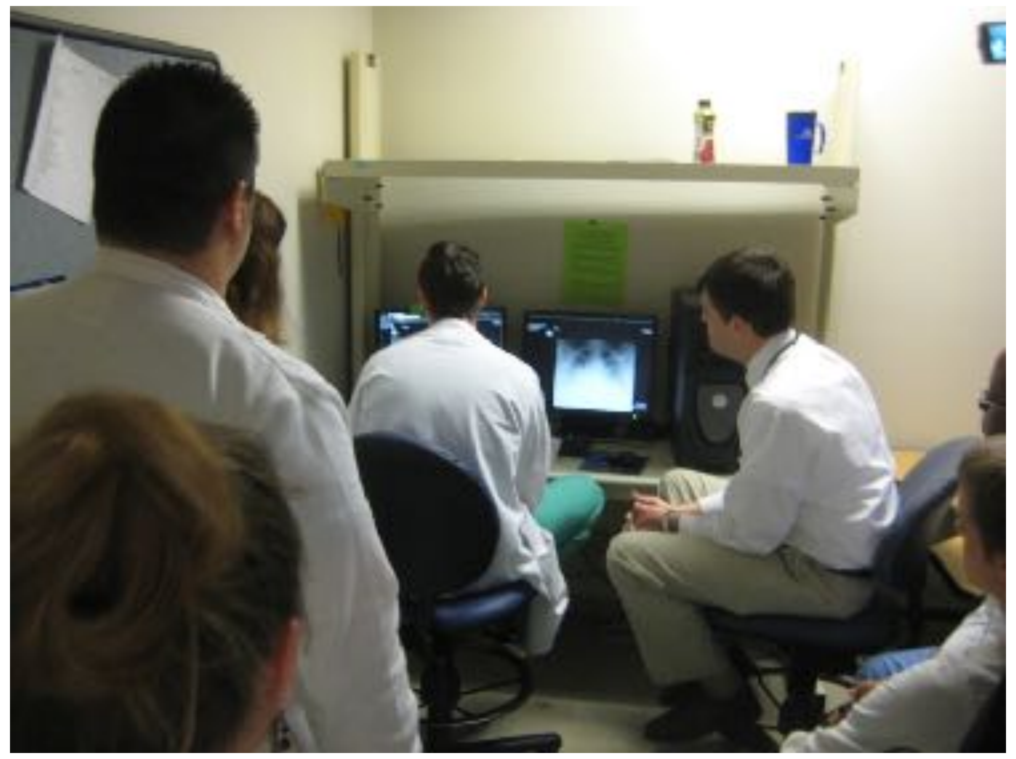


Ilya Efimovich Repin's *An Unexpected Visitor* (Yarbus, 1967)

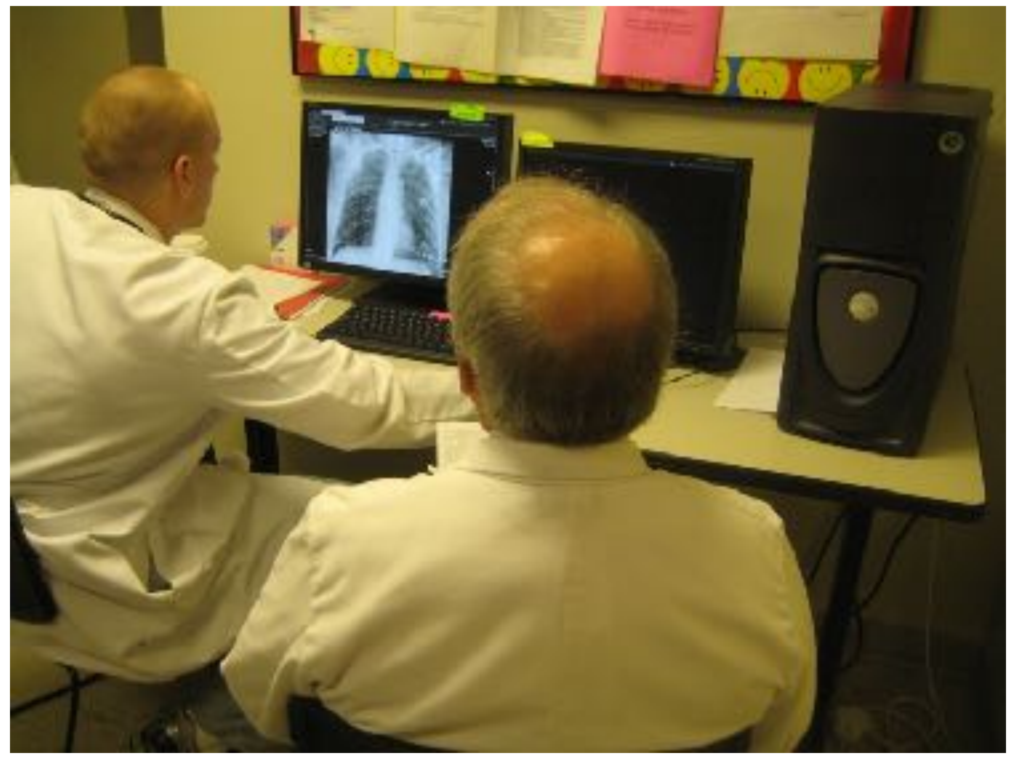
Task dependency

Ilya Efimovich Repin's *Vsevolod Mikhailovich Garshin (1855-1888)*, 1884
Oil on canvas, Gift of Humanities Fund, Inc., 1972, The Metropolitan Museum of Art, New York, NY

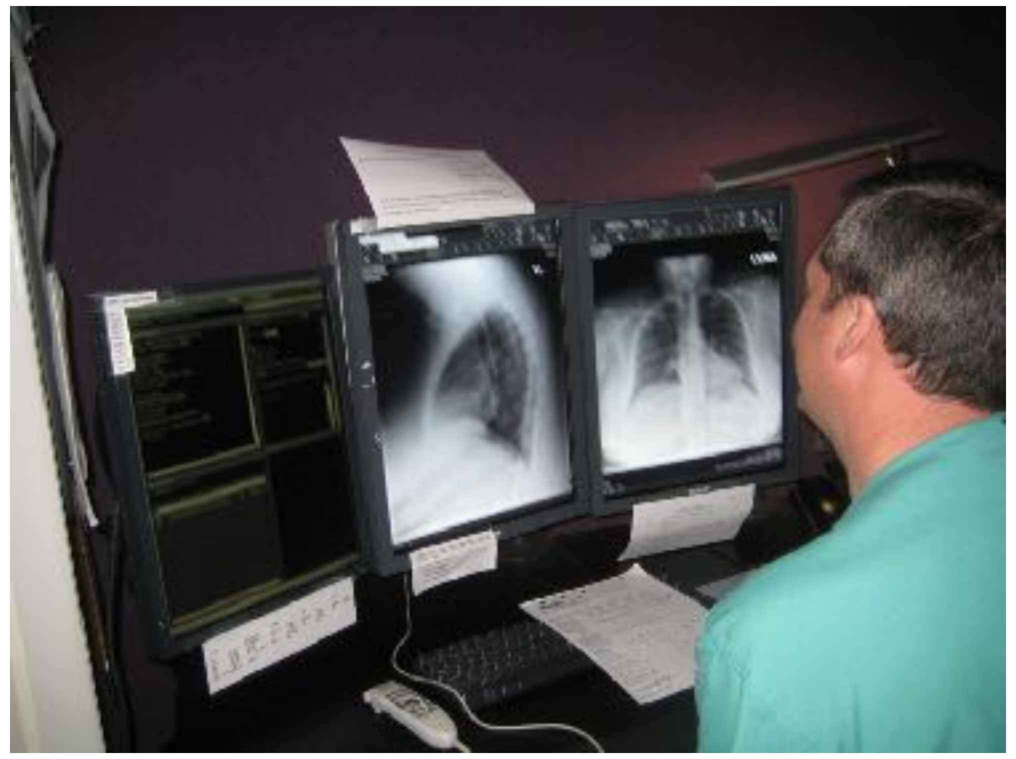
Expert/novice assessment



intern

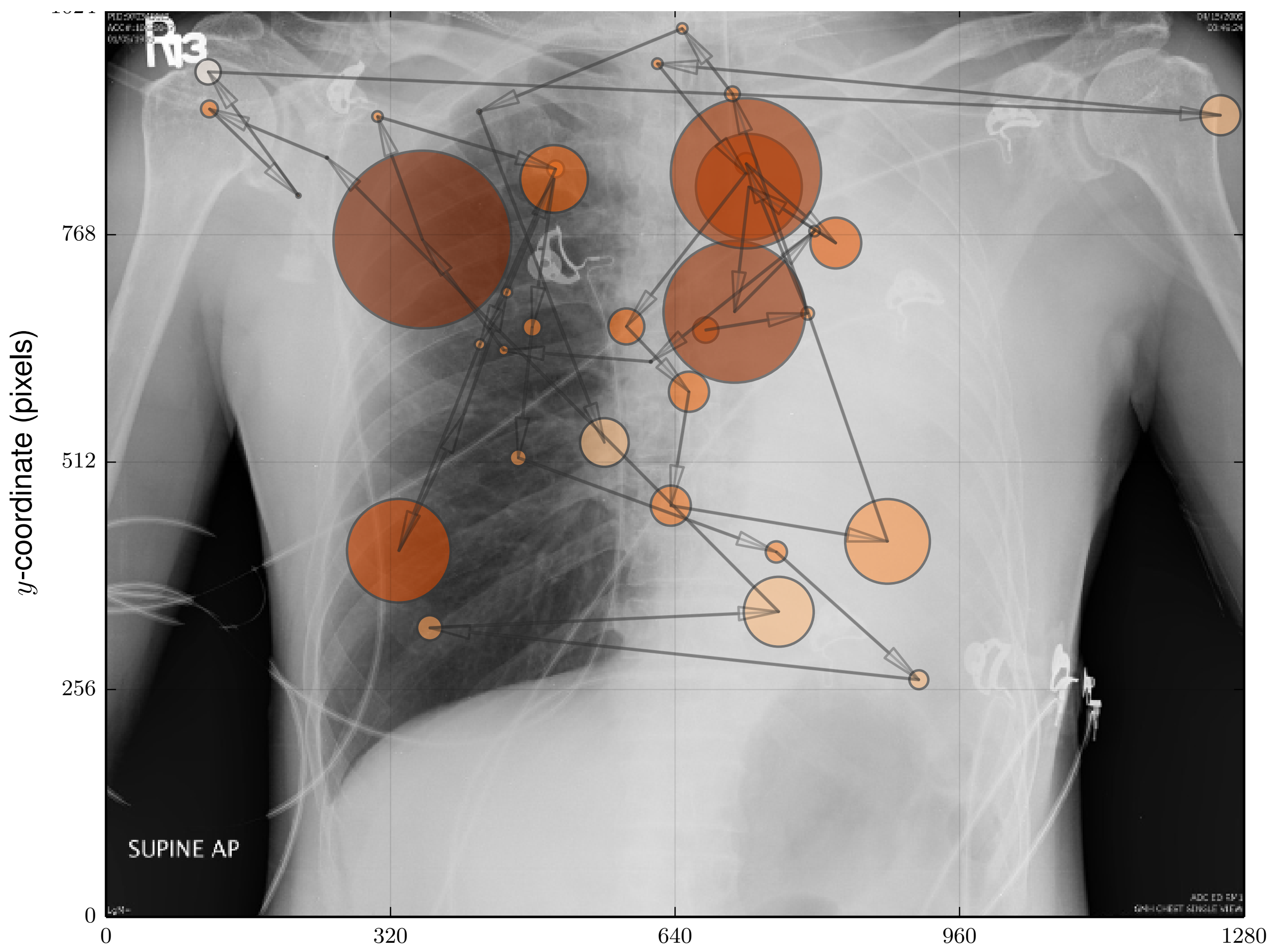


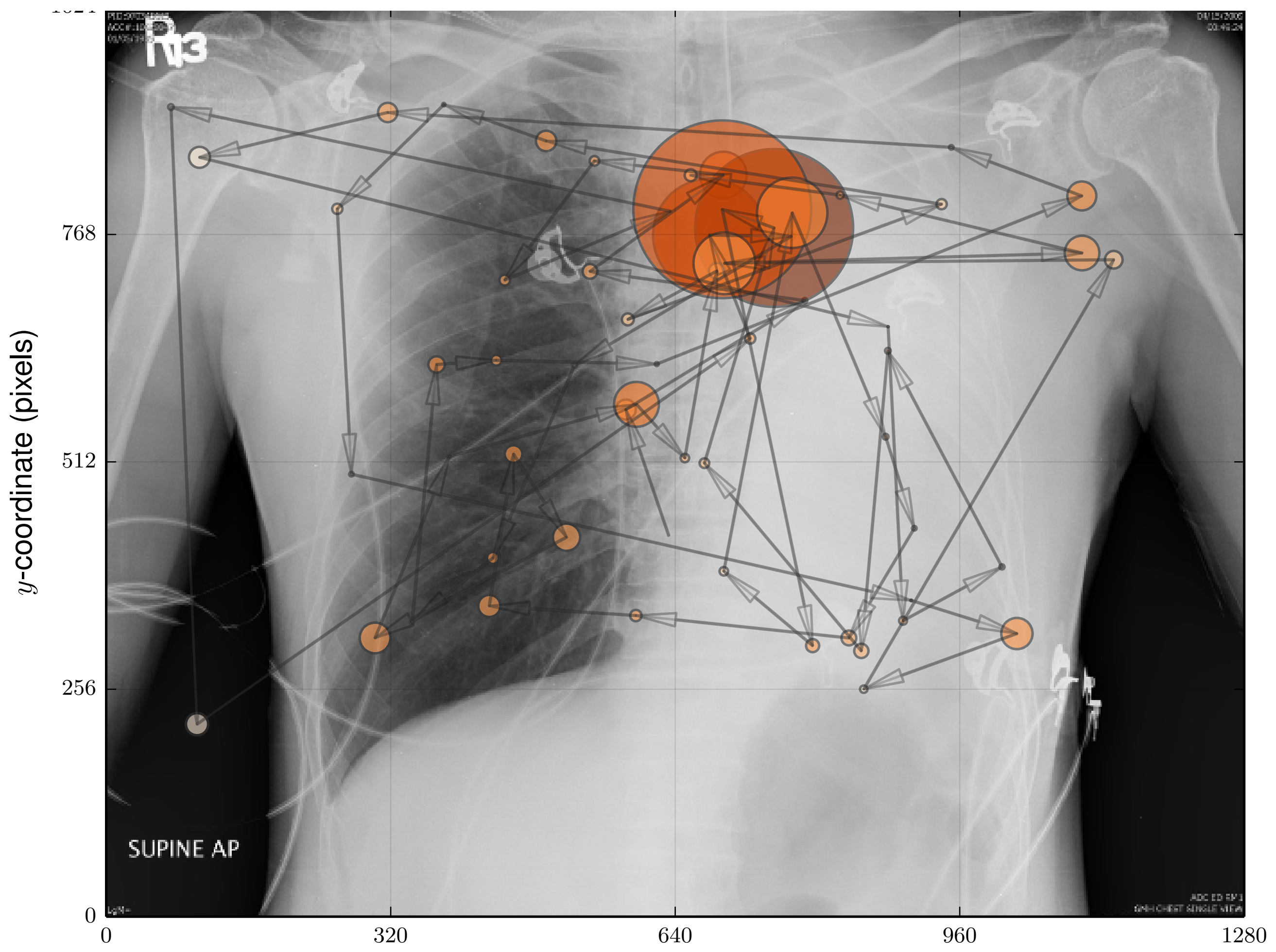
resident



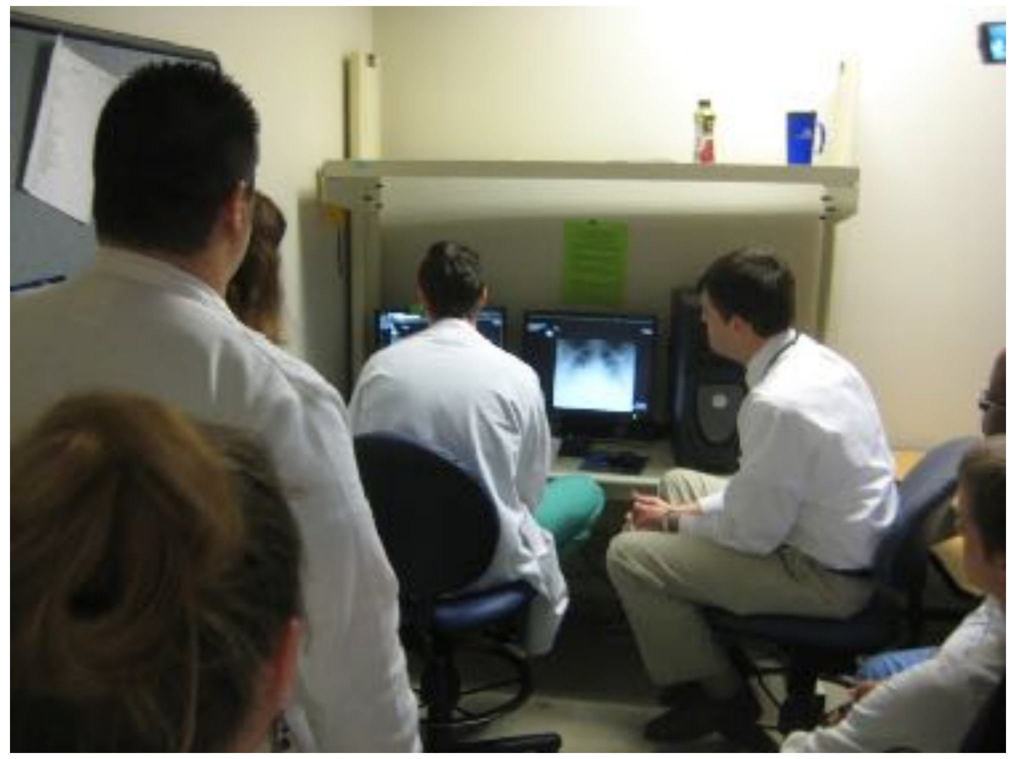
radiologist

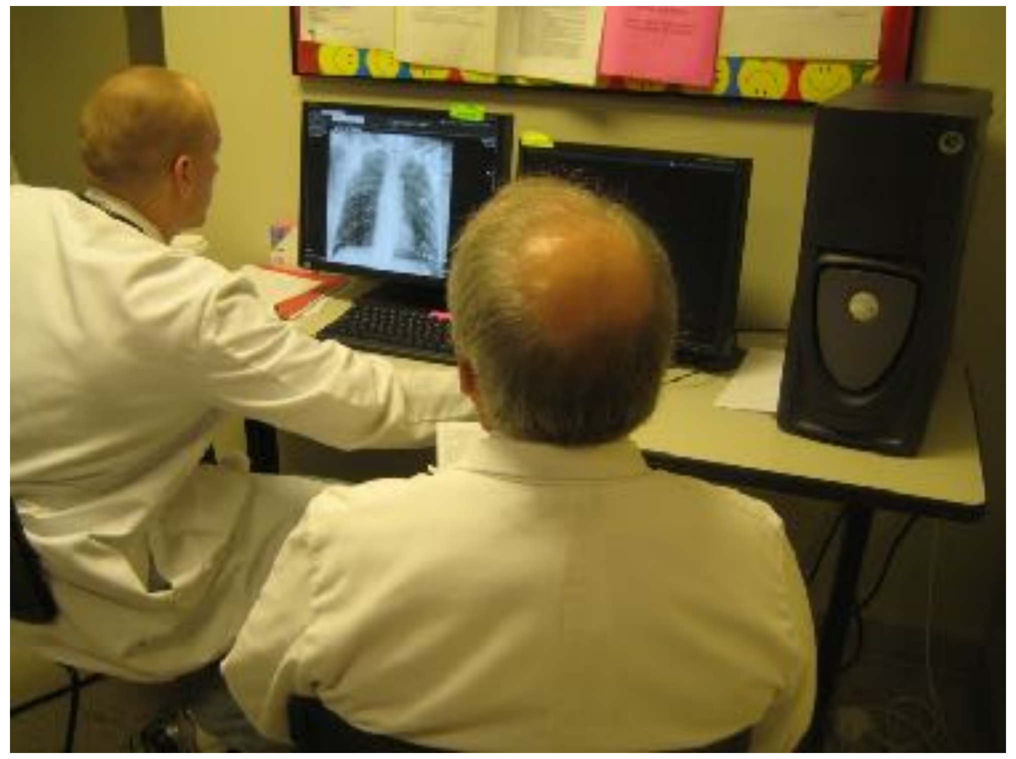
Which is expert, which is novice?

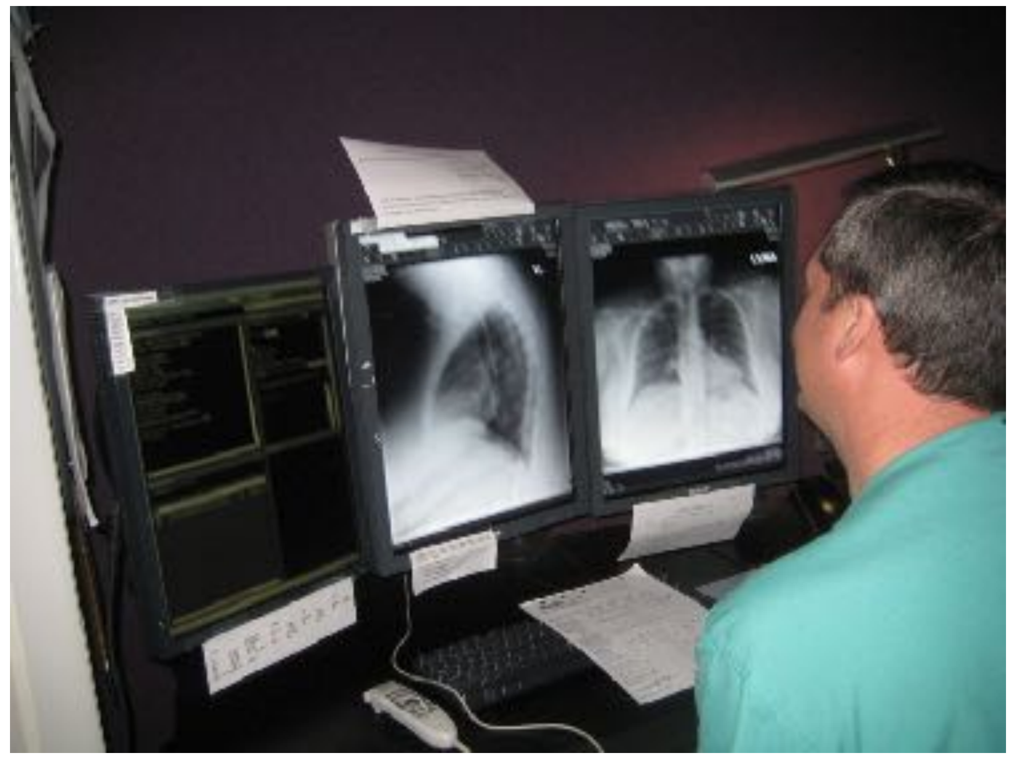




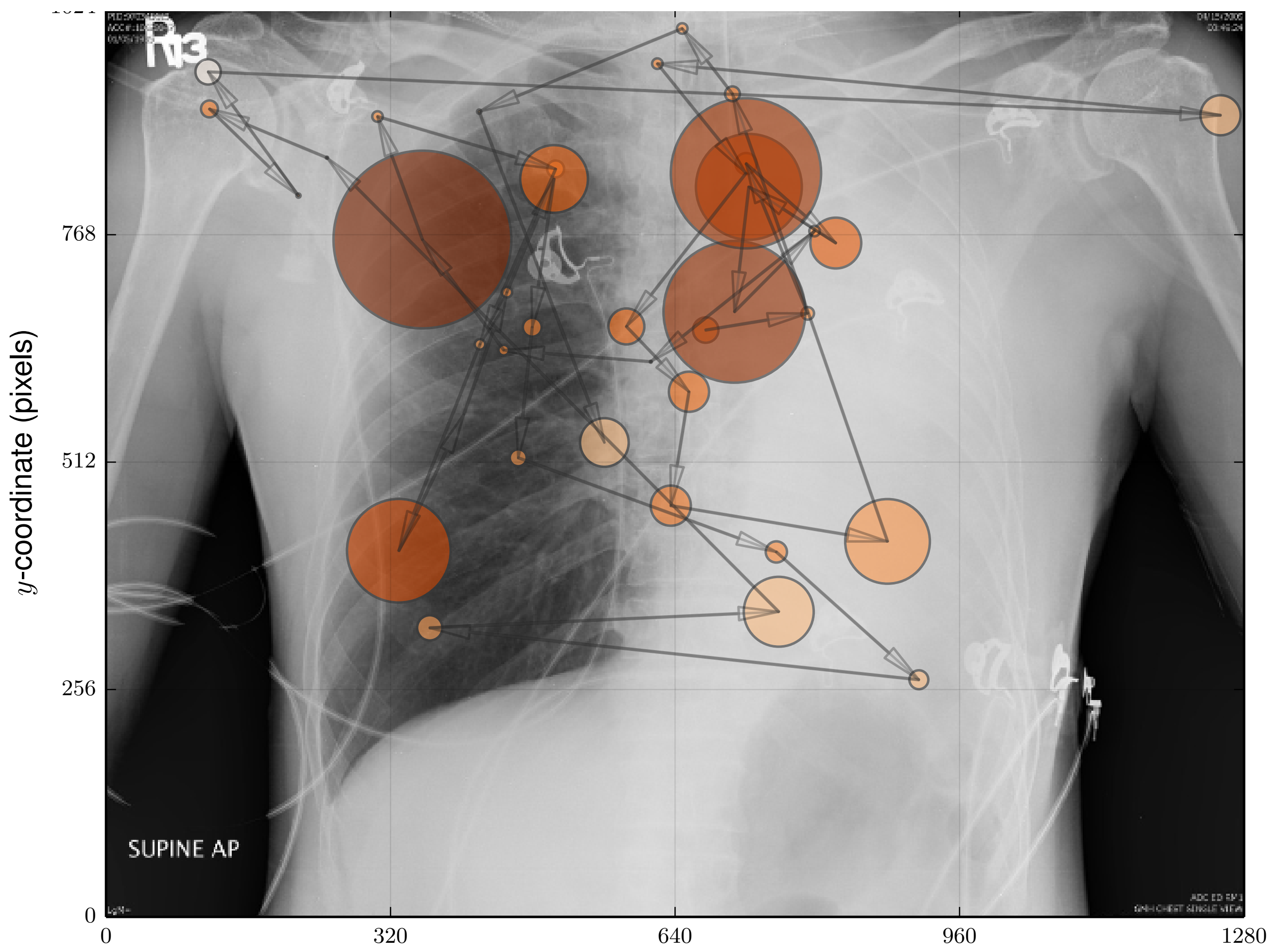
Expert/novice assessment


intern

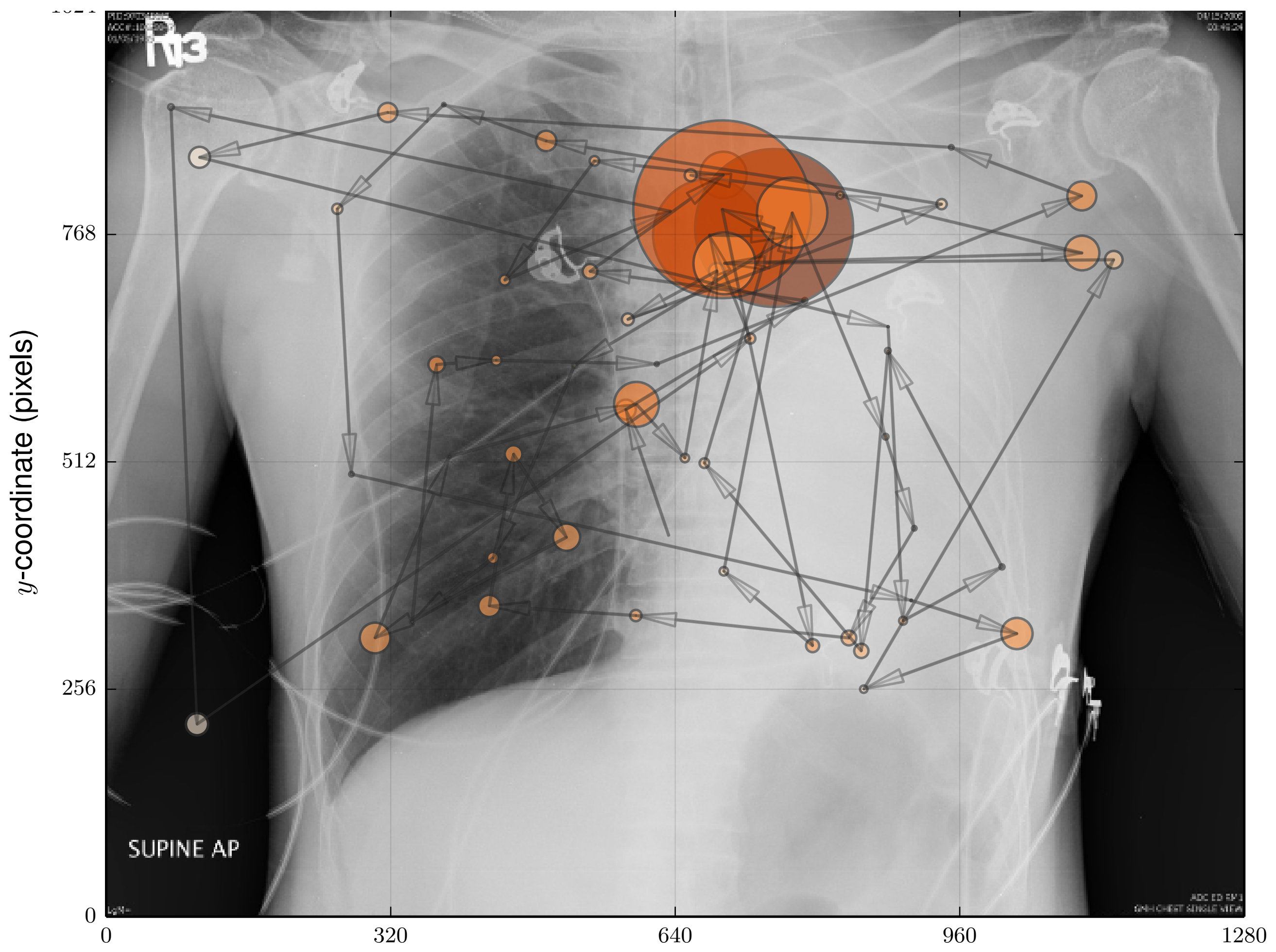

resident


radiologist

Airway, **B**ones, **C**ardiac silhouette, **D**iaphragm, **E**xtern tissue...

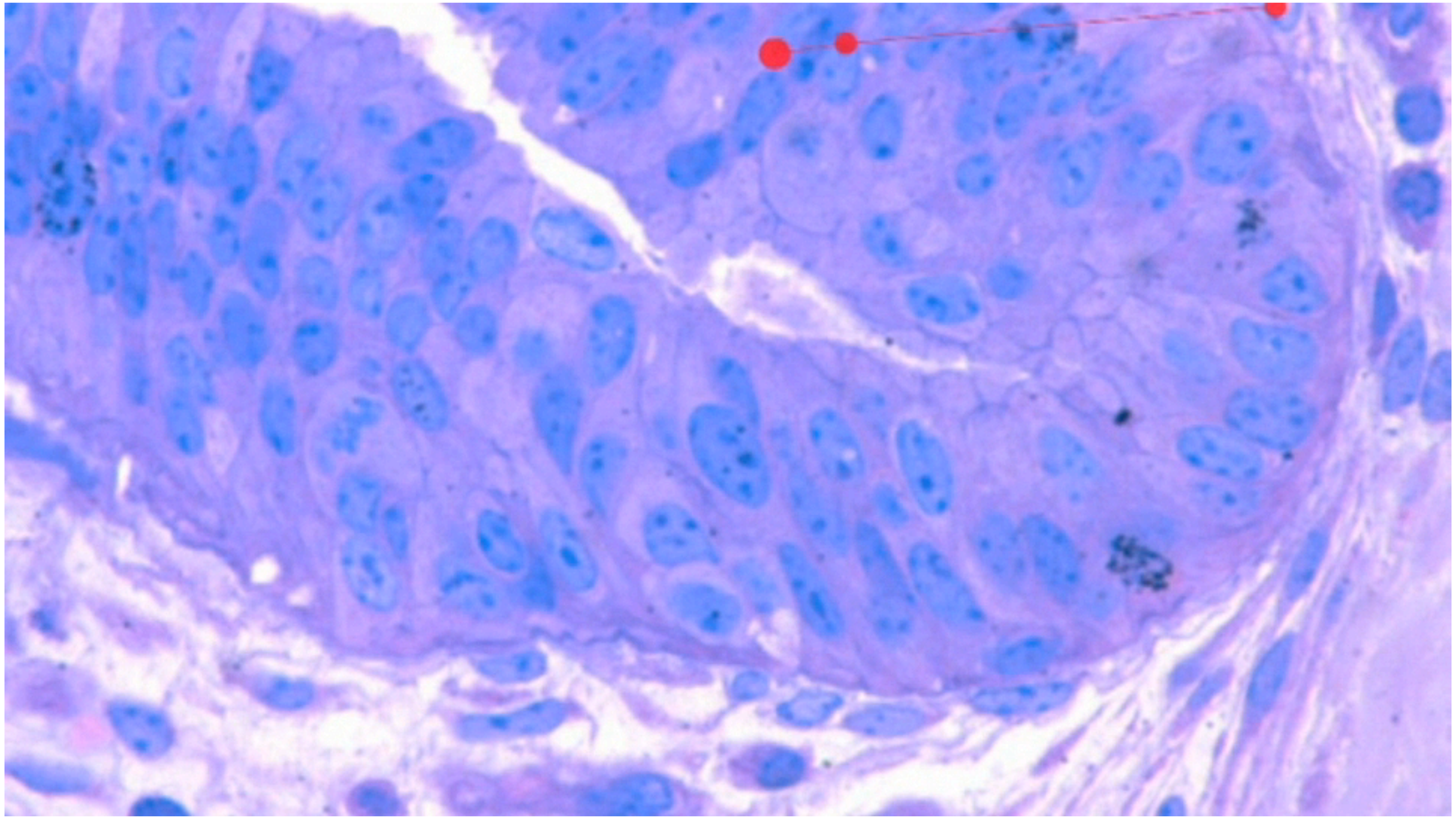


expert



novice

Training



Task: count immunogold (BrdU) stained epithelial cells in bovine mammary tissue

Gaze-Augmented Think-Aloud (Vitak et al., CHI 2012)

Training

- Effects on accuracy?
  - no effect on true positive rate (hits)
  - significant effect on false positive rate (error)

- GATA reduced making mistakes

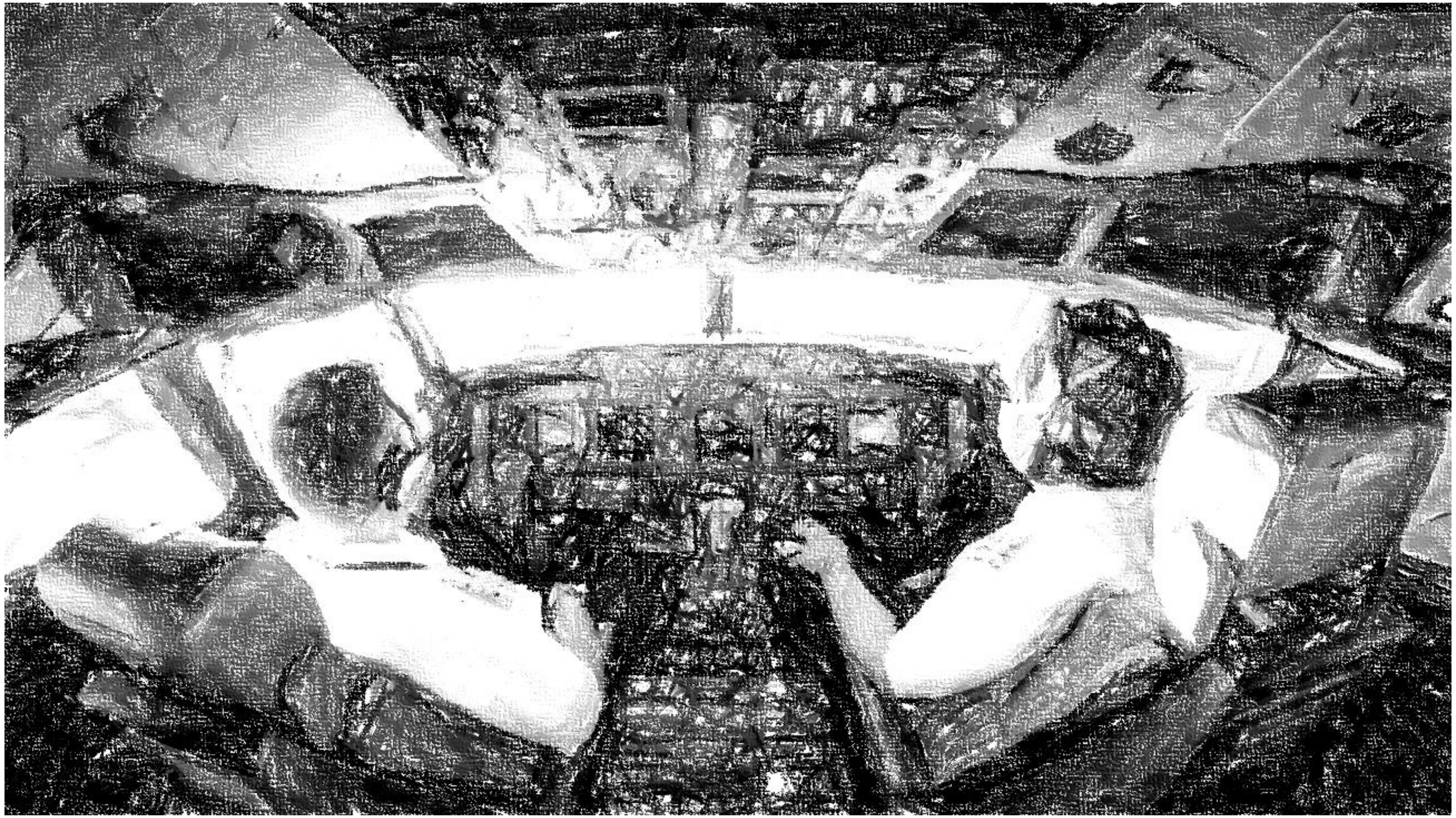
Gaze-Augmented Think-Aloud (Vitak et al., CHI 2012)

Tracking experts

- Ericsson et al. (2006) surveyed experts' gaze:
  - search strategies are task dependent
  - dwell times are shorter
  - make better use of extrafoveal/peripheral information
  - patterns of visual analysis develop with training
  - make use of larger visual span (area around fixation)

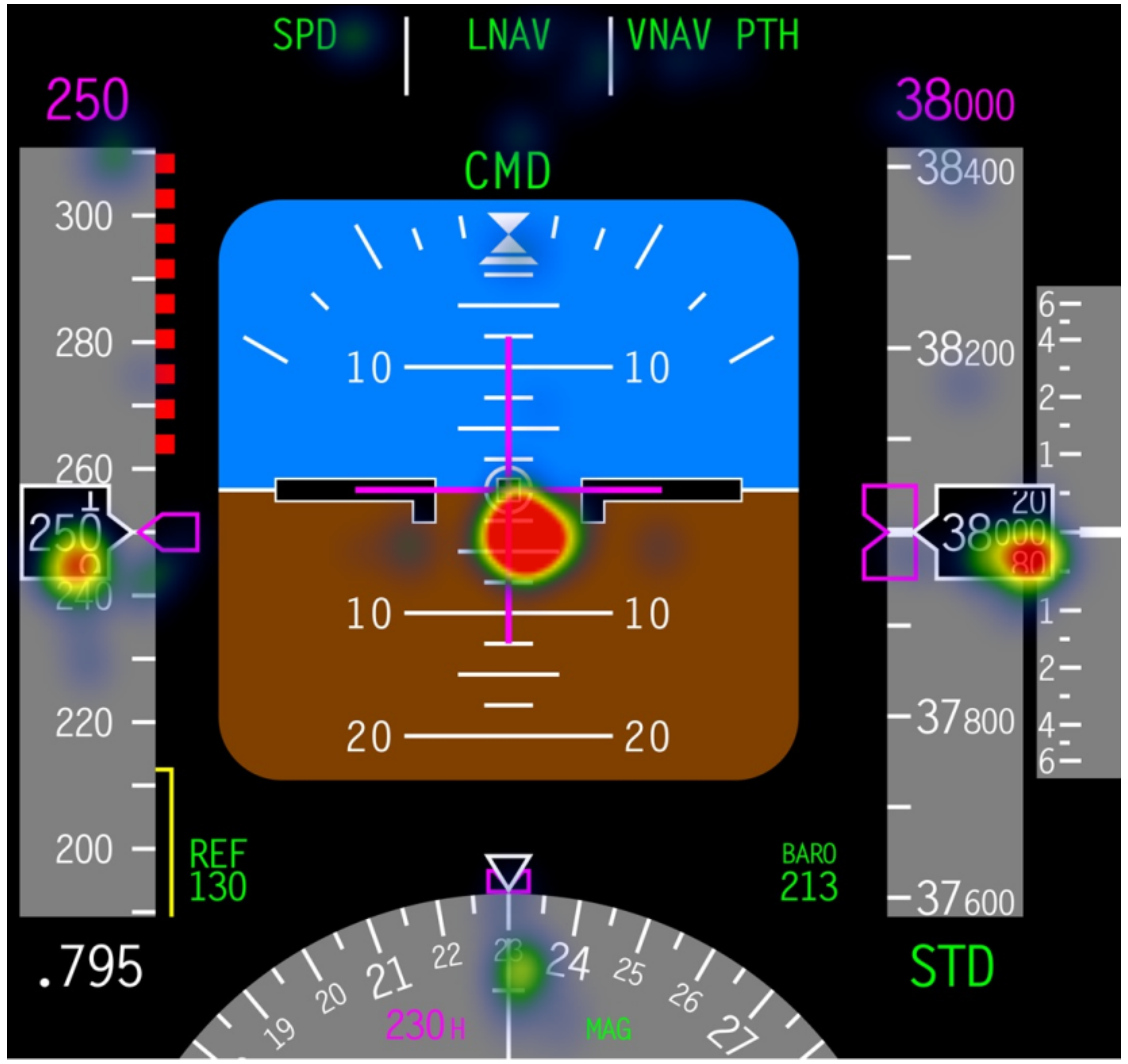
Ronaldo (Ergoneers), pilots (Weibel et al., ETRA 2012), laparoscopic surgeons (courtesy of Stella Atkins, Bin Zheng)

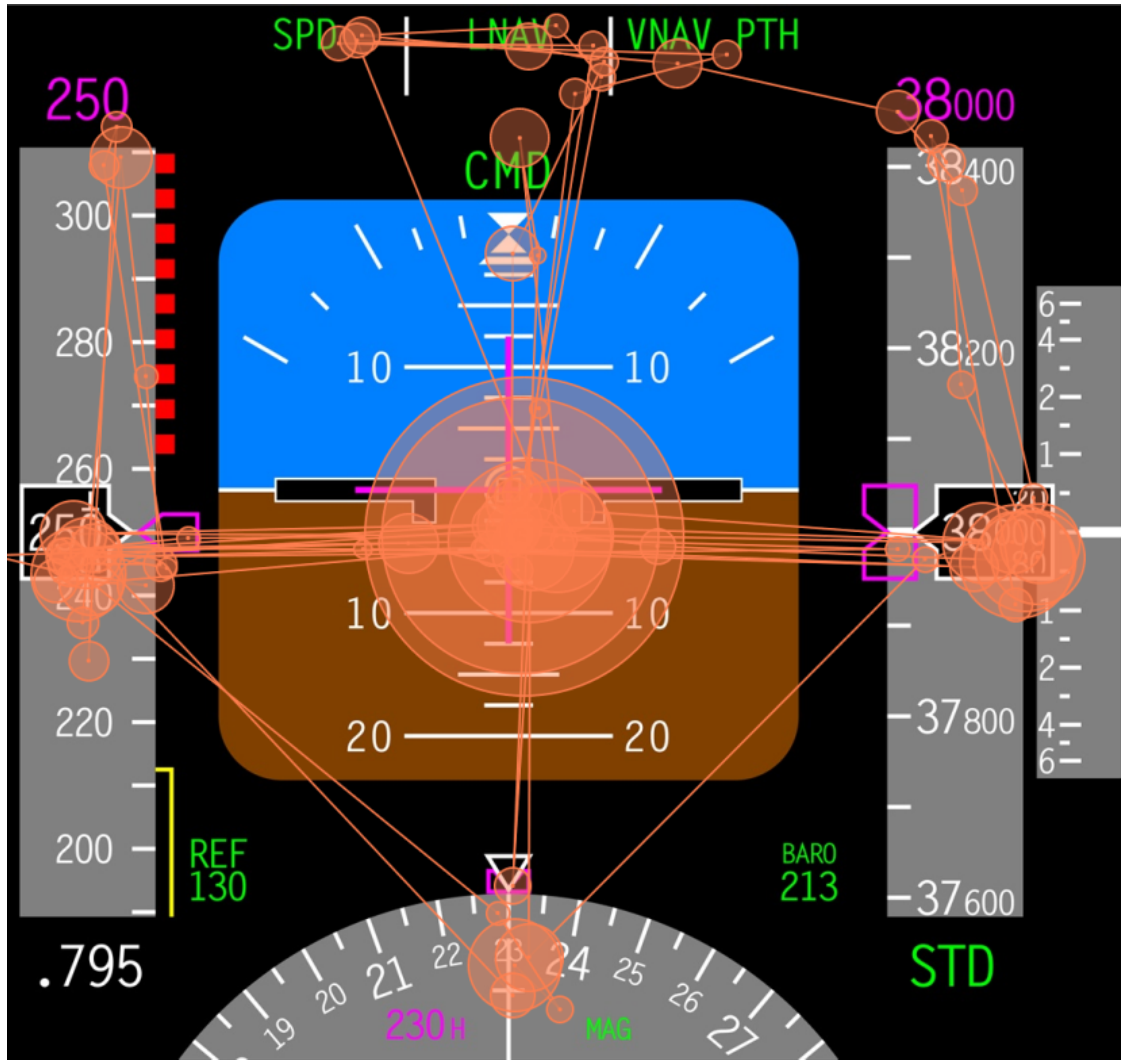
Serious applications



Peysakhovich (PhD Defense, 2016)

Serious applications





- Visual monitoring

Peysakhovich (PhD Defense, 2016)

Serious applications

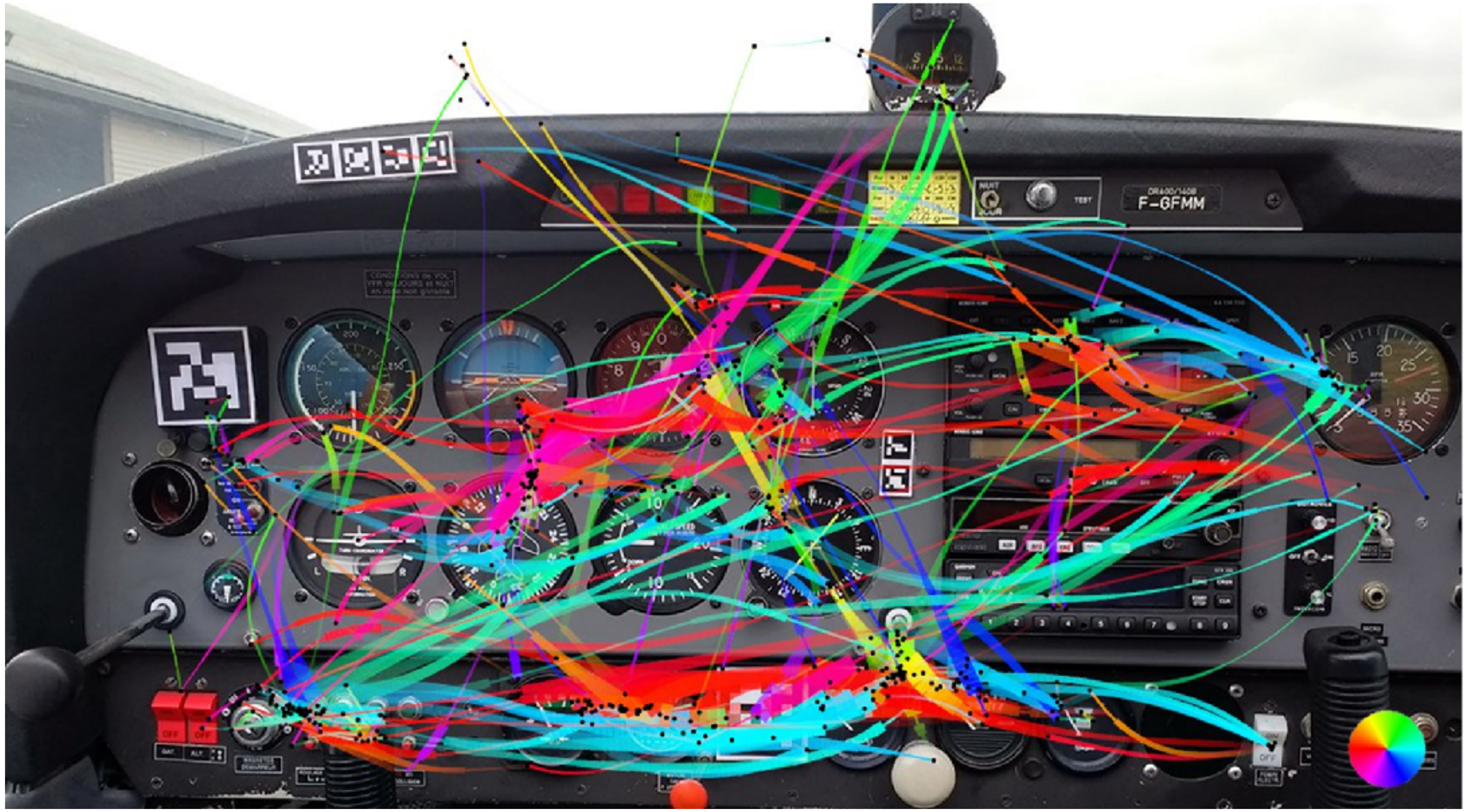
- DR 400

Serious applications

Novice pilot (20 h) with instructor going over startup checklist.

Université Fédérale Toulouse Midi-Pyrénées GROUPE ISAE

Serious applications



- Edge bundling for visualization

Peysakhovich (PhD Defense, 2016)

Serious applications

- Flight / driving simulators

Serious applications

- Flight / driving simulators

Serious applications

Expert

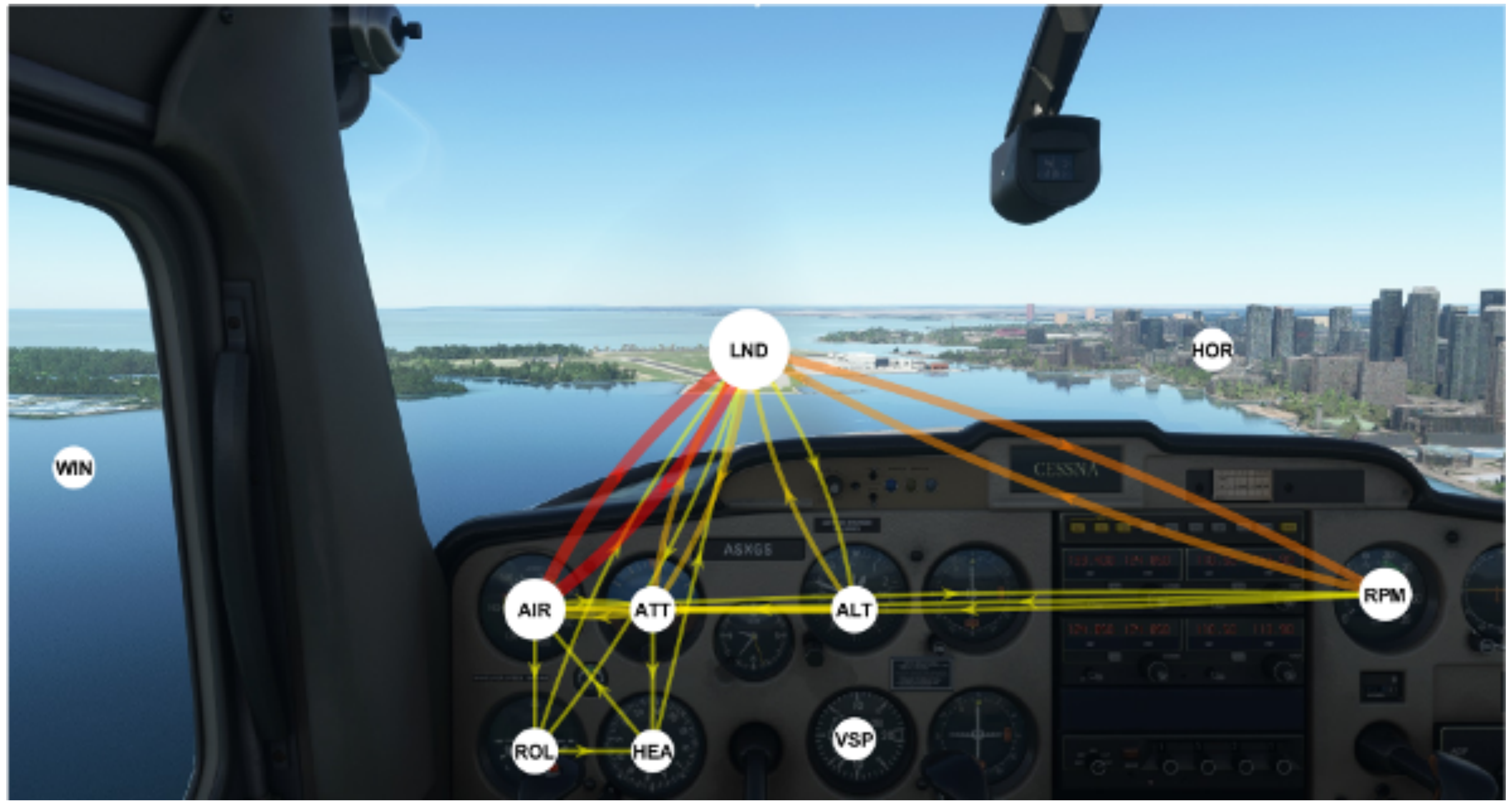
Novice

UNIVERSITY OF WATERLOO | WISA Waterloo Institute for Sustainable Aeronautics

- Flight / driving simulators

Serious applications

Expert



Novice

UNIVERSITY OF WATERLOO | WISA Waterloo Institute for Sustainable Aeronautics

- Flight / driving simulators

Challenges: Areas Of Interest (AOIs)

Duchowski et al. (EMDPA 2020)

- ArUco markers are popular
- OpenCV / OpenGL integration for visualization

Challenges: Areas Of Interest (AOIs)

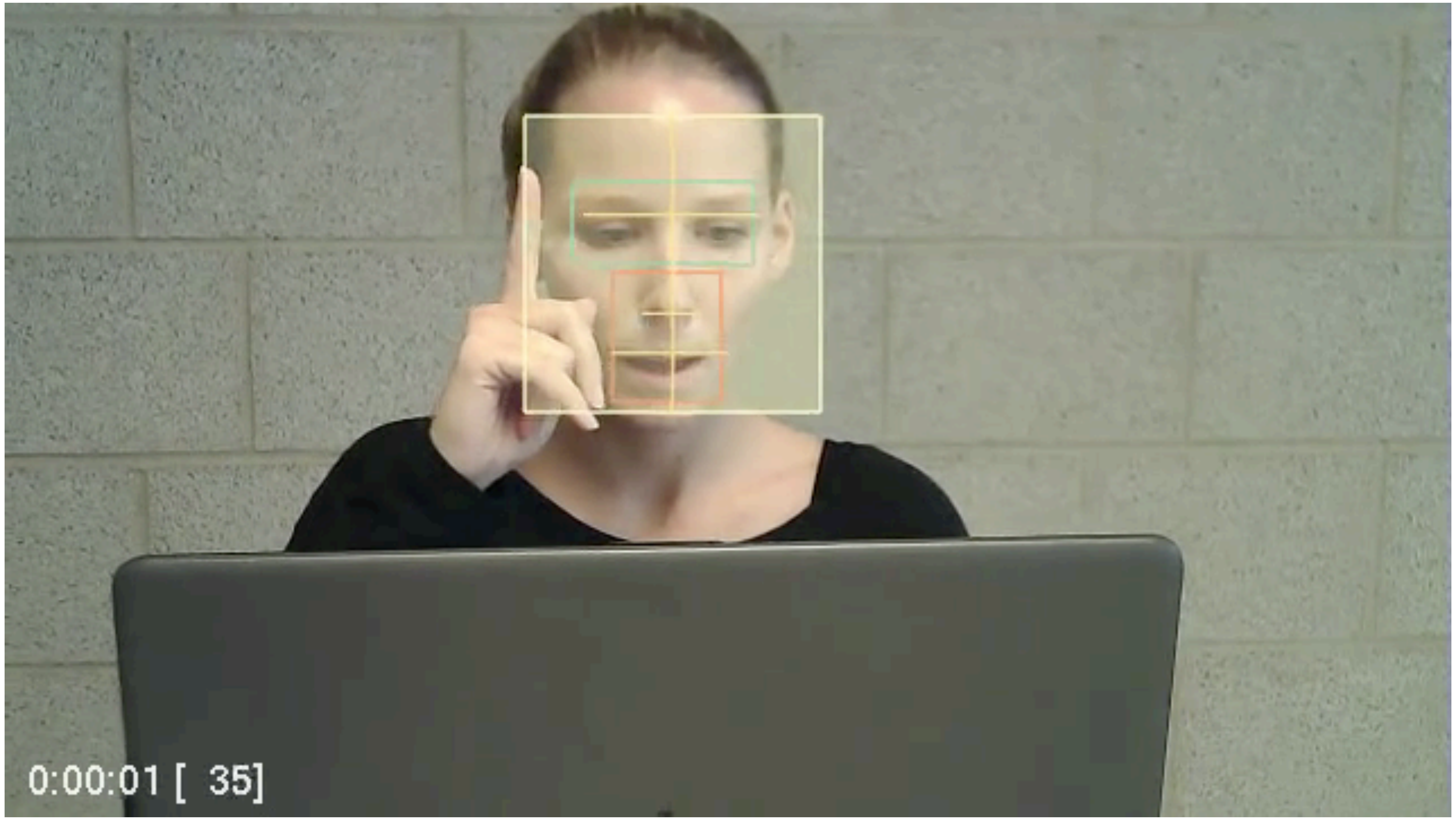
- Dynamic AOIs using SubRip format

Challenges: Areas Of Interest (AOIs)

```
1
0:00:18,250000 --> 0:00:31,916667
v 0.53 0.33 0.56 0.27
v 0.53 0.33 0.58 0.27

2
0:00:31,916667 --> 0:00:36,516667
v 0.53 0.33 0.58 0.27
v 0.53 0.37 0.60 0.24

3
0:00:36,516667 --> 0:00:41,516667
v 0.53 0.37 0.60 0.24
v 0.53 0.37 0.63 0.21

4
0:00:41,516667 --> 0:00:44,700000
v 0.53 0.37 0.63 0.21
v 0.55 0.37 0.66 0.21

...
```

- Dynamic AOIs using SubRip format

Challenges: Automatic AOI Segmentation

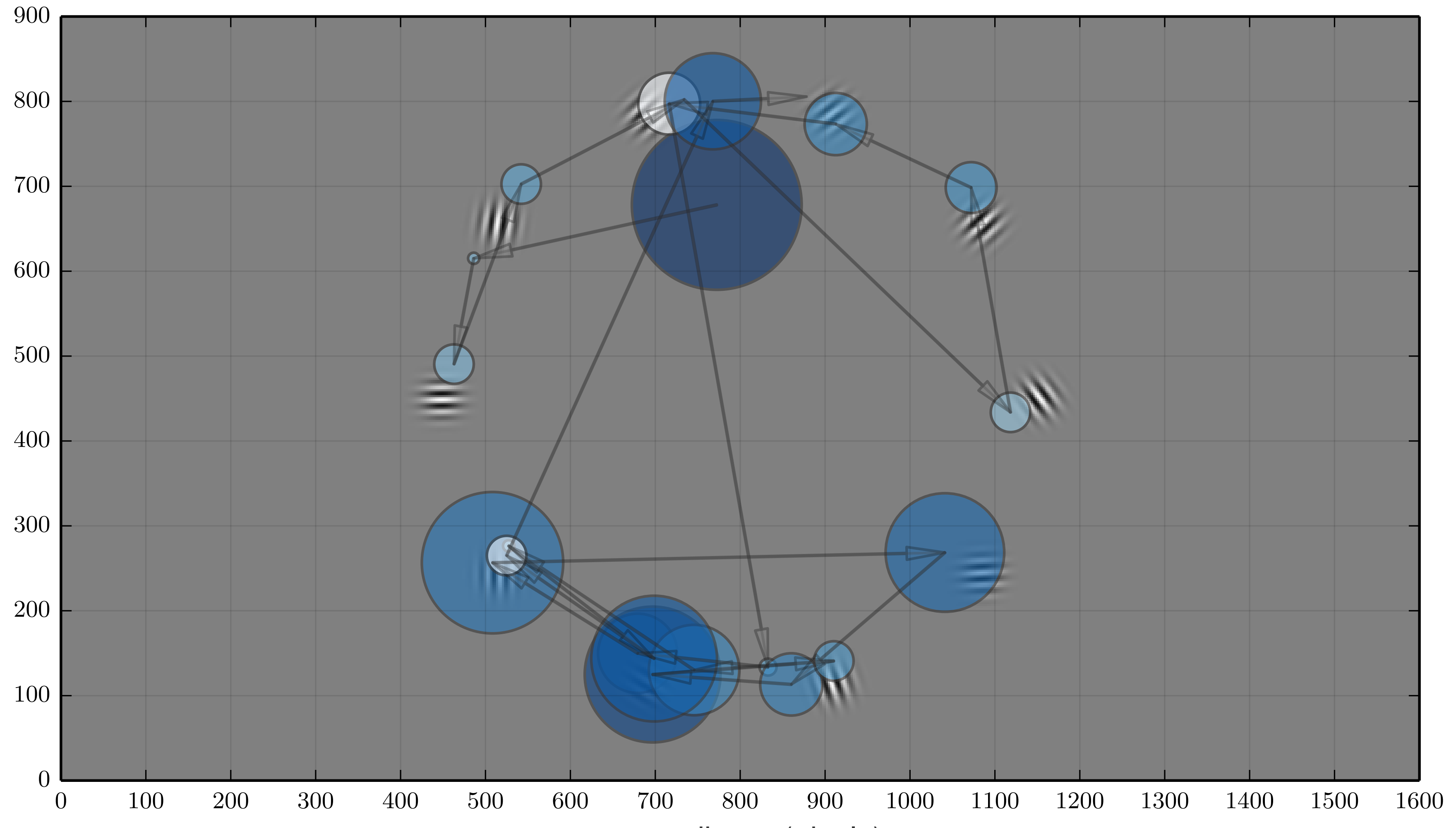


Duchowski et al. (ETVIS @ ETRA 2019)

- Heuristics for eye, nose, mouth regions

Summary: Diagnostics

Ambient/focal visualization



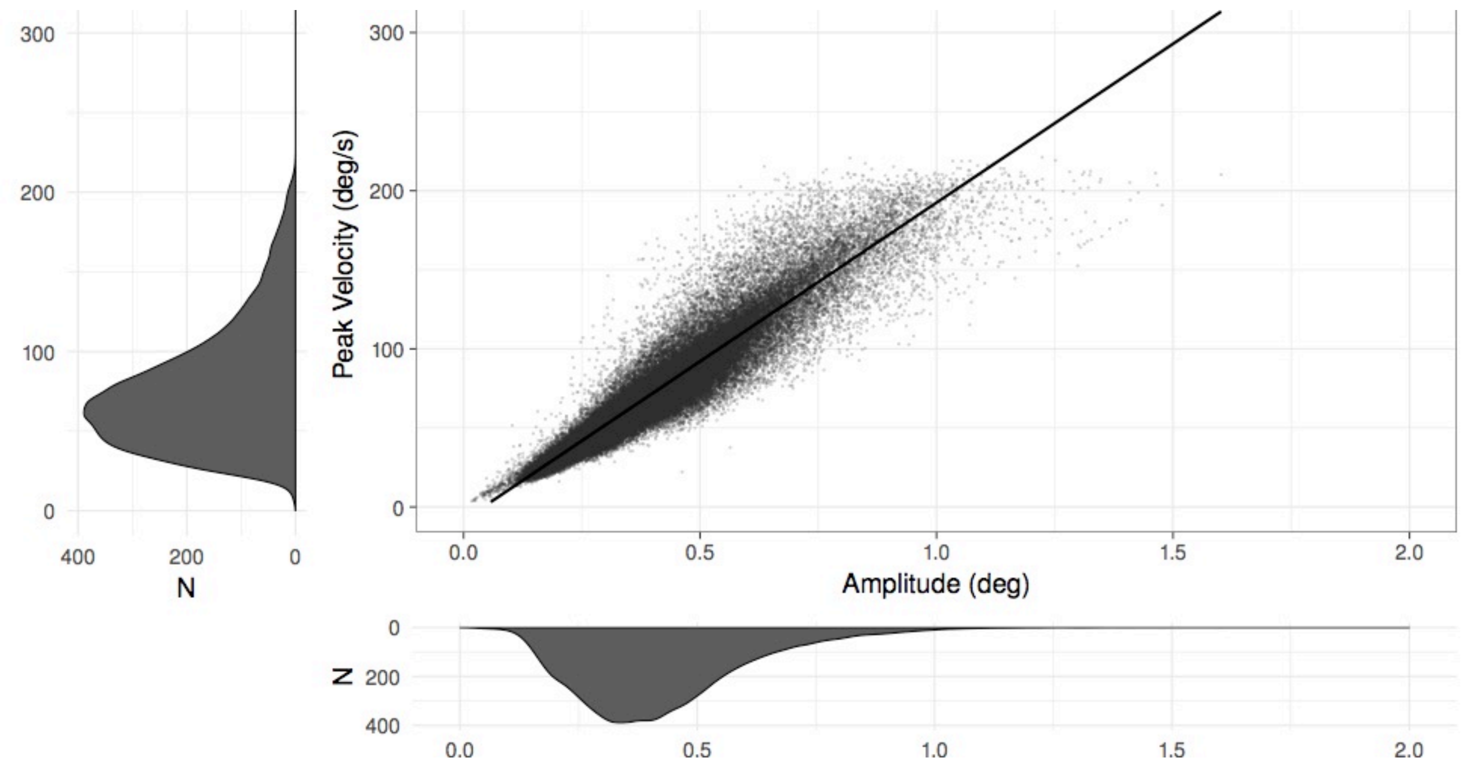
$$\mathcal{K}_i = \frac{d_i - \mu_d}{\sigma_d} - \frac{a_i - \mu_a}{\sigma_a}$$

Transition entropy

$$H_t = -\sum_{i \in \mathcal{S}} \pi_i \sum_{j \in \mathcal{S}} \log p_{ij}$$

- Outstanding problems:
  - various analysis algorithms needed, e.g., comparison
  - visualization innovations

Summary: Diagnostics

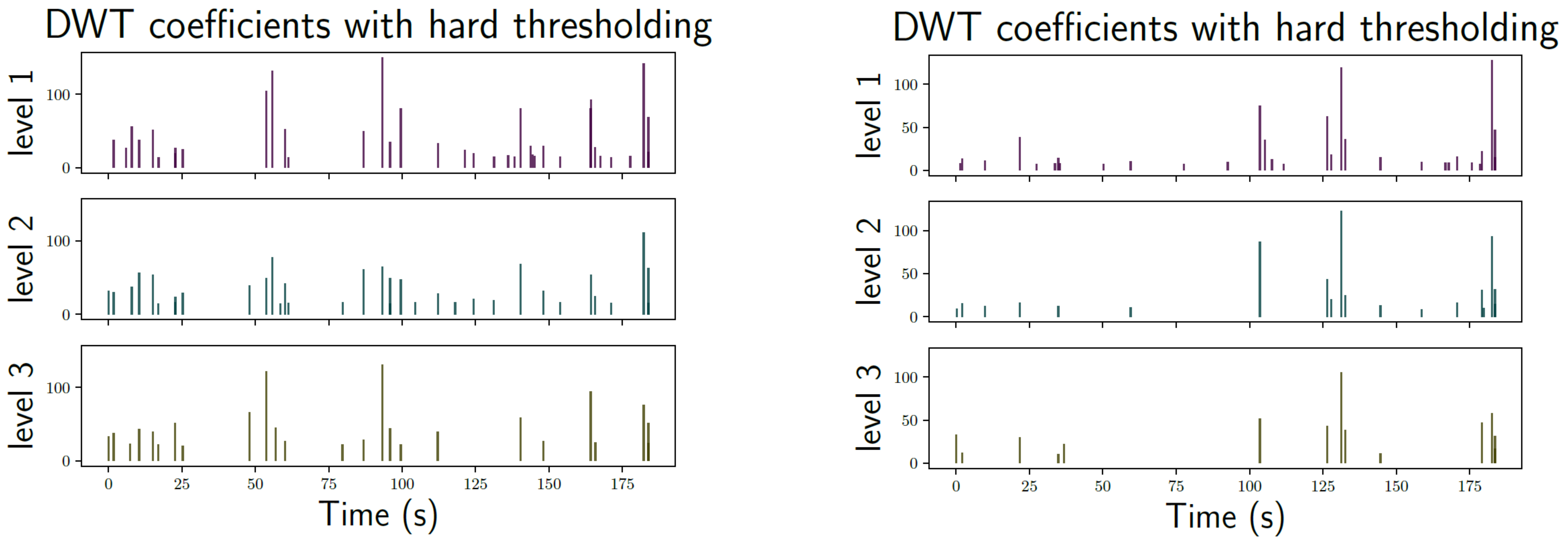


$$\dot{x}_n = \frac{x_{n+2} + x_{n+1} - x_{n-1} - x_{n-2}}{6\Delta t}$$

$$\sigma_x = \sqrt{\langle \dot{x}^2 \rangle - \langle \dot{x} \rangle^2}, \quad \sigma_y = \sqrt{\langle \dot{y}^2 \rangle - \langle \dot{y} \rangle^2}$$

$$\eta_x = \lambda \sigma_x, \quad \eta_y = \lambda \sigma_y$$

Index of Pupillary Activity



$$x(t) = \sum_{j,k=-\infty}^{\infty} c_{j,k} \psi_{j,k}, \quad j,k \in \mathbf{Z}$$

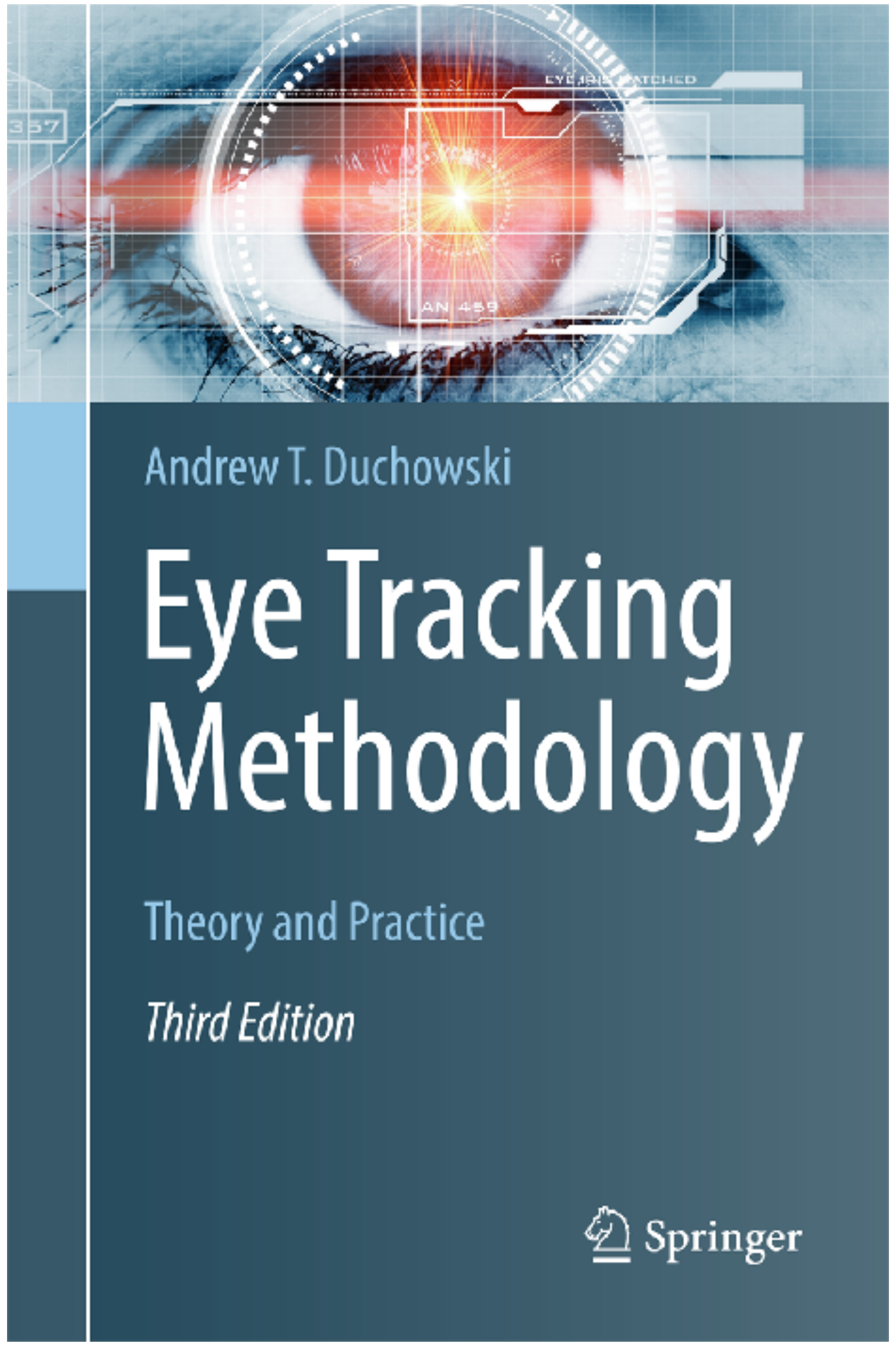
Duchowski et al. (CHI 2018)

- Outstanding problems:
  - measuring user state: microsaccades, pupil diameter
  - e.g., cognitive load

For more information…

- Eye Tracking Methodology, **3rd ed.** 2017
  - ISBN: 978-3-319-57881-1
  - over 4,000 citations

- Updated with:
  - advanced metrics
  - gaze analytics pipeline
  - and more…



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- Eye Tracking Methodology, **3rd ed.** 2017
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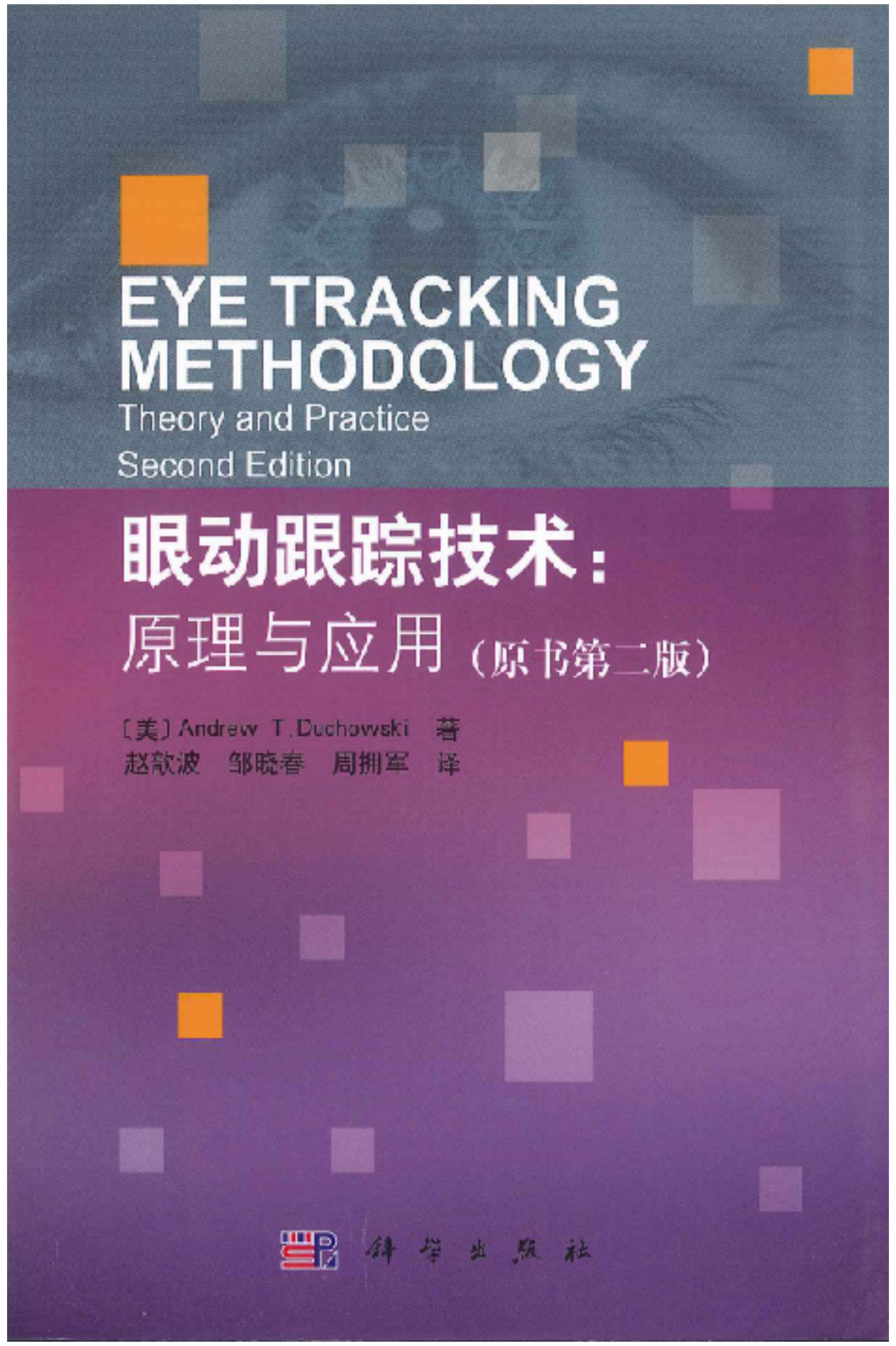
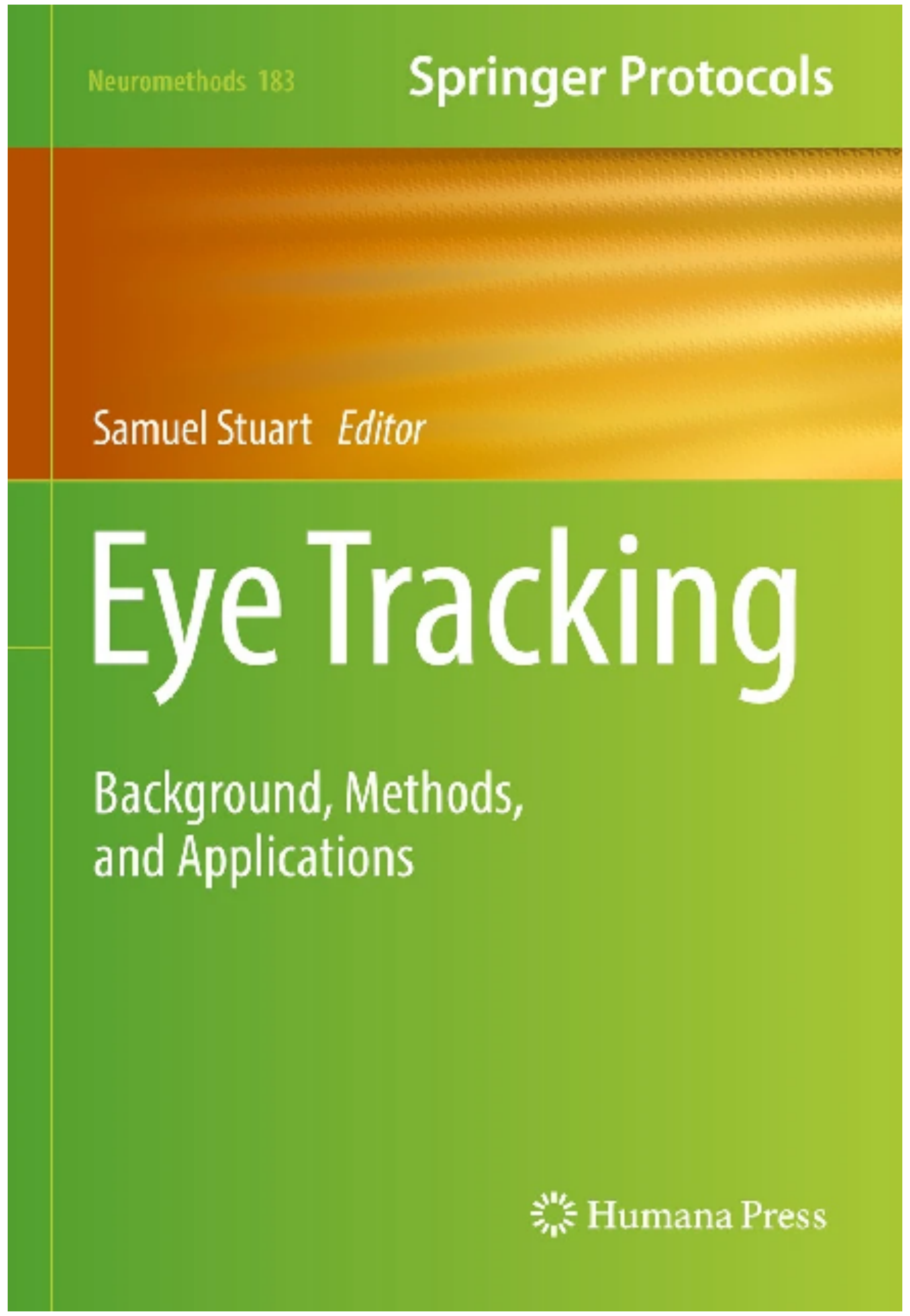
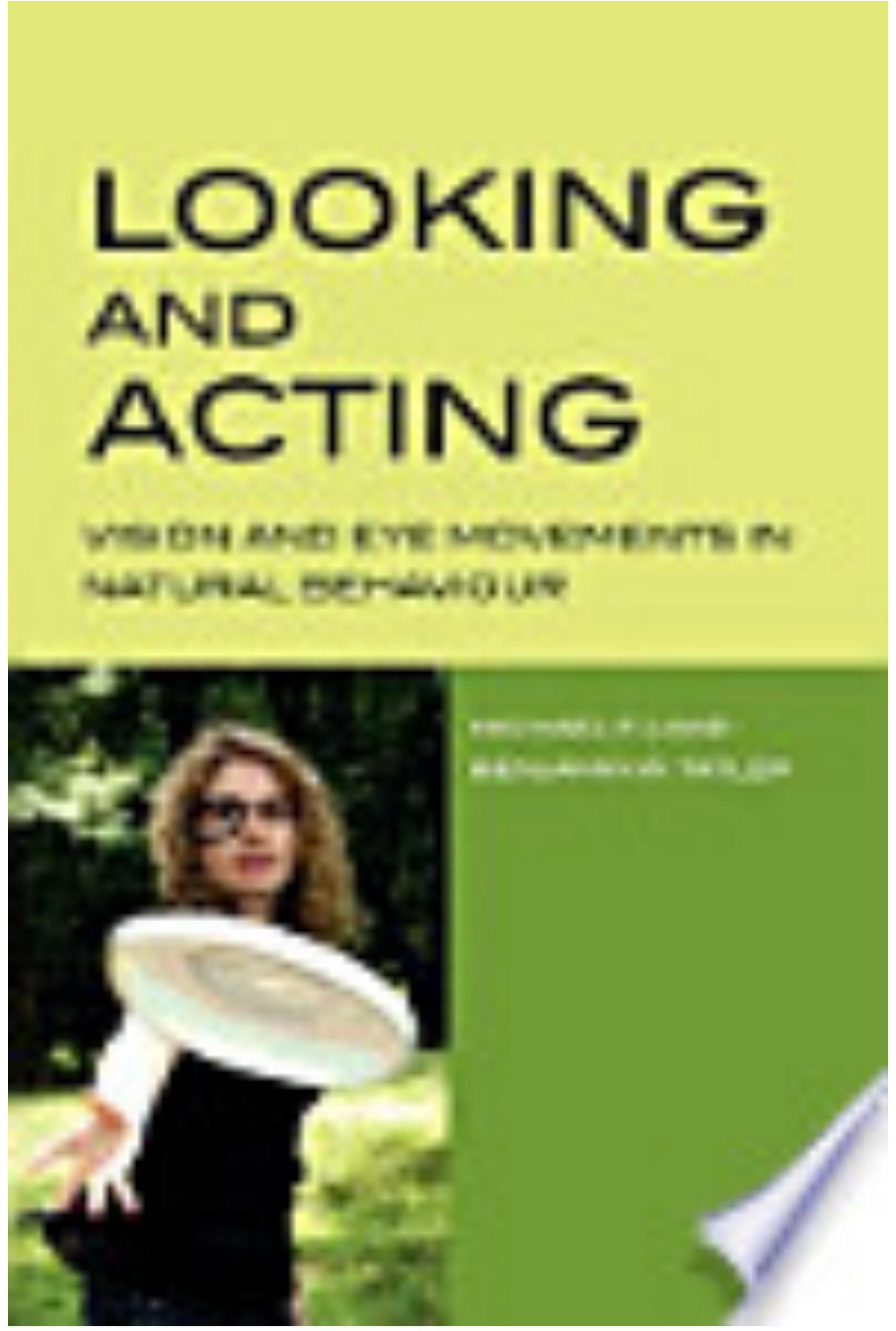
- Updated with:
  - advanced metrics
  - gaze analytics pipeline
  - also available in Chinese



For more information...





Eye Tracking

Future Directions

assistive

- subtitles
- training

active

- multi-modality
- gaze gestures

passive

- high-speed tracking
- saccade prediction

expressive

- expressiveness
- periocular skin animation

diagnostic (off-line)

- advanced analysis
- visualization

Eye Tracking

Gaze Analytics

Andrew T. Duchowski *duchowski@clemson.edu*

Gaze Analytics Pipeline

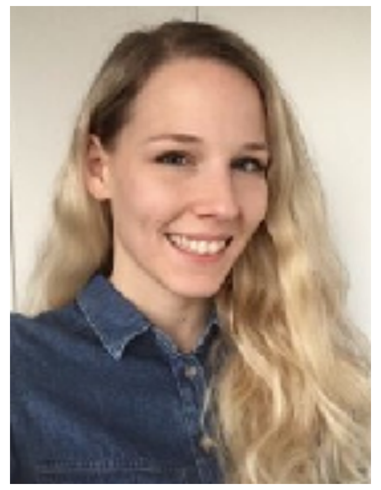
Andrew T. Duchowski

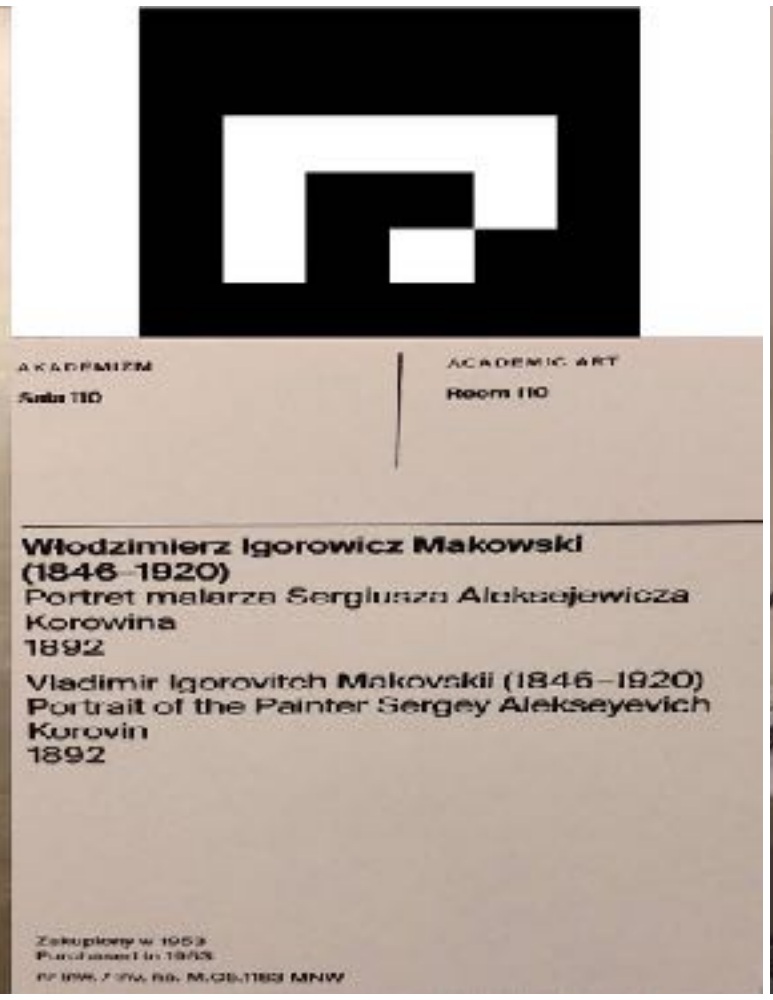
CLEMSON UNIVERSITY

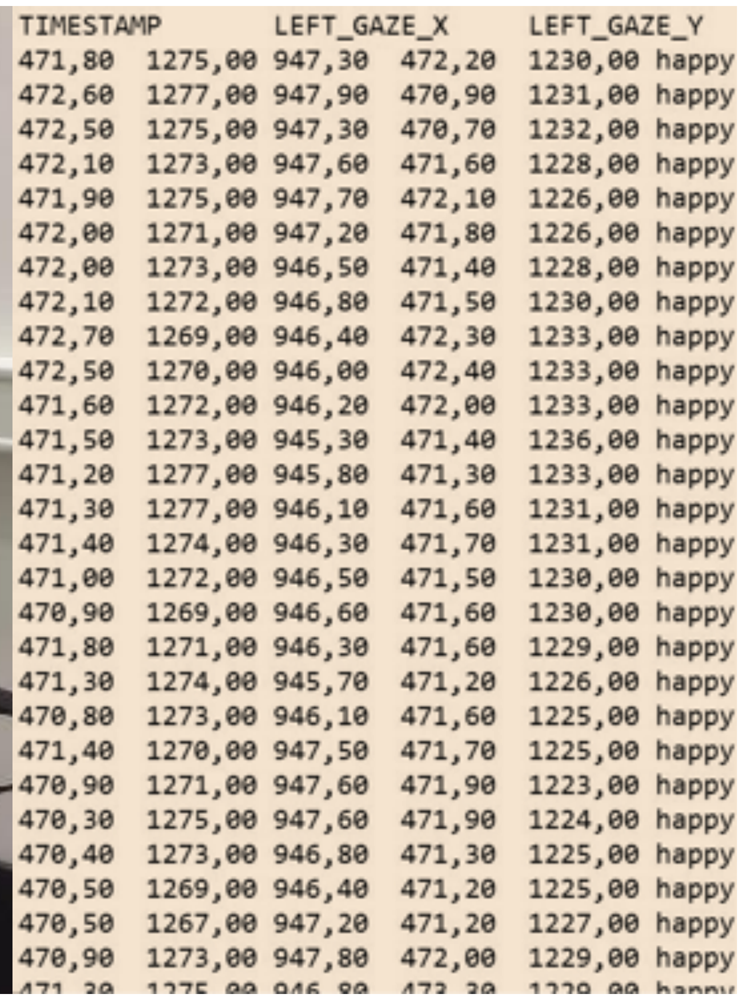
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

FACULTY OF SCIENCE
Department of Psychology

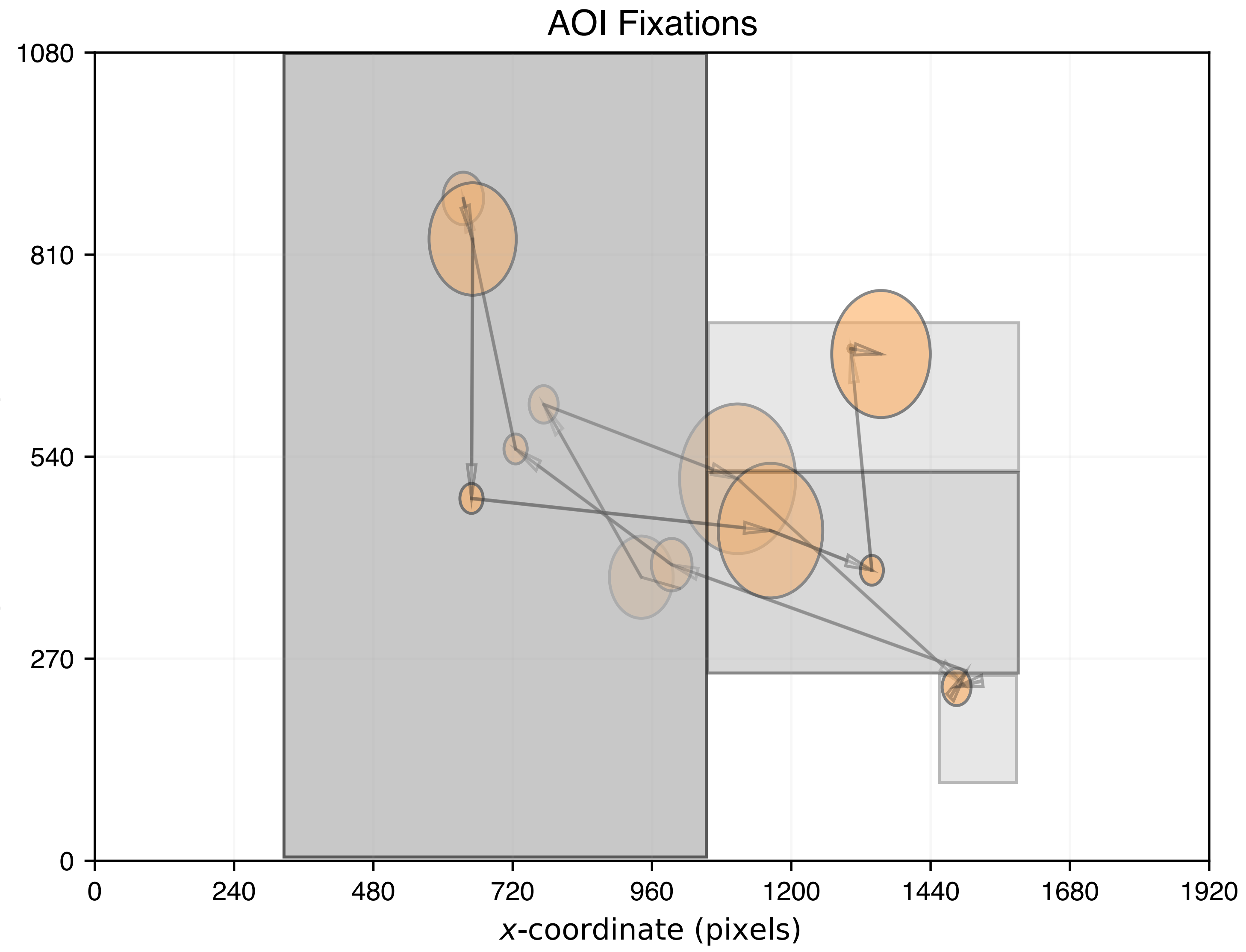
Nina Gehrer







TIMESTAMP		LEFT_GAZE_X		LEFT_GAZE_Y	
471,80	1275,00	947,30	472,20	1230,00	happy
472,60	1277,00	947,90	470,90	1231,00	happy
472,50	1275,00	947,30	470,70	1232,00	happy
472,10	1273,00	947,60	471,60	1228,00	happy
471,90	1275,00	947,70	472,10	1226,00	happy
472,00	1271,00	947,20	471,80	1226,00	happy
472,00	1273,00	946,50	471,40	1228,00	happy
472,10	1272,00	946,80	471,50	1230,00	happy
472,70	1269,00	946,40	472,30	1233,00	happy
472,50	1270,00	946,00	472,40	1233,00	happy
471,60	1272,00	946,20	472,00	1233,00	happy
471,50	1273,00	945,30	471,40	1236,00	happy
471,20	1277,00	945,80	471,30	1233,00	happy
471,30	1277,00	946,10	471,60	1231,00	happy
471,40	1274,00	946,30	471,70	1231,00	happy
471,00	1272,00	946,50	471,50	1230,00	happy
470,90	1269,00	946,60	471,60	1230,00	happy
471,80	1271,00	946,30	471,60	1229,00	happy
471,30	1274,00	945,70	471,20	1226,00	happy
470,80	1273,00	946,10	471,60	1225,00	happy
471,40	1270,00	947,50	471,70	1225,00	happy
470,90	1271,00	947,60	471,90	1223,00	happy
470,30	1275,00	947,60	471,90	1224,00	happy
470,40	1273,00	946,80	471,30	1225,00	happy
470,50	1269,00	946,40	471,20	1225,00	happy
470,50	1267,00	947,20	471,20	1227,00	happy
470,90	1273,00	947,80	472,00	1229,00	happy



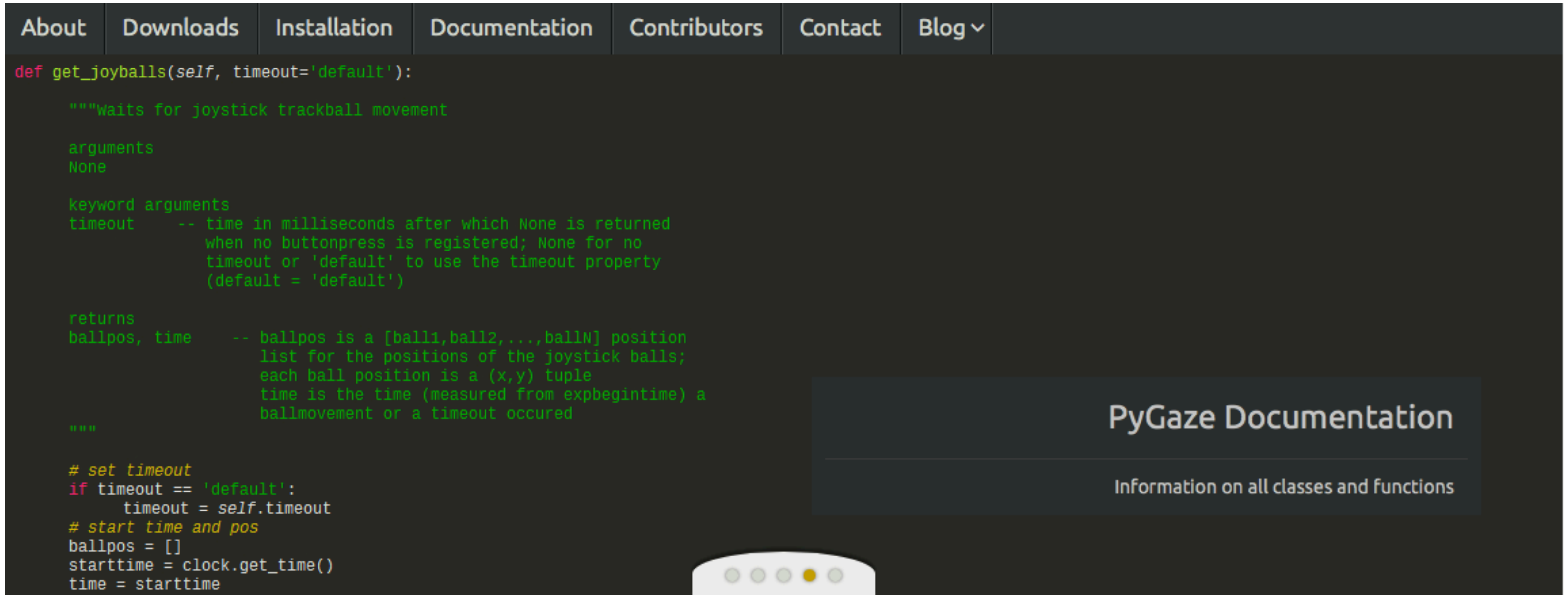
Gaze Analytics Pipeline: Origins

- What is it?
  - series of Python scripts followed by analysis in R
  - goal: automation

- How did it start, evolve?
  - ETH Winter School 2016

Gaze Analytics Pipeline: Ontology

- Where does it fit?
  - Note quite PyGaze (www.pygaze.org)

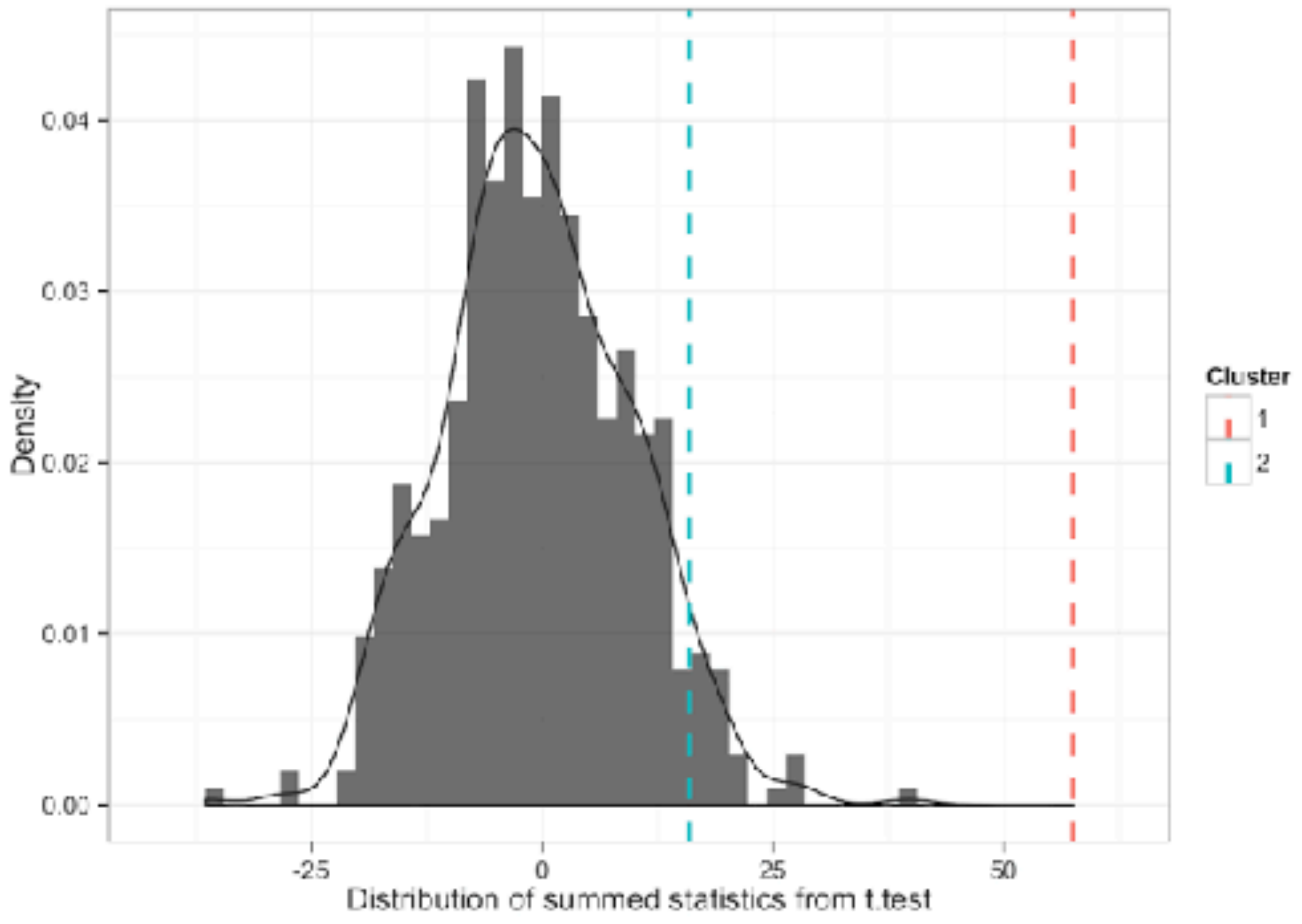


Gaze Analytics Pipeline: Ontology

- Where does it fit?
  - Note quite `eyetrackingR` (www.eyetracking-r.com)

What is *eyetrackingR*?

eyetrackingR is an R package designed to make dealing with eye-tracking data easier. It handles tasks along the pipeline from raw data to analysis and visualization – as illustrated in the eyetrackingR workflow. Check out the vignettes to the left for some gentle introductions to using eyetrackingR for several popular types of analyses, including growth-curve analysis, onset-contingent reaction time analyses, as well as several non-parametric bootstrapping approaches.

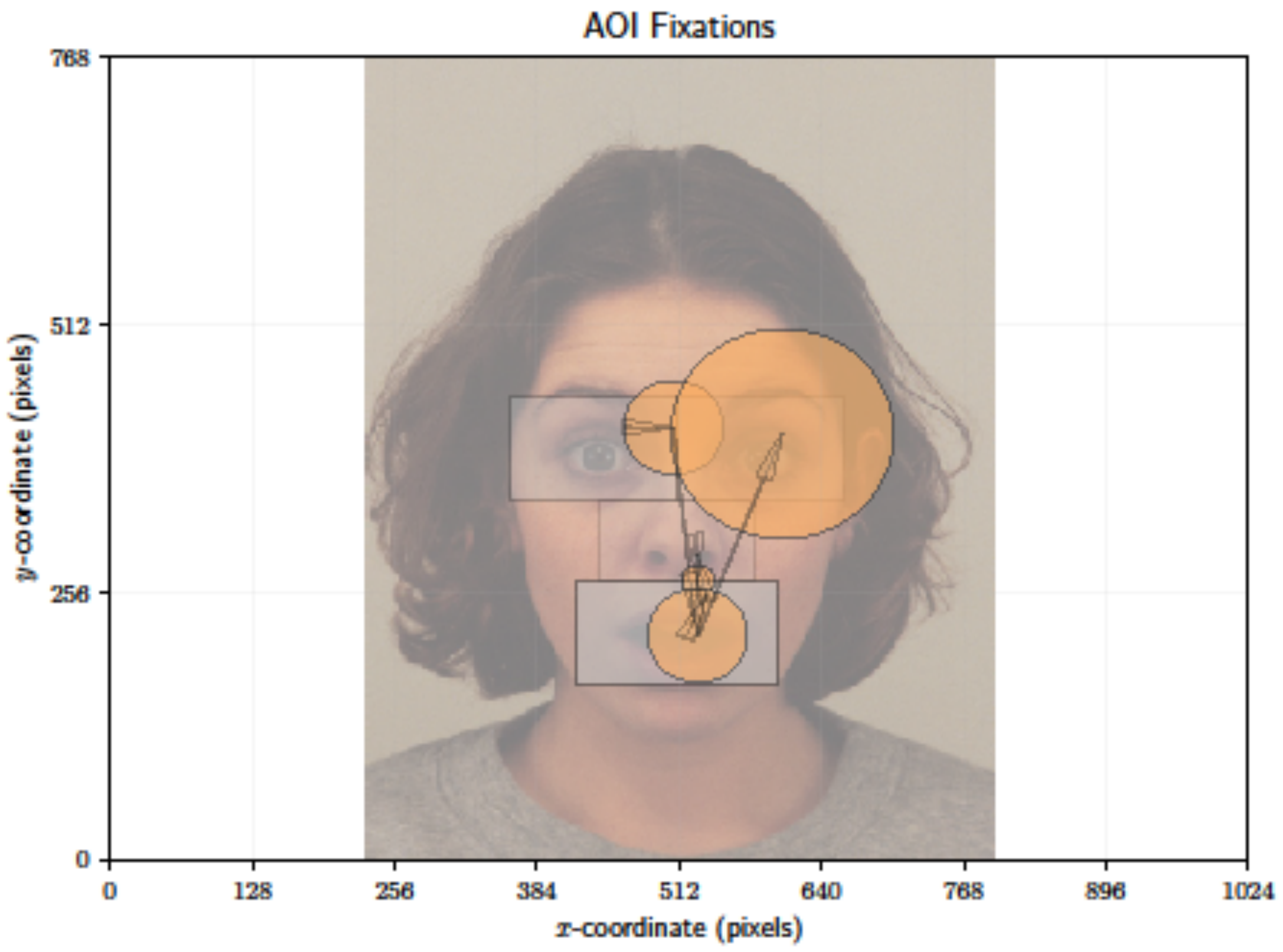


Bootstrapped cluster analysis distribution plot

Gaze Analytics Pipeline: Objectives

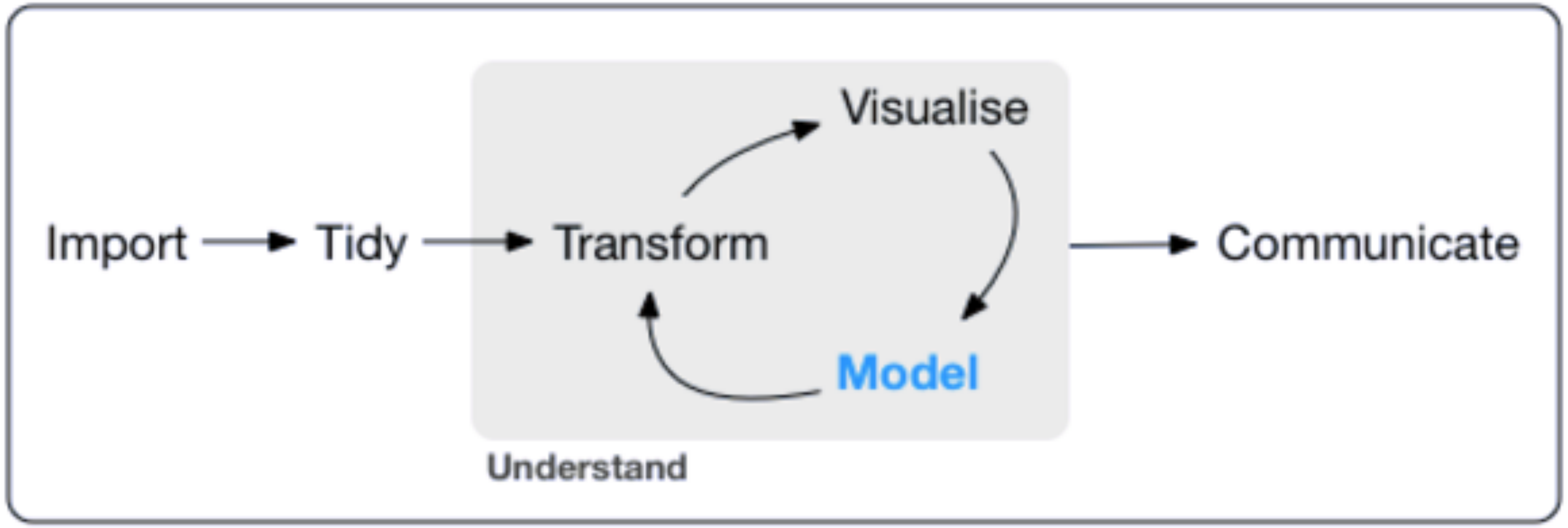
- How does it work?
  - key goals: visualization and analysis

see Gehrer et al., [2018], *Gaze Analytic Methods in Clinical Psychology*, ETRA 2018



Gaze Analytics Pipeline: Objectives

- How does it work?
  - key goals: visualization and analysis
  - like R's *tidyverse*, sort of
  - idea is the same: import data, tidy, visualize, collate, analyze
  - each step a different Python script

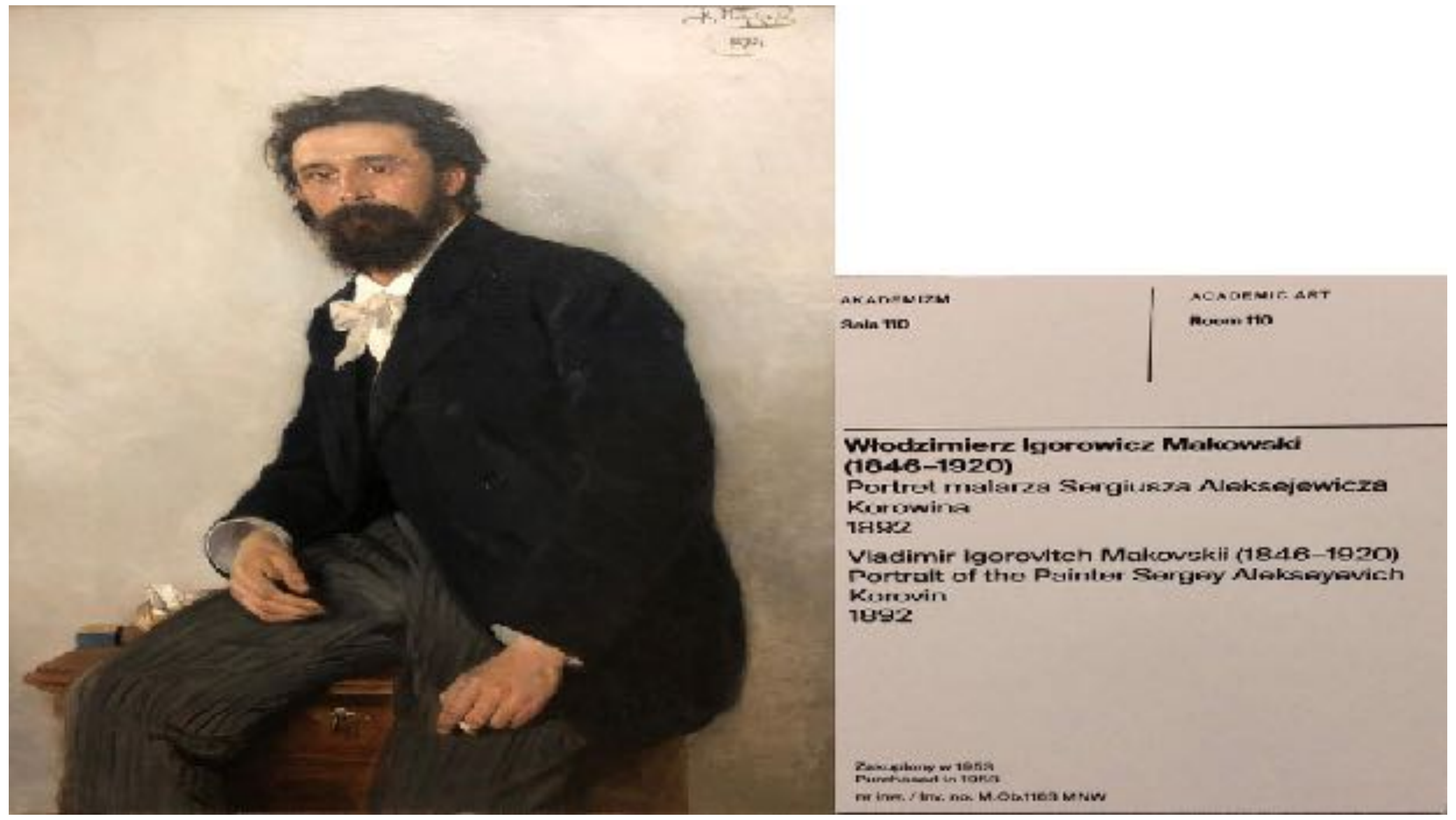


Gaze Analytics Pipeline: Objectives

- How does it work?
  - key goals: visualization and analysis

Mock study on visibility of fiducial markers

- Modeled on art gallery display, e.g., mobile eye-tracking study
  - need to vary size and presence of maker (3 levels)
  - ideally cannot use same portrait more than once



Mock study on visibility of fiducial markers

- Modeled on art gallery display, e.g., mobile eye-tracking study
  - need to vary size and presence of maker (3 levels)
  - add another portrait (2 levels…or more)

Mock study on visibility of fiducial markers

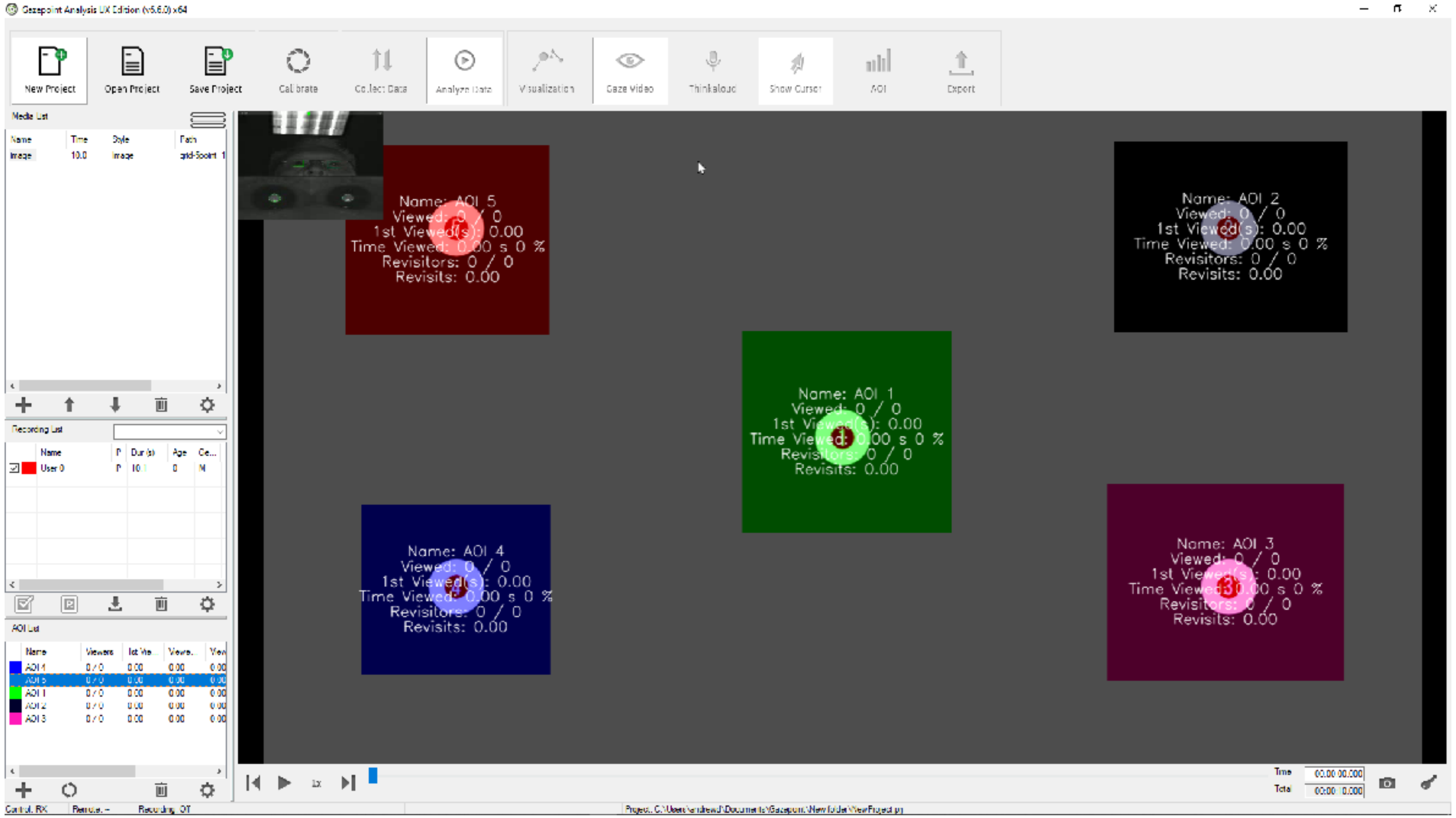
- Stimulus presentation (PsychoPy)
  - shown for 4 s (arbitrary)
  - size of display and images matters (a lot!)

Apparatus

- EyeLink 1000 Eye Tracker (SR Research) or Gazepoint GP3
- Sampling at 500, 150, or 60 Hz
- Screen size: 22 inch
- Screen resolution: 1920 x 1080 pixels
- Screen distance: 60 cm
- 5-point calibration

Gaze Analytics Pipeline: Record

- How to record data (for offline analysis)?
  - can use vendor software (e.g., Gazepoint Analysis, EyeLink, ...)



Gaze Analytics Pipeline: Record

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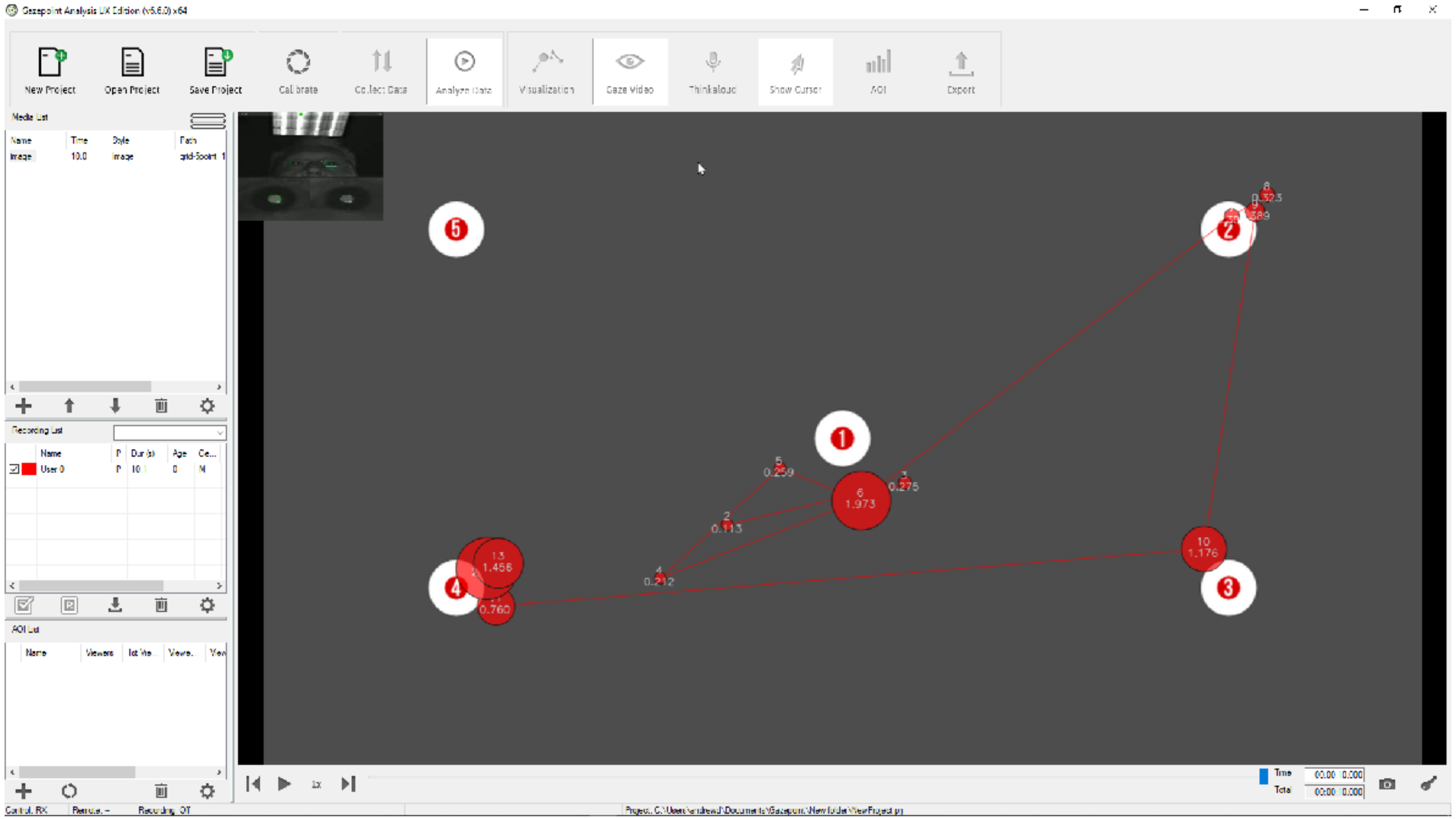
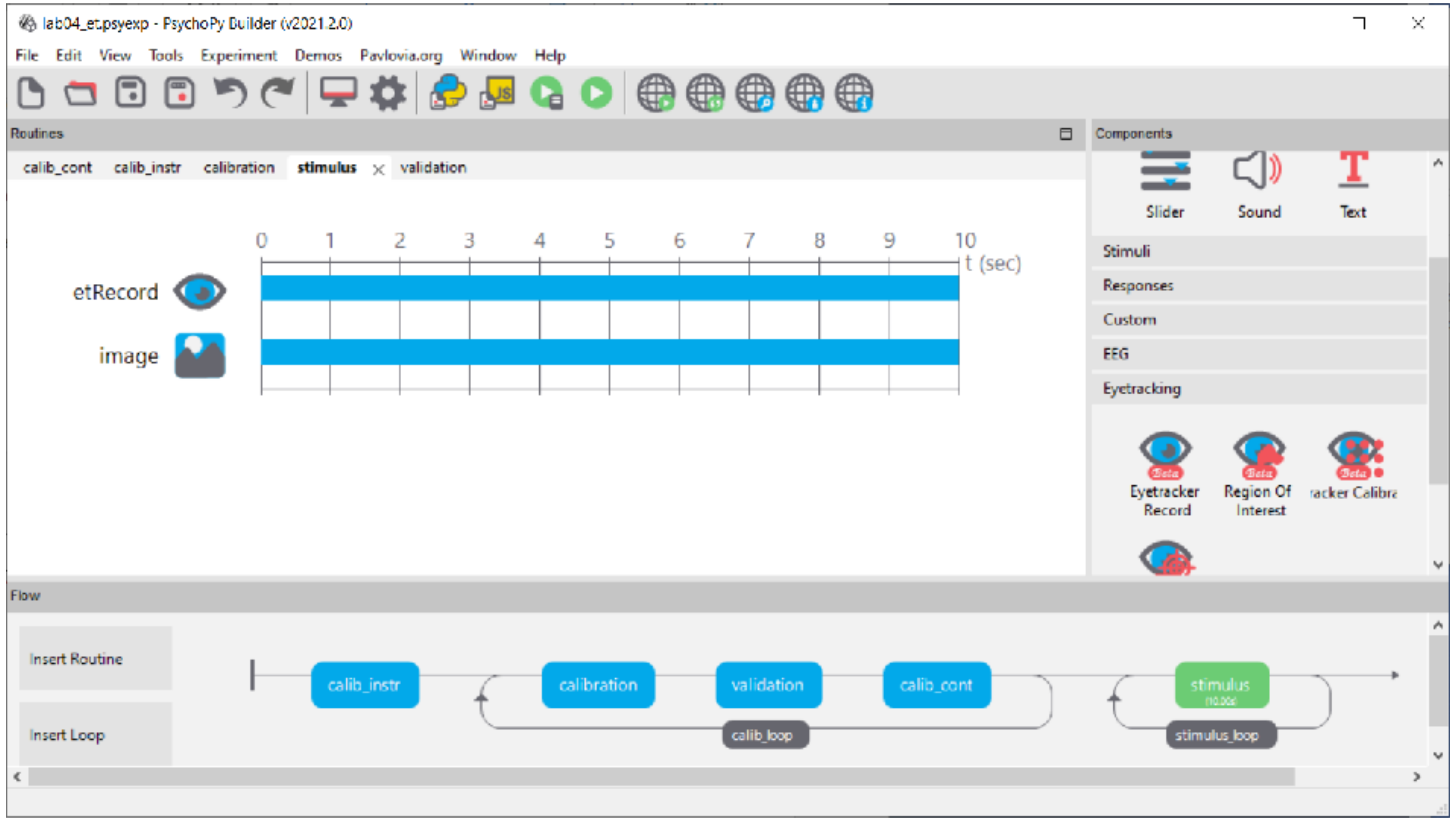


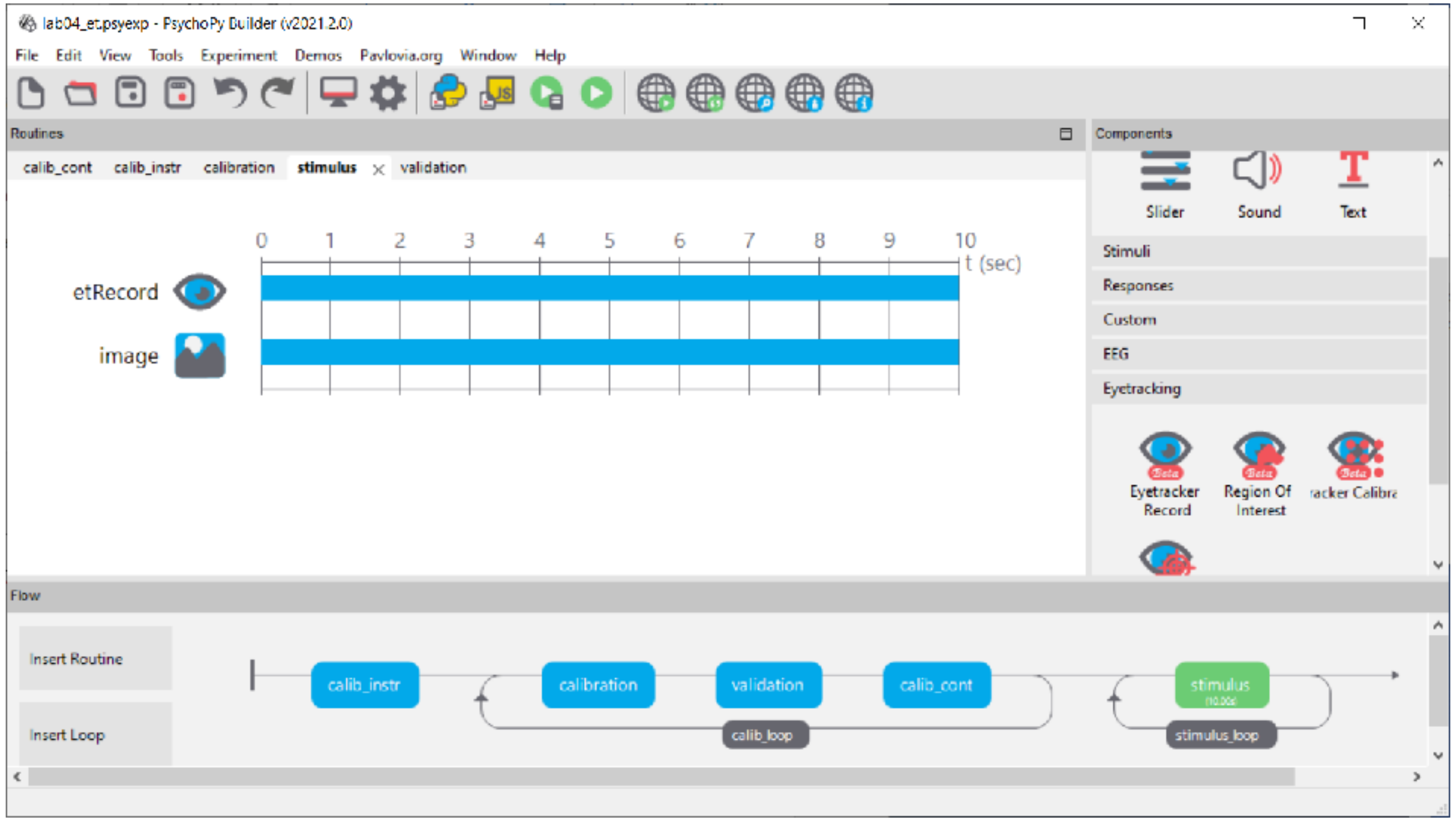
Gaze Analytics Pipeline: Record

- How to record data (for offline analysis)?
  - can use vendor software (e.g., Gazepoint Analysis, EyeLink, ...)
  - can use free software: PsychoPy



Gaze Analytics Pipeline: Record

- PychoPy and EyeLink, GazePoint, Tobii:
  - uses ioHub to communicate with eye trackers
  - saves data to HDF5 files

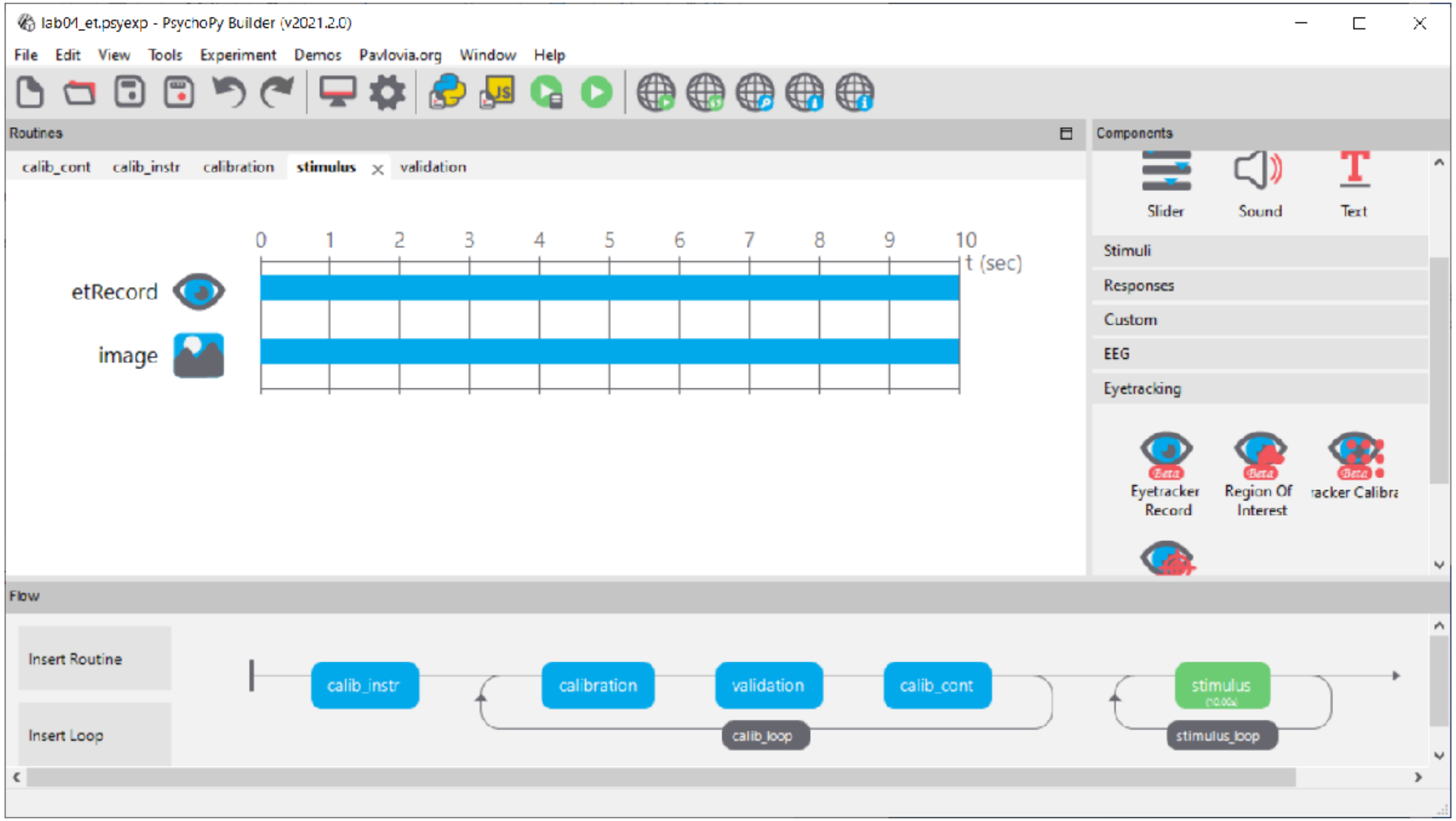


Gaze Analytics Pipeline: Record

Routines

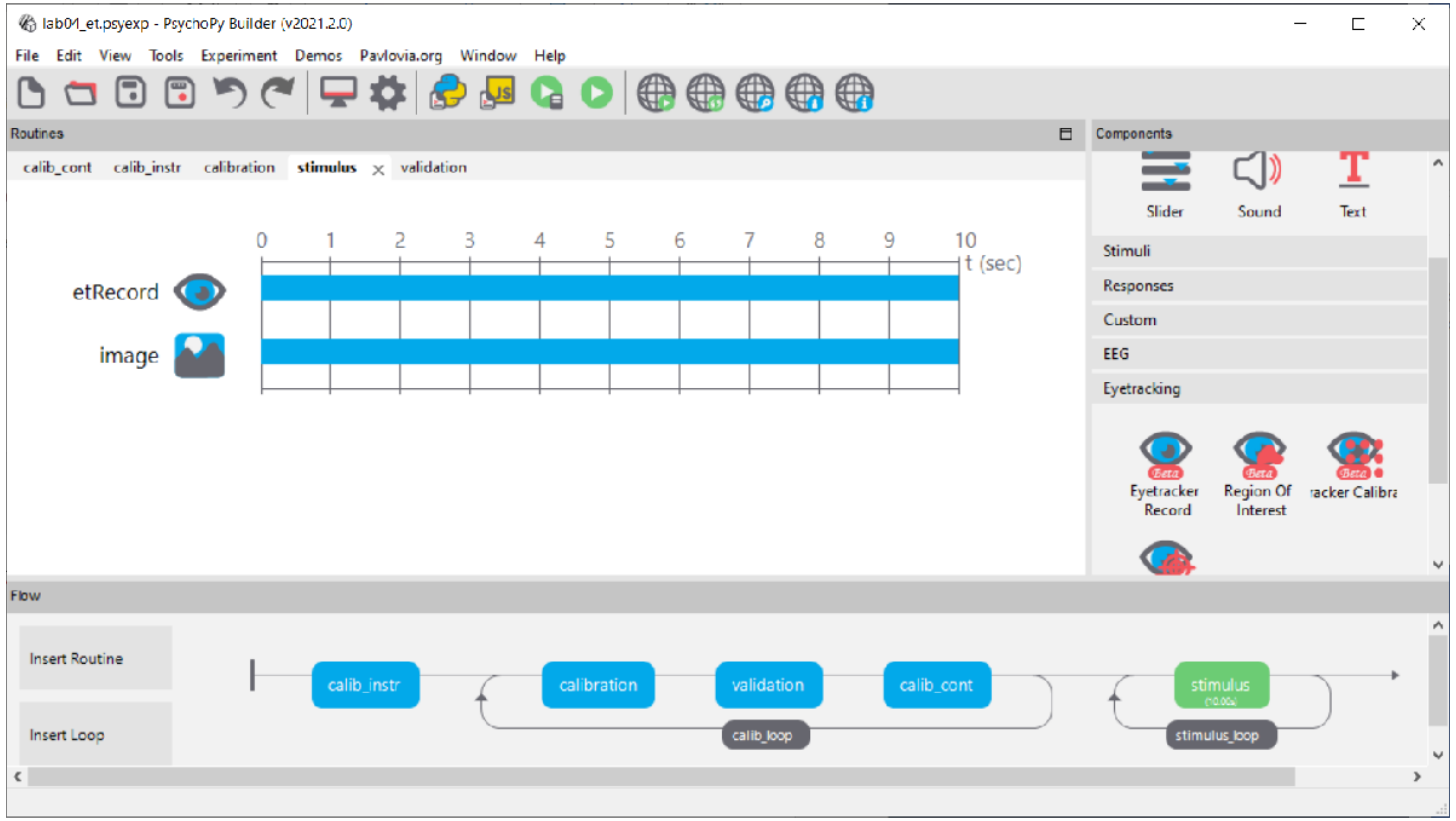
Components

Flow



Gaze Analytics Pipeline: Record

- PsychoPy and EyeLink, GazePoint, Tobii:
  - limited AOI functionality (but could be good, e.g., real-time)
  - need to code in Python various events, conditions (HDF5)



Gaze Analytics Pipeline: Record

- PsychoPy and HDF5:
  - many files and folders in one large file (.hdf5)
  - each data "file" stored as table (can be queried!)

MessageEvent at /data_collection/events/experiment/ [s02_lab04_et_live_2021_Jul_09_1537.hdf5 in D:\rainbow\research\eyelab\exp\PsychoPy2021\lab04\data]

Table Import/Export Data

0-based

	experiment_id	session_id	device_id	event_id	type	device_time	logged_time	time	confidence_interval	delay	filter_id	msg_offset	category	text
515	1	1	0	1419	151	95.003880...	95.004507...	95.0038...	0.0	6.263E-4	0	0.0	VALIDA...	Done Target Position Resul...
516	1	1	0	1420	151	95.004849...	95.005415...	95.0048...	0.0	5.661E-4	0	0.0	VALIDA...	reporting_unit_type: height
517	1	1	0	1421	151	95.005802...	95.006176...	95.0058...	0.0	3.742E-4	0	0.0	VALIDA...	min_error: 0.01492847415...
518	1	1	0	1422	151	95.006461...	95.006899...	95.0064...	0.0	4.37900...	0	0.0	VALIDA...	max_error: 0.09683009667...
519	1	1	0	1423	151	95.007186...	95.007737...	95.0071...	0.0	5.519E-4	0	0.0	VALIDA...	mean_error: 0.0490289721...
520	1	1	0	1424	151	95.008017...	95.008549...	95.0080...	0.0	5.322E-4	0	0.0	VALIDA...	passed: True
521	1	1	0	1425	151	95.008989...	95.009694...	95.0089...	0.0	7.049E-4	0	0.0	VALIDA...	positions_failed_processin...
522	1	1	0	1426	151	95.010034...	95.014391...	95.0100...	0.0	0.0043572	0	0.0	VALIDA...	Validation Report Complete
523	1	1	0	1430	151	97.681777...	97.682218...	97.6817...	0.0	4.411E-4	0	0.0	trial	start
524	1	1	0	2090	151	107.68264...	107.68326...	107.682...	0.0	6.246E-4	0	0.0	trial	stop

Gaze Analytics Pipeline: Record

- PsychoPy and HDF5:
  - gaze data needs to be extracted between start/stop timestamps
  - timestamps need to be recorded in event table

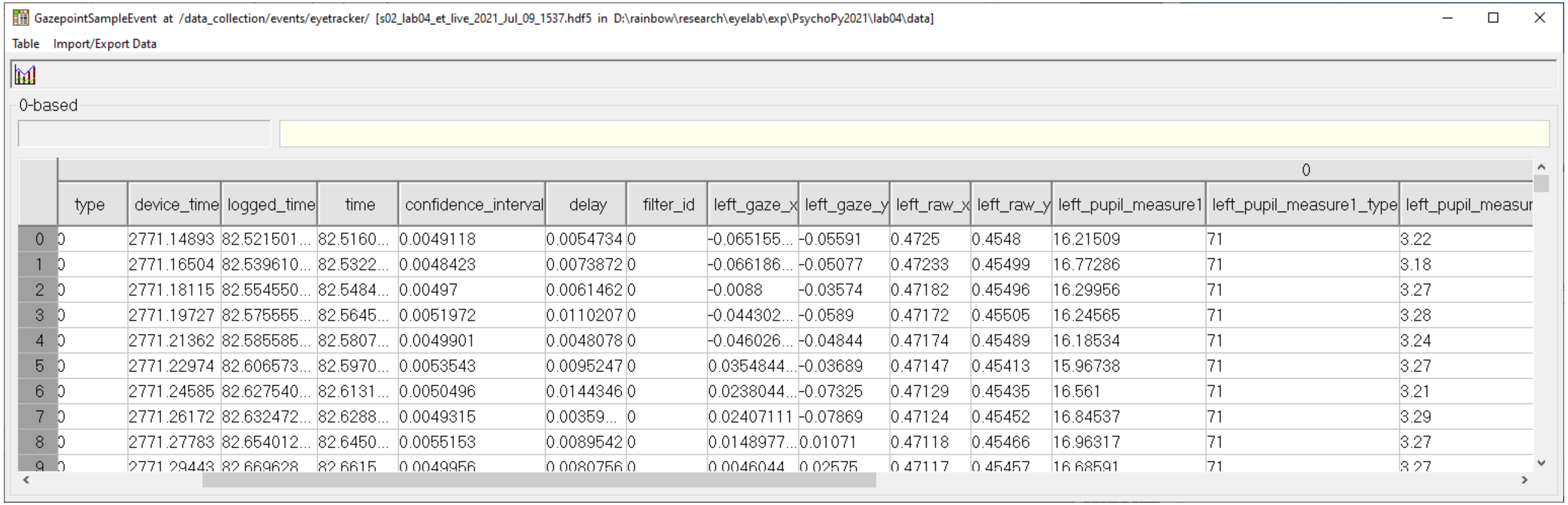

GazepointSampleEvent at /data_collection/events/eyetracker/ [s02_lab04_et_live_2021_Jul_09_1537.hdf5 in D:\rainbow\research\eyelab\exp\PsychoPy2021\lab04\data]

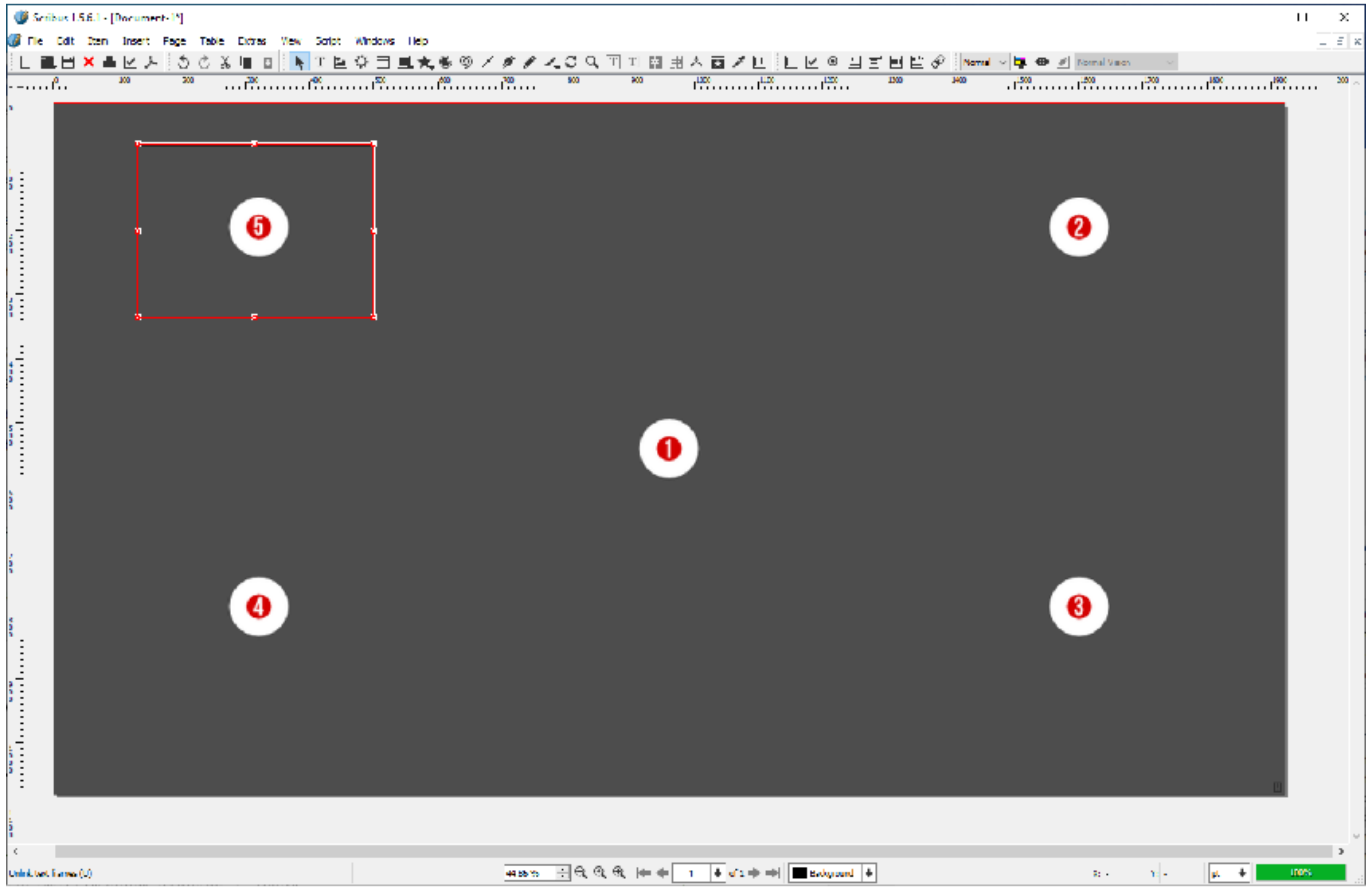
Table Import/Export Data

0-based

	type	device_time	logged_time	time	confidence_interval	delay	filter_id	left_gaze_x	left_gaze_y	left_raw_x	left_raw_y	left_pupil_measure1	left_pupil_measure1_type	left_pupil_measur
0	0	2771.14893	82.521501...	82.5160...	0.0049118	0.0054734	0	-0.065155...	-0.05591	0.4725	0.4548	16.21509	71	3.22
1	0	2771.16504	82.539610...	82.5322...	0.0048423	0.0073872	0	-0.066186...	-0.05077	0.47233	0.45499	16.77286	71	3.18
2	0	2771.18115	82.554550...	82.5484...	0.00497	0.0061462	0	-0.0088	-0.03574	0.47182	0.45496	16.29956	71	3.27
3	0	2771.19727	82.575555...	82.5645...	0.0051972	0.0110207	0	-0.044302...	-0.0589	0.47172	0.45505	16.24565	71	3.28
4	0	2771.21362	82.585585...	82.5807...	0.0049901	0.0048078	0	-0.046026...	-0.04844	0.47174	0.45489	16.18534	71	3.24
5	0	2771.22974	82.606573...	82.5970...	0.0053543	0.0095247	0	0.0354844...	-0.03689	0.47147	0.45413	15.96738	71	3.27
6	0	2771.24585	82.627540...	82.6131...	0.0050496	0.0144346	0	0.0238044...	-0.07325	0.47129	0.45435	16.561	71	3.21
7	0	2771.26172	82.632472...	82.6288...	0.0049315	0.00359...	0	0.02407111	-0.07869	0.47124	0.45452	16.84537	71	3.29
8	0	2771.27783	82.654012...	82.6450...	0.0055153	0.0089542	0	0.0148977...	0.01071	0.47118	0.45466	16.96317	71	3.27
9	0	2771.29443	82.669628...	82.6615...	0.0049956	0.0080756	0	0.0046044...	0.02575	0.47117	0.45457	16.68591	71	3.27

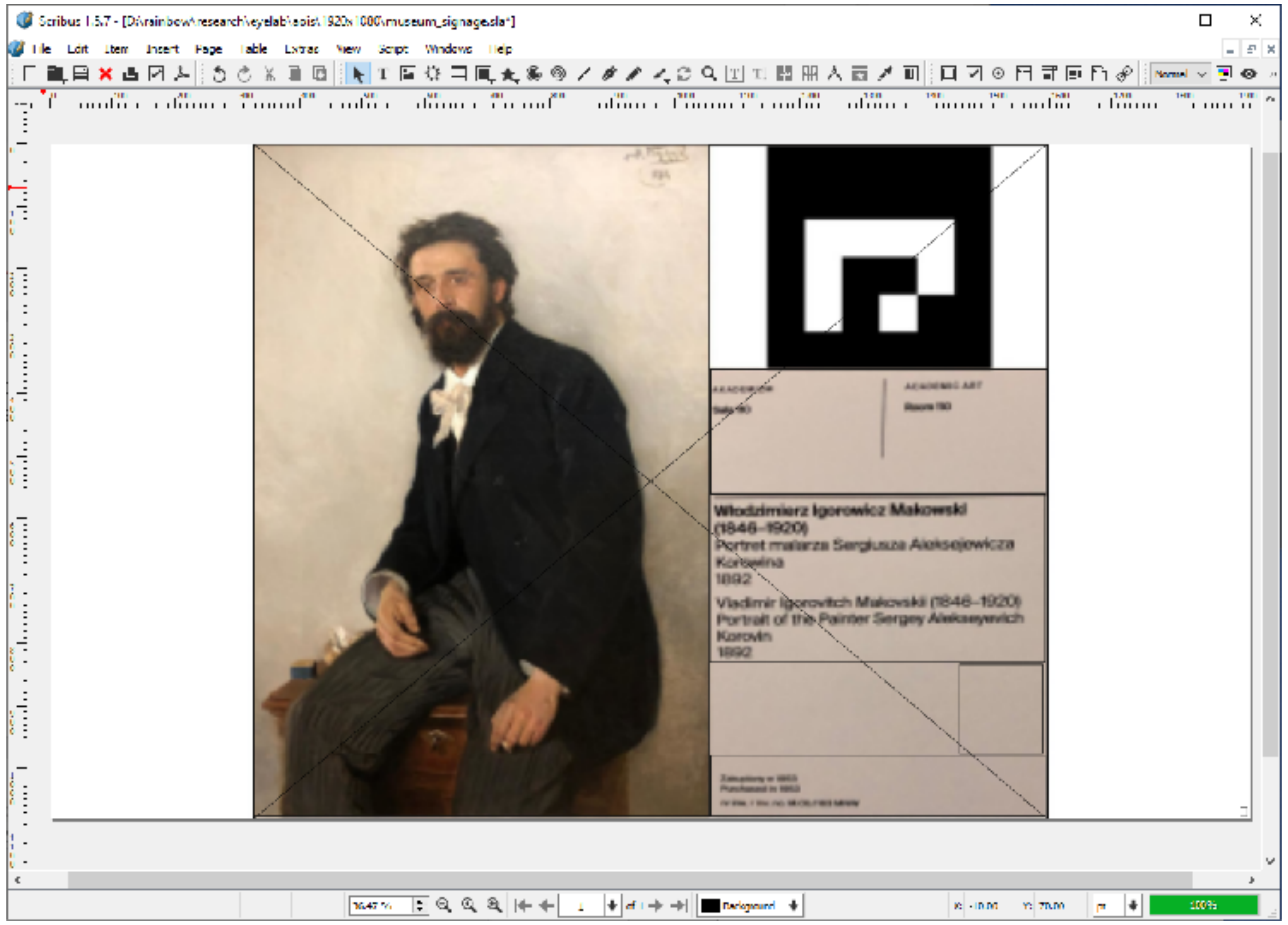
Gaze Analytics Pipeline: Record

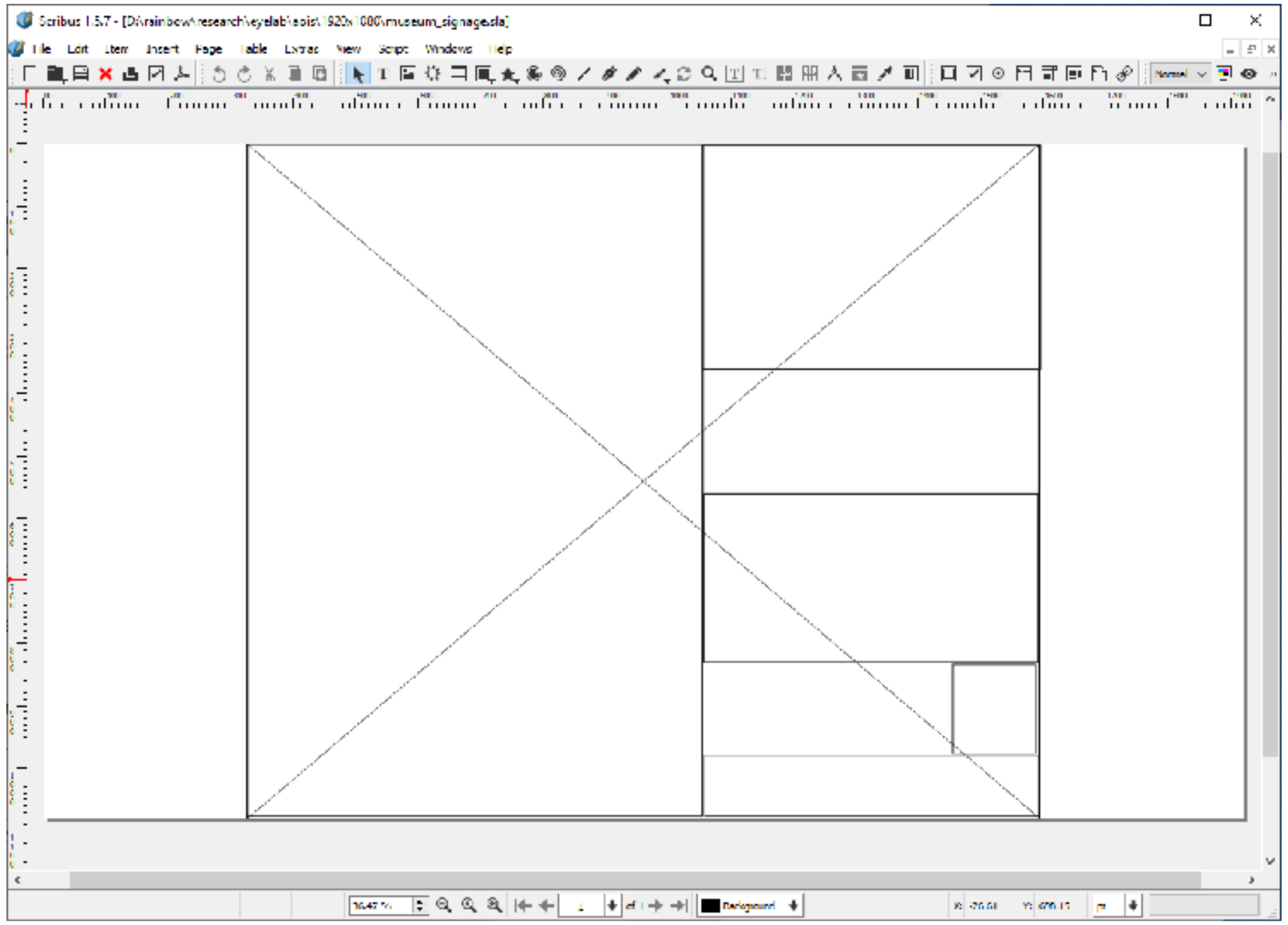
- PsychoPy and Scribus:
  - AOIs can be defined by yet another (free) program: Scribus
  - files saved as .sla (xml) files that can be parsed (e.g., Python)



Gaze Analytics Pipeline: Record

- Putting it all together: PsychoPy, HDF5, Scribus
  - all held together by Python (and R for statistics)
  - all multi-platform (macOS, Windows, Linux too [I think])





Data

http://andrewd.ces.clemson.edu/hcii23/demo.zip

Data

Participants: 24 students

SOR_es01mb.txt	18.01.2018 13:34	Textdokument	15.982 KB
SOR_es02te.txt	18.01.2018 13:34	Textdokument	16.179 KB
SOR_es03lb.txt	18.01.2018 13:34	Textdokument	16.260 KB
SOR_es05sk.txt	18.01.2018 13:34	Textdokument	15.928 KB
SOR_es06ss.txt	18.01.2018 13:34	Textdokument	16.260 KB
SOR_es07sg.txt	18.01.2018 13:34	Textdokument	16.261 KB
SOR_es09ls.txt	18.01.2018 13:34	Textdokument	16.405 KB
SOR_es10aw.txt	18.01.2018 13:34	Textdokument	15.984 KB
SOR_es13lg.txt	18.01.2018 13:34	Textdokument	16.458 KB
SOR_es14mh.txt	18.01.2018 13:34	Textdokument	16.222 KB

…

Traditional and advanced gaze analytics

1) Measures related to Areas of Interest (AOIs)

- Number of fixations, fixation durations
- Frequency of the initial fixation after stimulus onset
- Number of transition between AOIs

2) Measures of scanning behavior in general

- IPA (Index of Pupillary Activity) / LHIPA (Low/High IPA)
- K coefficient (ambient / focal fixations)
- Microsaccades (rate, amplitude)
- Transition matrices and transition entropy

traditional

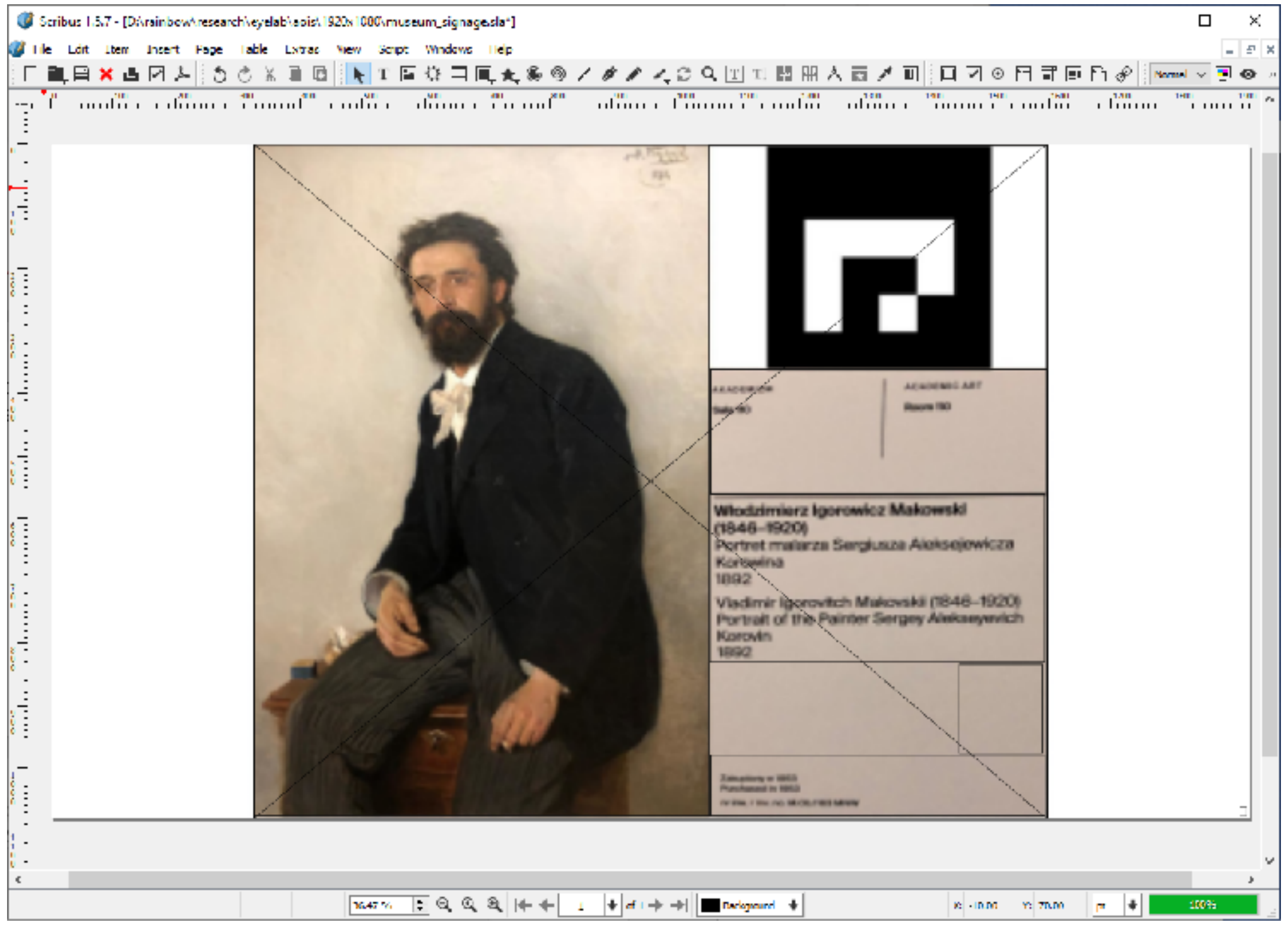
advanced

Preparation for Analysis:

Structure of directories and files

- aois: AOI (Scribus) files
- exp: data, stimuli, and PsychoPy experiment
- src: Python, R source code

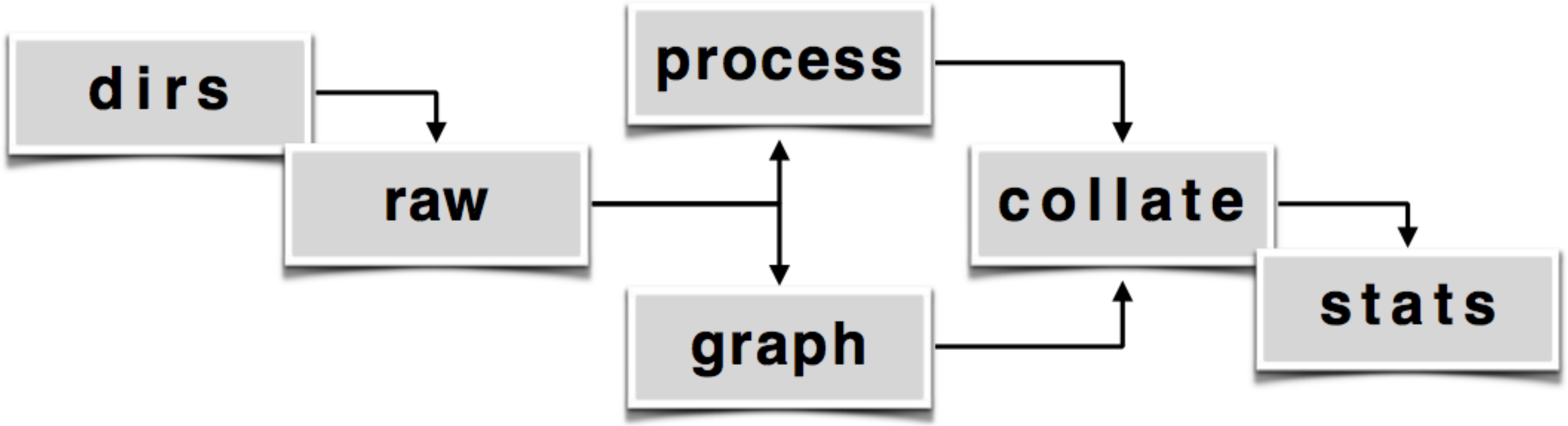
Definition of AOIs in Scribus:
painting,
largeQRcode,
location,
painter_tile,
smallQRcode,
acquisition



museum_signage.sla

Gaze analytics pipeline overview

- Main targets (e.g., *nix `Makefile` or Windows `bat` files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps

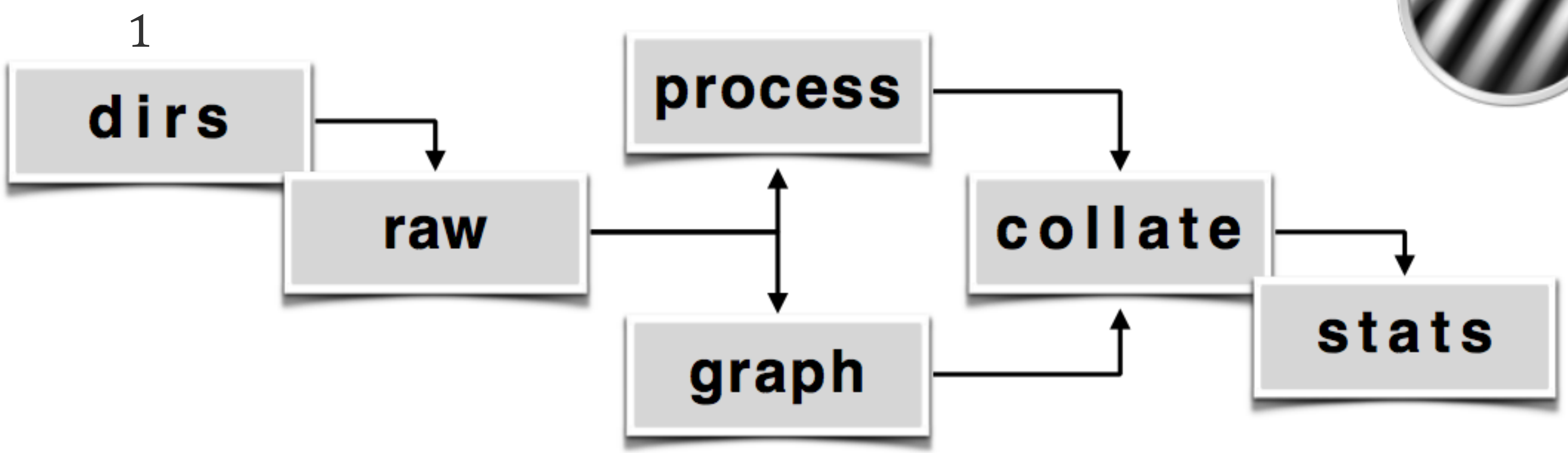


Gaze analytics pipeline overview

- Main targets (e.g., *nix `Makefile` or Windows `bat` files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps

  1. `dirs`

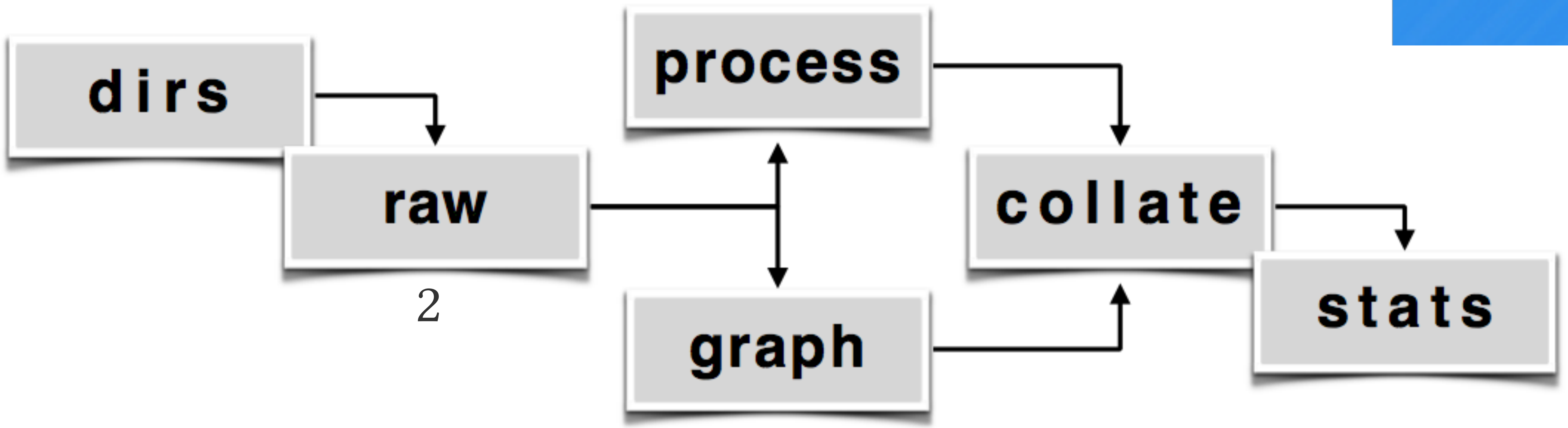
PsychoPy
Now running studies online



Gaze analytics pipeline overview

- Main targets (e.g., *nix `Makefile` or Windows `bat` files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps:

`1. dirs; 2. raw`

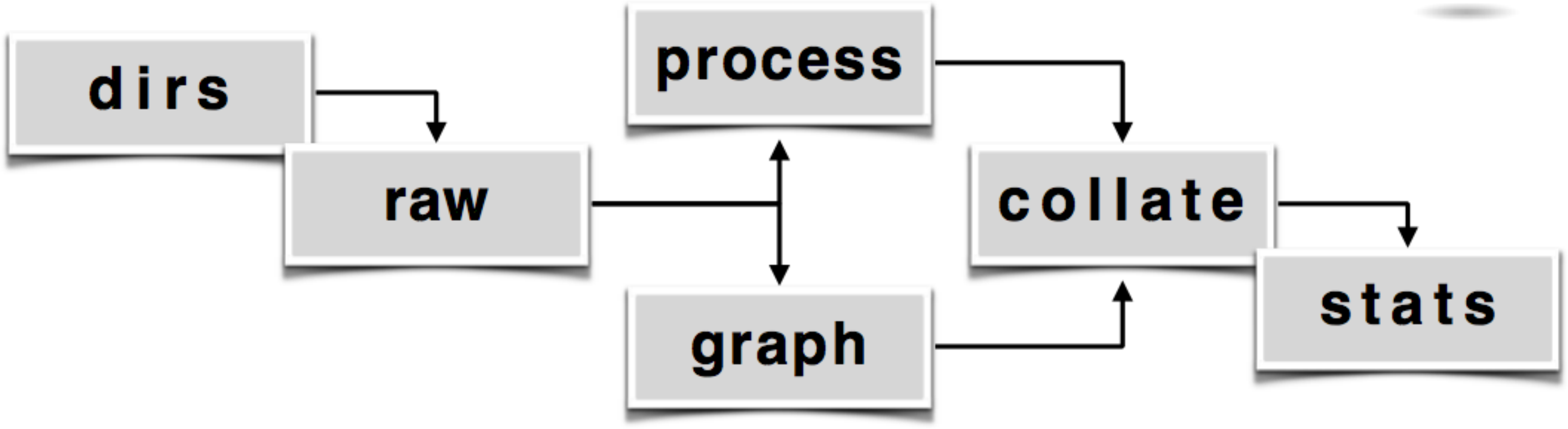


Gaze analytics pipeline overview

- Main targets (e.g., *nix `Makefile` or Windows `bat` files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps:

`1. dirs; 2. raw; 3. process`

3

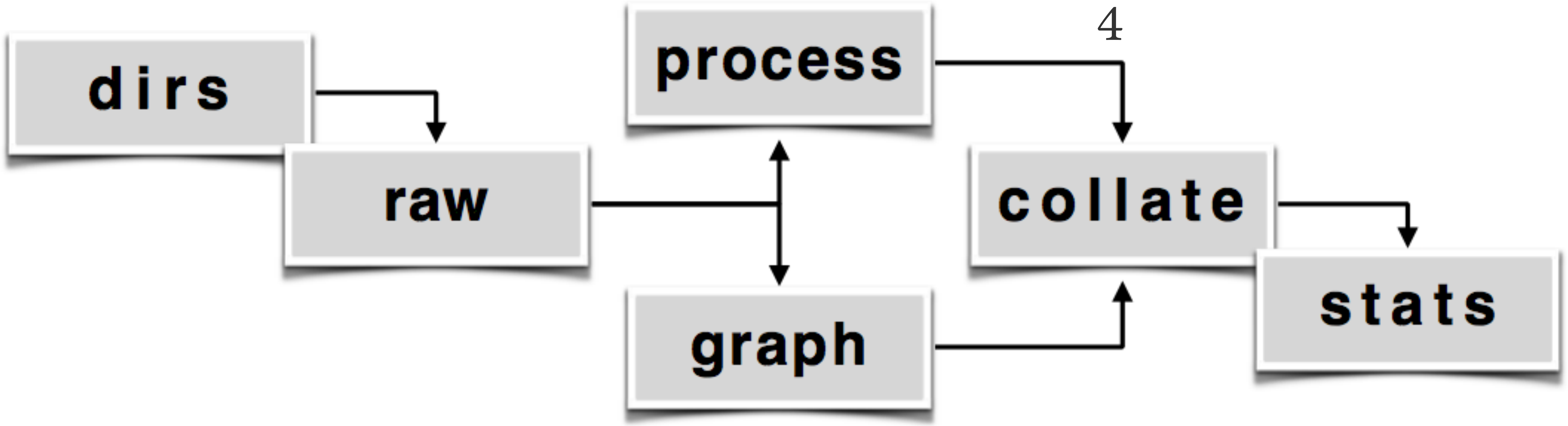


Gaze analytics pipeline overview

- Main targets (e.g., *nix `Makefile` or Windows `bat` files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps:

Scribus
Open Source Desktop Publishing

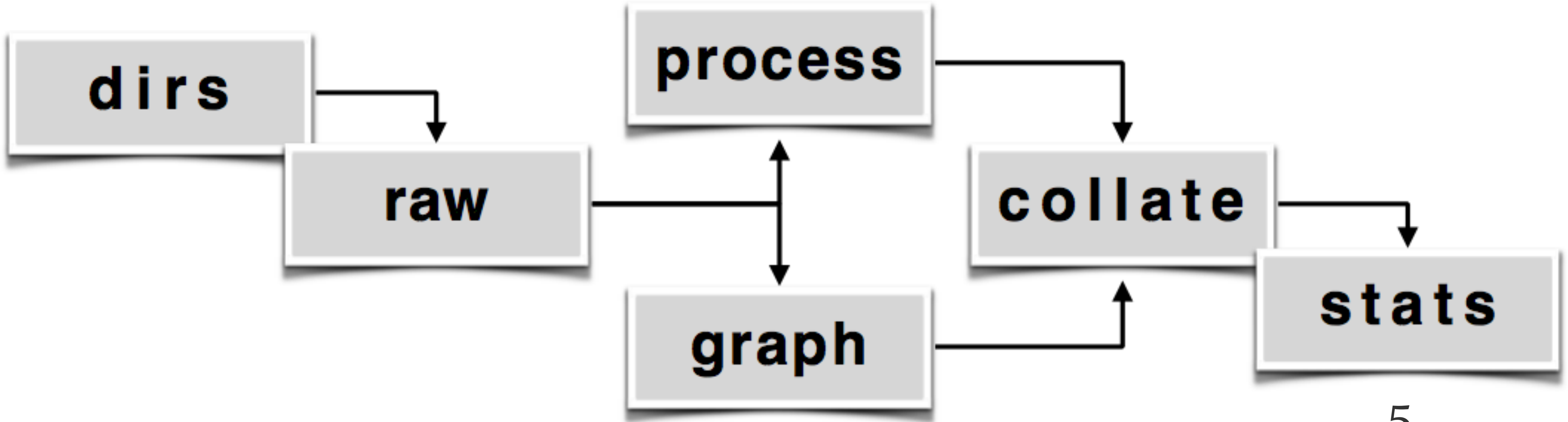
`1. dirs; 2. raw; 3. process; 4. collate`



Gaze analytics pipeline overview

- Main targets (e.g., *nix `Makefile` or Windows `bat` files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps:

`1. dirs; 2. raw; 3. process; 4. collate; 5. stats`



Gaze analytics pipeline overview

The python and R scripts:

1. mkdir	set up directory (basic OS command)
2. hdf52raw.py	parse vendor data into .raw data
3. filter.py	process .raw data (event detection)
graph.py	visualize data
4. collate-*.py	collate to .csv data
5. *.R	do the stats

Linux or macOS:	use Makefile
Windows:	use .bat files

Gaze analytics pipeline overview

Windows (using .bat files):

1. .\dirs.bat	set up directory (basic OS command)
2. .\raw.bat	parse vendor data into .raw data
3. .\process.bat	process .raw data (event detection)
.\graph.bat	visualize data
4. .\collate.bat	collate to .csv data
5. .\stats.bat	do the stats

Windows: or use .\make.bat file

Gaze analytics pipeline overview

Linux or macOS (using Makefile):

1. make dirs	set up directory
2. make raw	parse vendor data into .raw data
3. make process	process .raw data (event detection)
make graph	visualize data
4. make collate	collate to .csv data
5. make stats	do the stats

Linux or macOS: or simply use make

Gaze analytics pipeline: essential information

- All of this information is used by scripts:
  - screen resolution: 1920 x 1080
  - screen dimensions (diagonal): 22 in
  - sampling rate: 60 Hz
  - viewing distance: 21.65 in (55 cm)
  - AOIs: software (Scribus)

- Also need directories (all paths relative!):
  - indir: ../../exp/data/
  - imgdir: ../../exp/stimuli/static/screenshots
  - pltdir: ./plots/
  - outdir: ./data
  - rawdir: ./data/raw

Gaze analytics pipeline: objectives

- Process raw gaze data into fixations, fixation count, etc.

visual angle conversion

- width, height of screen (e.g., 1920 x 1080)
- screen dimensions (diagonal, e.g., 22 inches)
- viewing distance (e.g., 21.65 inches)

Gaze analytics pipeline: objectives

- Process raw gaze data into fixations, fixation count, etc.

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- width, height of screen (e.g., 1920 x 1080)
- screen dimensions (diagonal, e.g., 22 inches)
- viewing distance (e.g., 21.65 inches)

Butterworth smoothing

- filter order (e.g., 2nd, 4th, etc.)
- sampling rate (e.g., 60 Hz)
- cutoff frequency (e.g., 6.15 Hz)

Gaze analytics pipeline: objectives

- Process raw gaze data into fixations, fixation count, etc.

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- width, height of screen (e.g., 1920 x 1080)
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Gaze analytics pipeline: objectives

- Process raw gaze data into fixations, fixation count, etc.

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- width, height of screen (e.g., 1920 x 1080)
- screen dimensions (diagonal, e.g., 22 inches)
- viewing distance (e.g., 21.65 inches)

~~**Butterworth smoothing**~~

- ~~filter order (e.g., 2nd, 4th, etc.)~~
- ~~sampling rate (e.g., 60 Hz)~~
- ~~cutoff frequency (e.g., 6.15 Hz)~~

Savitzky-Golay differentiation

- filter width (e.g., 3)
- degree (e.g., 3, 3rd order)
- order (e.g., 1 for differentiation, 0 for smoothing)

Gaze analytics pipeline: objectives

- Process raw gaze data into fixations, fixation count, etc.

visual angle conversion

- width, height of screen (e.g., 1920 x 1080)
- screen dimensions (diagonal, e.g., 22 inches)
- viewing distance (e.g., 21.65 inches)

Butterworth smoothing

- filter order (e.g., 2nd, 4th, etc.)
- sampling rate (e.g., 60 Hz)
- cutoff frequency (e.g., 6.15 Hz)

Savitzky-Golay differentiation

- filter width (e.g., 3)
- degree (e.g., 3, 3rd order)
- order (e.g., 1 for differentiation, 0 for smoothing)

thresholding

- velocity (e.g., 36 deg/s)

Critical notes on scripts

- None of the scripts are ready “out of the box”
- None of the scripts can easily be ported to other projects

- Why? Not possible to predict future study design

- What needs to be adapted?
  - file name composition, e.g.,

  s01-1-1-absent-female.raw
  - file name encodes (and can accommodate many more parameters):

  subj-exp_id-ses_id-marker-object

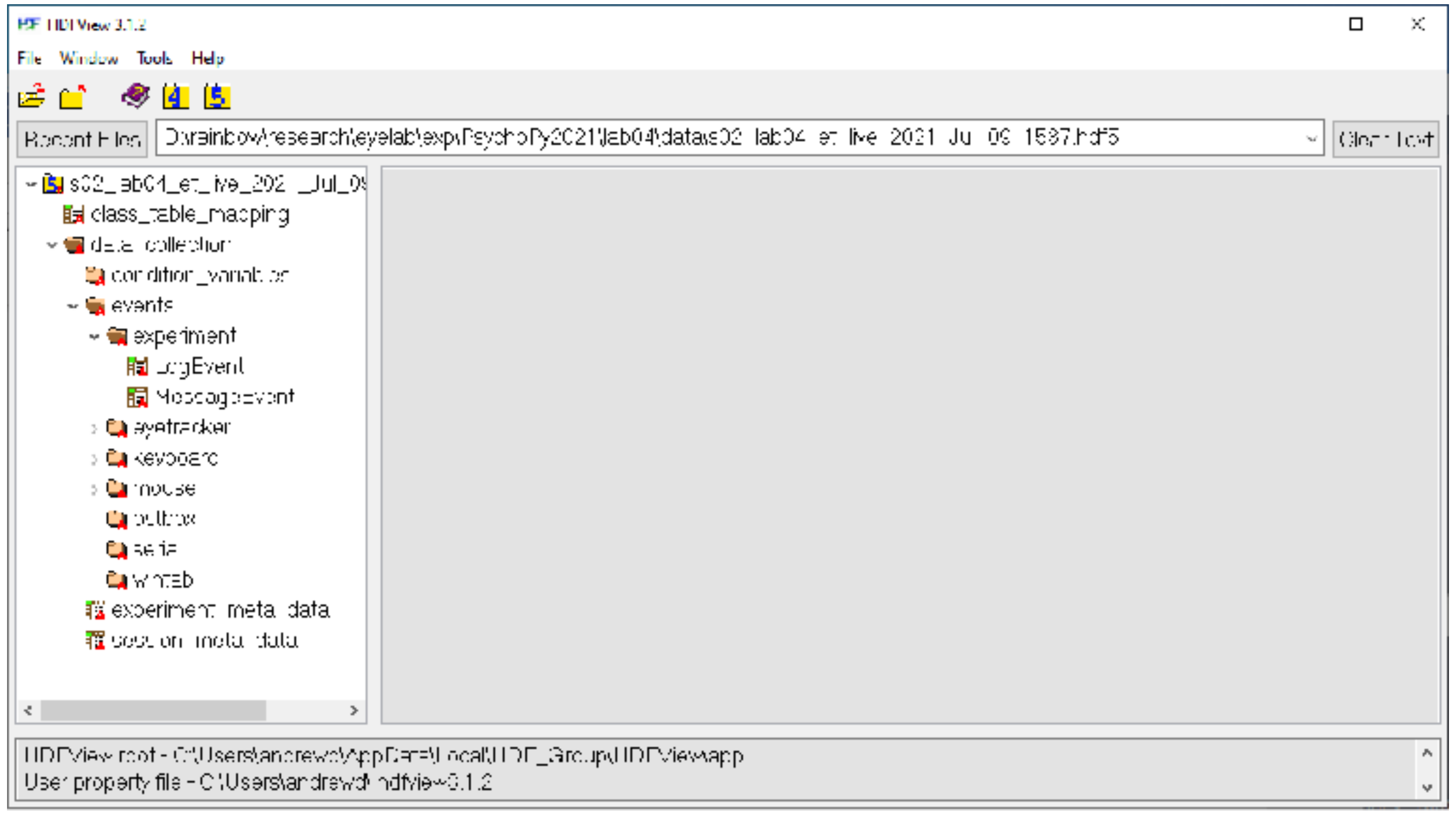
Gaze analytics pipeline: vendor data

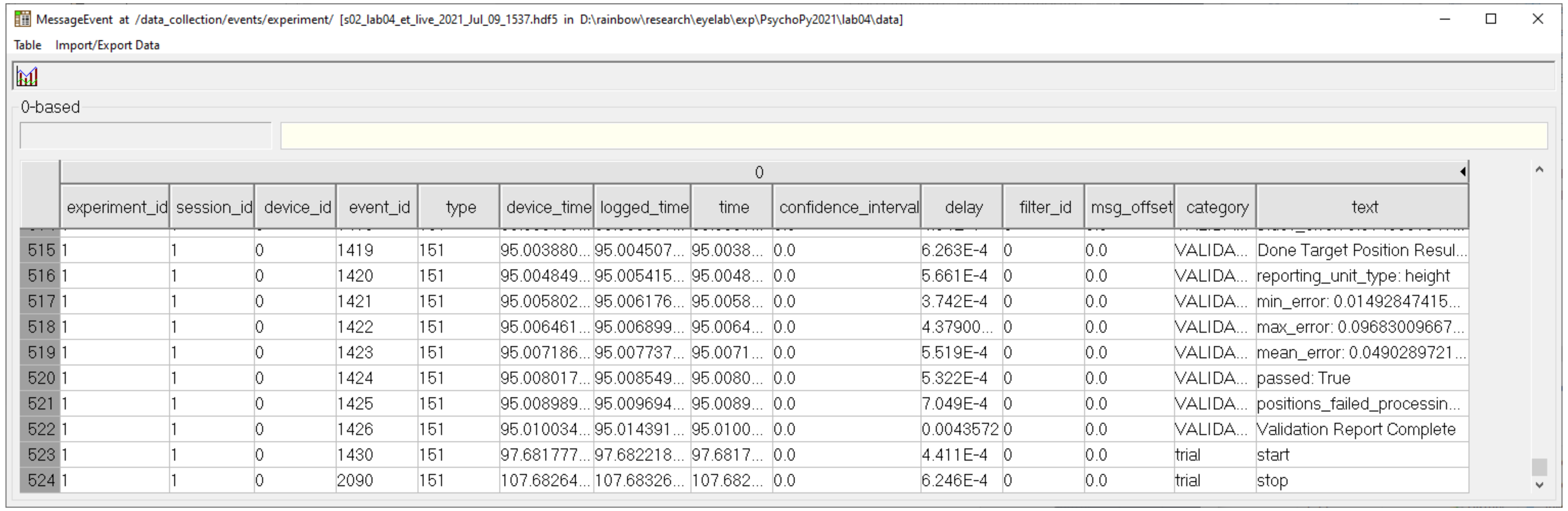
- Vendor data comes in various formats, usually plain text

```
RECORDING_SESSION_LABEL Group_VP        blocknr trialnr task    emotion gender  face    dc_x
list    TIMESTAMP       LEFT_GAZE_X     LEFT_GAZE_Y     LEFT_PUPIL_SIZE RIGHT_GAZE_X
RIGHT_GAZE_Y    RIGHT_PUPIL_SIZE        RESPONSE        IS_CORRECT
es01mb  stud    1       1       emotion surprised       male    M08     80      1
2154988,00      78,10   463,20  1296,00 126,00  467,40  1205,00 surprised       Correct
es01mb  stud    1       1       emotion surprised       male    M08     80      1
2154990,00      77,80   464,10  1299,00 126,30  467,20  1204,00 surprised       Correct
es01mb  stud    1       1       emotion surprised       male    M08     80      1
2154992,00      79,30   464,50  1296,00 125,50  467,00  1202,00 surprised       Correct
es01mb  stud    1       1       emotion surprised       male    M08     80      1
2154994,00      80,50   464,50  1294,00 125,00  467,00  1201,00 surprised       Correct
…
```

Gaze analytics pipeline: vendor data

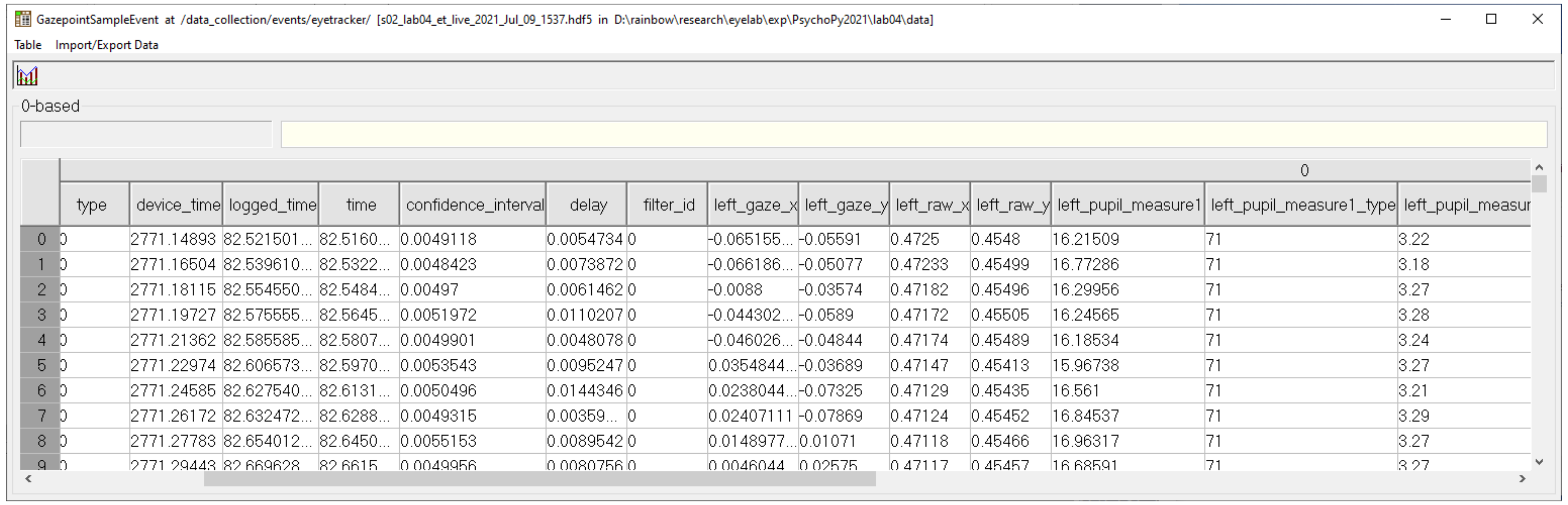
- Vendor data comes in various formats, usually plain text
- Or HDF5 (organized as tables or data frames)





MessageEvent at /data_collection/events/experiment/ [s02_lab04_et_live_2021_Jul_09_1537.hdf5 in D:\rainbow\research\eyelab\exp\PsychoPy2021\lab04\data]

	experiment_id	session_id	device_id	event_id	type	device_time	logged_time	time	confidence_interval	delay	filter_id	msg_offset	category	text
515	1	1	0	1419	151	95.003880...	95.004507...	95.0038...	0.0	6.263E-4	0	0.0	VALIDA...	Done Target Position Resul...
516	1	1	0	1420	151	95.004849...	95.005415...	95.0048...	0.0	5.661E-4	0	0.0	VALIDA...	reporting_unit_type: height
517	1	1	0	1421	151	95.005802...	95.006176...	95.0058...	0.0	3.742E-4	0	0.0	VALIDA...	min_error: 0.01492847415...
518	1	1	0	1422	151	95.006461...	95.006899...	95.0064...	0.0	4.37900...	0	0.0	VALIDA...	max_error: 0.09683009667...
519	1	1	0	1423	151	95.007186...	95.007737...	95.0071...	0.0	5.519E-4	0	0.0	VALIDA...	mean_error: 0.0490289721...
520	1	1	0	1424	151	95.008017...	95.008549...	95.0080...	0.0	5.322E-4	0	0.0	VALIDA...	passed: True
521	1	1	0	1425	151	95.008989...	95.009694...	95.0089...	0.0	7.049E-4	0	0.0	VALIDA...	positions_failed_processin...
522	1	1	0	1426	151	95.010034...	95.014391...	95.0100...	0.0	0.0043572	0	0.0	VALIDA...	Validation Report Complete
523	1	1	0	1430	151	97.681777...	97.682218...	97.6817...	0.0	4.411E-4	0	0.0	trial	start
524	1	1	0	2090	151	107.68264...	107.68326...	107.682...	0.0	6.246E-4	0	0.0	trial	stop



GazepointSampleEvent at /data_collection/events/eyetracker/ [s02_lab04_et_live_2021_Jul_09_1537.hdf5 in D:\rainbow\research\eyelab\exp\PsychoPy2021\lab04\data]

	type	device_time	logged_time	time	confidence_interval	delay	filter_id	left_gaze_x	left_gaze_y	left_raw_x	left_raw_y	left_pupil_measure1	left_pupil_measure1_type	left_pupil_measur
0	0	2771.14893	82.521501...	82.5160...	0.0049118	0.0054734	0	-0.065155...	-0.05591	0.4725	0.4548	16.21509	71	3.22
1	0	2771.16504	82.539610...	82.5322...	0.0048423	0.0073872	0	-0.066186...	-0.05077	0.47233	0.45499	16.77286	71	3.18
2	0	2771.18115	82.554550...	82.5484...	0.00497	0.0061462	0	-0.0088	-0.03574	0.47182	0.45496	16.29956	71	3.27
3	0	2771.19727	82.575555...	82.5645...	0.0051972	0.0110207	0	-0.044302...	-0.0589	0.47172	0.45505	16.24565	71	3.28
4	0	2771.21362	82.585585...	82.5807...	0.0049901	0.0048078	0	-0.046026...	-0.04844	0.47174	0.45489	16.18534	71	3.24
5	0	2771.22974	82.606573...	82.5970...	0.0053543	0.0095247	0	0.0354844...	-0.03689	0.47147	0.45413	15.96738	71	3.27
6	0	2771.24585	82.627540...	82.6131...	0.0050496	0.0144346	0	0.0238044...	-0.07325	0.47129	0.45435	16.561	71	3.21
7	0	2771.26172	82.632472...	82.6288...	0.0049315	0.00359...	0	0.02407111	-0.07869	0.47124	0.45452	16.84537	71	3.29
8	0	2771.27783	82.654012...	82.6450...	0.0055153	0.0089542	0	0.0148977...	0.01071	0.47118	0.45466	16.96317	71	3.27
9	0	2771.29443	82.669628	82.6615	0.0049956	0.0080756	0	0.0046044	0.02575	0.47117	0.45457	16.68591	71	3.27

Gaze analytics pipeline: parse vendor data

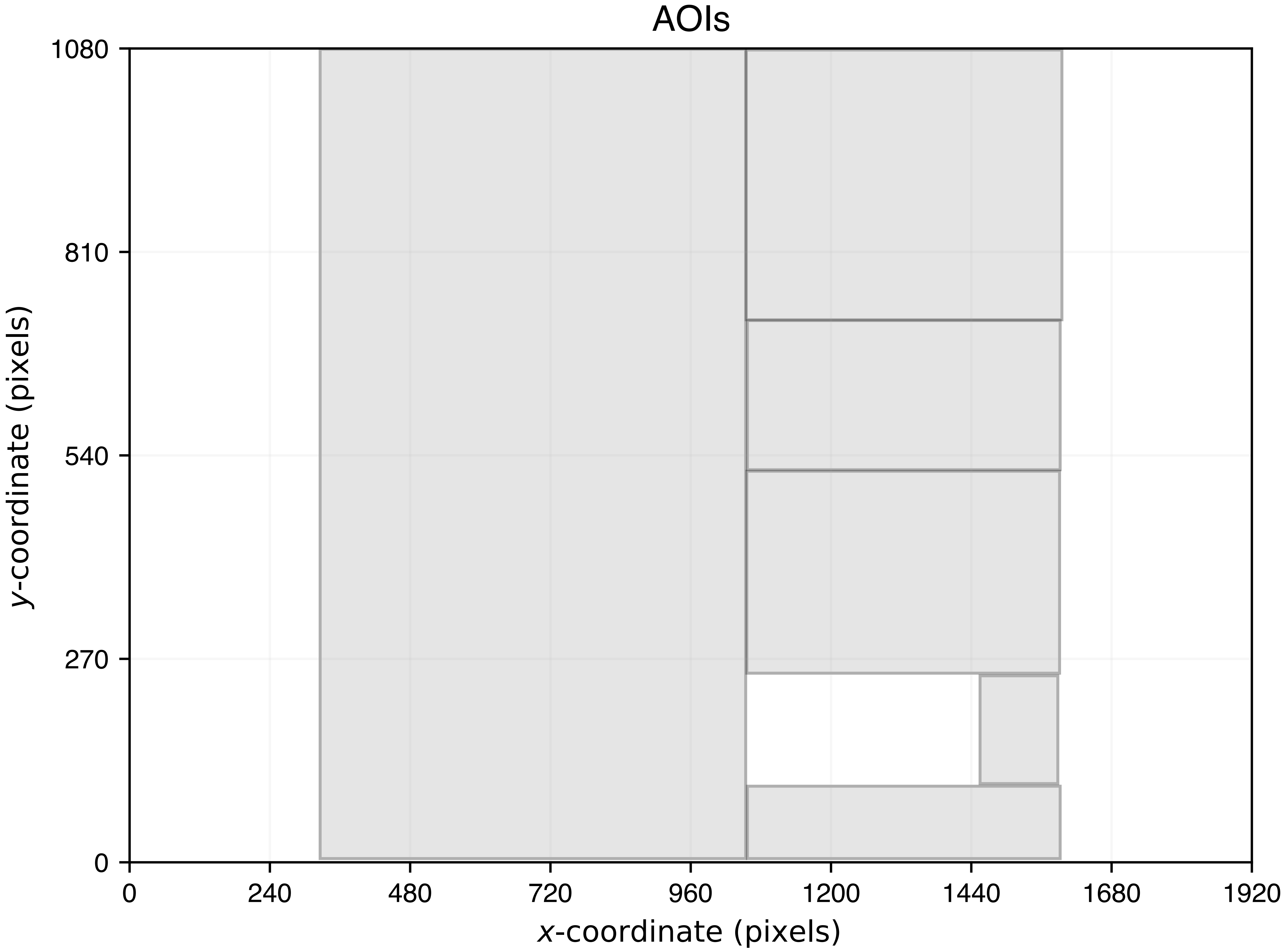
- Just want to extract raw (unprocessed) data: (x, y, t)

```
0.079785 0.613216 61.449674 2235252.000000
0.079443 0.612891 61.602661 2235254.000000
0.079785 0.612630 61.602661 2235256.000000
0.079980 0.613411 61.398678 2235258.000000
0.080029 0.613802 61.398678 2235260.000000
0.080029 0.613997 61.398678 2235262.000000
0.079736 0.613932 61.398678 2235264.000000
0.079443 0.613411 61.398678 2235266.000000
0.079541 0.613086 61.449674 2235268.000000
0.079541 0.612956 61.347683 2235270.000000
0.079395 0.612760 61.245692 2235272.000000
0.079297 0.612630 61.398678 2235274.000000
0.079932 0.612370 61.602661 2235276.000000
0.080127 0.612500 61.500669 2235278.000000
0.079541 0.612891 61.500669 2235280.000000
0.079541 0.612760 61.551665 2235282.000000
0.079590 0.613411 61.551665 2235284.000000
...
```

Gaze analytics pipeline: graph

- Check stimulus image and AOI position
- Important to verify coordinates

*-aois.pdf

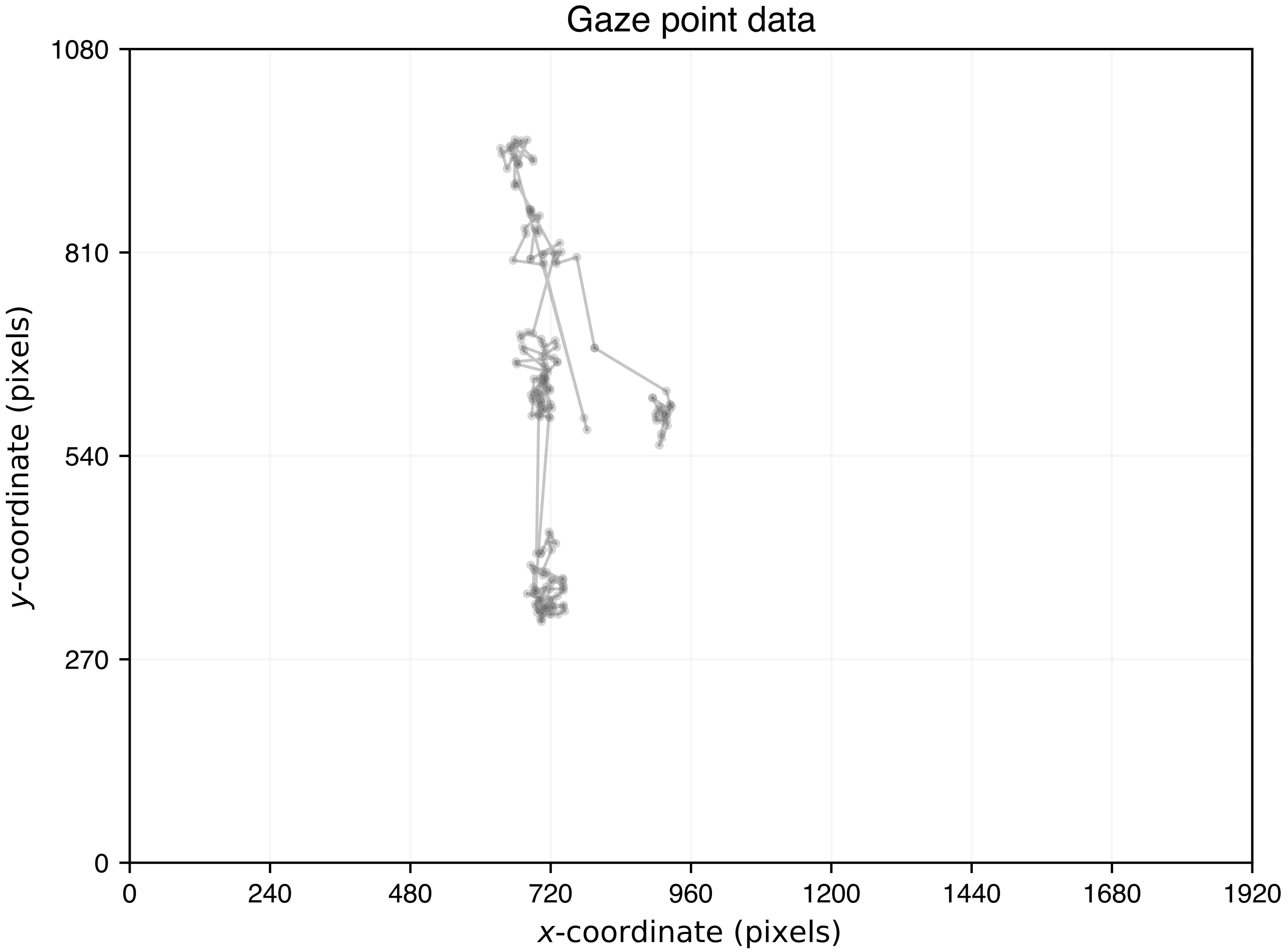


Gaze analytics pipeline: graph

- Check raw data (2D)

$$g_i = (x_i, y_i, t_i)$$

*-gzpt.pdf



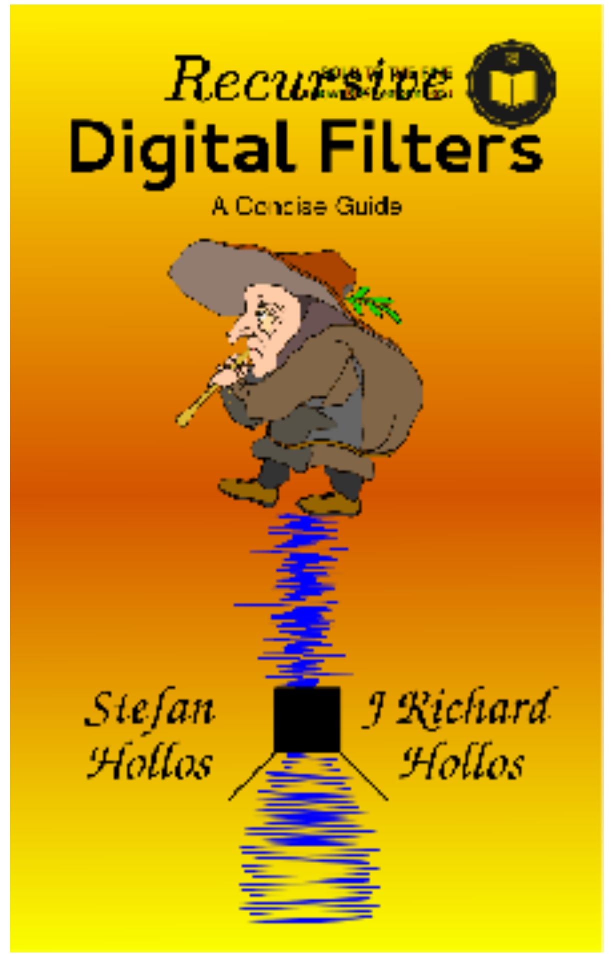
Gaze analytics pipeline: graph

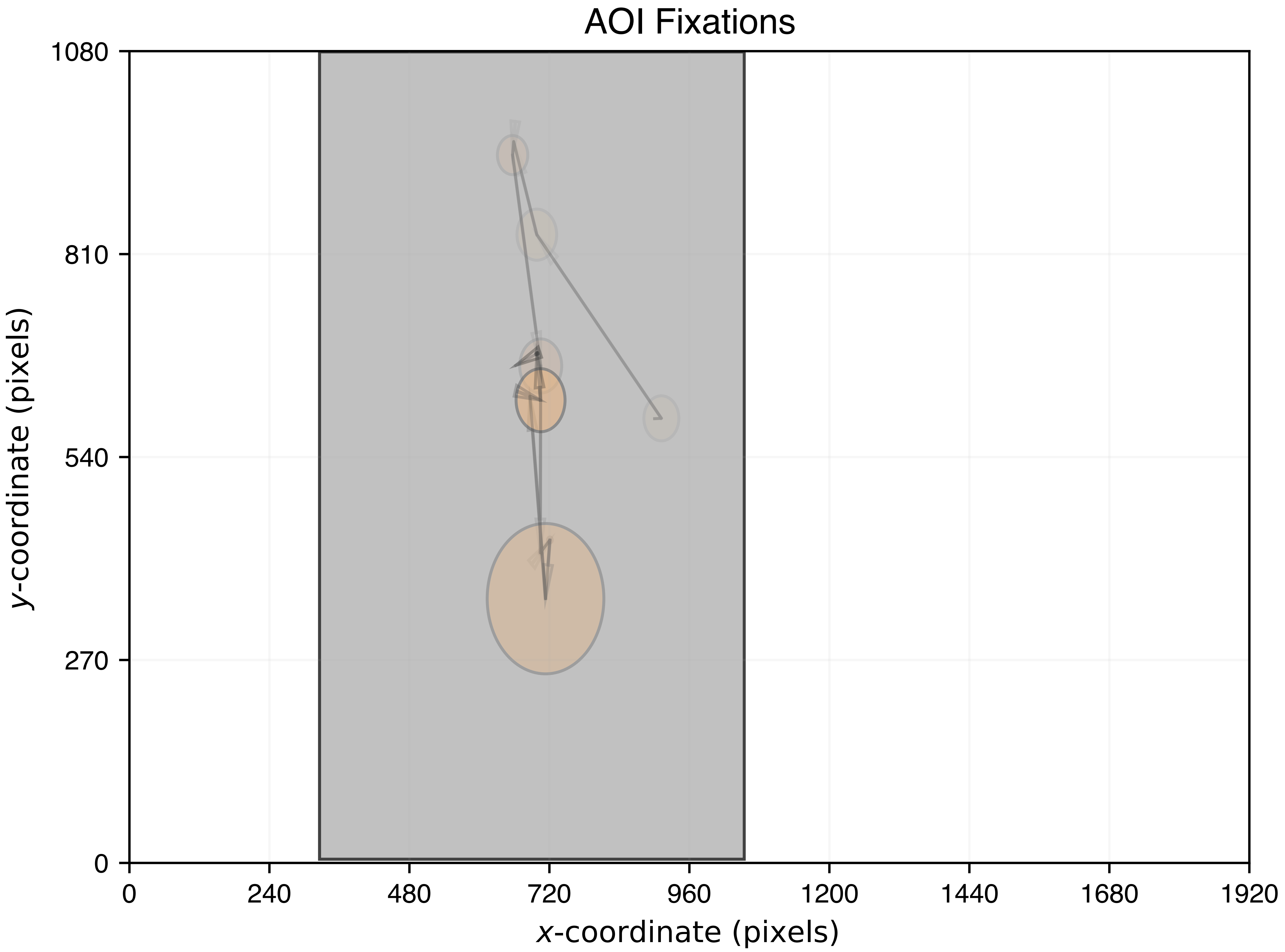
- Check fixations in AOIs

$$\dot{x}_n^s(t) = 1/(\Delta t^s)\left(\sum_{i=-p}^{p} h_i^{t,s} x_{n-i} - \sum_{i=-q}^{q} g_i^{t,s} \dot{x}_{n-i}\right)$$

*-fxtn-aoi.pdf

  - Savitzy-Golay filter





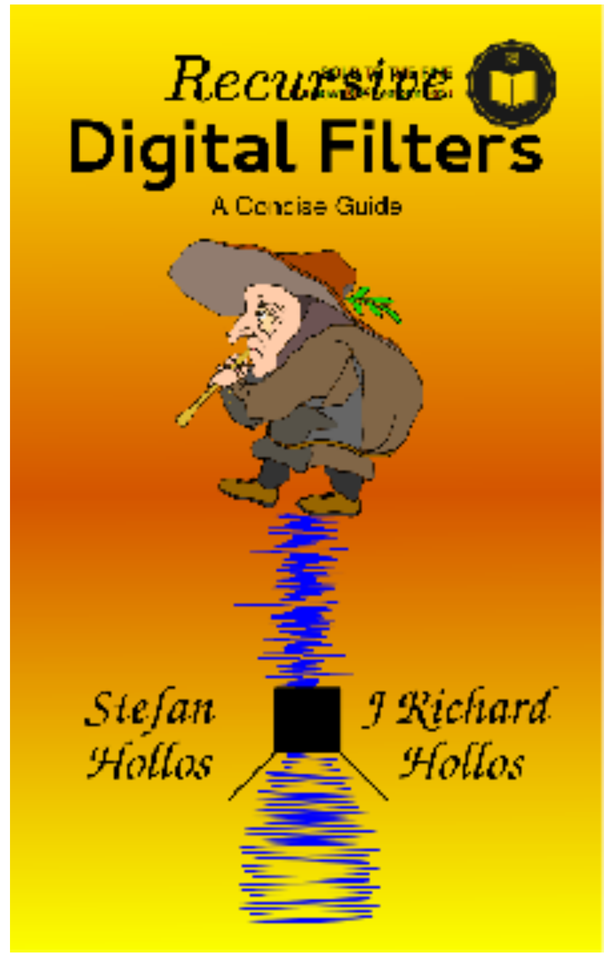
Gaze analytics pipeline: graph

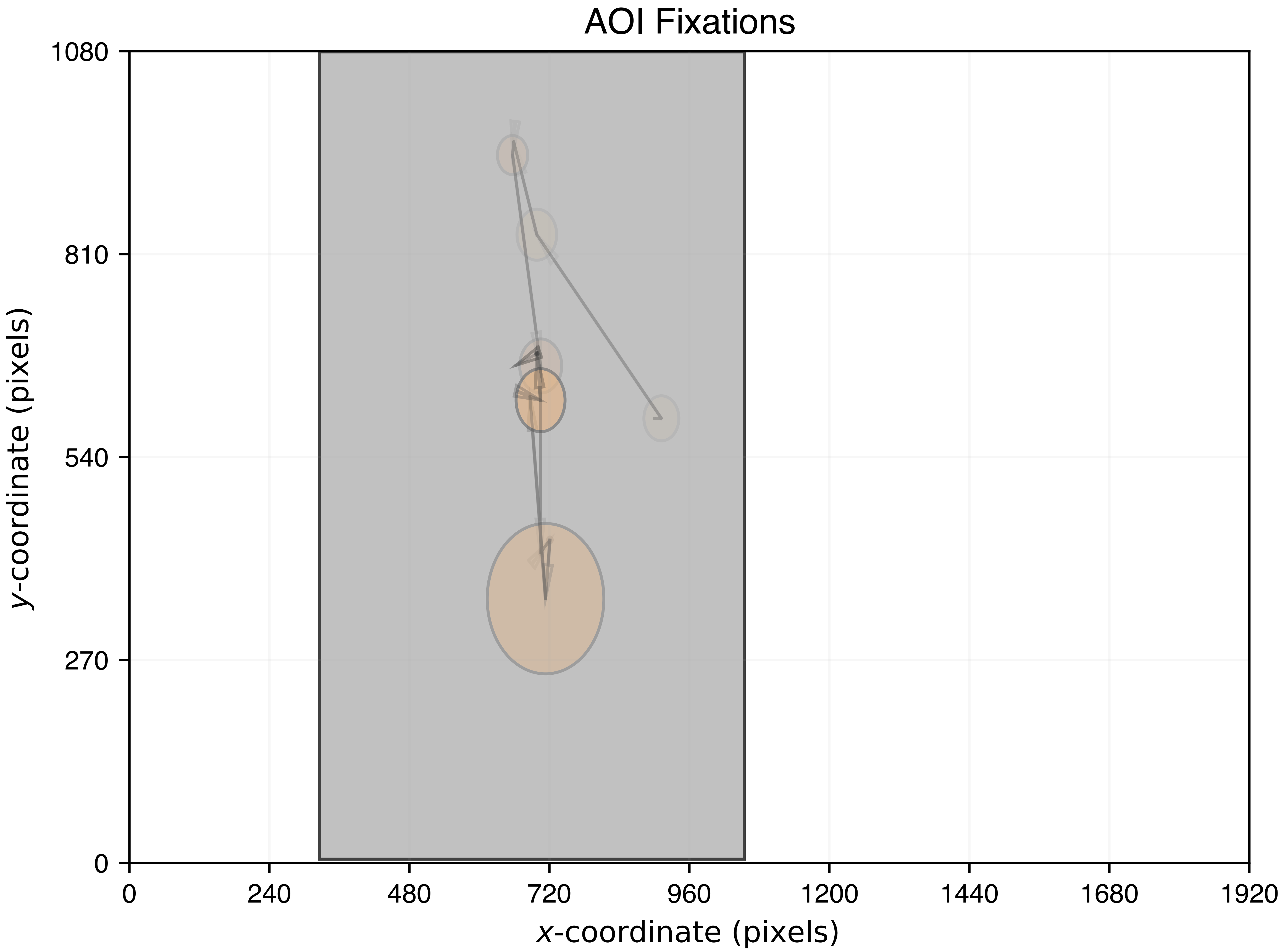
- Check fixations in AOIs

$$\dot{x}_n^s(t) = 1/(\Delta t^s)\left(\sum_{i=-p}^{p} h_i^{t,s} x_{n-i} - \sum_{i=-q}^{q} g_i^{t,s} \dot{x}_{n-i}\right)$$

*-fxtn-aoi.pdf

- Savitzy-Golay filter





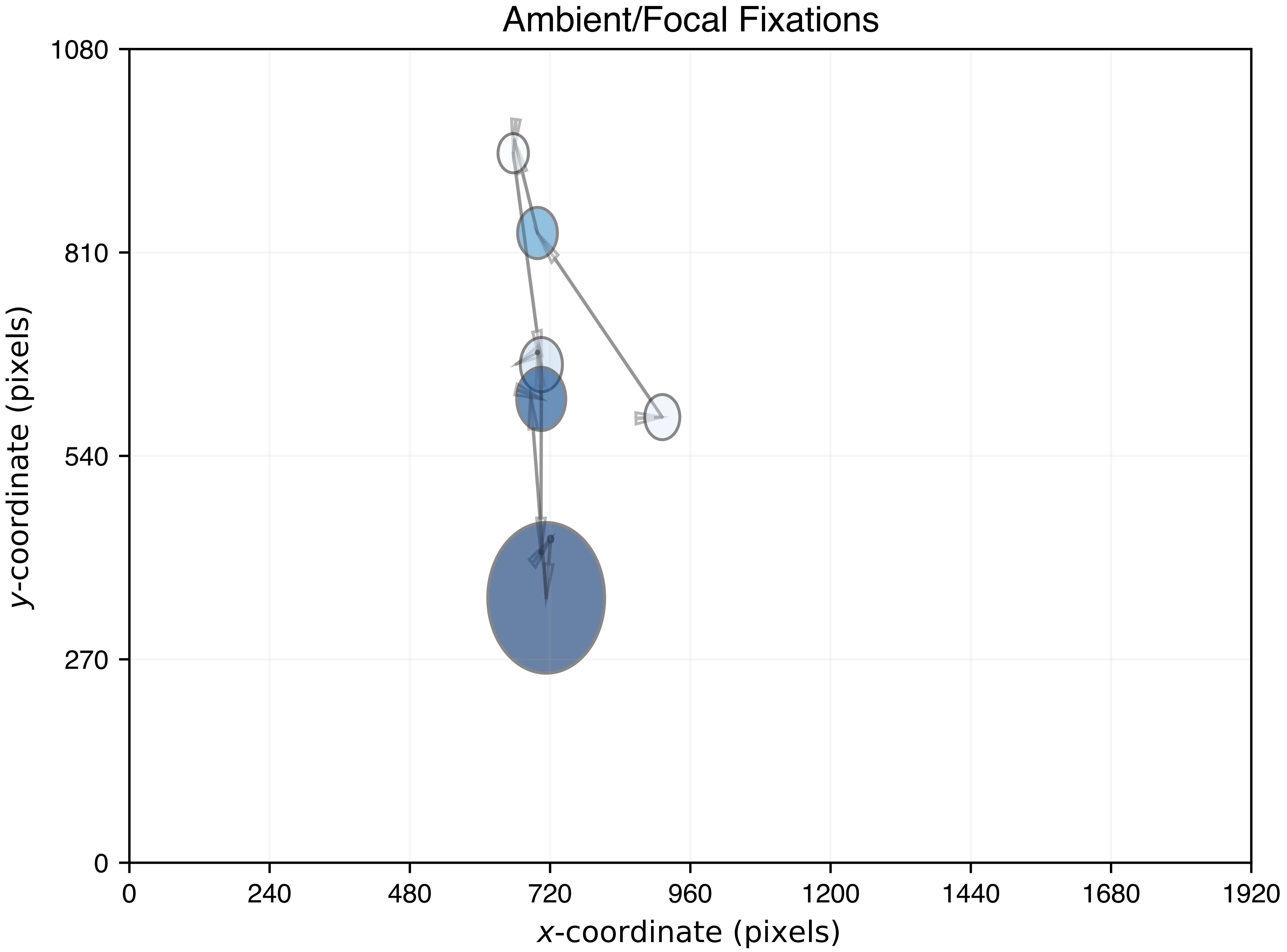
Gaze analytics pipeline: graph

- Check ambient/focal fixations

$$\mathcal{K}_i = \frac{d_i - \mu_d}{\sigma_d} - \frac{a_{i+1} - \mu_a}{\sigma_a}$$

*-affx.pdf

- fixation dur. – sacc. ampl.
- z-scores
- $\mathcal{K} > 0$ focal viewing
- $\mathcal{K} < 0$ ambient viewing



Gaze analytics pipeline: graph

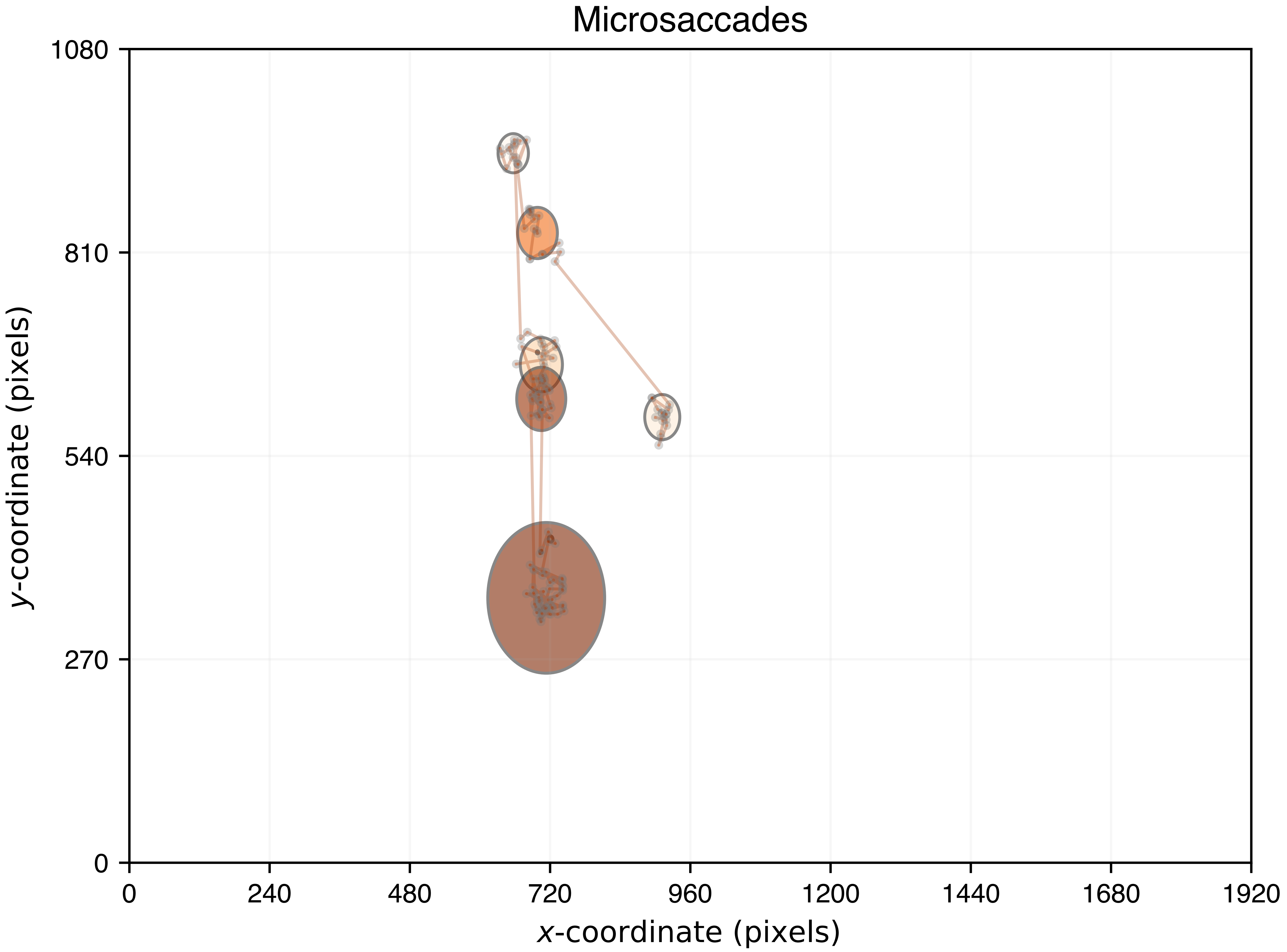
- Check microsaccades within ambient/focal fixations

*-ksac.pdf

$$\dot{x}_n = \frac{x_{n+2} + x_{n+1} - x_{n-1} - x_{n-2}}{6\Delta t}$$

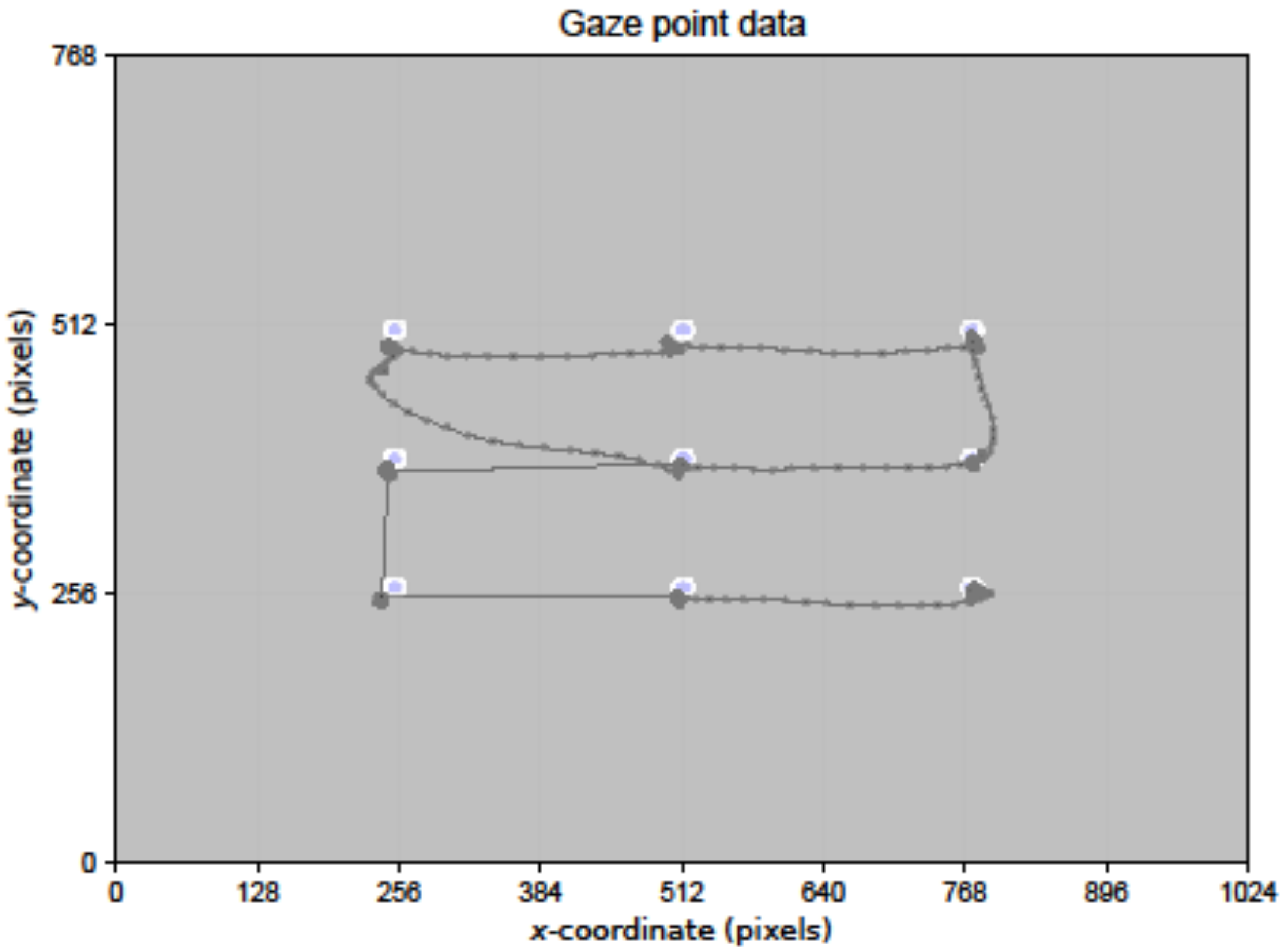
$$\sigma_x = \sqrt{\langle \dot{x}^2 \rangle - \langle \dot{x} \rangle^2}, \quad \sigma_y = \sqrt{\langle \dot{y}^2 \rangle - \langle \dot{y} \rangle^2}$$

$$\eta_x = \lambda \sigma_x, \quad \eta_y = \lambda \sigma_y$$



Gaze analytics pipeline: graph

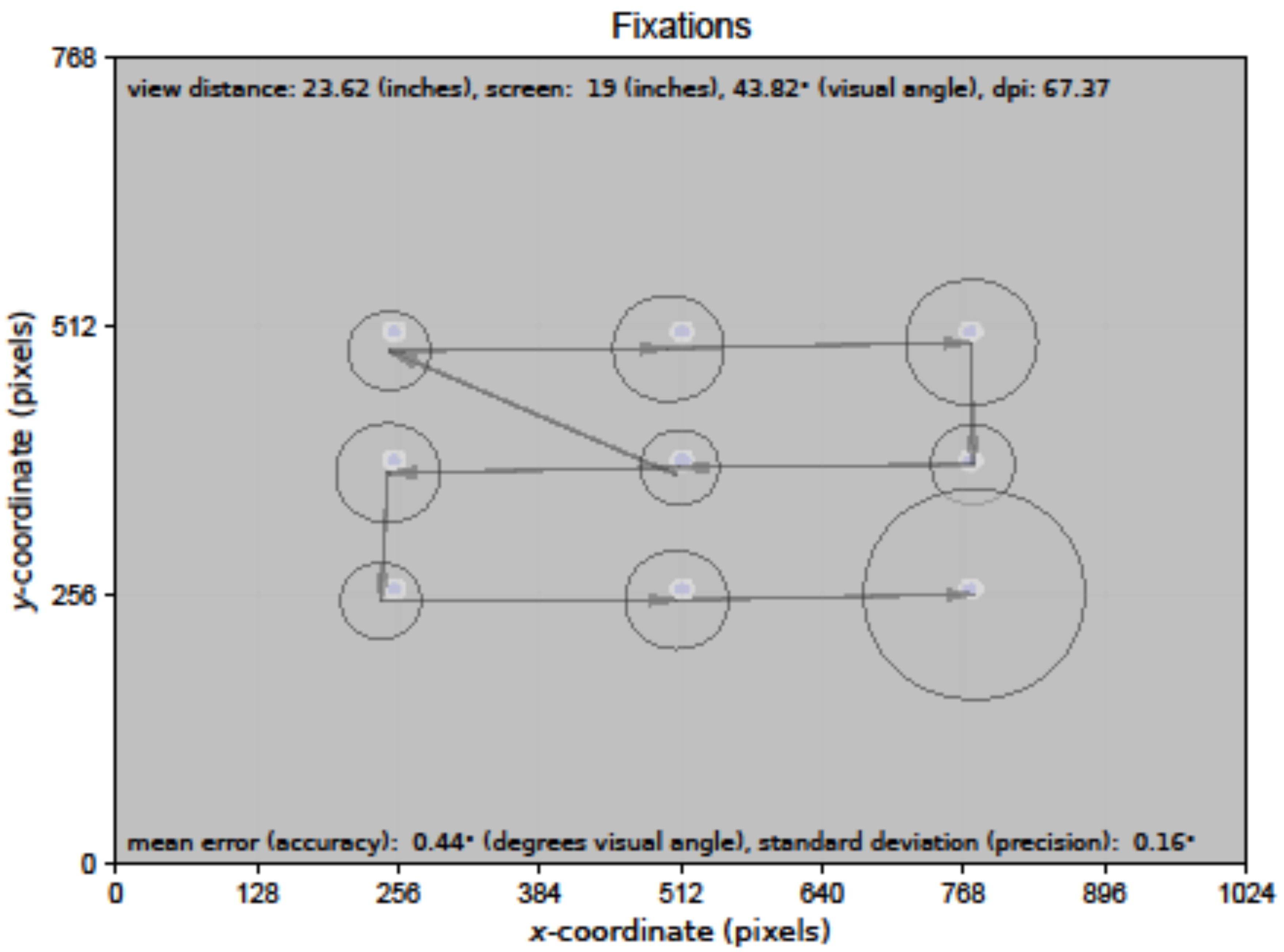
- Can do this over grid / calibration image (validation)
- Did you remember to include this in the stimuli?



Gaze analytics pipeline: graph

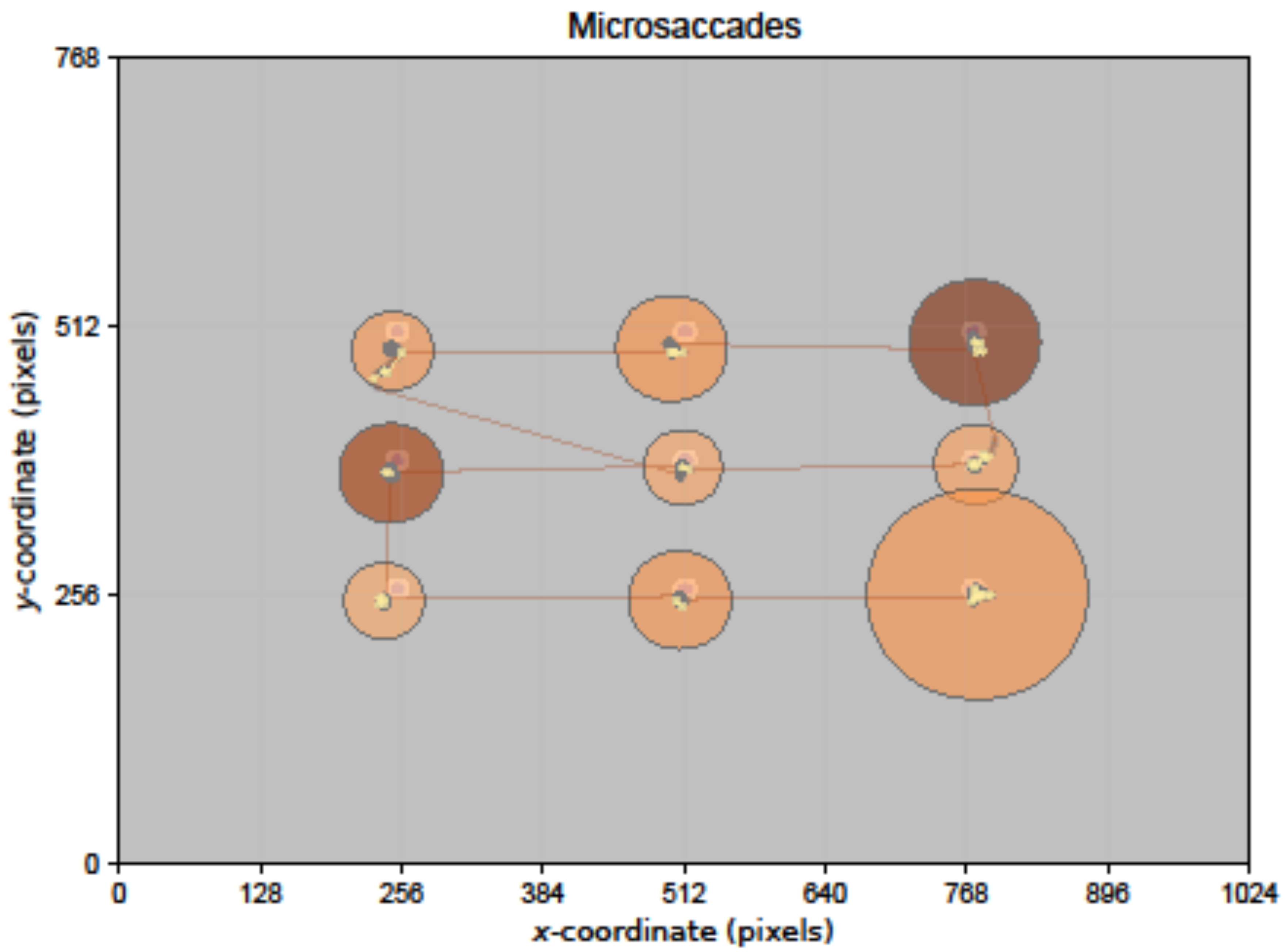
- This really helps in fine-tuning event detection filters
- Can also compute your own accuracy & precision
  - really useful for reporting

$$A = \sum_{i=1}^{M} \left(\frac{\sum_{j=1}^{N} \frac{\|T_i - P_{i,j}\|}{N}}{M} \right)$$



Gaze analytics pipeline: graph

- Look at microsaccades in ambient/focal fixations again
- Cause they're cool



Gaze analytics pipeline: process

- Once happy with visualizations, process data
- Will end up with various *.dat files, one per subject:

1. *-pdwt.dat wavelet transform (nothing to see here)
2. *-pICA.dat Index of Pupillary Activity (IPA)
3. *-pups.dat pupil diameter data (tricky)
4. *-smth.dat smoothed (Butterworth) data
5. *-fxtn.dat fixations
6. *-sacc.dat saccades
7. *-msac.dat microsaccades
8. *-msrt.dat microsaccade rate
9. *-amfo.dat ambient/focal K coefficient
10. *-fxtn-aois.dat fixations in AOIs

Gaze analytics pipeline: collate

- Now collate data to prepare for stats processing
- Will end up with various *.csv files, one per metric:

1. ~~pdwt.csv~~ wavelet transform (wouldn't make sense)
2. pICA.csv Index of Pupillary Activity (IPA)
3. ~~pups.csv~~ pupil diameter (can get this, need baseline)
4. ~~smth.csv~~ smoothed (Butterworth) data
5. fxtn.csv fixations
6. sacc.csv saccades
7. msac.csv microsaccades
8. msrt.csv microsaccade rate
9. amfo.csv ambient/focal K coefficient
10. fxtn-aois.csv fixations in AOIs

Gaze analytics pipeline: analyze

1

- Traditional metrics
  - fixations
  - fixation durations

- Novel / advanced metrics
  - **ambient / focal fixations**
  - Index of Pupillary Activity
  - microsaccade amplitude, rate

Discerning Ambient/Focal Attention with Coefficient $\mathcal{K}$

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ANDREW DUCHOWSKI, Clemson University, Clemson, SC, USA
IZABELA KREJTZ, University of Social Sciences and Humanities, Warsaw, Poland
AGNIESZKA SZARKOWSKA, University of Warsaw, Warsaw, Poland
AGATA KOPACZ, National Information Processing Institute, Warsaw, Poland

We introduce coefficient $\mathcal{K}$, defined on a novel parametric scale, derived from processing a traditionally eye-tracked time course of eye movements. Positive and negative ordinates of $\mathcal{K}$ indicate *focal* or *ambient* viewing, respectively, while the abscissa serves to indicate time, so that $\mathcal{K}$ acts as a dynamic indicator of fluctuation between ambient/focal visual behavior. The coefficient indicates the difference between fixation duration and its subsequent saccade amplitude expressed in standard deviation units, facilitating parametric statistical testing. To validate $\mathcal{K}$ empirically, we test its utility by capturing ambient and focal attention during serial and parallel visual search tasks (Study 1). We then show how $\mathcal{K}$ quantitatively depicts the difference in scanning behaviors when attention is guided by audio description during perception of art (Study 2).

Categories and Subject Descriptors: J.4 [**Computer Applications**]: Social and Behavioural Sciences—*Psychology*.

General Terms: Human Factors

Additional Key Words and Phrases: ambient focal attention, visual attention dynamics, serial vs. parallel search

1. INTRODUCTION

There is an increasing demand for characterization of viewer behavior through analysis of eye movements. Efforts are underway to surpass traditional categorization of the captured eye gaze sequence (x_i, y_i, t_i) as fixations and saccades into higher-level descriptors of visual behavior. For example, Bednarik et al. [2012] explored eye movement features that could best describe the differences in gaze behavior during intentional and non-intentional interaction, e.g., deciding if the user is about to issue a command. They used a Support Vector Machine (SVM) approach to differentiate pupil diameter from a baseline recording for this purpose. Bulling et al. [2013] attempted to classify continuous electrooculography (EOG) signals into a vector of binary descriptors of everyday life situations, i.e., whether or not the user is interacting socially, concentrating on a mental task, engaging in a physical activ-

This work has been partly supported by research grant "Audio description in education" awarded by the Faculty of Applied Languages, University of Warsaw.
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DOI 10.1145/0000000.0000000 http://doi.acm.org/10.1145/0000000.0000000

Gaze analytics pipeline: analyze

- Traditional metrics
  - fixations
  - fixation durations
- Novel / advanced metrics
  - ambient / focal fixations
  - **Index of Pupillary Activity**
  - microsaccade amplitude, rate

The Index of Pupillary Activity

Measuring Cognitive Load *vis-à-vis* Task Difficulty with Pupil Oscillation

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ABSTRACT
A novel eye-tracked measure of the frequency of pupil diameter oscillation is proposed for capturing what is thought to be an indicator of cognitive load. The proposed metric, termed the Index of Pupillary Activity, is shown to discriminate task difficulty *vis-à-vis* cognitive load (if the implied causality can be assumed) in an experiment where participants performed easy and difficult mental arithmetic tasks while fixating a central target (a requirement for replication of prior work). The paper's contribution is twofold: full documentation is provided for the calculation of the proposed measurement which can be considered as an alternative to the existing proprietary Index of Cognitive Activity (ICA). Thus, it is possible for researchers to replicate the experiment and build their own software which implements this measurement. Second, several aspects of the ICA are approached in a more data-sensitive way with the goal of improving the measurement's performance.

Author Keywords
pupillometry; eye tracking; task difficulty

ACM Classification Keywords
H.1 Models and Principles: User/Machine Systems; J.4 Computer Applications: Social and Behavioral Sciences

INTRODUCTION
Systems that can detect and respond to their users' cognitive load have the potential to improve both users' experiences and outcomes in many domains: students and teachers, drivers, pilots, and surgeons may all benefit from systems that can detect when their jobs are too hard or easy and dynamically adapt the difficulty [3, 20, 41, 71, 11]. Key to this functionality is the ability to accurately estimate a person's cognitive load without distracting them from their tasks.

CHI 2018, April 21–26, 2018, Montréal, Québec, Canada.
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https://doi.org/10.1145/3173574.3173856

Estimation of human workload is couched in Cognitive Load Theory (CLT) [65]. Because CLT aims to model cognitive aspects of human behavior, it is relevant to several Human-Computer Interaction (HCI) research areas, including human-centered design, human cognition modeling, usability, and learning systems (e.g., e-learning) [48, 24]. Estimating the user's workload is helpful for many situations where people interact with computing devices or machines [20]. Minimizing cognitive load is suggested as an integral part of human-centered design [10]. Pfleging et al. [53] and Palinko and Kun [50] provide notable examples related to HCI, including automotive and online learning domains. Bailey and Iqbal [3] show how moment-to-moment detection of mental workload can help reduce the interruption cost of notifications when performing interactive tasks such as driving. Other important applications include surgery [28, 29] and flight safety [52].

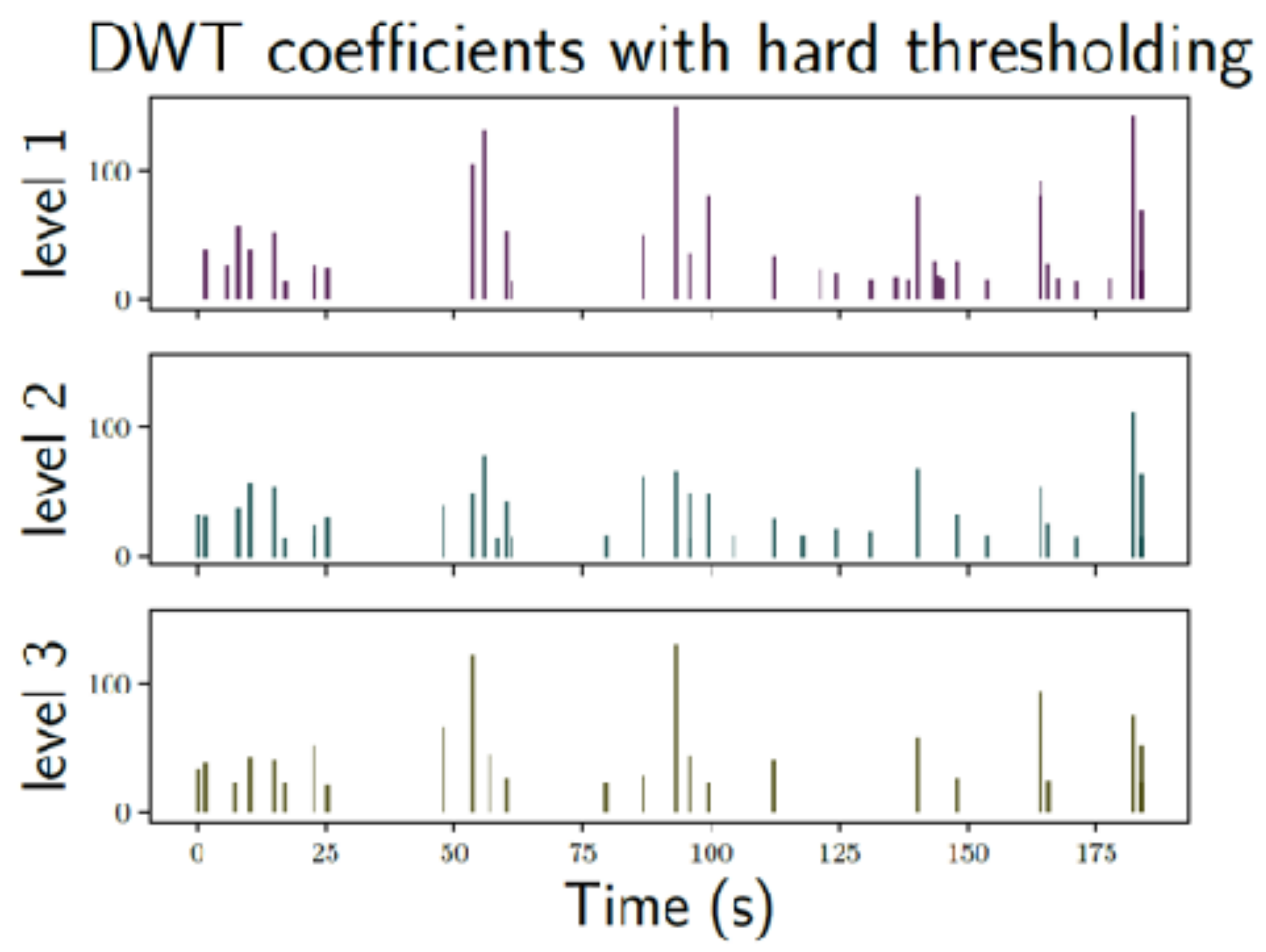
Cognitive Load Theory can play an important role in the design of interactive systems as it can guide designers of such systems to avoid overloading users. For example, Yuksel et al. [71] devised an interactive music learning interface that adapts to the user's level of cognitive load as measured by functional near-infrared spectroscopy (fNIRS). They note, however, that reliable measurement of cognitive load is the weak link between CLT and HCI. Other physiological measures include heart rate variability (HRV), electrodermal activity (EDA, previously galvanic skin response (GSR)), photoplethysmogram-based stress induced vascular index (sVRI), and blink rate [9]. With the exception of blink rate, all of these methods are invasive, relying on physical contact with the user. A non-invasive, reliable measure of cognitive load is thus highly desirable.

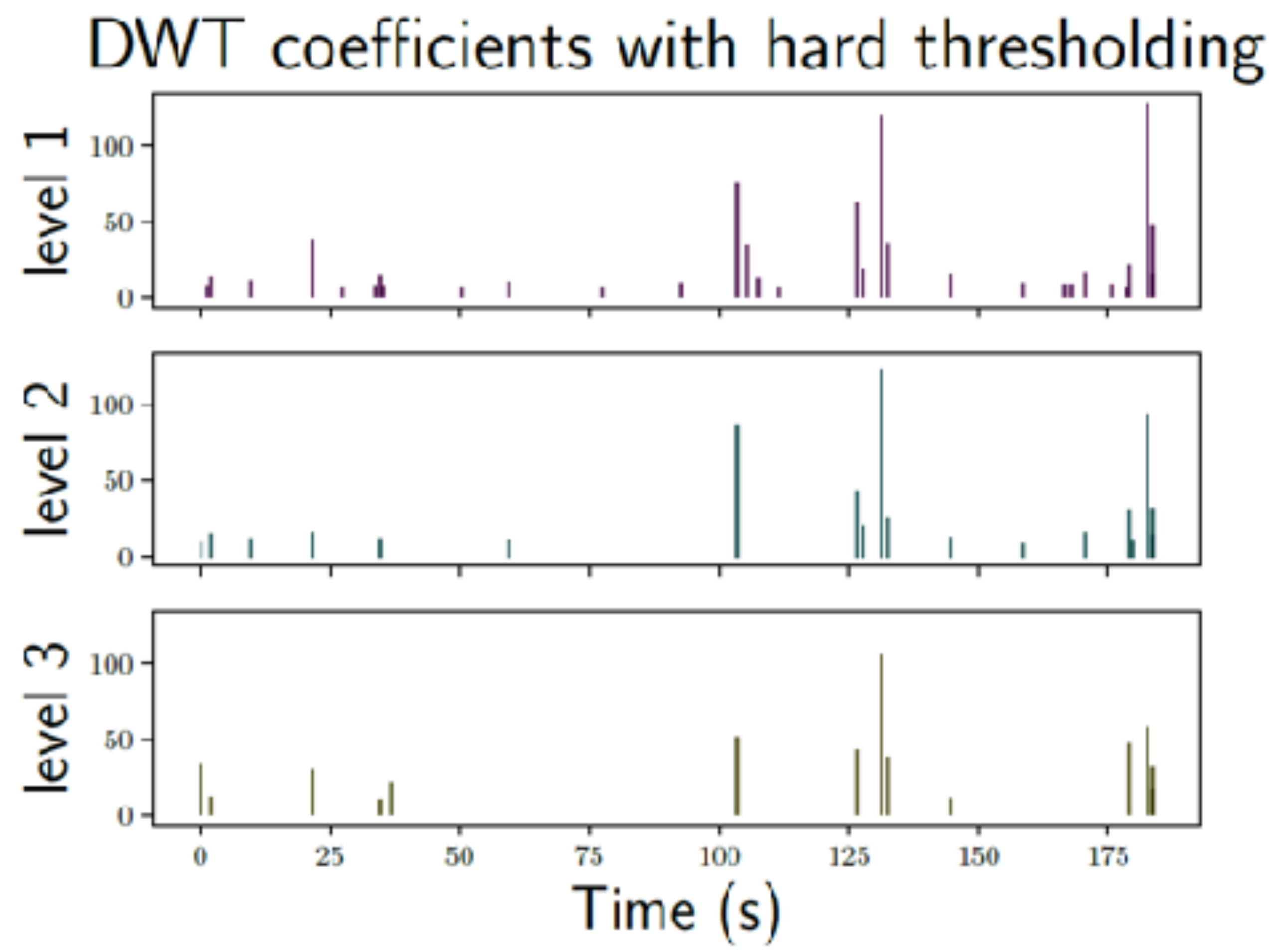
Of the three predominant cognitive load measurement methods in CLT studies, namely self-reporting, the dual-task paradigm, and physiological measures [71], eye tracking, of the latter type, offers the greatest potential for delivering a non-invasive estimate of cognitive load (for an excellent recent review of psychophysiological measures with a focus on HCI, see Cowley et al. [11]). Measurement of gaze for estimating cognitive

Gaze analytics pipeline: analyze

- Traditional metrics
  - fixations
  - fixation durations

- Novel / advanced metrics
  - ambient / focal fixations
  - **Index of Pupillary Activity**
  - microsaccade amplitude, rate





Gaze analytics pipeline: analyze

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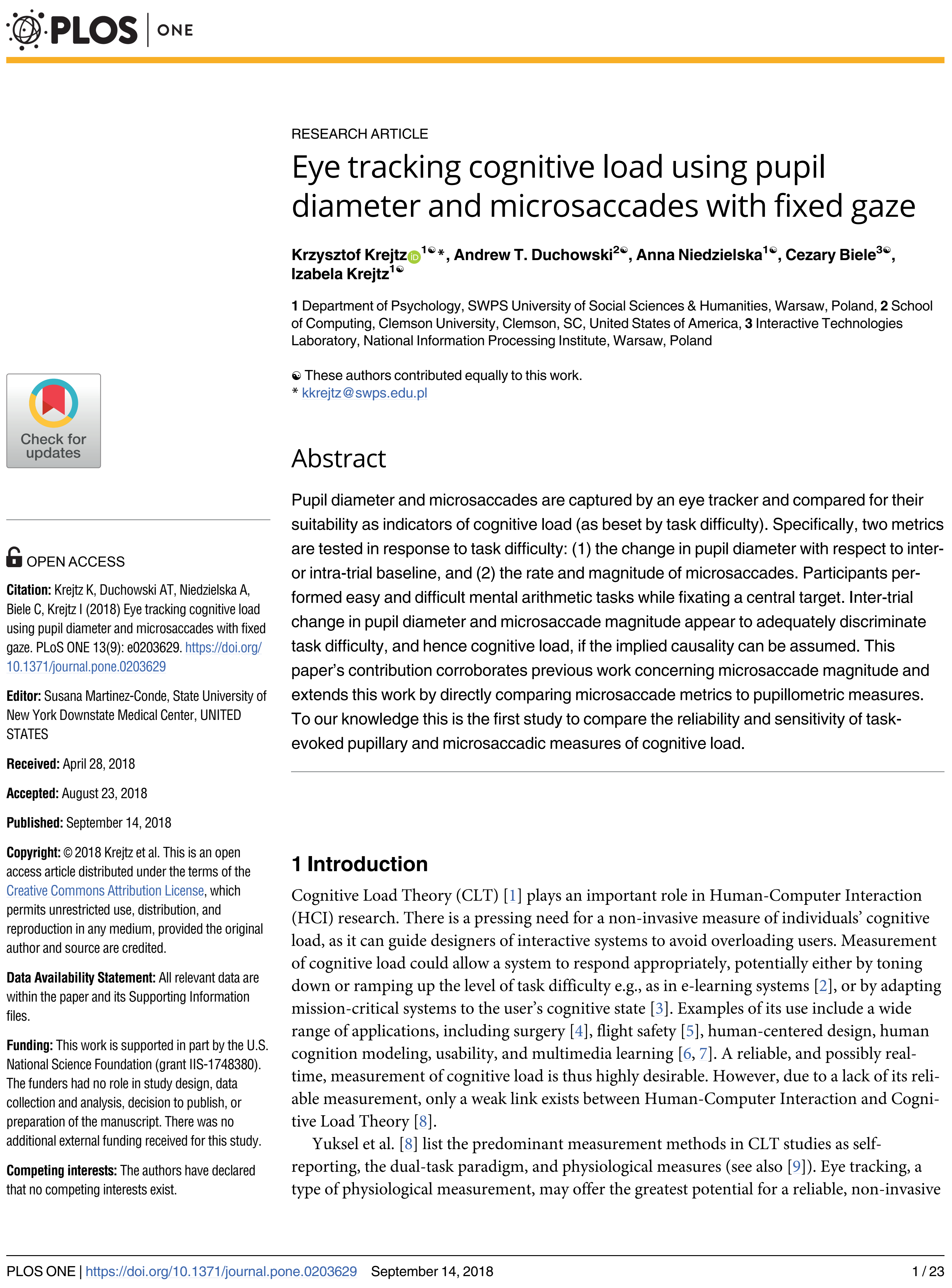
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RESEARCH ARTICLE

Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze

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Citation: Krejtz K, Duchowski AT, Niedzielska A, Biele C, Krejtz I (2018) Eye tracking cognitive load using pupil diameter and microsaccades with fixed gaze. PLoS ONE 13(9): e0203629. https://doi.org/10.1371/journal.pone.0203629

Editor: Susana Martinez-Conde, State University of New York Downstate Medical Center, UNITED STATES

Received: April 28, 2018

Accepted: August 23, 2018

Published: September 14, 2018

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: This work is supported in part by the U.S. National Science Foundation (grant IIS-1748380). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. There was no additional external funding received for this study.

Competing interests: The authors have declared that no competing interests exist.

Abstract

Pupil diameter and microsaccades are captured by an eye tracker and compared for their suitability as indicators of cognitive load (as beset by task difficulty). Specifically, two metrics are tested in response to task difficulty: (1) the change in pupil diameter with respect to inter- or intra-trial baseline, and (2) the rate and magnitude of microsaccades. Participants performed easy and difficult mental arithmetic tasks while fixating a central target. Inter-trial change in pupil diameter and microsaccade magnitude appear to adequately discriminate task difficulty, and hence cognitive load, if the implied causality can be assumed. This paper's contribution corroborates previous work concerning microsaccade magnitude and extends this work by directly comparing microsaccade metrics to pupillometric measures. To our knowledge this is the first study to compare the reliability and sensitivity of task-evoked pupillary and microsaccadic measures of cognitive load.

1 Introduction

Cognitive Load Theory (CLT) [1] plays an important role in Human-Computer Interaction (HCI) research. There is a pressing need for a non-invasive measure of individuals' cognitive load, as it can guide designers of interactive systems to avoid overloading users. Measurement of cognitive load could allow a system to respond appropriately, potentially either by toning down or ramping up the level of task difficulty e.g., as in e-learning systems [2], or by adapting mission-critical systems to the user's cognitive state [3]. Examples of its use include a wide range of applications, including surgery [4], flight safety [5], human-centered design, human cognition modeling, usability, and multimedia learning [6, 7]. A reliable, and possibly real-time, measurement of cognitive load is thus highly desirable. However, due to a lack of its reliable measurement, only a weak link exists between Human-Computer Interaction and Cognitive Load Theory [8].

Yuksel et al. [8] list the predominant measurement methods in CLT studies as self-reporting, the dual-task paradigm, and physiological measures (see also [9]). Eye tracking, a type of physiological measurement, may offer the greatest potential for a reliable, non-invasive

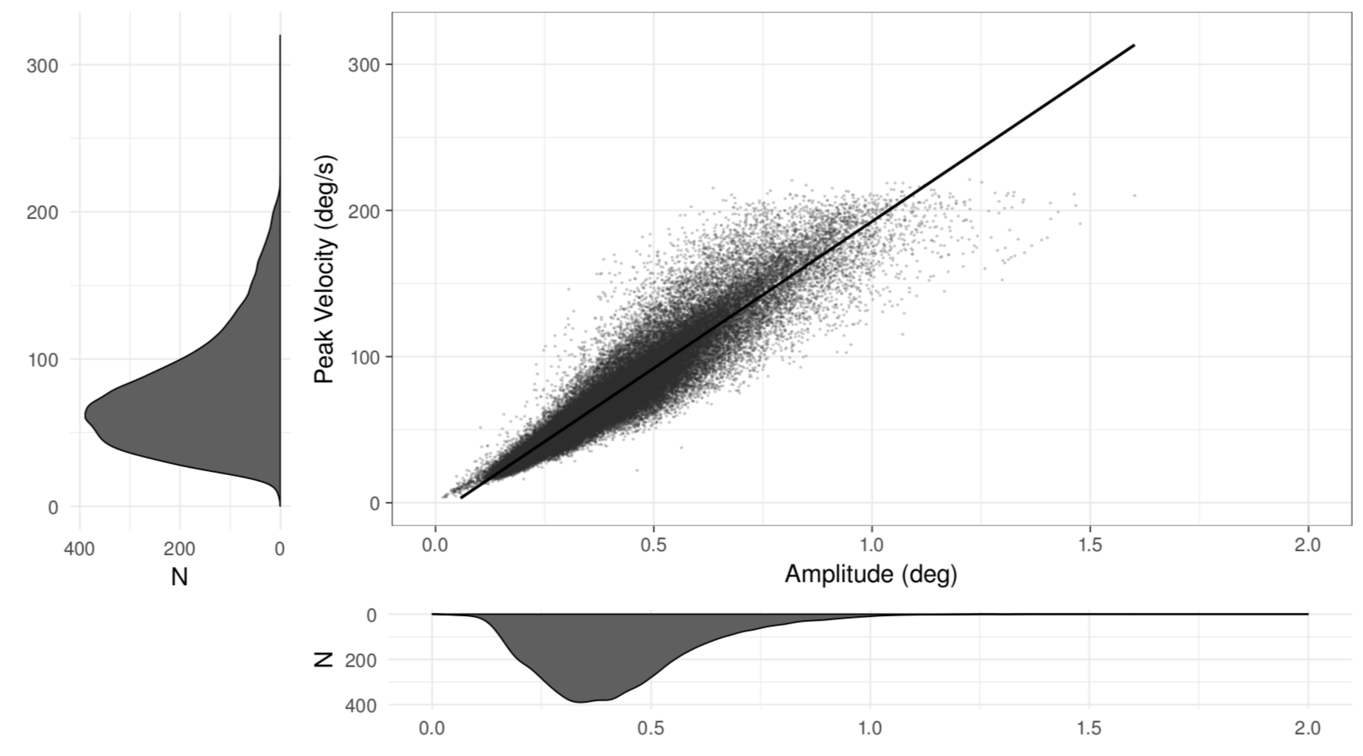
Gaze analytics pipeline: analyze

- Traditional metrics
  - fixations
  - fixation durations
- Novel / advanced metrics
  - ambient / focal fixations
  - Index of Pupillary Activity
  - **microsaccade amplitude, rate**

$$\dot{x}_n = \frac{x_{n+2} + x_{n+1} - x_{n-1} - x_{n-2}}{6\Delta t}$$

$$\sigma_x = \sqrt{\langle \dot{x}^2 \rangle - \langle \dot{x} \rangle^2}, \quad \sigma_y = \sqrt{\langle \dot{y}^2 \rangle - \langle \dot{y} \rangle^2}$$

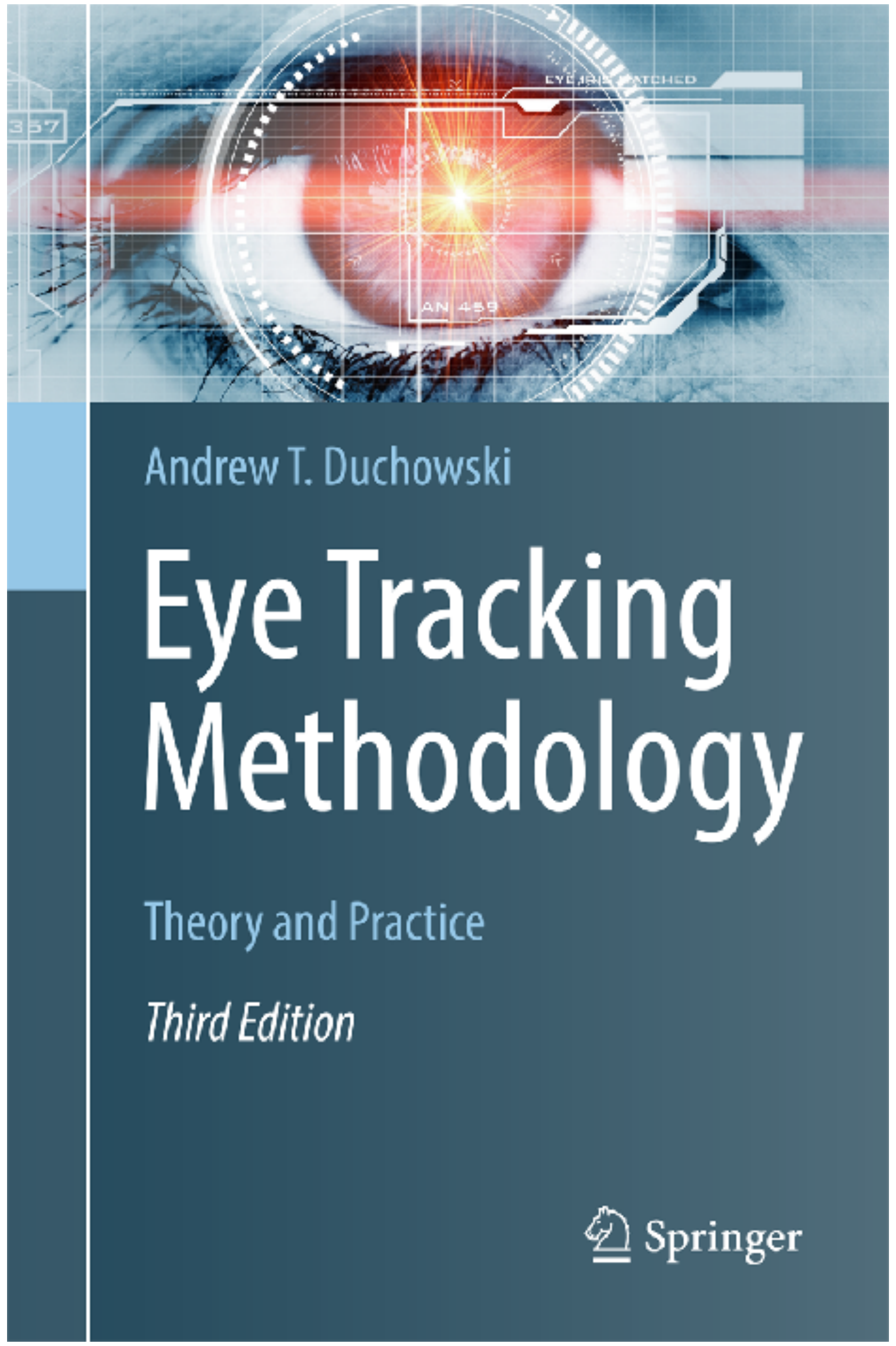
$$\eta_x = \lambda \sigma_x, \quad \eta_y = \lambda \sigma_y$$



Gaze analytics pipeline: read

- Eye Tracking Methodology, **3rd ed.** 2017
  - ISBN: 978-3-319-57881-1

- More details found in book:
  - additional metrics (NNI)
  - microsaccades
  - heatmap visualization
  - binocular eye movement analysis
  - etc.



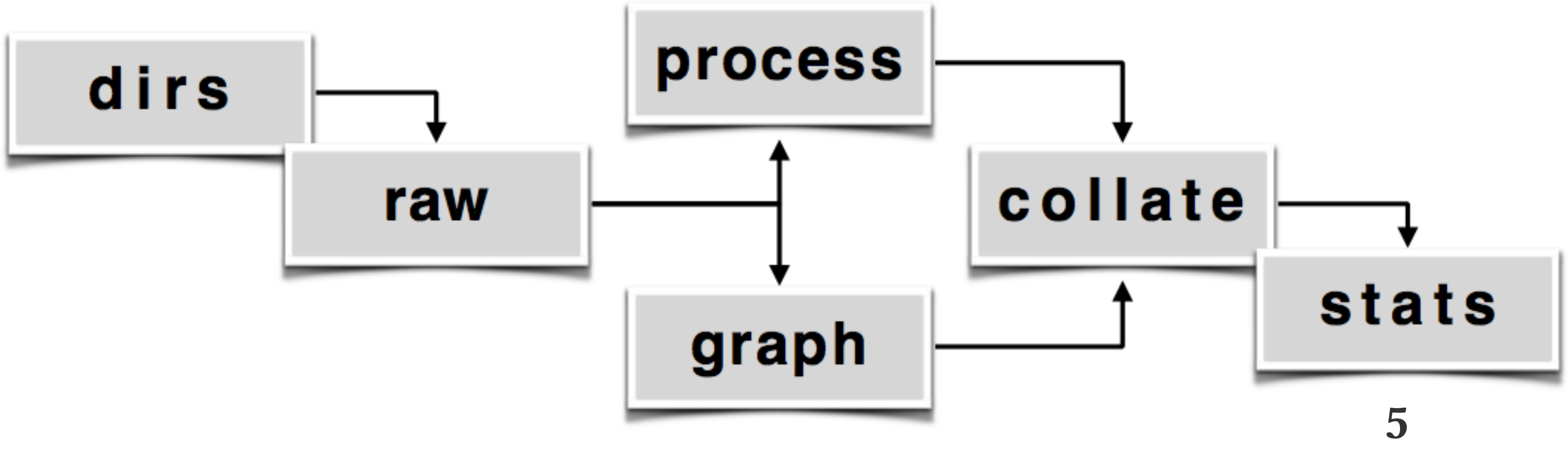
Gaze analytics pipeline: statistics

- Excellent online references for R (maybe dated by now):
  - Baron and Li's Notes on the use of R for psychology experiments and questionnaires:
    - http://www.psych.upenn.edu/~baron/rpsych.html
  - The Personality Project
    - http://www.personality-project.org/r

Gaze analytics pipeline overview

- Main targets (e.g., *nix Makefile or Windows bat files)
- Idea is to type one command and go for coffee
- Return from coffee and write paper
- 5 easy steps:

1. dirs; 2. raw; 3. process; 4. collate; 5. stats



Gaze analytics pipeline:

*.csv files, one per metric:

amfo.csv	ambient/focal K coefficient
fxtn.csv	fixations
fxtn-aois.csv	fixations in AOIs
msac.csv	microsaccades
msrt.csv	microsaccade rate
pICA.csv	Index of Pupillary Activity (IPA)
pICALH.csv	Low/High Index of Pupillary Activity (LHIPA)
sacc.csv	saccades

Gaze analytics pipeline:

<u>One row per fixation:</u>

amfo.csv	ambient/focal K coefficient
fxtn.csv	fixations
msrt.csv	microsaccade rate

<u>One row per fixation in one of the AOIs:</u>

fxtn-aois.csv	fixations in AOIs

<u>One row per microsaccade</u>

msac.csv	microsaccades

<u>One row per trial (per subject)</u>

pICA.csv	Index of Pupillary Activity (IPA)
pICALH.csv	Low/High Index of Pupillary Activity (IPA)

<u>One row per saccade:</u>

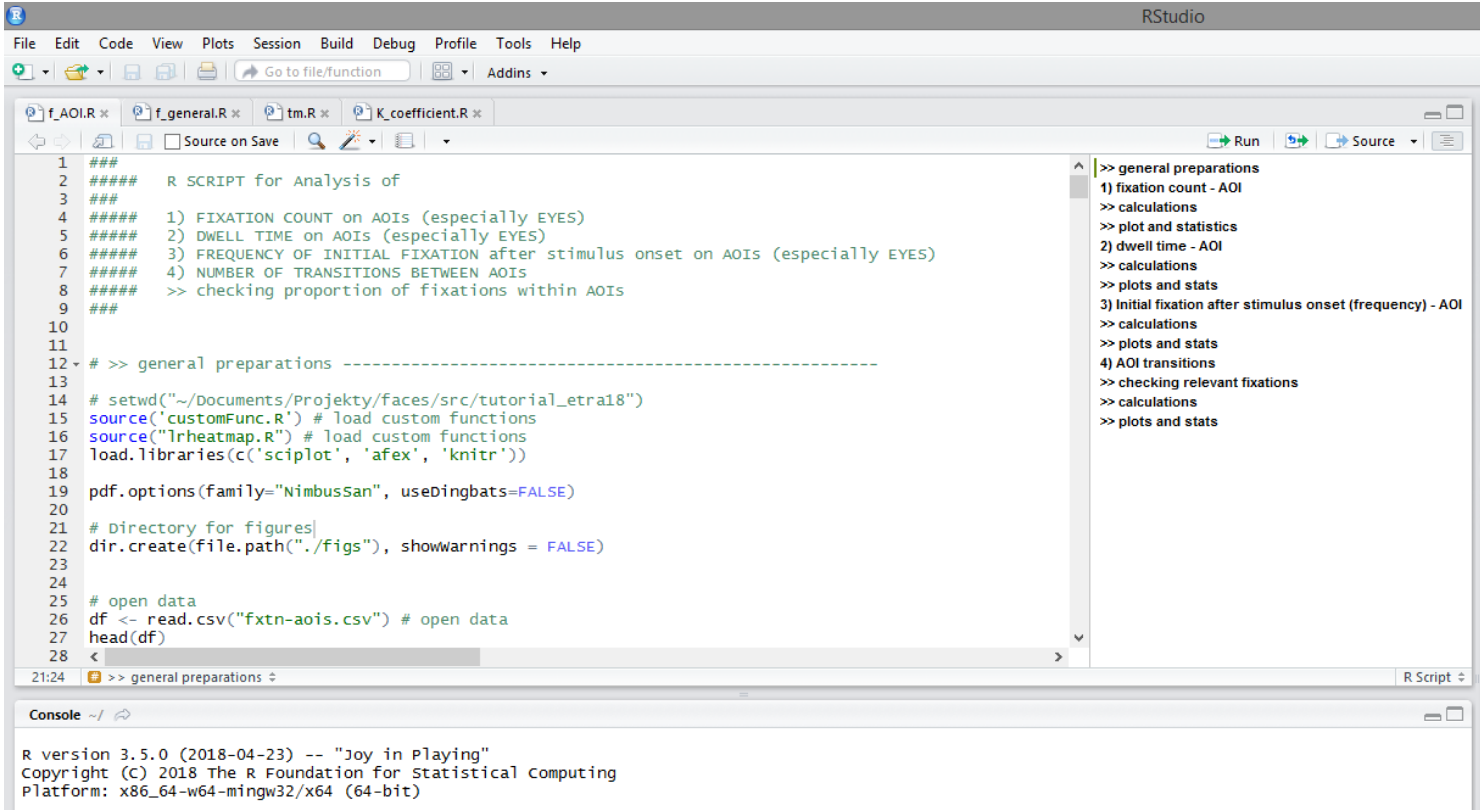
sacc.csv	saccades

Gaze analytics pipeline: statistics

1. fxtn.R — gaze analytics related to fixations, AOIs
2. tm.R — transition matrices and transition entropy

For all others, write your own

Gaze analytics pipeline: statistics



Gaze analytics pipeline: statistics

1. fxtn.R gaze analytics related to fixations, AOIs
2. tm.R transition matrices and transition entropy

Will end up with figures in ./figs and 4 *.out files, one per R script:

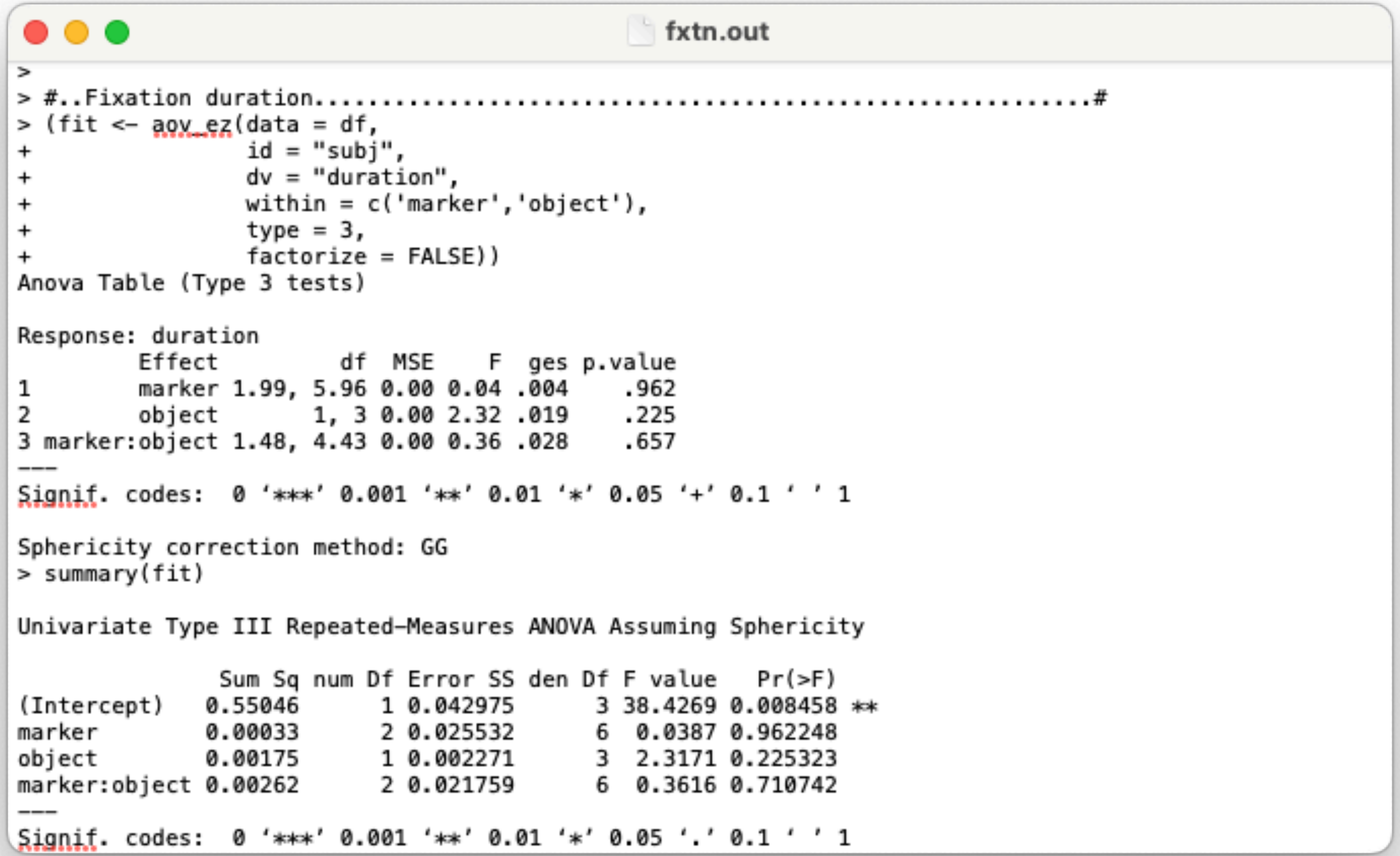
fxtn.out

tm.out

Gaze analytics pipeline: statistics

Code and output/statistics in the *.out files:

fxtn.out



calculated from fxtn.csv

Gaze analytics pipeline: statistics

Code and output/statistics in the *.out files:

TM.out

tm.out

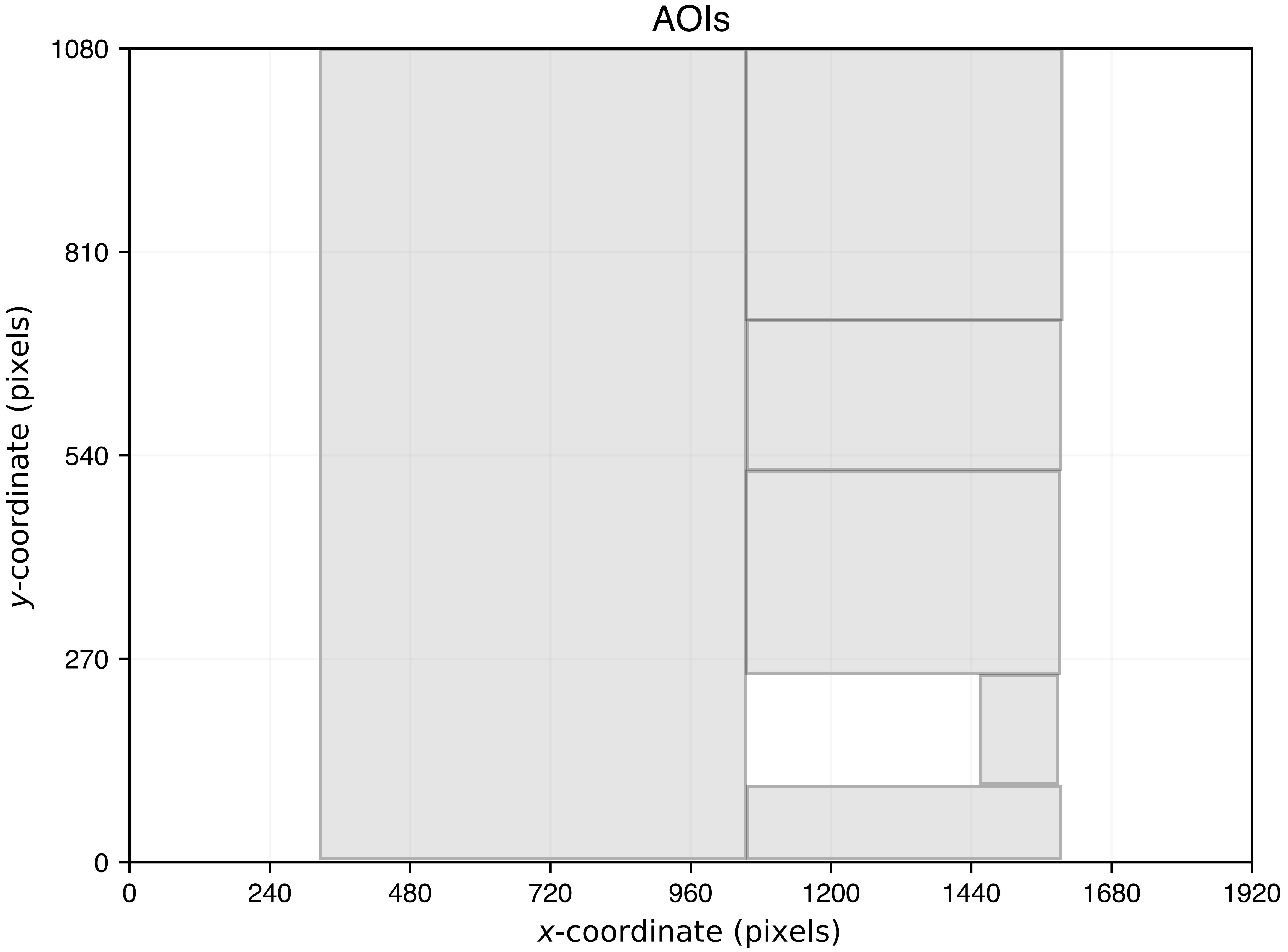
```
> naois <- as.integer(args[1])
> print(sprintf("naois = %d\n",naois))
[1] "naois = 6\n"
>
> df <- read.csv("fxtn-aois.csv")
>
> # ---------------------------------------------------------------------
> # main analyses
>
> M <- zeroTM(naois)
> M
  1 2 3 4 5 6
1 0 0 0 0 0 0
2 0 0 0 0 0 0
3 0 0 0 0 0 0
4 0 0 0 0 0 0
5 0 0 0 0 0 0
6 0 0 0 0 0 0
>
> ddf <- df
> ddf
    subj exp_id ses_id marker object timestamp         x         y duration
1    s03      1      1  large   male  0.048479 1373.0208  93.28500 0.016120
2    s03      1      1  large   male  0.080980 1365.1017  91.01602 0.177426
3    s03      1      1  large   male  0.274906 1358.2080  91.69200 0.015980
4    s03      1      1  large   male  0.388075 1253.9232 625.09860 0.016155
5    s03      1      1  large   male  0.420441 1223.0428 625.18320 0.388319
6    s03      1      1  large   male  0.889471 1185.3912 731.46870 0.194014
7    s03      1      1  large   male  1.099834 1180.5408 726.70500 0.016002
8    s03      1      1  large   male  1.196911 1334.3032 747.09675 0.193978
```

calculated from fxtn-aois.csv

Effect of markers on fixation duration

1) Measures related to Areas of Interest (AOIs) such as the marker and object (painting):

AOIs:
object (painting),
large marker, small
marker, painter info,
acquisition info

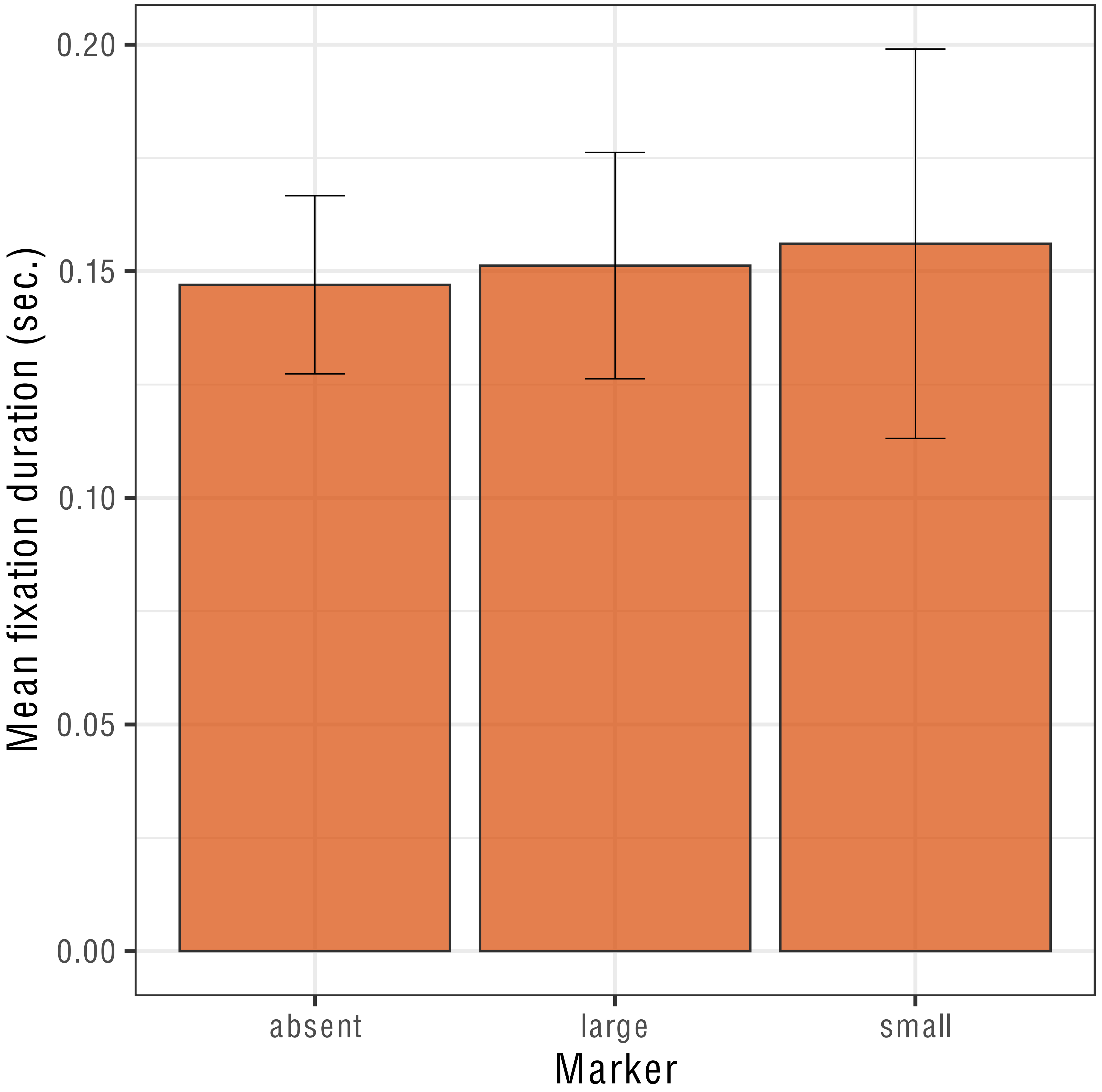


Effect of markers on fixation duration

1) Measures related to Areas of Interest (AOIs) such as the marker and object (painting):
e.g., fixation duration

Hypothesis (coincides with null hypothesis):
no difference expected (because markers are not distracting)

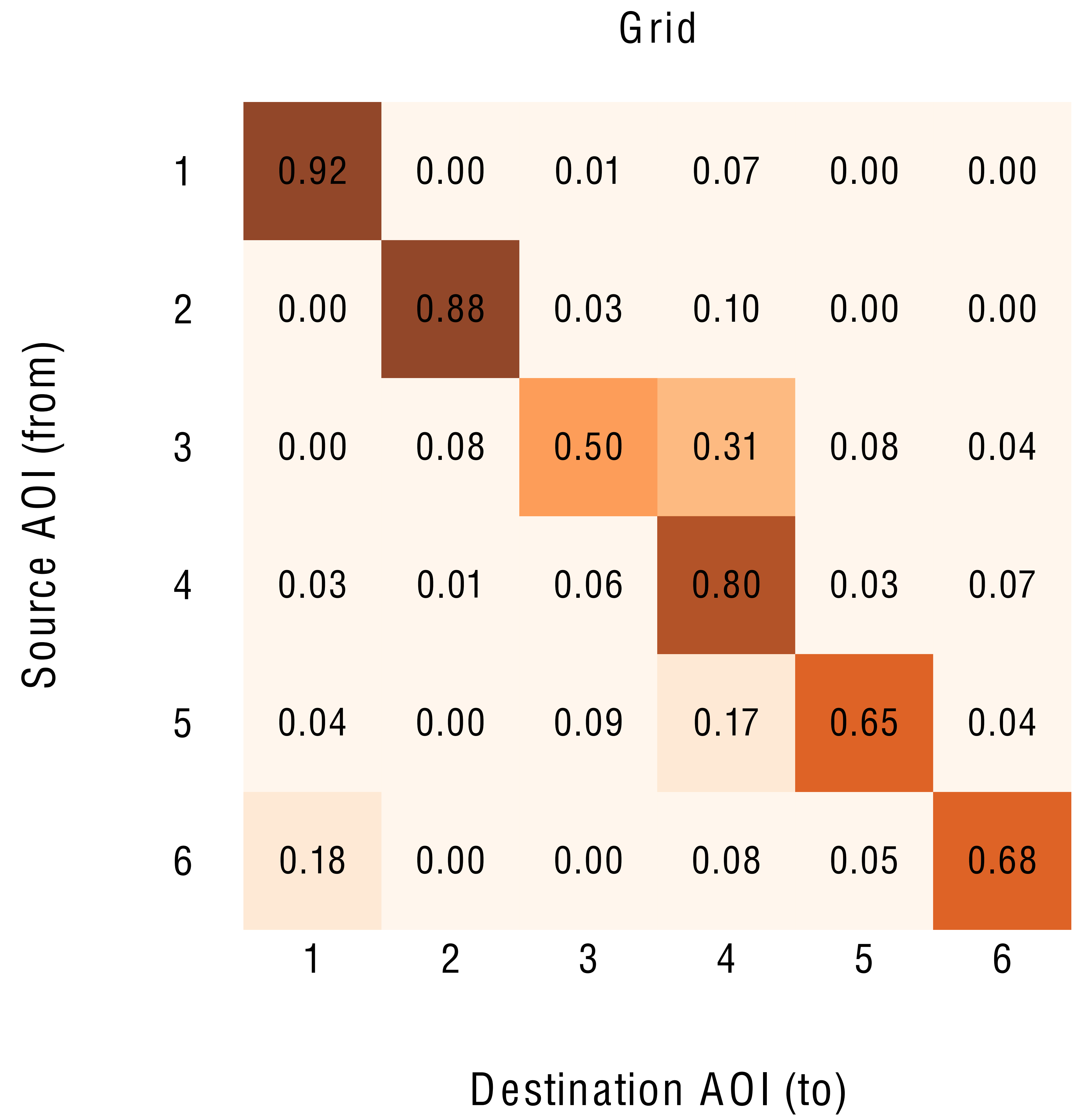
Effect	df	MSE	F	ges	p.value
marker	1.06, 3.19	4870.47	0.24	.020	.671
object	1, 3	2498.45	0.67	.027	.474
marker:object	1.44, 4.31	2400.13	1.22	.065	.356



Effect of markers on gaze transition

1) Measures related to Areas of Interest (AOIs) such as the marker and object (painting): e.g., gaze transition

Hypothesis (coincides with null hypothesis):
no difference expected (because markers are not distracting)

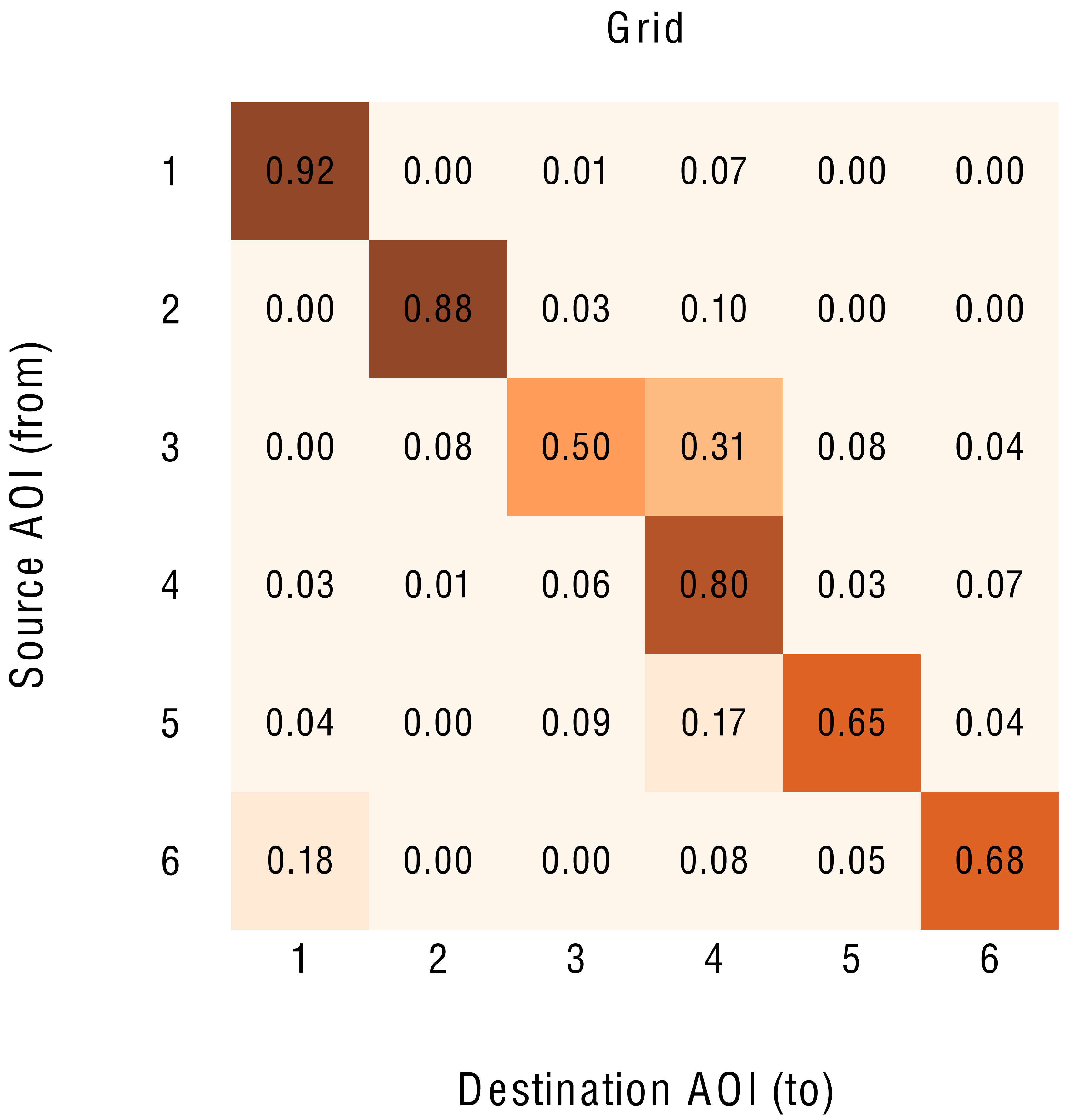


`Need ANOVA on entropy between conditions (exercise for the reader)`

Gaze analytics pipeline: transition entropy

- Normalized transition entropy
- Higher entropy means "surprise!"

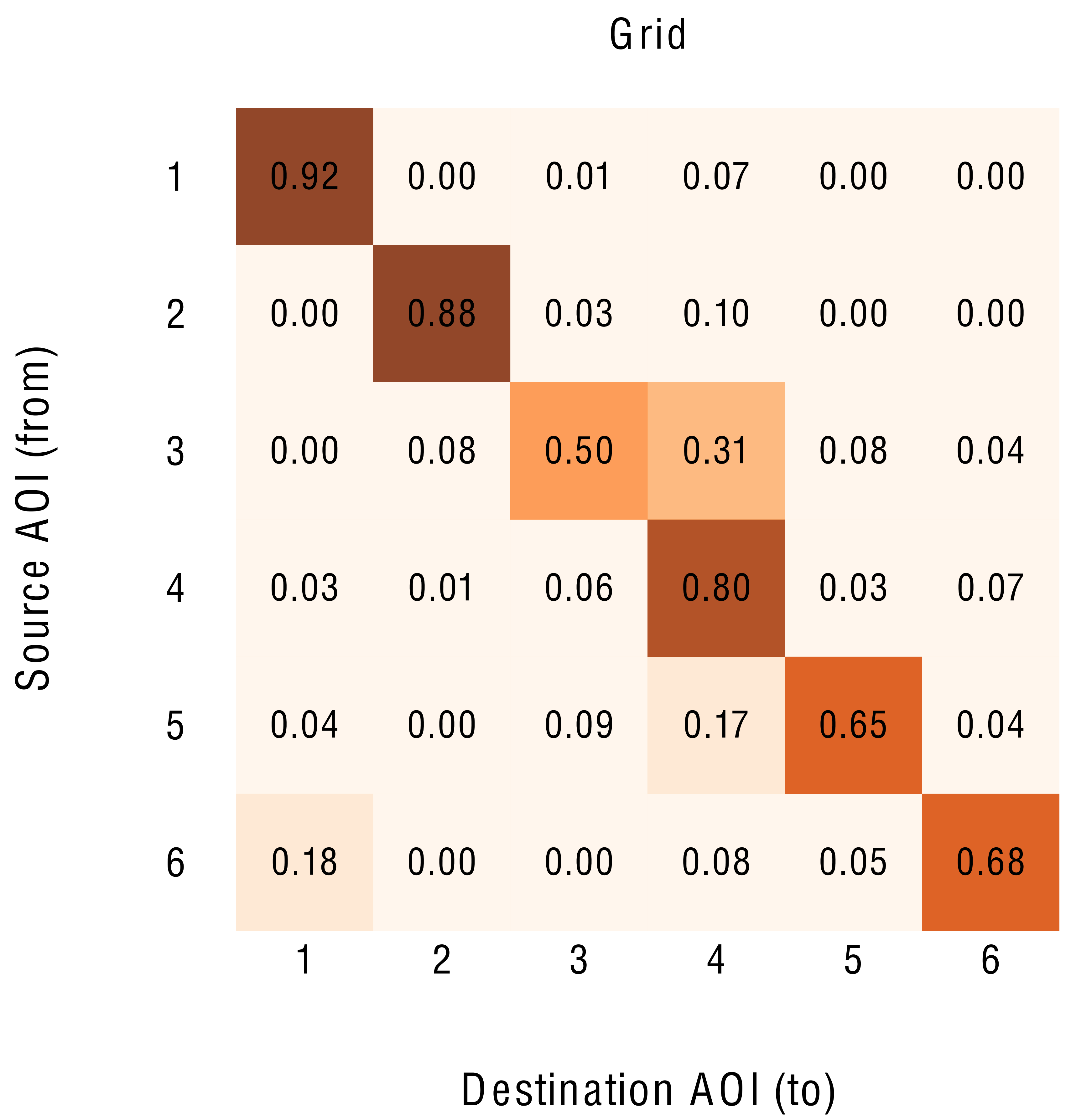
$$H_t = -\frac{1}{\log_2 s} \sum_{i \in \mathcal{S}} \pi_i \sum_{j \in \mathcal{S}} p_{ij} \log_2 p_{ij}$$



Gaze analytics pipeline: transition entropy

- Normalized transition entropy
- Higher entropy means “surprise!”
- Stationary entropy: long run

$$H_s = -\sum_{i \in \mathcal{S}} \pi_i \log \pi_i$$



Stationary entropy: example

- Predicting the weather:
  - if rainy, probability it remains rainy is .51
  - if sunny, 21% chance it become cloudy

$$\mathbf{P} = \begin{array}{r} \\ \text{rainy} \\ \text{cloudy} \\ \text{sunny} \end{array} \begin{array}{c} \begin{array}{ccc} \text{rainy} & \text{cloudy} & \text{sunny} \end{array} \\ \begin{pmatrix} 0.51 & 0.39 & 0.10 \\ 0.32 & 0.35 & 0.33 \\ 0.15 & 0.21 & 0.64 \end{pmatrix} \end{array} \begin{array}{l} \\ \sum_{p_i} = 1 \\ \sum_{p_i} = 1 \\ \sum_{p_i} = 1 \end{array}$$

Stationary entropy: example

- Predicting the weather:
  - if rainy, probability it remains rainy is .51
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$$\mathbf{P} = \begin{array}{r} \\ \text{rainy} \\ \text{cloudy} \\ \text{sunny} \end{array} \begin{array}{c} \begin{array}{ccc} \text{rainy} & \text{cloudy} & \text{sunny} \end{array} \\ \begin{pmatrix} \boxed{0.51} & 0.39 & 0.10 \\ 0.32 & 0.35 & 0.33 \\ 0.15 & 0.21 & 0.64 \end{pmatrix} \end{array} \begin{array}{l} \\ \sum_{p_i} = 1 \\ \sum_{p_i} = 1 \\ \sum_{p_i} = 1 \end{array}$$

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- Transition matrix gives likelihood of next period
- What about next two periods?

Stationary entropy: example

- What about next two periods? $\mathbf{PP} = \mathbf{P_2}$
  - if it's rainy today, chance it will be sunny in 2 days is .25

$$\mathbf{P_2} = \begin{pmatrix} 0.51 & 0.39 & 0.10 \\ 0.32 & 0.35 & 0.33 \\ 0.15 & 0.21 & 0.64 \end{pmatrix} \begin{pmatrix} 0.51 & 0.39 & 0.10 \\ 0.32 & 0.35 & 0.33 \\ 0.15 & 0.21 & 0.64 \end{pmatrix}$$

$$= \begin{pmatrix} 0.40 & 0.36 & \boxed{0.25} \\ 0.32 & 0.32 & 0.36 \\ 0.24 & 0.27 & 0.49 \end{pmatrix}$$

- Similarly, probability in the long is $\mathbf{P}_n = \mathbf{P}^n$

Stationary entropy: example

- In the long run $\mathbf{P}_n = \mathbf{P}^n$
  - steady-state (stationary) transition probabilities converge
  - steady-state vector π is eigenvector of $\mathbf{P}$ with eigenvalue $\lambda = 1$

$$\mathbf{x}\mathbf{P}^n \to \pi \quad \forall\, \mathbf{x} \quad \text{if} \quad \pi\mathbf{P} = \lambda\pi$$

Stationary entropy: transition vs. stationary entropy?

- Ultimately, not super certain of stationary entropy's utility

- Because: $$H_t = -\frac{1}{log_2 s} \sum_{i \in \mathcal{S}} \pi_i \sum_{j \in \mathcal{S}} p_{ij} \log_2 p_{ij} \qquad H_s = -\sum_{i \in \mathcal{S}} \pi_i \log \pi_i$$

  transition entropy is always smaller $H_t \leq H_s$

- Long-term distribution of transitions is expected to be more uniform

Gaze analytics pipeline: where to go from here?

- Important to remember what the pipeline offers: metrics
- Which metrics to use will depend on study **hypothesis**

- General strategy "recipe" for <u>controlled experiments</u>:
  - formulate hypothesis
    - don't start with "I wonder what would happen if…"
    - start with "I bet this would happen if…"
  - design experiment (e.g., within-, between-subjects)
  - choose metrics
    - gaze metrics (process metrics) often supplement performance metrics
  - choose analytical tools (stats, e.g., ANOVA, something else)

- Can do exploratory research or pilot studies beforehand

Gaze analytics pipeline: write paper

- Remember analytics pipeline is meant to help automate analysis

- Once that's done, write the paper

- This too has a basic "recipe":
  - abstract, intro, background
  - hypothesis
    - recent trend is to register this a priori
  - methodology
    - design, stimulus, apparatus, procedure, participants
  - results
  - discussion
  - conclusions

Implementing Innovative Gaze Analytic Methods in Clinical Psychology

A Study on Eye Movements in Antisocial Violent Offenders

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ABSTRACT

A variety of psychological disorders like antisocial personality disorder have been linked to impairments in facial emotion recognition. Exploring eye movements during categorization of emotional faces is a promising approach with the potential to reveal possible differences in cognitive processes underlying these deficits. Based on this premise we investigated whether antisocial violent offenders exhibit different scan patterns compared to a matched healthy control group while categorizing emotional faces. Group differences were analyzed in terms of attention to the eyes, extent of exploration behavior and structure of switching patterns between Areas of Interest. While we were not able to show clear group differences, the present study is one of the first that demonstrates the feasibility and utility of incorporating recently developed eye movement metrics such as gaze transition entropy into clinical psychology.

CCS CONCEPTS

• **Applied computing → Psychology;**

KEYWORDS

eye tracking, antisocial offenders, facial emotion recognition

ACM Reference format:
Nina A. Gehrer, Michael Schönenberg, Andrew T. Duchowski, and Krzysztof Krejtz. 2018. Implementing Innovative Gaze Analytic Methods in Clinical Psychology. In *Proceedings of ETRA '18: 2018 Symposium on Eye Tracking Research & Applications, Warsaw, Poland, June 14–17, 2018 (ETRA'18)*, 9 pages. https://doi.org/10.1145/3204493.3204543

*This study was funded by the German Research Foundation (Scho 1448/3-1)
†This work was supported by the U.S. National Science Foundation (grant IIS-1748380).

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ETRA'18, June 14–17, 2018, Warsaw, Poland
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ACM ISBN 978-1-4503-5706-7/18/06...$15.00
https://doi.org/10.1145/3204493.3204543

1 INTRODUCTION

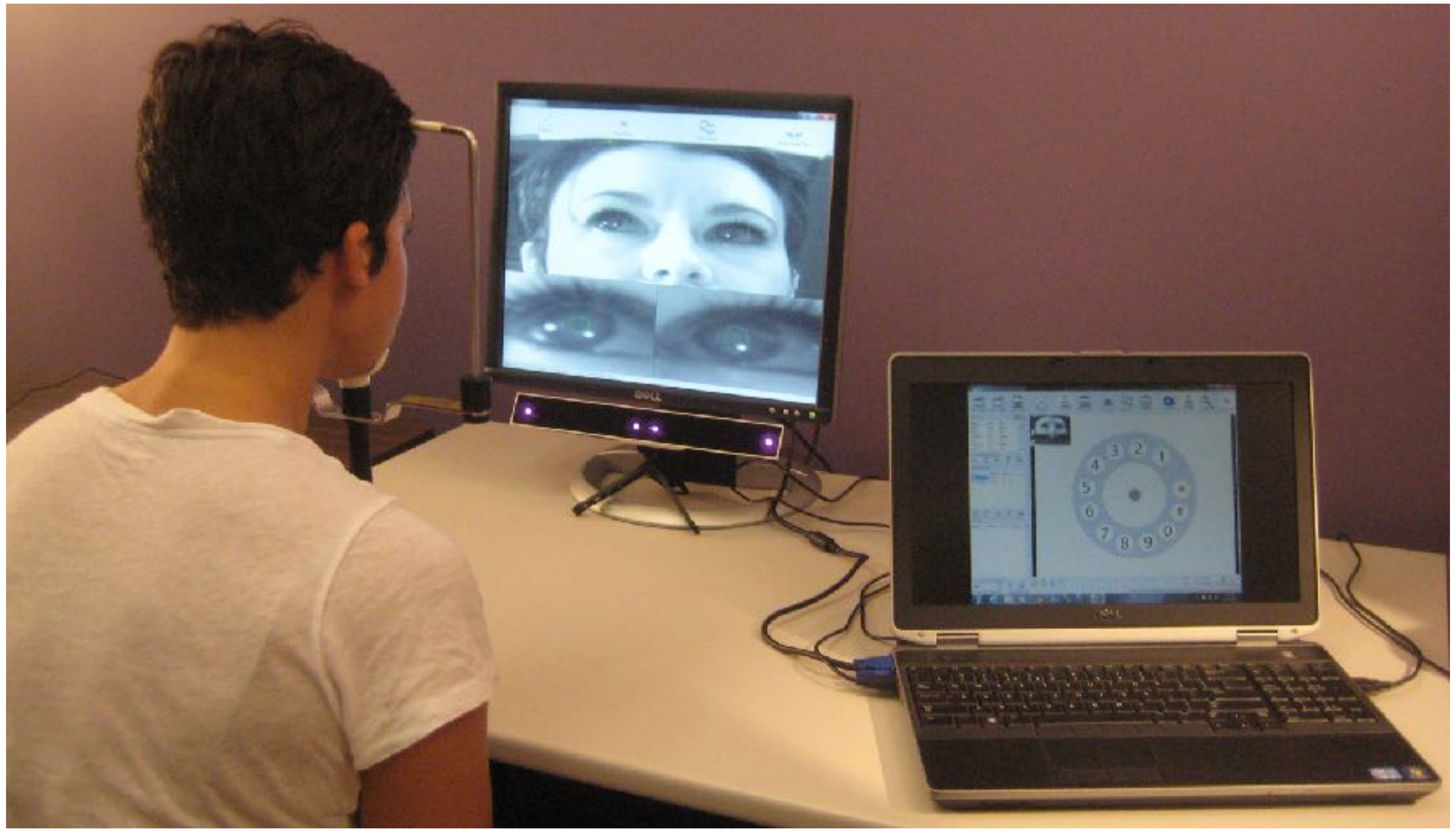
The ability to decode nonverbal social information in order to infer the emotional state of an interaction partner is crucial for effective social interaction. Accordingly, individuals are able to quickly and efficiently identify emotional expressions from specific facial cues [Smith et al. 2005; Tracy and Robins 2008]. These cues are similar across cultures, at least for the six basic emotions, i.e., anger, disgust, fear, happiness, sadness, and surprise [Ekman 1999; Ekman and Friesen 1971]. The accurate interpretation of emotional expressions is based on the processing of relevant regions of the face and directing visual attention to them (e.g., wide-open fearful eyes or smiling happy mouth) [Eisenbarth and Alpers 2011; Schurgin et al. 2014]. Thus, tracking eye movements while viewing emotional faces is a promising approach to gain insight into the processes underlying categorization of emotions.

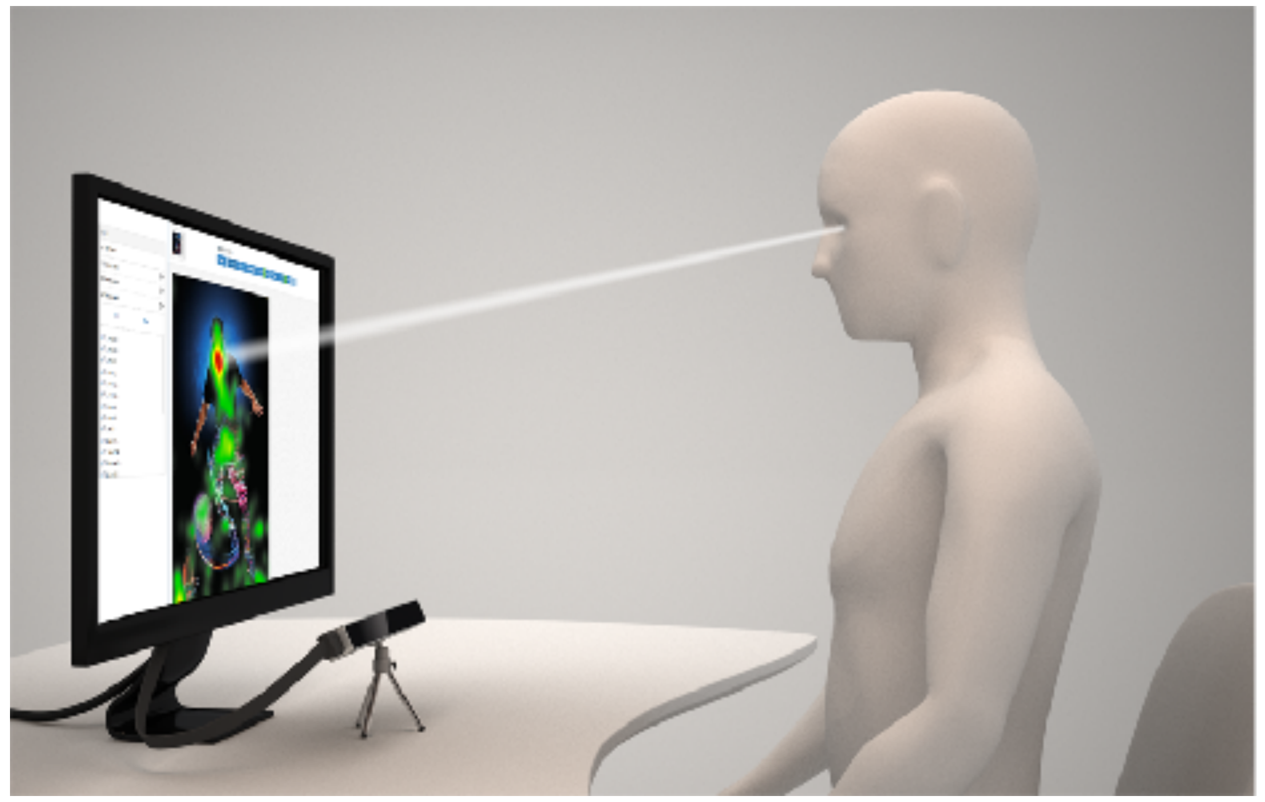
In clinical research, eye tracking can be a useful tool to explore deviations in scanning patterns that could account for emotion recognition impairments associated with psychological disorders. Impairments in facial affect recognition have been linked to the development and maintenance of various psychological disorders including autism [Uljarevic and Hamilton 2013], depression [Dalili et al. 2015], anxiety disorders [Demenescu et al. 2010], schizophrenia [Kohler et al. 2009], attention-deficit hyperactivity disorder [Bora and Pantelis 2016], and antisocial personality disorder (ASPD) and psychopathy [Dawel et al. 2012; Marsh and Blair 2008].

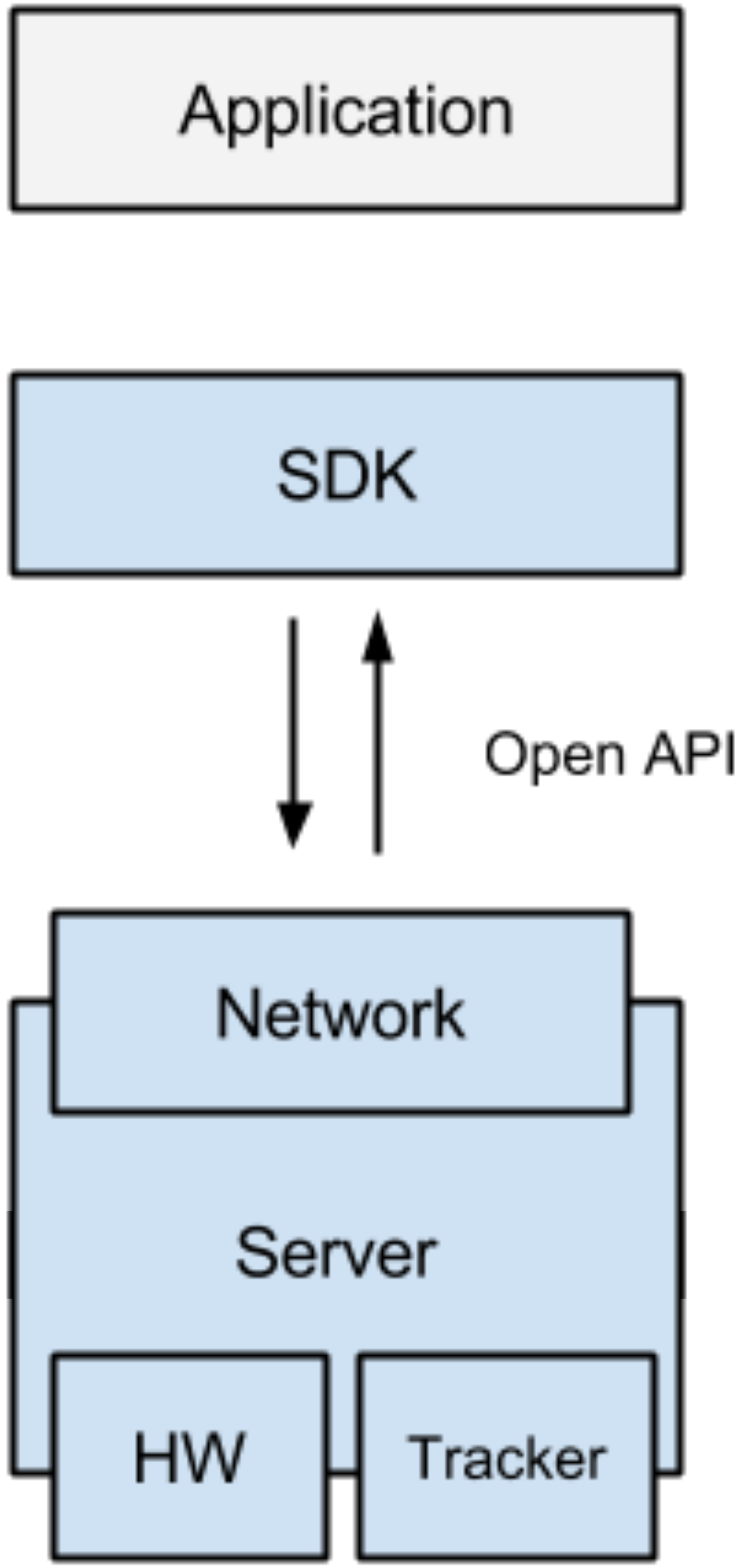
The majority of clinical studies exploring eye movements while viewing faces does not tap the potential of the myriad analytical methods available. Although analysis of dwell time or number of fixations to certain Areas of Interest (AOIs) can yield interesting findings, an inclusion of more innovative and complex analytical methods (e.g., sequential analysis of eye movements) may add valuable information. Here, we present an analysis of scan patterns while viewing faces including widely-used standard eye movement parameters (e.g., total dwell time) as well as more recently developed metrics such as gaze transition entropy [Krejtz et al. 2015]. Based on these measures, we investigate group differences in attention orienting to the eyes, extent of exploration behavior and structure of switching patterns between AOIs in antisocial violent offenders (AVOs) and a matched healthy control group.

Eye Tracking

Gaze Interaction

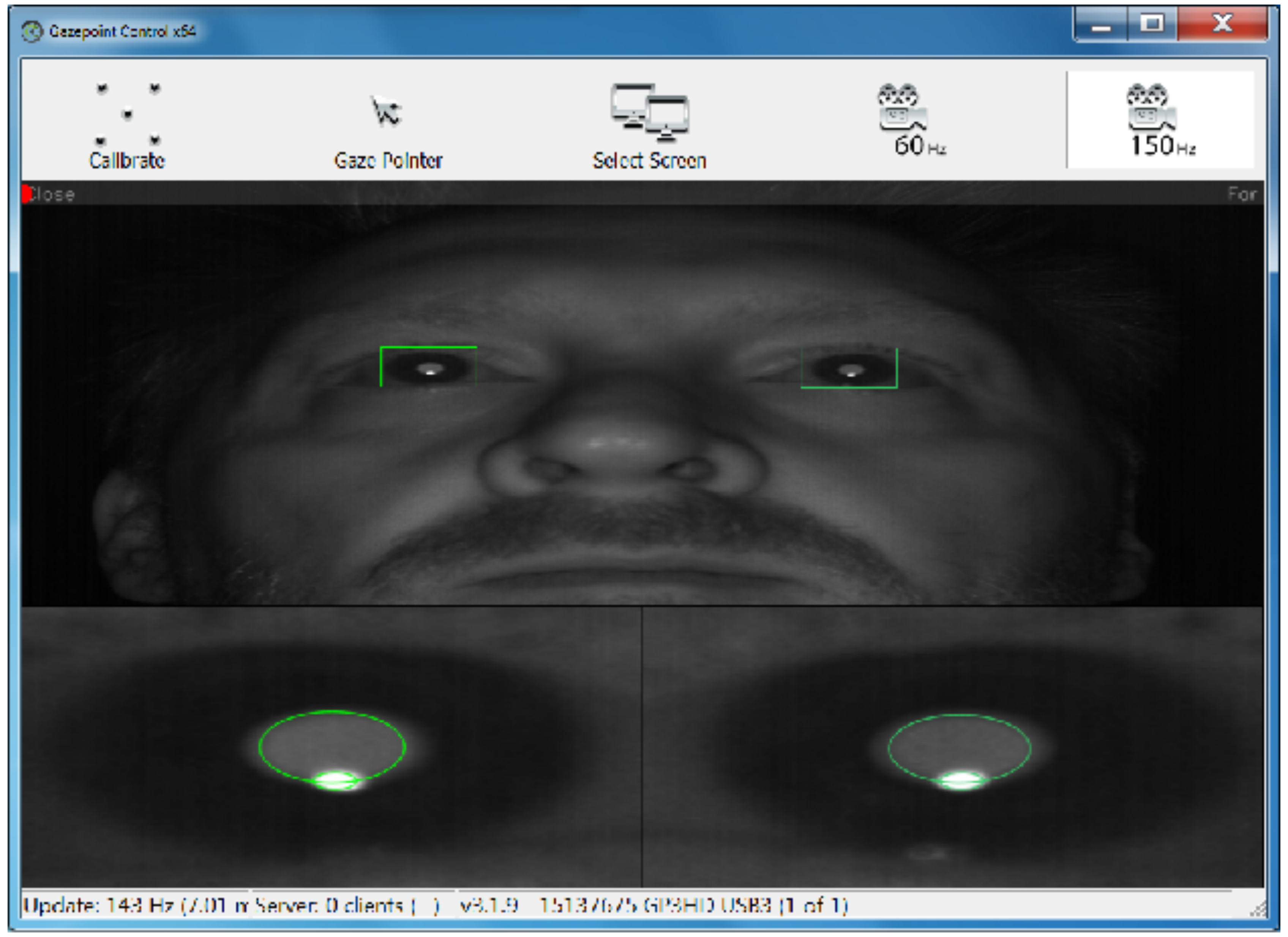


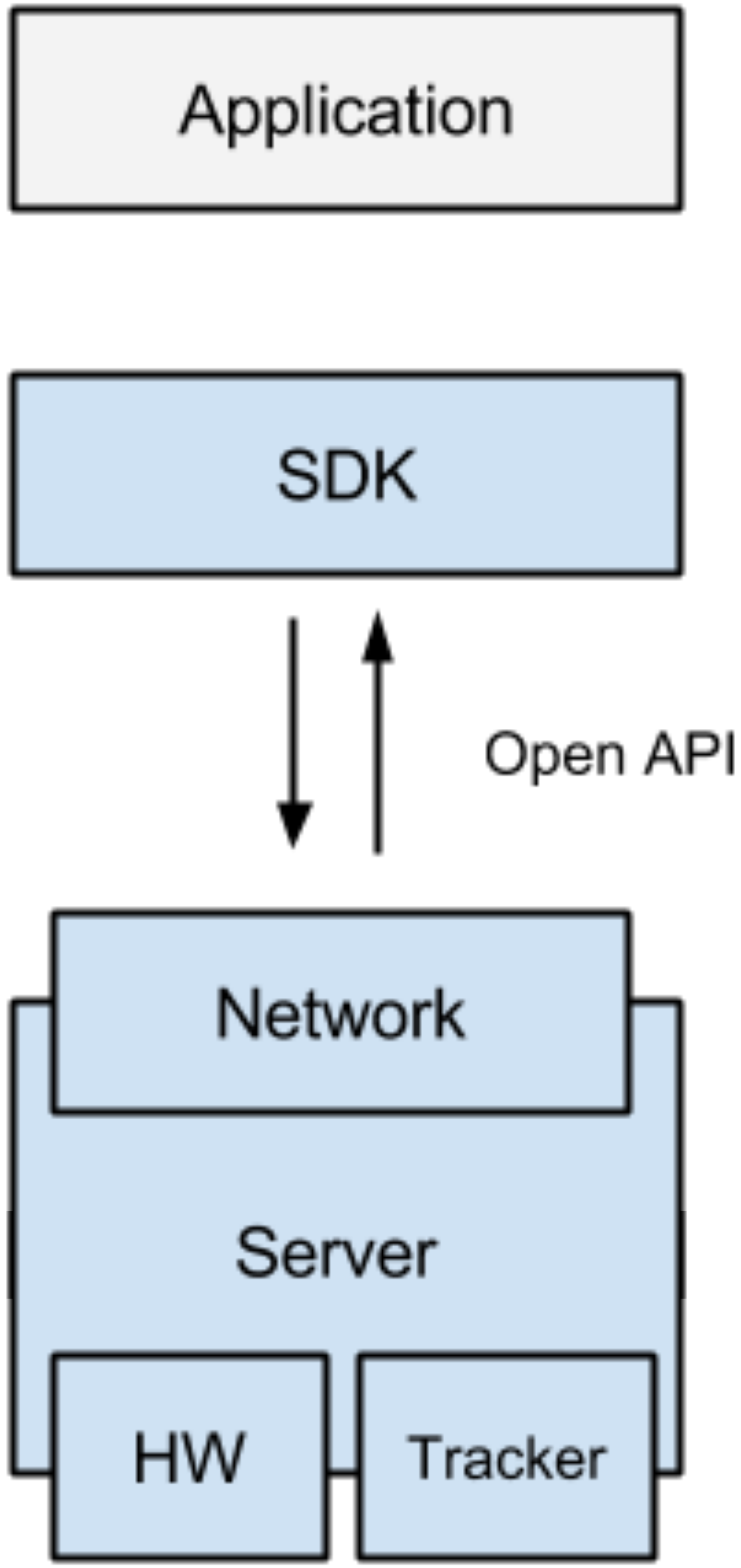




Gaze Interaction

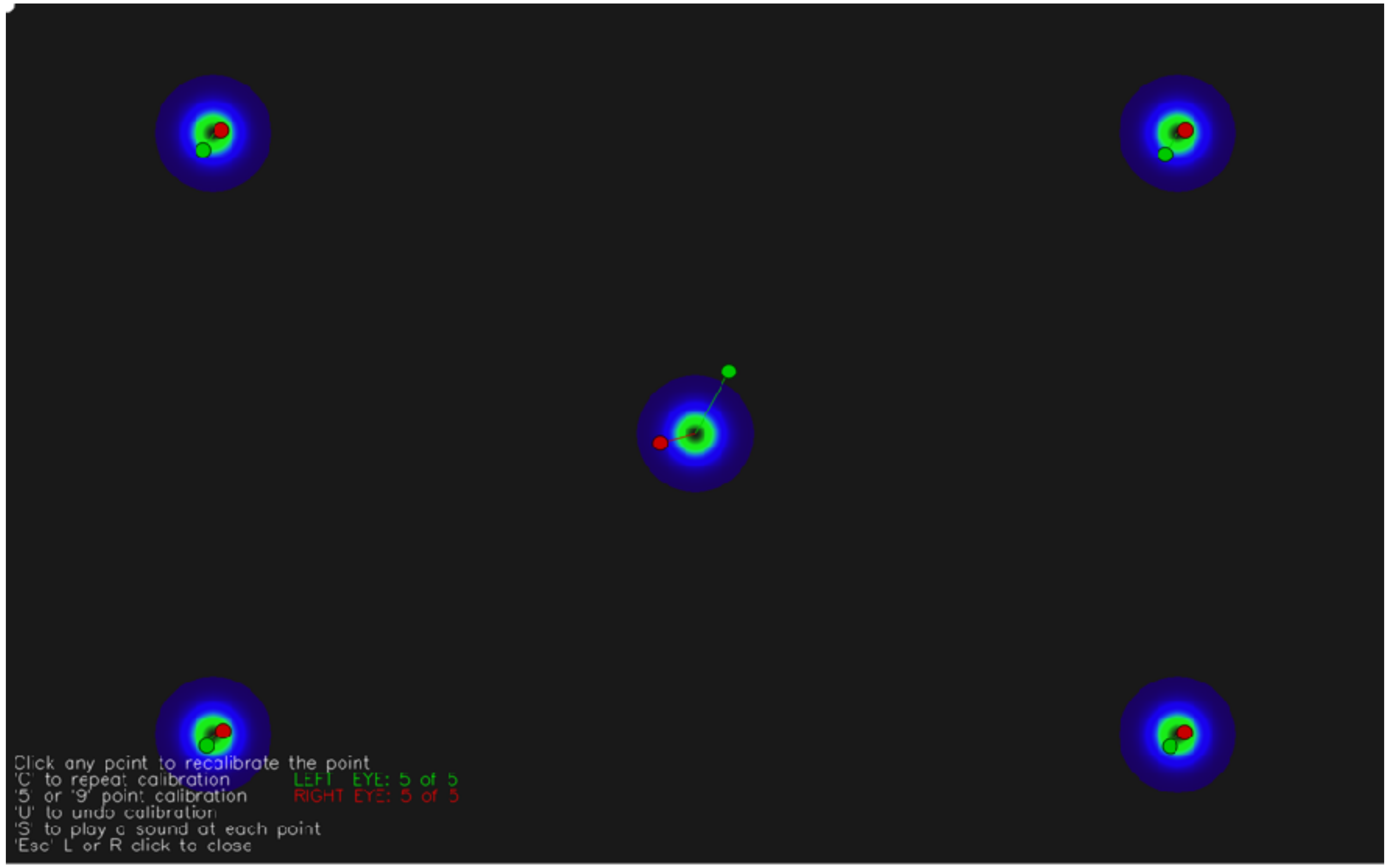
- Real-time gaze input:
  - usually obtained from server via SDK / API
  - hardware driver may need to be running
  - e.g., Gazepoint Control
  - stream raw data (x, y, t)

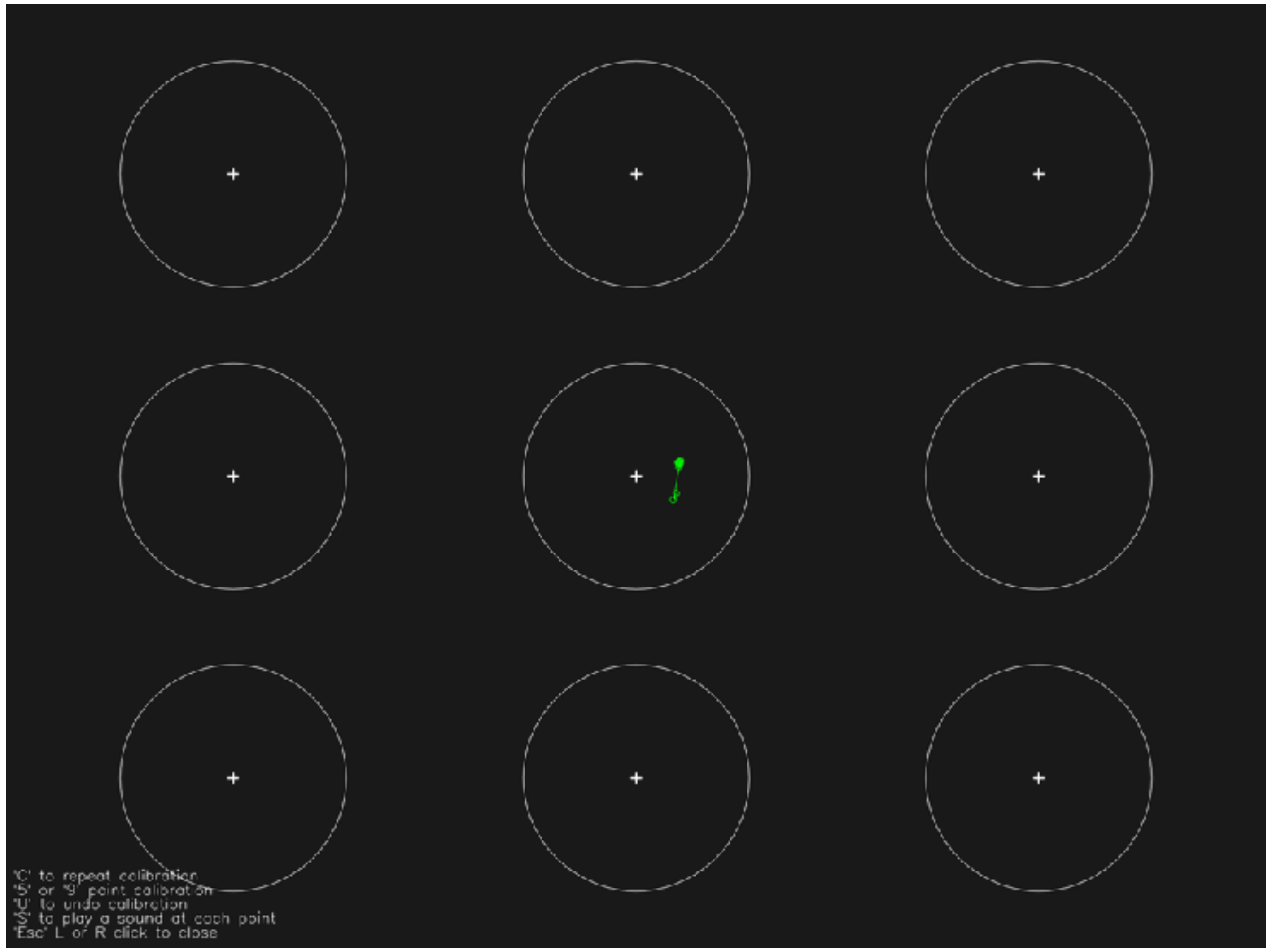




Calibration

- Use vendor-provide or write your own
  - either way, collect error, keep track of acuracy

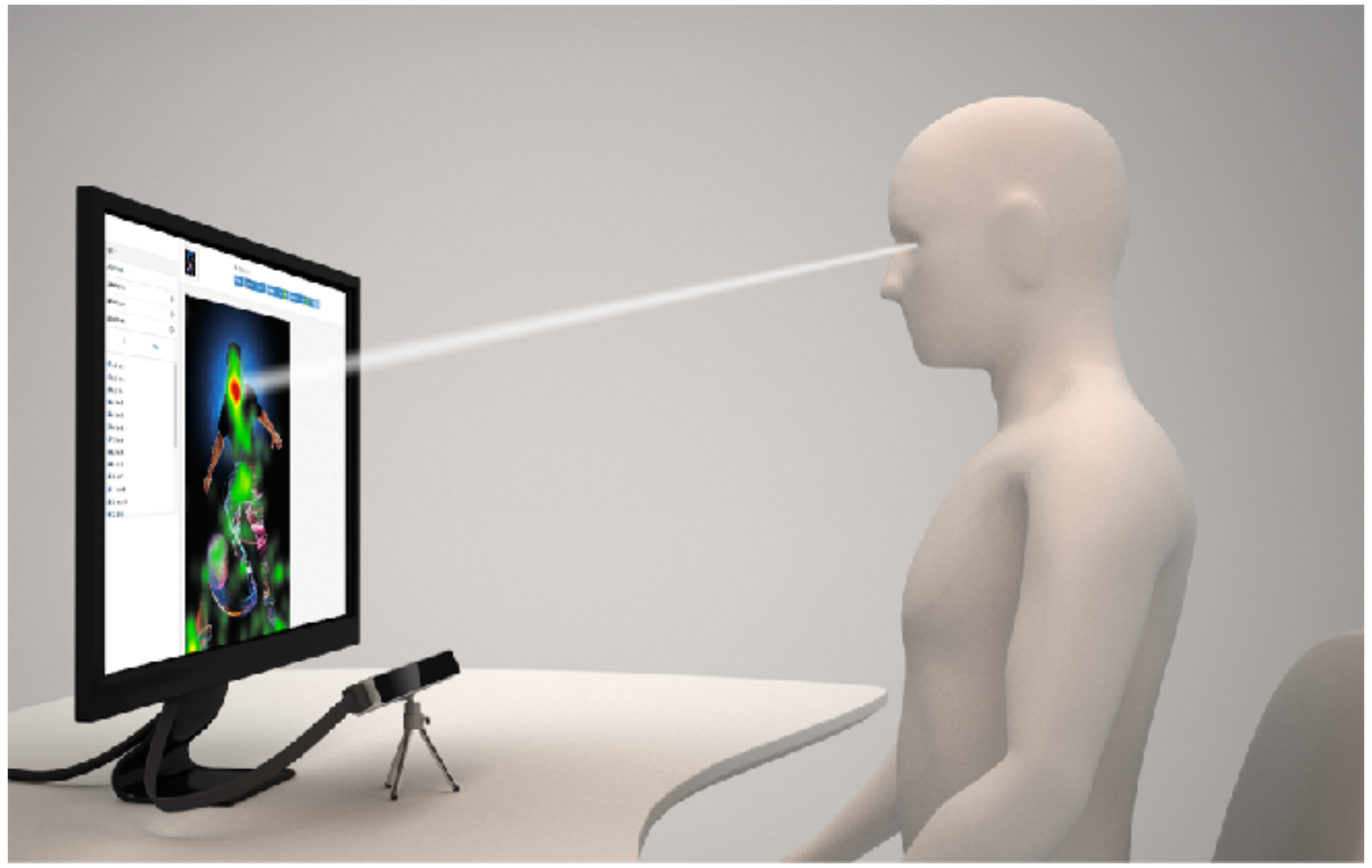




The Gazepoint eye tracker

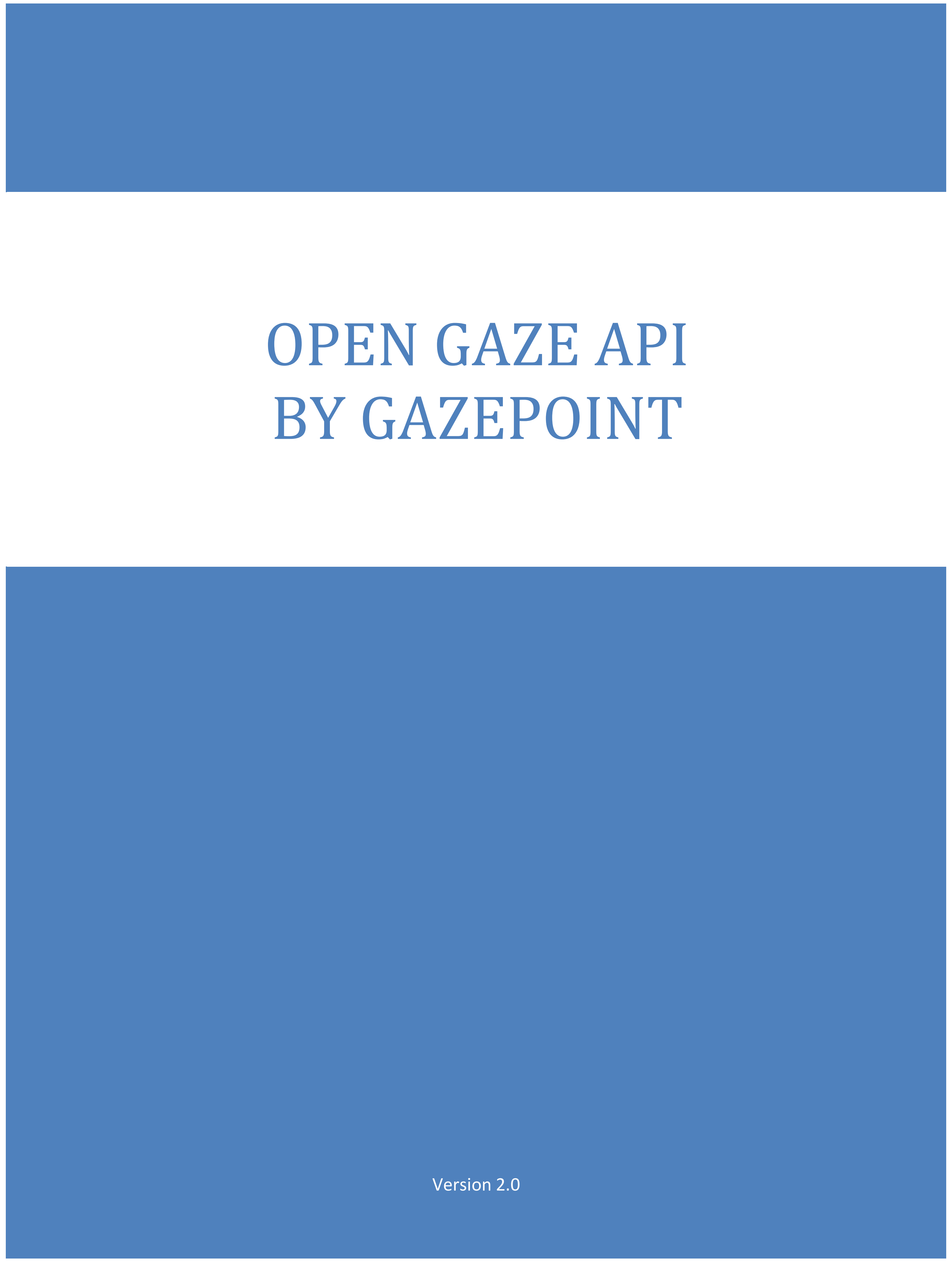
- OpenGaze API (protocol)

- Key features:
  - no libraries/DLLs required
  - language-independent
  - standard TCP/IP socket
  - XML “packets”



How to start?

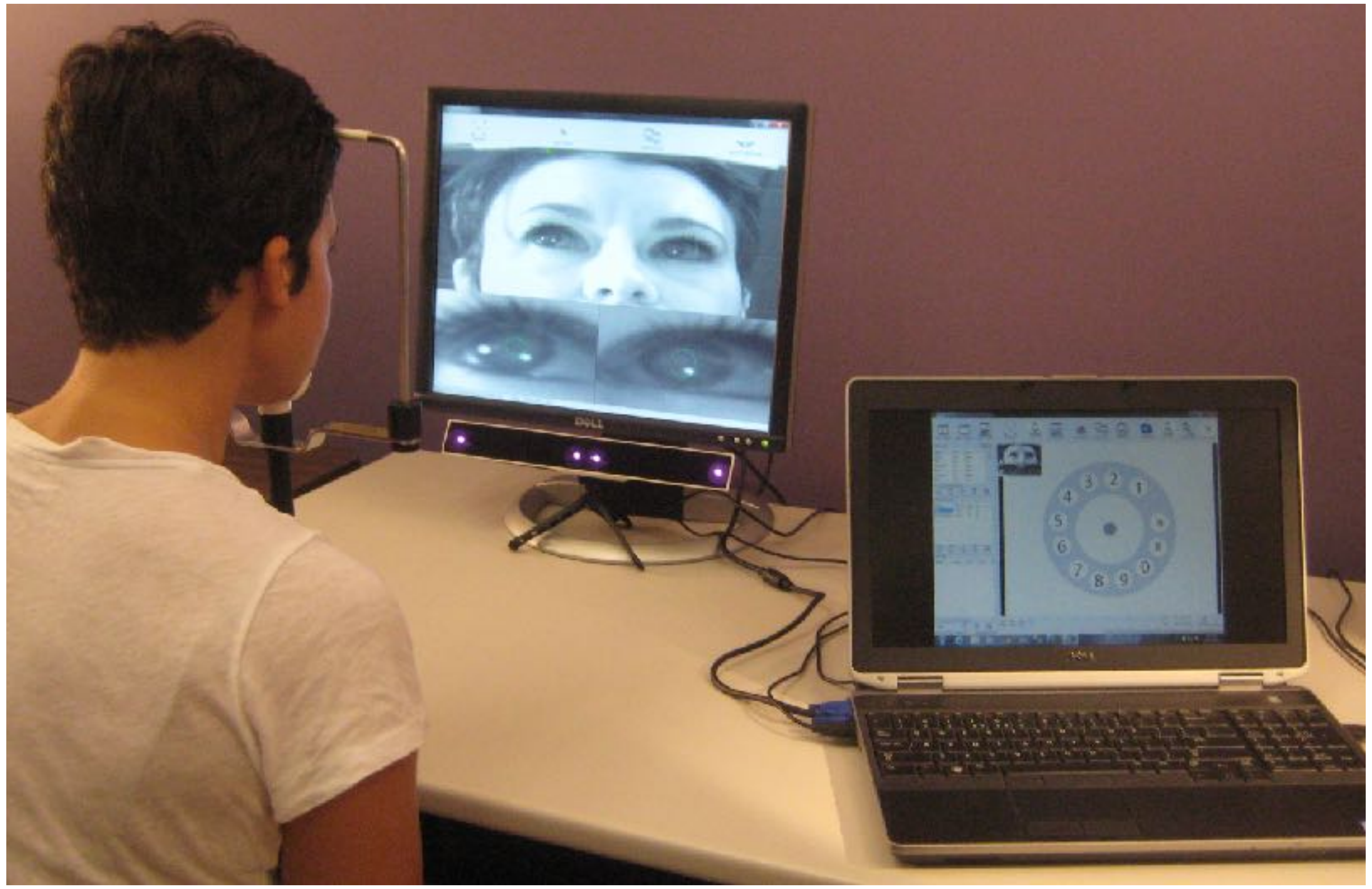
- Gazepoint's API
  - not really an API, a protocol, really
- Eye tracking server
  - controls eye tracking device
  - streams out data
- Client app (e.g., Unity 3D)
  - connects (TCP/IP) to server


OPEN GAZE API
BY GAZEPOINT

Version 2.0

Example client/server architecture

- From Gazepoint:
  - no SDK
  - you write networking code
  - send/receive XML packets
  - over network or to 127.0.0.1



Eye tracker communication

- Generally, communication with an eye tracker entails:
  - network connection, e.g., open TCP/IP socket
  - can be embodied in an object
  - usually a thread is created to accept streaming data

```
class Gazept:
  def __init__(self,server="127.0.0.1",port=4242):
    self.server = server
    self.port = port
    try:
      self.sock = socket.socket(socket.AF_INET,socket.SOCK_STREAM)
      self.sock.connect((server,port))
      self.receiving_thread = threading.Thread(target=self.communication_loop)
      self.receiving_thread.start()
    except:
      print "couldn't connect to ",server," on port ",port
      sys.exit()
```

Eye tracker states

- The eye tracker is generally in one of three states:
  - idle, calibrating, running
- Your application (e.g., Unity) controls the tracker
- Two threads run simultaneously:
  - one controls UI and graphics display (UI thread)
  - second accepts streaming data from tracker (ET thread)
- State and gaze data passed through shared memory
  - usually a global object is created
  - tracking thread writes, UI thread reads

Eye tracker communication

- GET and SET XML tags

```
CLIENT SEND: <GET ID="TRACKER_DISPLAY" />
SERVER SEND: <ACK ID="TRACKER_DISPLAY" STATE="1" />
```

```
CLIENT SEND: <SET ID="TRACKER_DISPLAY" STATE="1" />
SERVER SEND: <ACK ID="TRACKER_DISPLAY" STATE="1" />
```

- Read and write to data variables on server

Eye tracking thread

- ET thread sends/receives packets to/from eye tracker
- Gazepoint tracker (Control program) accepts XML data
  - can get/set tracker settings:

```
CLIENT SEND: <GET ID="TRACKER_DISPLAY" />
SERVER SEND: <ACK ID="TRACKER_DISPLAY" STATE="1" />
```

  - various other info:
    - TIME_TICK_FREQUENCY
    - SCREEN_SIZE, CAMERA_SIZE
    - PRODUCT_ID, SERIAL_ID
    - etc.

Eye tracking thread

- Application needs to tell tracker what to send
  - ENABLE_SEND_COUNTER
  - ENABLE_SEND_POG_LEFT
  - ENABLE_SEND_POG_RIGHT
  - ENABLE_SEND_POG_BEST
  - ENABLE_SEND_PUPIL_LEFT
  - ENABLE_SEND_PUPIL_RIGHT
- And then tell tracker to stream data

```
CLIENT SEND: <SET ID="ENABLE_SEND_DATA" STATE="1" />
SERVER SEND: <ACK ID="ENABLE_SEND_DATA" STATE="1" />
SERVER SEND: <REC ... />
SERVER SEND: <REC ... />
SERVER SEND: <REC ... />
```

Eye tracking thread

- Don't forget to gracefully shutdown the tracker

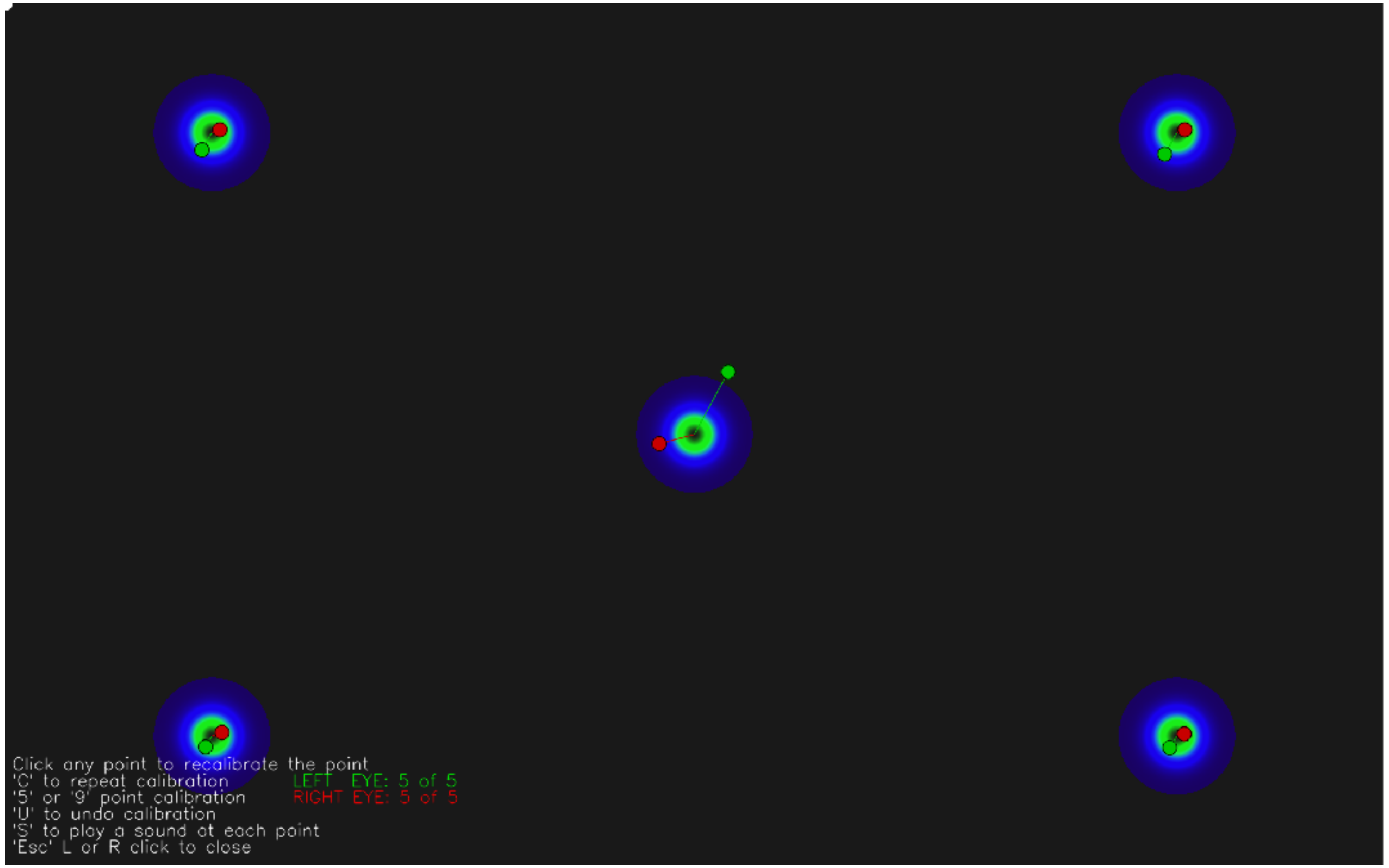
```
CLIENT SEND: <SET ID="ENABLE_SEND_DATA" STATE="0" />
```

- Processing data:
  - parse XML strings
  - for Gazepoint, mind the ending tokens `\r\n`
  - these characters must be appended to each string as well

- Trickiest part: calibration
  - need to either call tracker's calibration routine or
  - synchronize drawing your own calibration points (preferred method)

Calibration

- Eye tracker's calibration screen (when finished)



Calibration (canned)

- If working on same display as eye tracker control:
  - can use tracker's own calibration, if available

```
CLIENT SEND: <SET ID="CALIBRATE_SHOW" STATE="1" />
SERVER SEND: <ACK ID="CALIBRATE_SHOW" STATE="1" />

CLIENT SEND: <SET ID="CALIBRATE_START" STATE="1" />
SERVER SEND: <ACK ID="CALIBRATE_START" STATE="1" />
```

  - this will take over the screen
- Advantages:
  - eye tracker does synchronization, reports calibration error
- Disadvantages:
  - your app gives up control

Calibration (custom)

- Timing (important!): must synchronize with tracker
- Two components:
  - time for stationary dot display (seconds)
    - when eye tracking camera samples eye image

```
CLIENT SEND: <SET ID="CALIBRATE_TIMEOUT" VALUE="2" />
SERVER SEND: <ACK ID="CALIBRATE_TIMEOUT" VALUE="2" />
```

  - time between dots
    - use this to animate dot moving from point to point

```
CLIENT SEND: <SET ID="CALIBRATE_DELAY" VALUE="1.0" />
SERVER SEND: <ACK ID="CALIBRATE_DELAY" VALUE="1.0" />
```

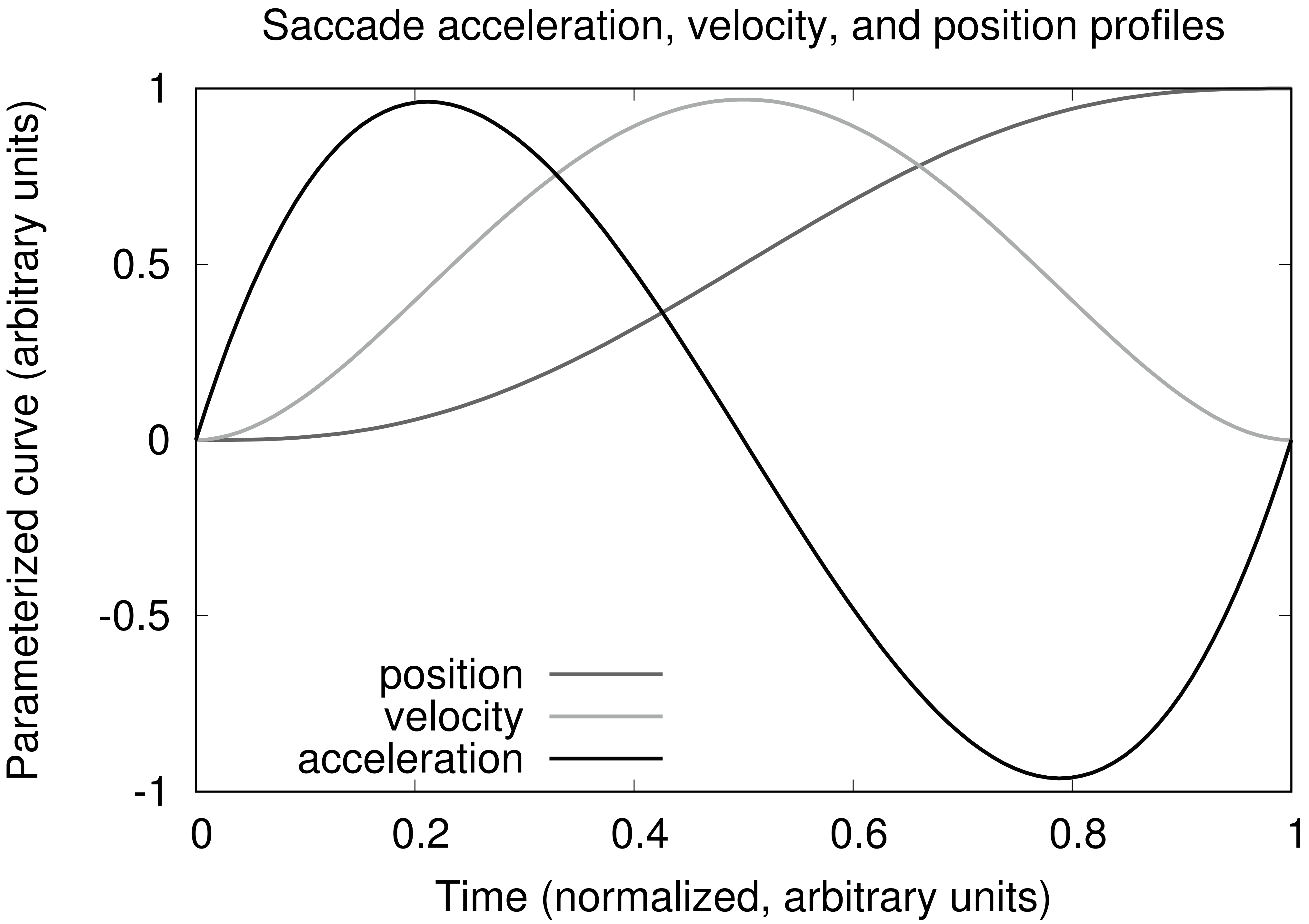
  - start calibration

```
CLIENT SEND: <SET ID="CALIBRATE_START" VALUE="1" />
CLIENT SEND: <ACK ID="CALIBRATE_START" VALUE="1" />
```

Drawing calibration dots (client side)

- If moving, interpolate position of dot
- Can use simple linear function or something more fancy

$$60(\frac{1}{10}t^5 - \frac{1}{4}t^4 + \frac{1}{6}t^3)$$



Duchowski, et al. (ETRA 2016)

Drawing calibration dots (client side)

- If moving, interpolate position of dot
- Can use simple linear function or something more fancy

$$60(\frac{1}{10}t^5 - \frac{1}{4}t^4 + \frac{1}{6}t^3)$$

```
if calibration.movement == 0:
  t = calibration.timer_elapsed_ms()/calibration.get_moveTime()
  i = calibration.get_dot_index()
  if i+1 < calibration.get_dot_len():
    v1 = calibration.get_dot(i)
    v2 = calibration.get_dot(i+1)
    t = 60.0*((1.0/10.0)*t**5 - (1.0/4.0)*t**4 + (1.0/6.0)*t**3)
    v = ((1.0 - t)*v1[0] + t*v2[0], (1.0 - t)*v1[1] + t*v2[1])
    calibration.set_xy(v)
  if calibration.timer_elapsed_ms() > calibration.get_moveTime():
    calibration.inc_dot_index()
    calibration.timer_start()
    # advance to dilation
    calibration.movement += 1
```

Duchowski, et al. (ETRA 2016)

Calibration setup

- Reset calibration to default points

```
CLIENT SEND: <SET ID="CALIBRATE_RESET" />
SERVER SEND: <ACK ID="CALIBRATE_RESET" PTS="5" />
```

- Or clear out calibration points and add your own

```
CLIENT SEND: <SET ID="CALIBRATE_CLEAR" />
SERVER SEND: <ACK ID="CALIBRATE_CLEAR" PTS="0" />
```

- Tell eye tracker where you will draw the dots
  - do this for as many points as you want (can do one at a time)

```
CLIENT SEND: <GET ID="CALIBRATE_ADDPOINT" />
SERVER SEND: <ACK ID="CALIBRATE_ADDPOINT" PTS="5" X1="0.50000"
Y1="0.50000" X2="0.85000" Y2="0.15000" X3="0.85000" Y3="0.85000"
X4="0.15000" Y4="0.85000" X5="0.15000" Y5="0.15000" />
```

After calibration

- If doing it yourself, can still get calibration report

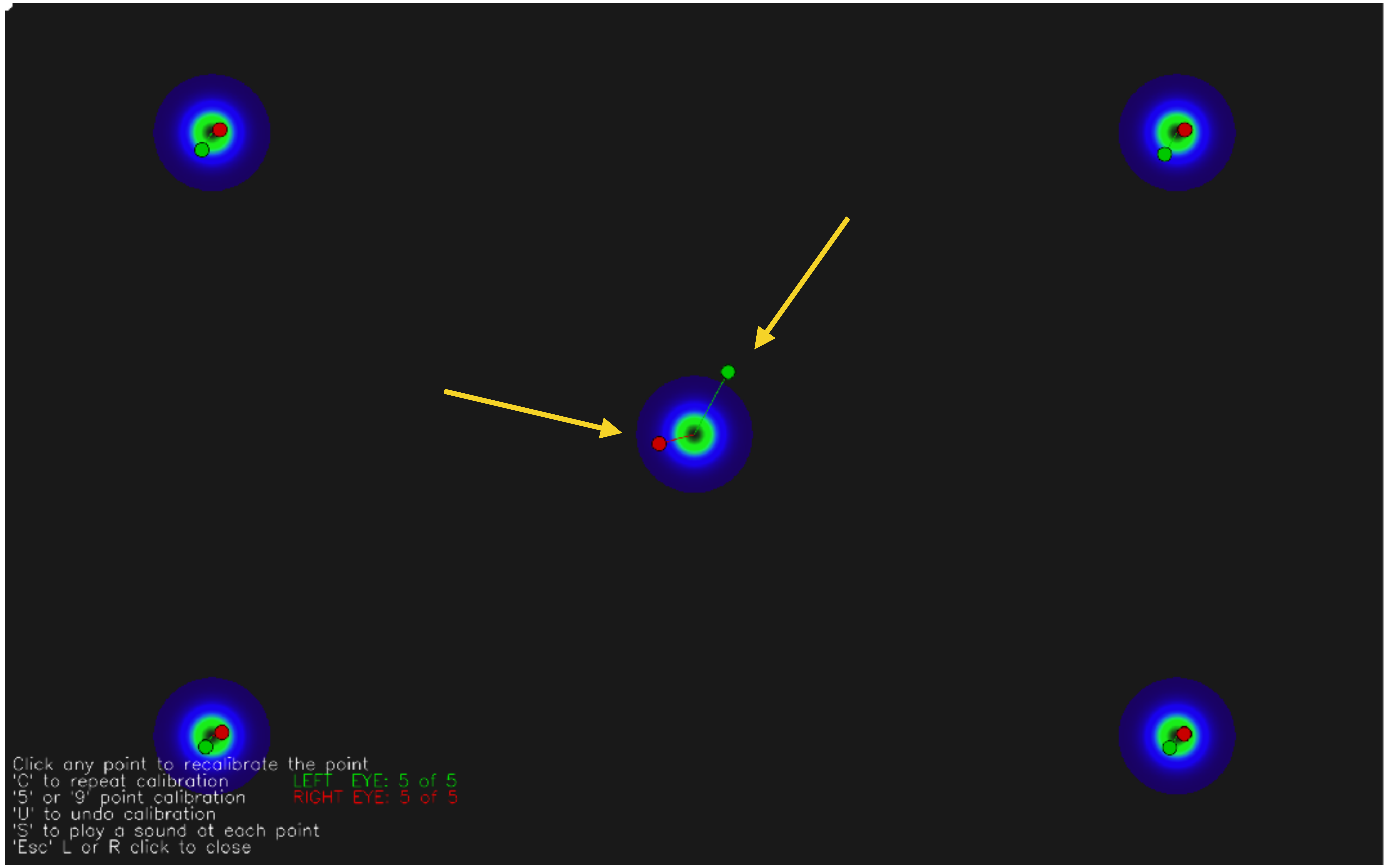
```
CLIENT SEND: <GET ID="CALIBRATE_RESULT_SUMMARY" />
SERVER SEND: <ACK ID="CALIBRATE_RESULT_SUMMARY" AVE_ERROR="19.43"
VALID_POINTS="5" />
```

- Can get more info as calibration proceeds:

```
…
SERVER SEND: <CAL ID=" CALIB_RESULT_PT" PT="5" CALX="0.1500"
CALY="0.1500" />
SERVER SEND: <CAL ID="CALIB_RESULT" CALX1="0.50000" CALY1="0.50000"
LX1="0.50229" LY1="0.50279 LV1="1" RX1="0.51467" RY1="0.50870
RV1="1" CALX2="0.85000" CALY2="0.15000" LX2="0.84943" LY2="0.14930
LV2="1" RX2="0.84600" RY2="0.14763 RV2="1" CALX3="0.85000"
CALY3="0.85000" LX3="0.84942" LY3="0.84929 LV3="1" RX3="0.84627"
RY3="0.84779 RV3="1" CALX4="0.15000" CALY4="0.85000" LX4="0.14943"
LY4="0.84930 LV4="1" RX4="0.14616" RY4="0.84772 RV4="1"
CALX5="0.15000" CALY5="0.15000" LX5="0.14944" LY5="0.14931 LV5="1"
RX5="0.14689" RY5="0.14815 RV5="1" />
```

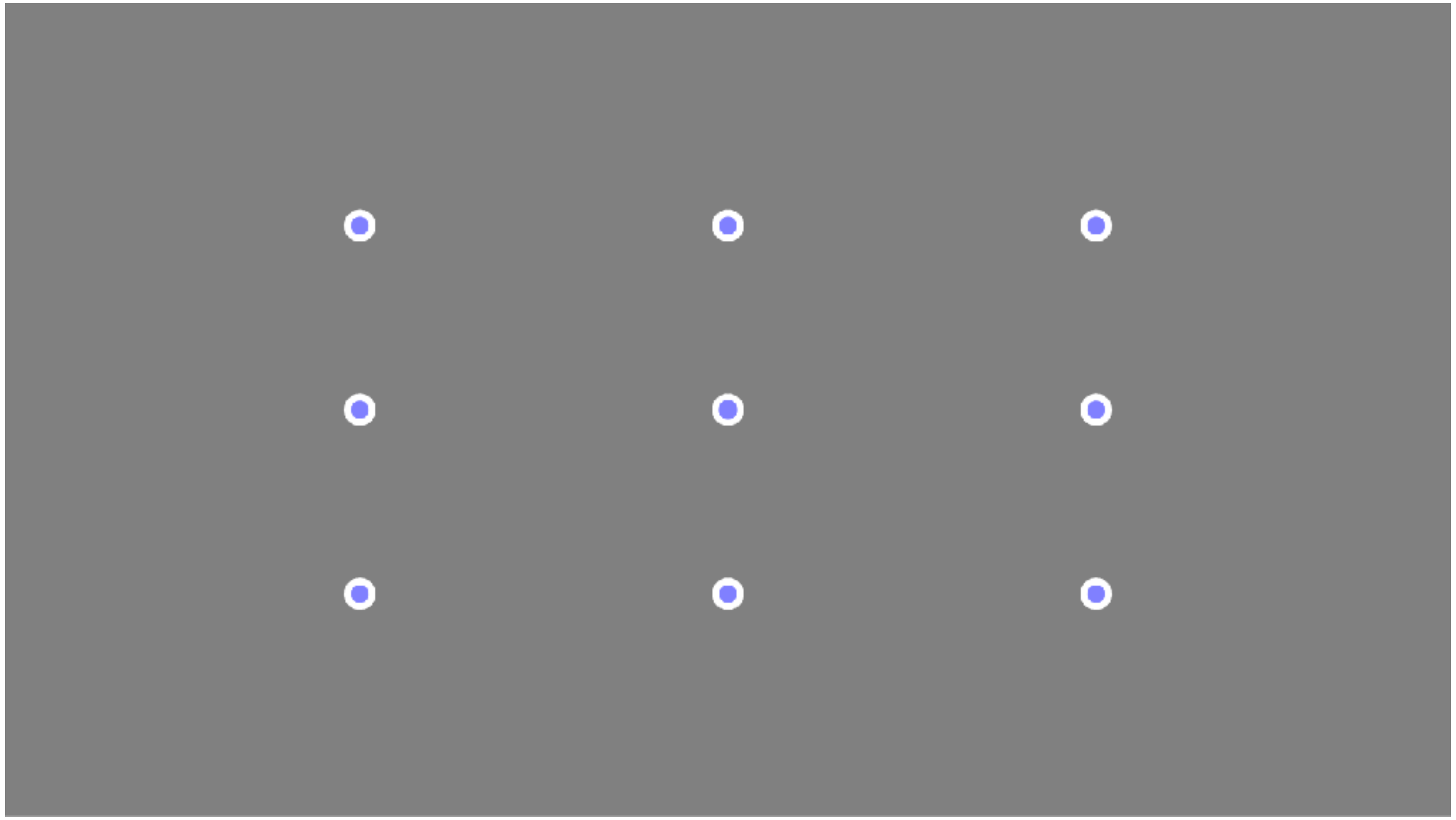
Calibration result

- Can use the results to reproduce summary screen



Do own calibration

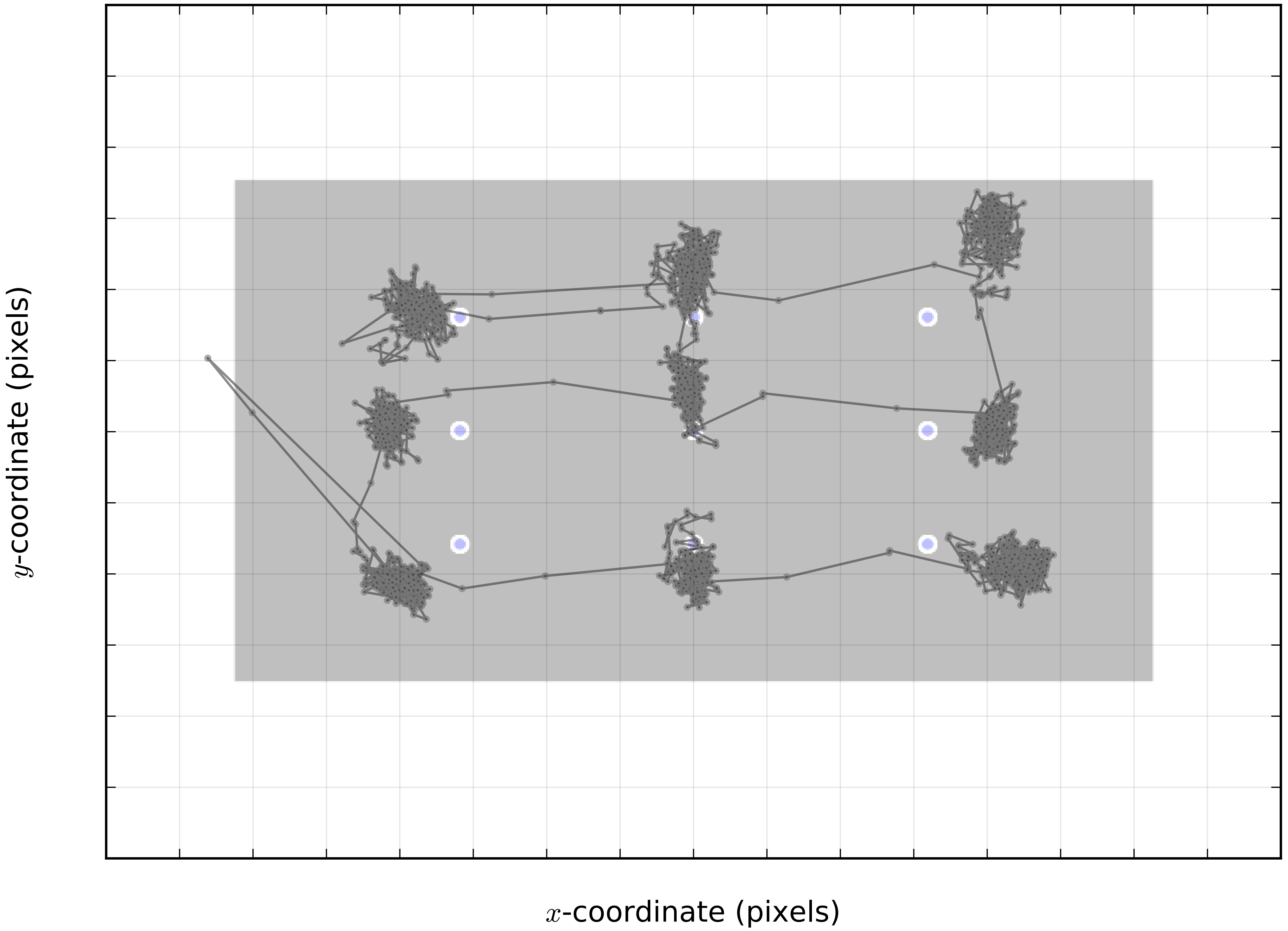
- Use another calibration image (1600 x 900)



Analytics pipeline

- Data processing:

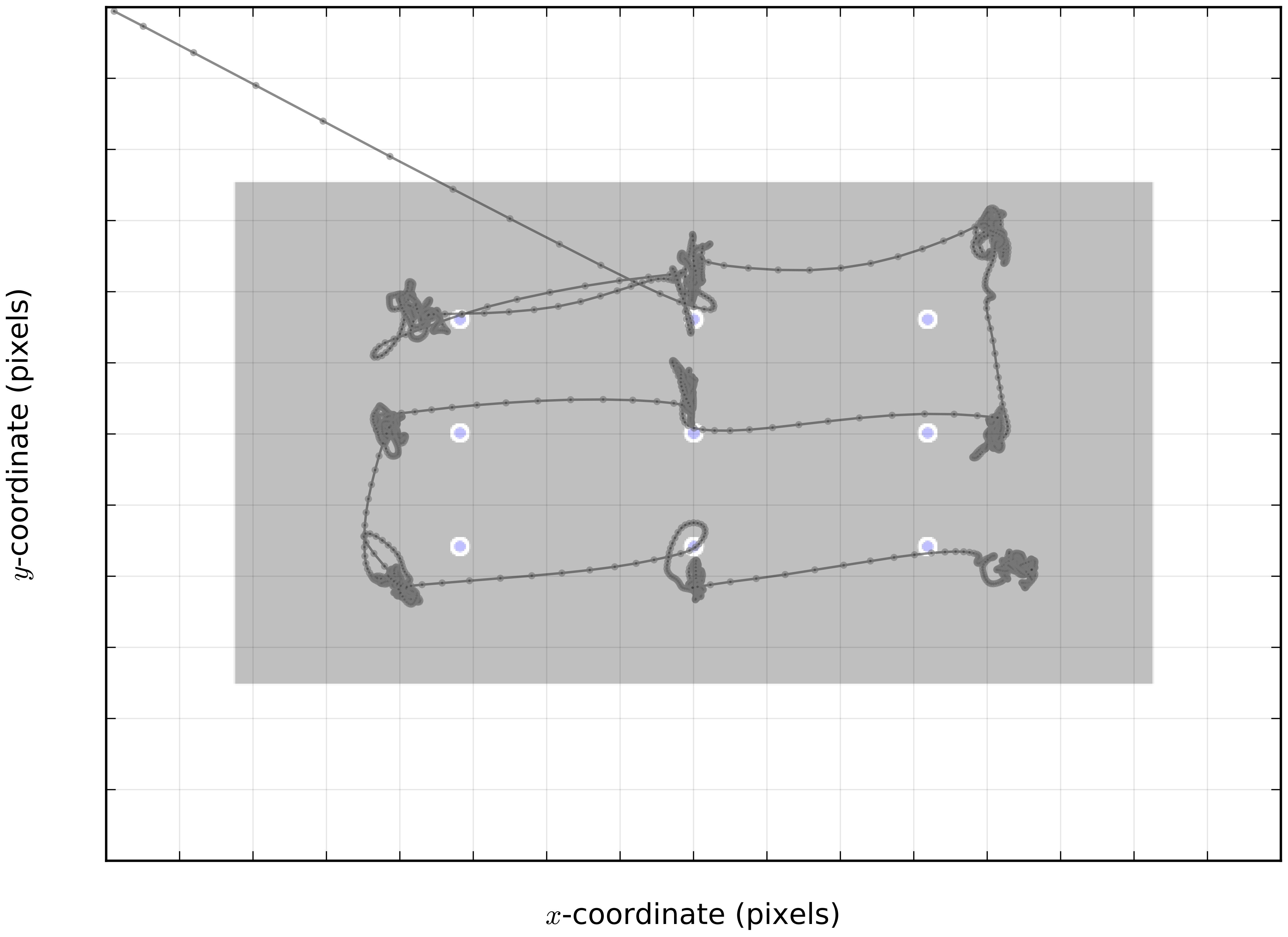
  1. raw data



Analytics pipeline

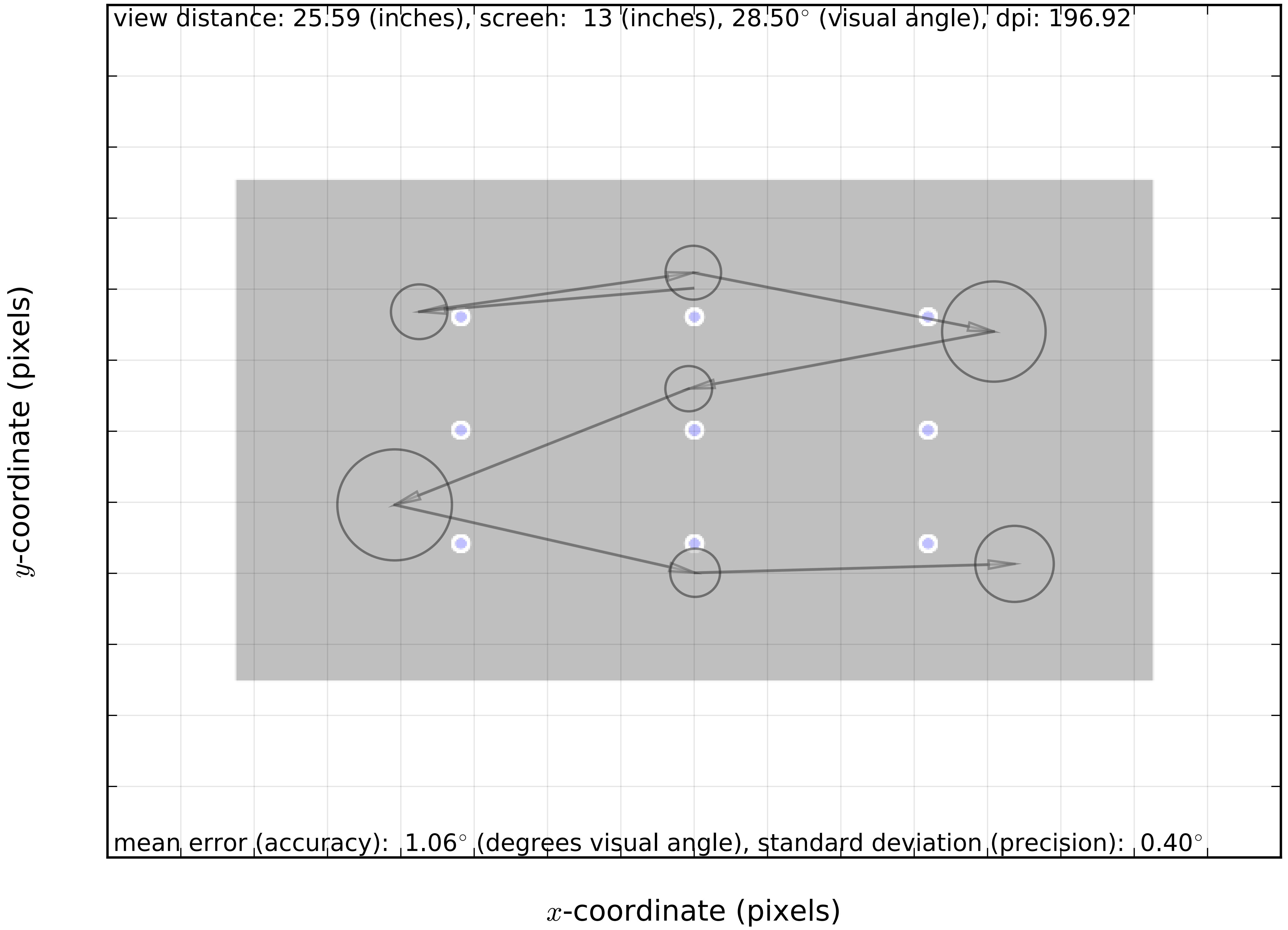
- Data processing:
  1. raw data
  2. smoothed data

$$\dot{x}_n^s(t) = 1/(\Delta t^s)\left(\sum_{i=-p}^{p} h_i^{t,s} x_{n-i} - \sum_{i=-q}^{q} g_i^{t,s} \dot{x}_{n-i}\right)$$



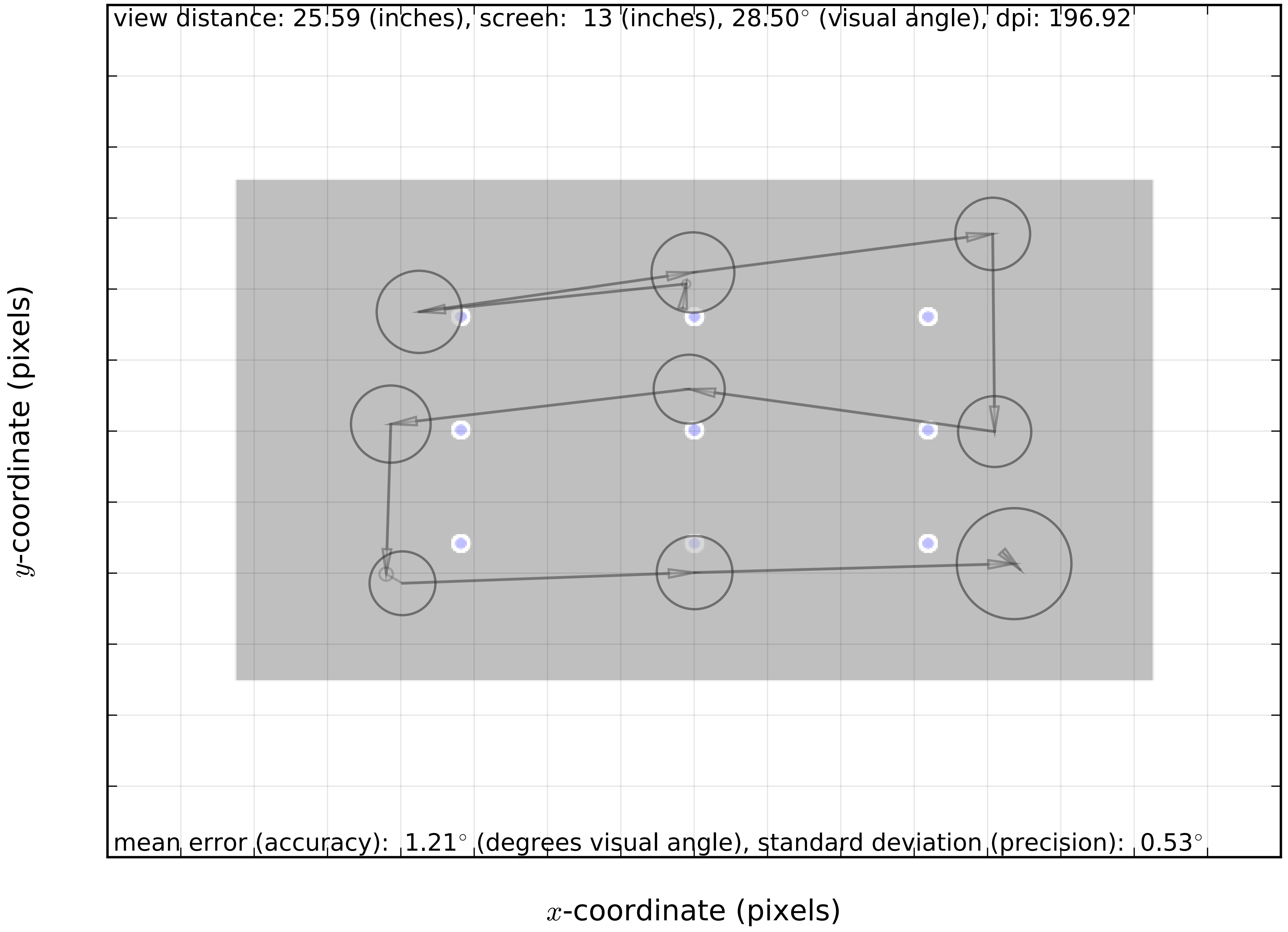
Analytics pipeline

- Data processing:
  1. raw data
  2. smoothed data
  3. fixations (after thresholding)



Analytics pipeline

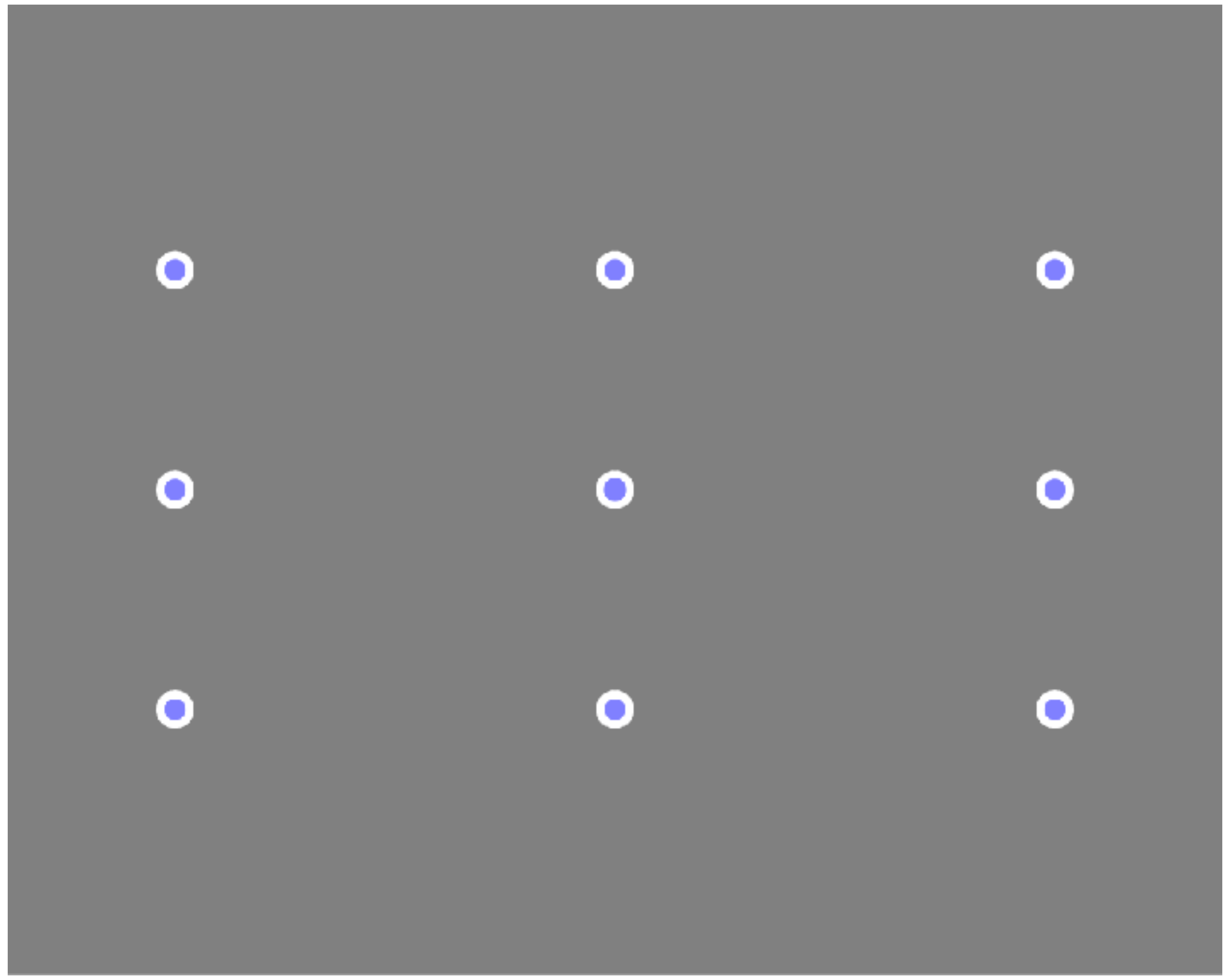
- Data processing:
  1. raw data
  2. ~~smoothed data~~
  3. fixations
     (after thresholding)

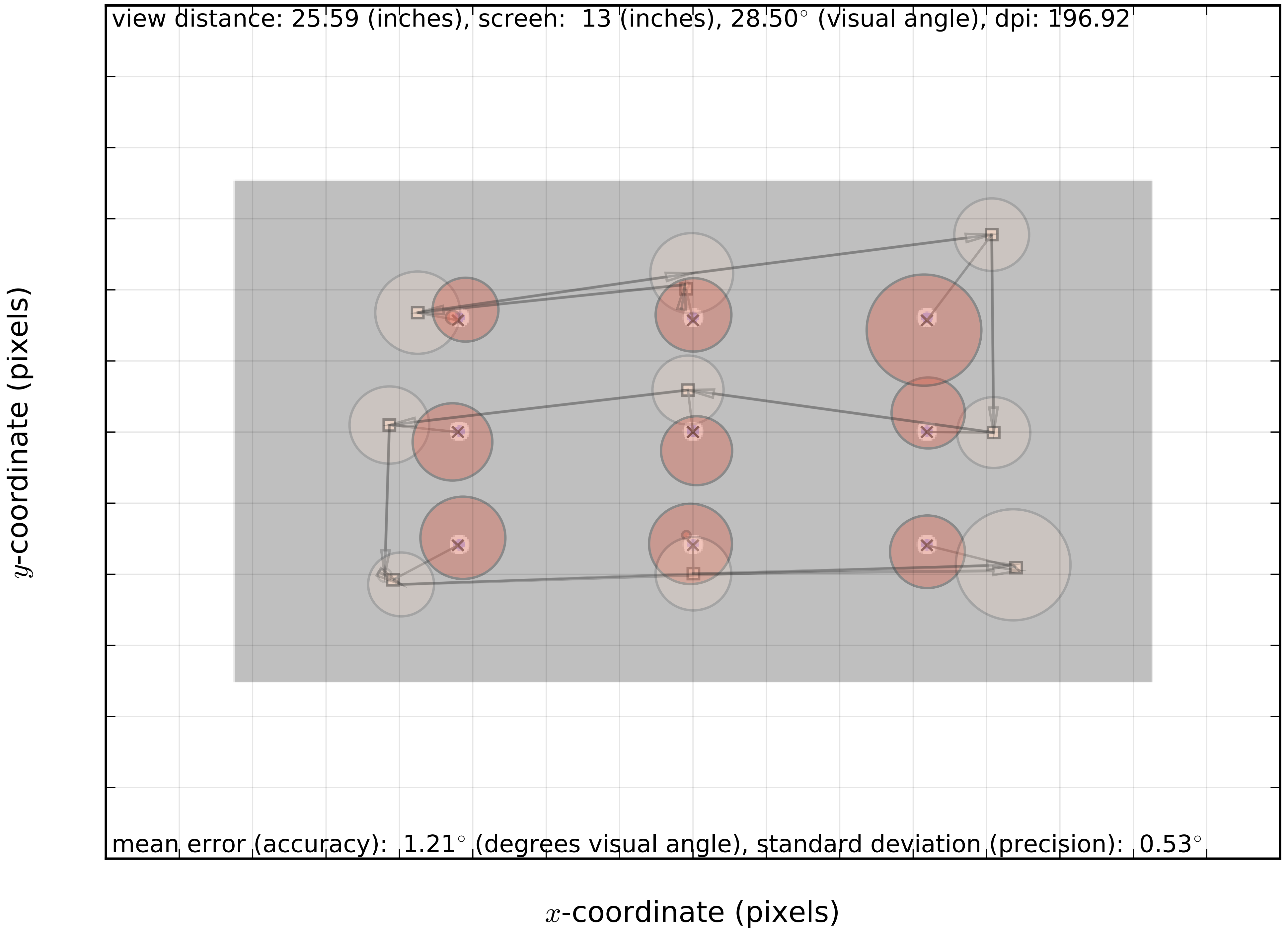


Consider accuracy & refitting

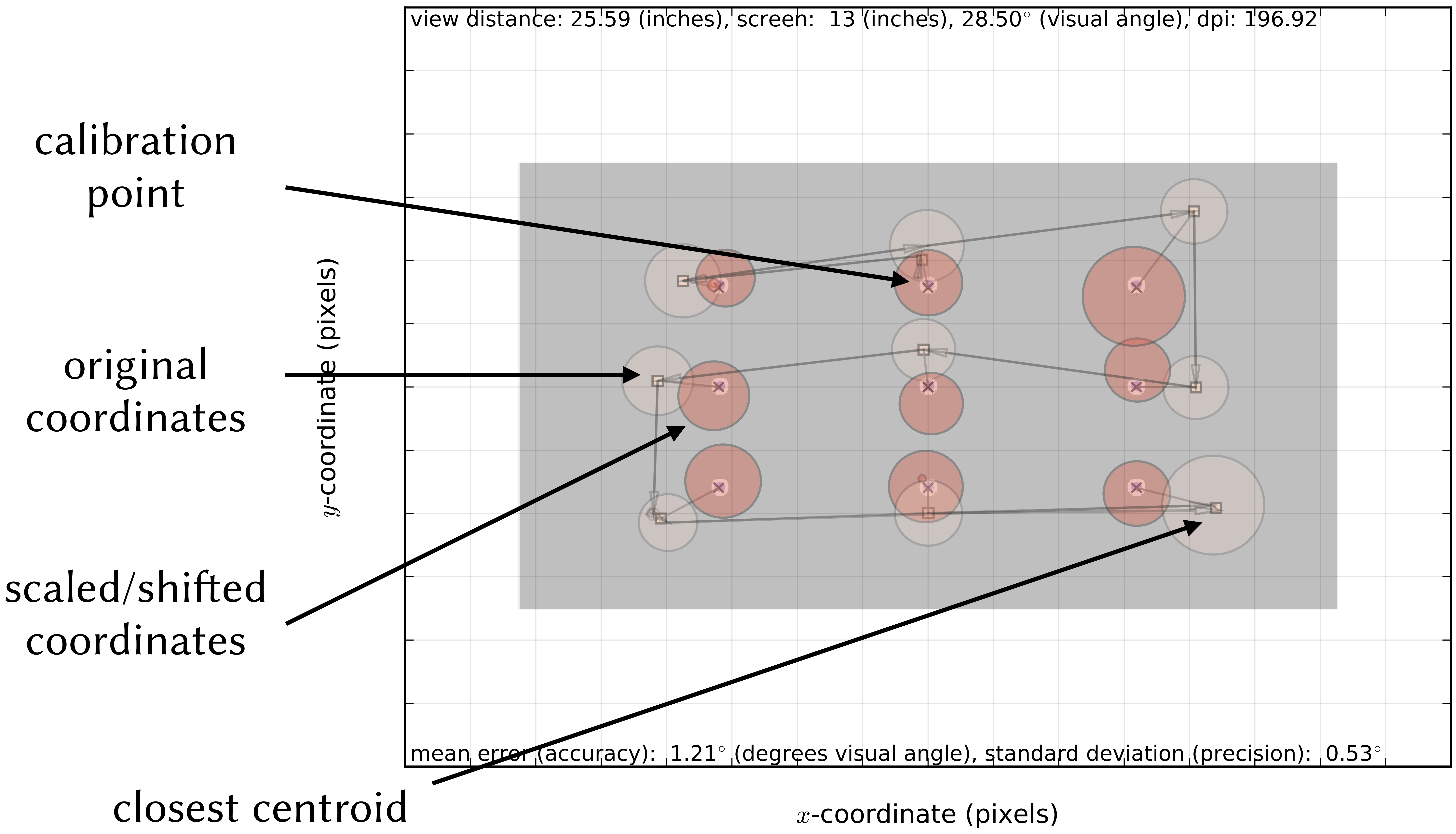
- Compute own accuracy and precision estimates
  - include own calibration in stimulus set

- Data allows fit correction via least-squares





Re-calibration plot



Method of least squares

- With $\{x_{i1}, x_{i2}\}$ and $\{s_{i1}, s_{i2}\}$ denoting observed and calibration points, resp., set up system of equations:

$$\begin{bmatrix} s_{1x} & s_{1y} \\ s_{2x} & s_{2y} \\ \vdots & \vdots \\ s_{nx} & s_{ny} \end{bmatrix} = \begin{bmatrix} 1 & x_1 & y_1 & xy_1 & x_1^2 & y_1^2 \\ 1 & x_2 & y_2 & xy_2 & x_2^2 & y_2^2 \\ \vdots & \vdots & \vdots & & & \\ 1 & x_n & y_n & xy_n & x_n^2 & y_n^2 \end{bmatrix} \begin{bmatrix} a_0 & b_0 \\ a_1 & b_1 \\ a_2 & b_2 \\ a_3 & b_3 \\ a_4 & b_4 \\ a_5 & b_5 \end{bmatrix}$$

using n calibration points

Method of least squares

- Solution is the 2nd order polynomial at each point:

$$s_x = a_0 + a_1 x + a_2 y + a_3 xy + a_4 x^2 + a_5 y^2$$
$$s_y = b_0 + b_1 x + b_2 y + b_3 xy + b_4 x^2 + b_5 y^2$$

or in matrix notation: $\mathbf{S} = \mathbf{X}\hat{\mathbf{B}}$

following Morimoto and Mimica (2005)

- Generalizes to Lagrange's method of least square (see Lancaster and Salkauskas (1986) for example)

Method of least squares

- Given $\mathbf{S} = \mathbf{X}\hat{\mathbf{B}}$

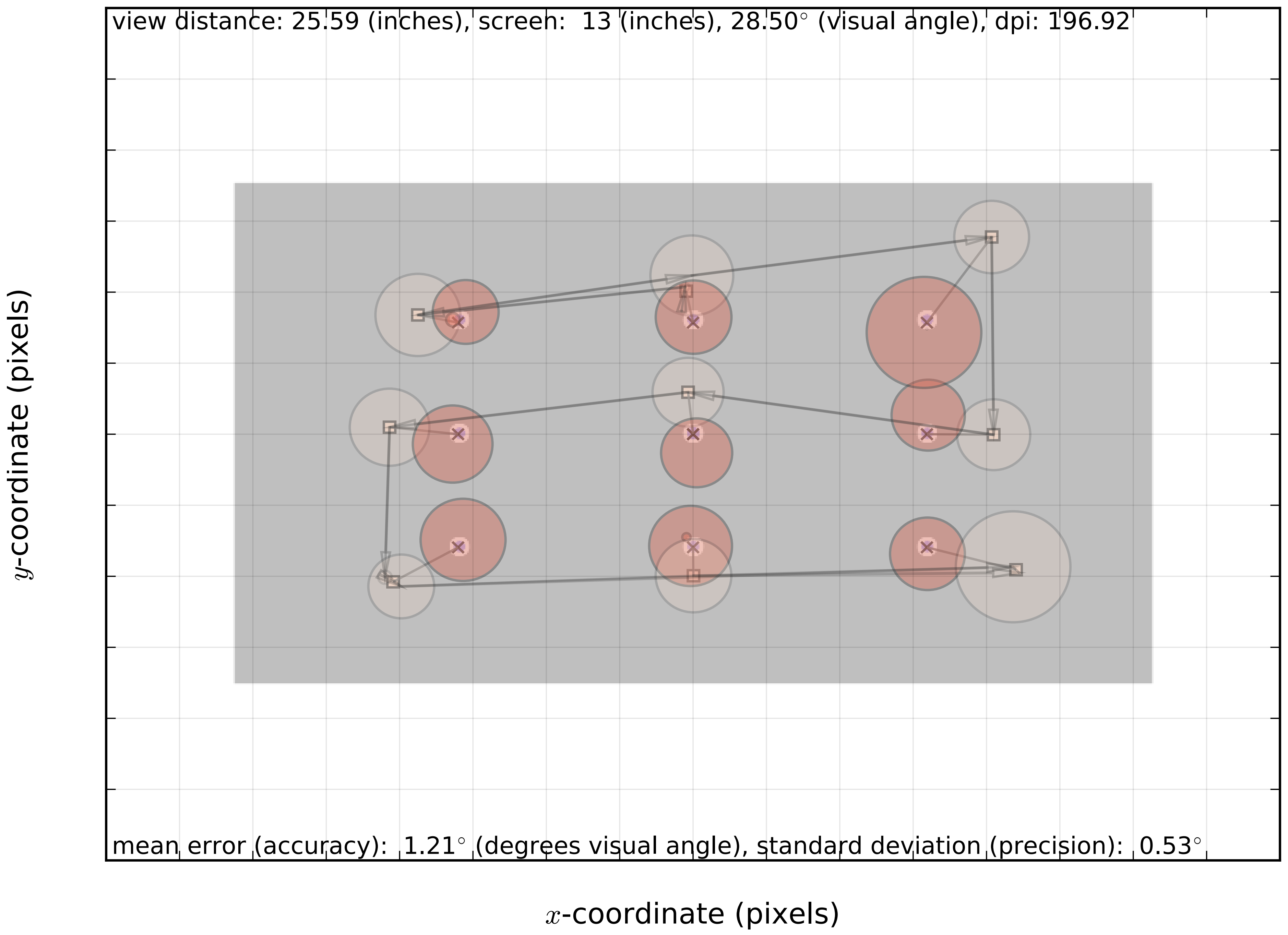
  solve for $\hat{\mathbf{B}}$: $\quad \hat{\mathbf{B}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y}$

  where $\mathbf{G}^{-1} = (\mathbf{X}^T\mathbf{X})^{-1}$ is called the pseudo-inverse

- We may have many fixations at each calibration point
  - use centroid (mean) at each calibration point
  - how to determine which fixations are closest?
  - use *k*d-tree

Accuracy / precision

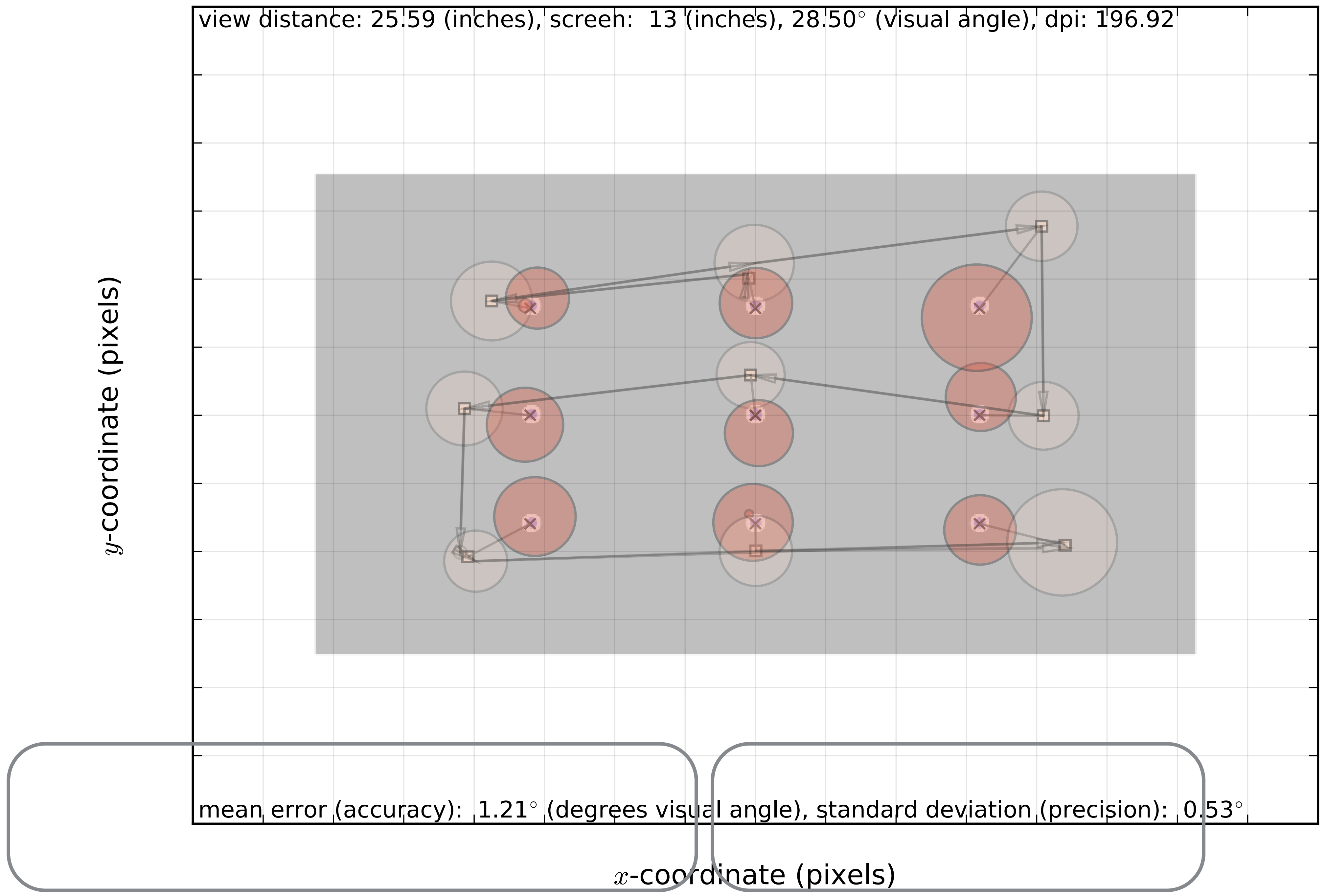
$$A = \sum_{i=1}^{M} \left(\frac{\sum_{j=1}^{N} \frac{\|T_i - P_{i,j}\|}{N}}{M} \right)$$



- Algorithm:
  - for each of N fixation points $P_{i,j}$:
    - using *k*d-tree, find closest of M calibration points T_i
    - compute distance to calibration point $\|T_i - P_{i,j}\|$

For a nice description, see:
Johansen et al., 2011

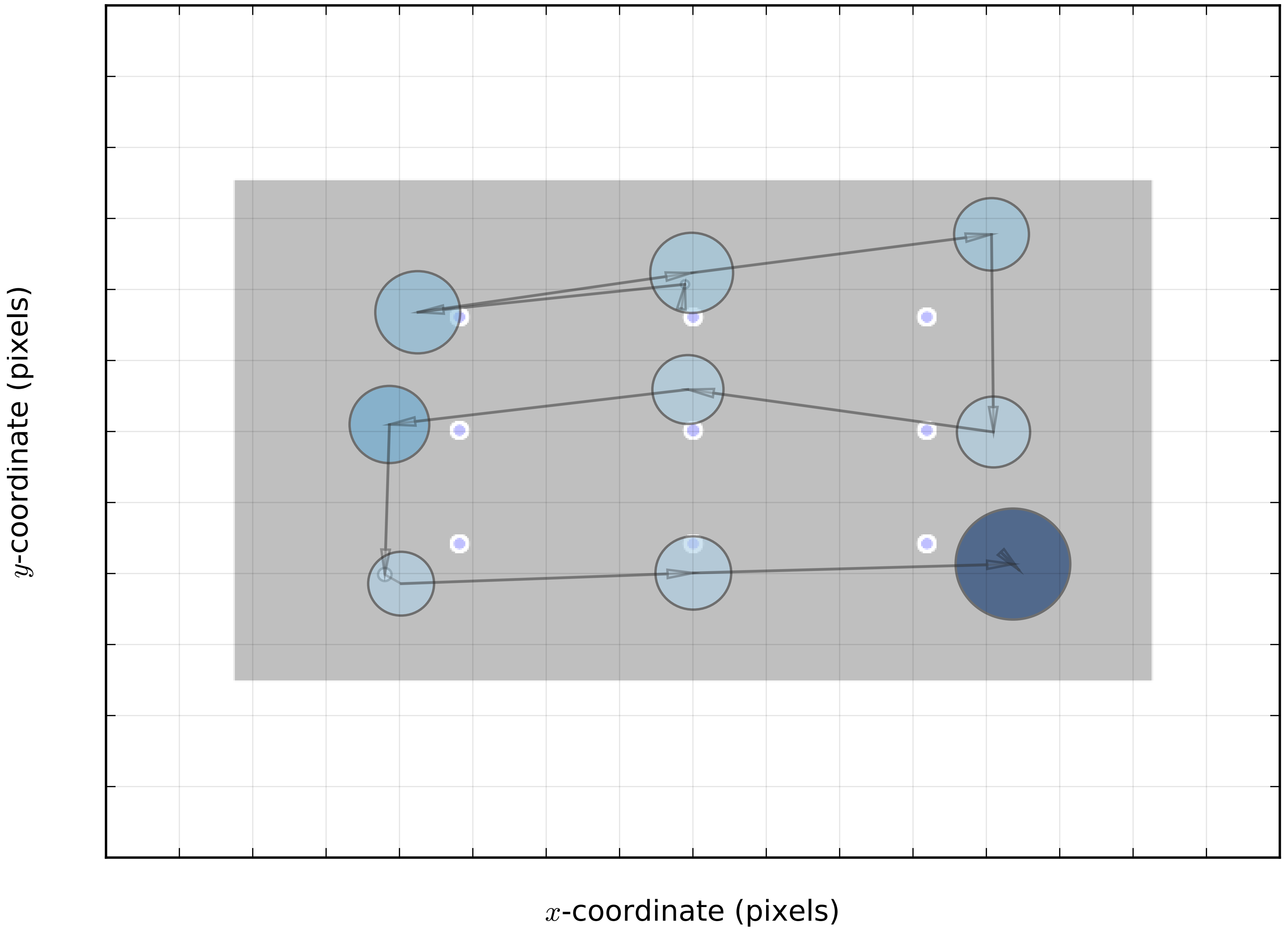
Accuracy / precision



- Algorithm:
  - compute mean of means (accuracy)
  - compute standard deviation (precision)
  - report error in deg. visual angle (Blignaut and Beelders, 2012)

$\mathcal{K}$ coefficient: ambient/focal coefficient

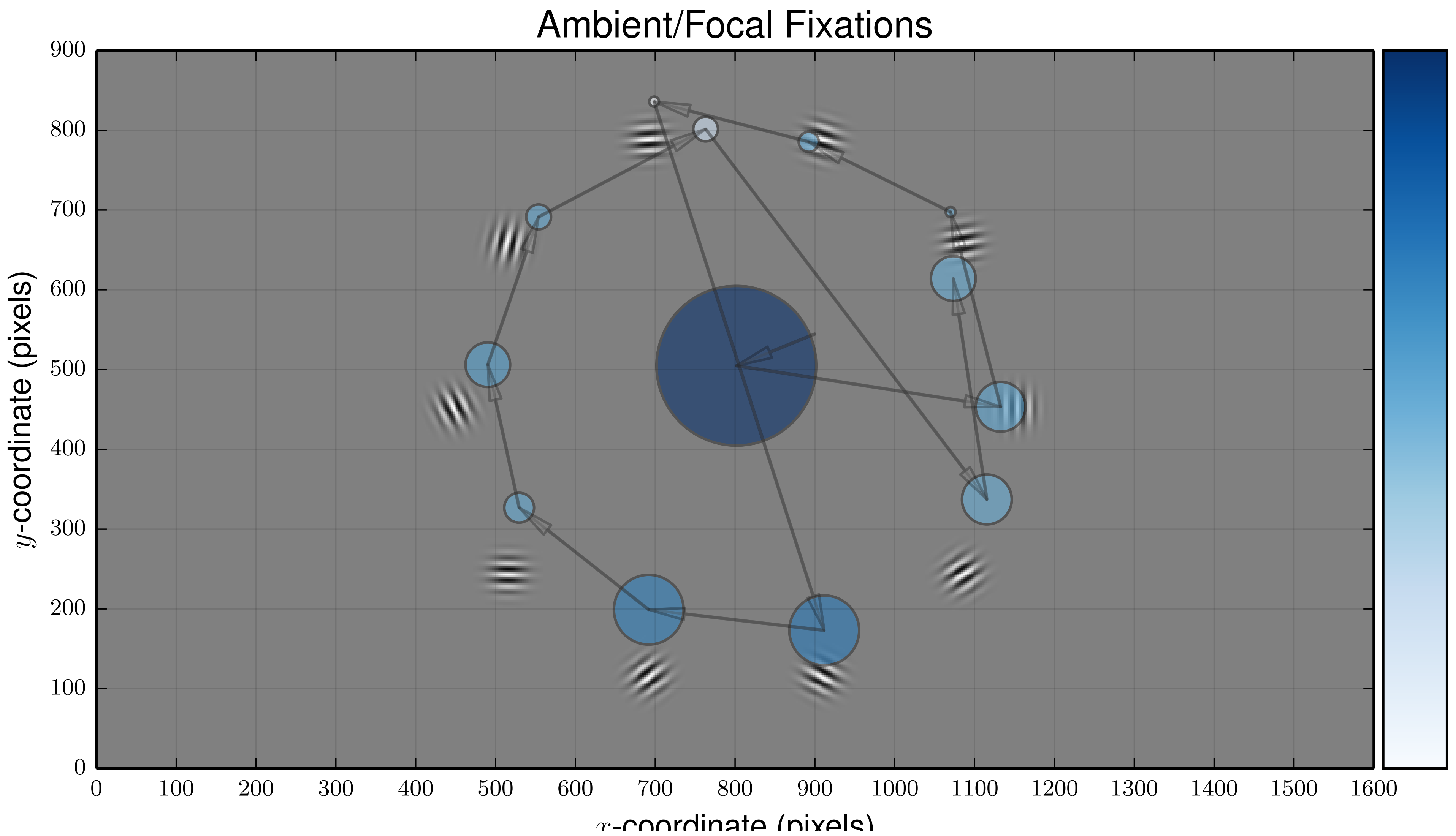
$$\mathcal{K}_i = \frac{d_i - \mu_d}{\sigma_d} - \frac{a_{i+1} - \mu_a}{\sigma_a}$$

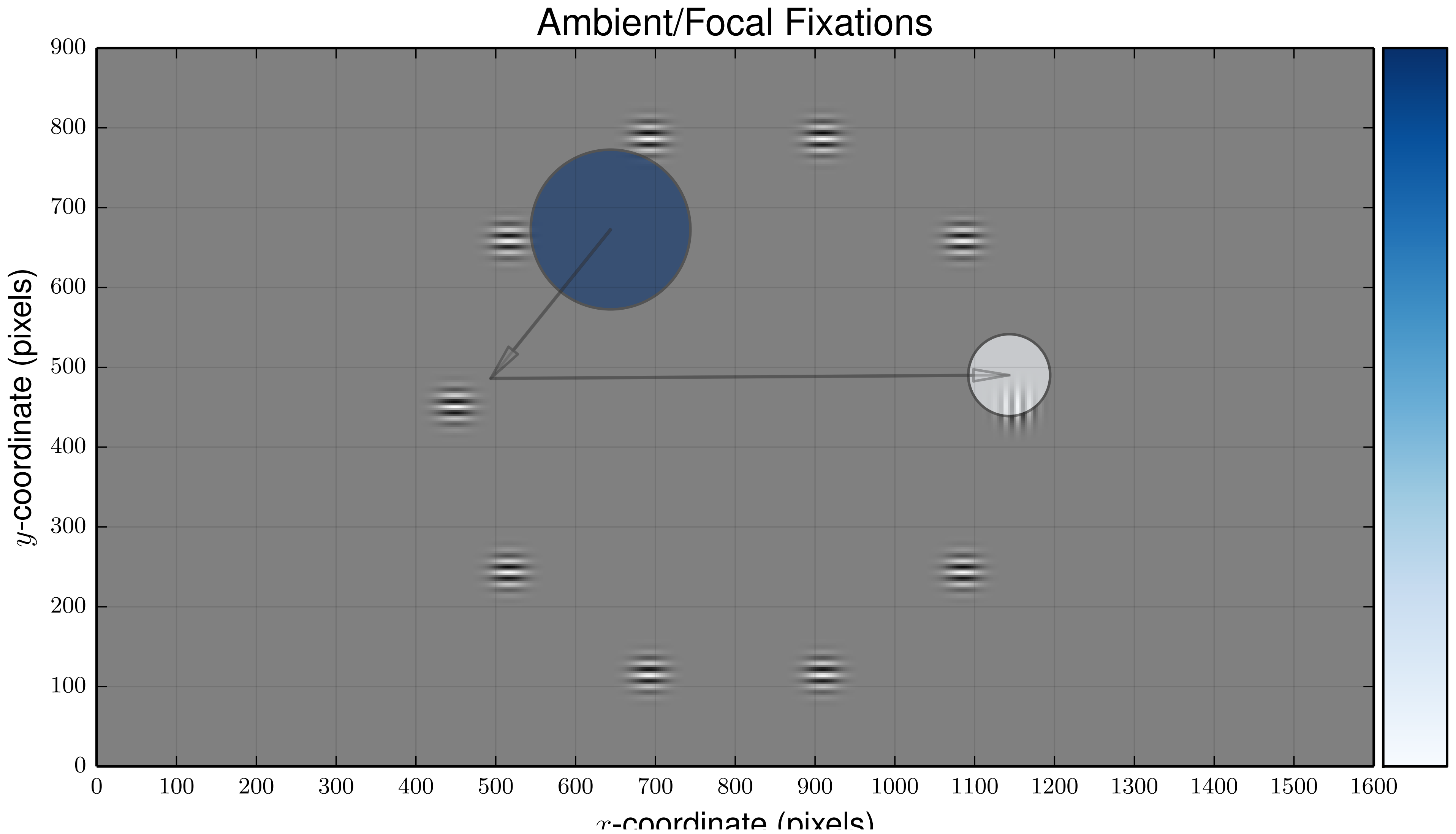


- Algorithm:
  - standardized fixation duration - standardized saccade amplitude
  - $\mathcal{K} > 0$ suggests focal viewing
  - $\mathcal{K} < 0$ suggests ambient viewing (visual search)

Coefficient as contextual cue

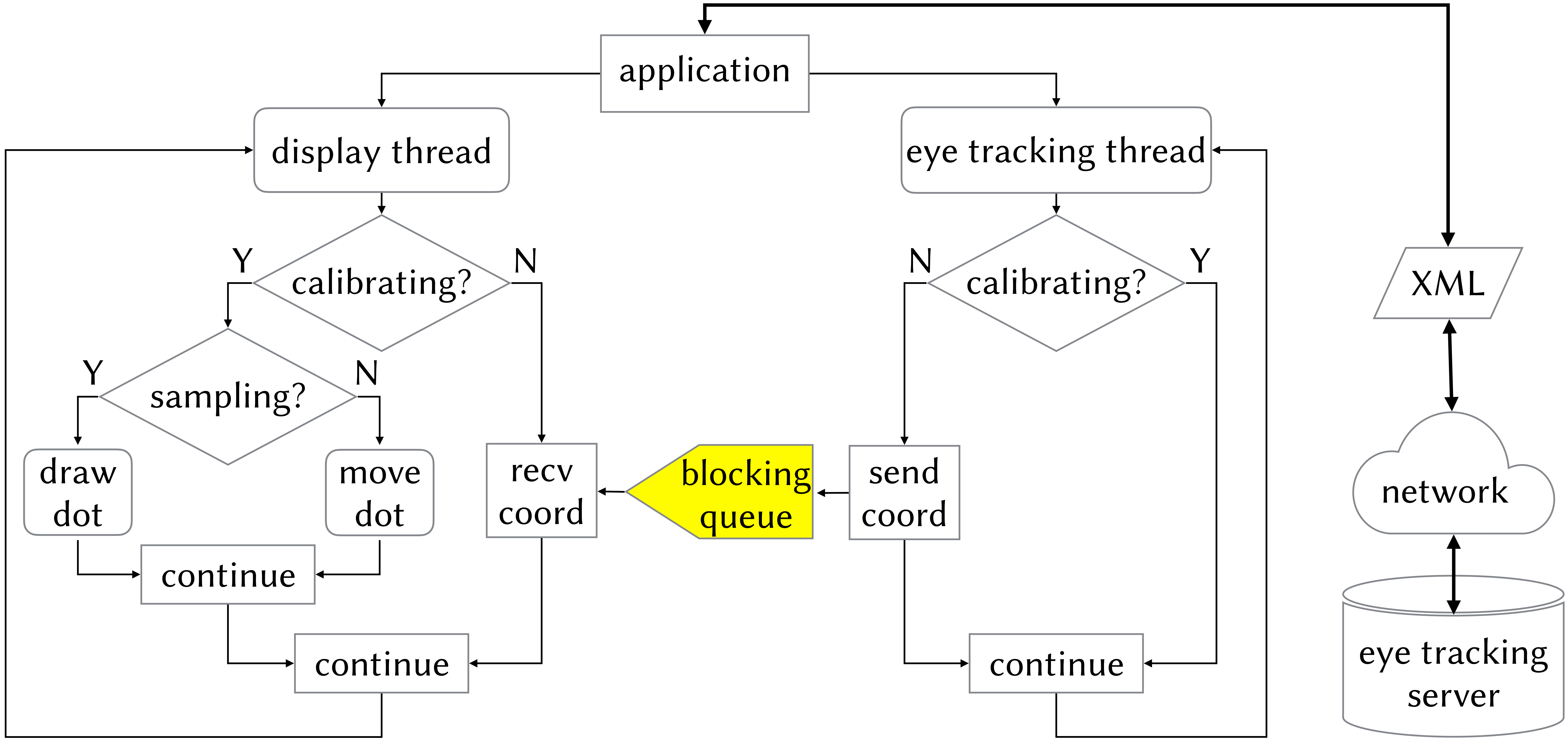
- $\mathcal{K}$ coefficient is examined over time
- Cognitive load could be indicated by:
  - becoming more focal over time, or
  - oscillating between focal and ambient
- Visual search could be indicated by:
  - largely ambient $\mathcal{K}$





Interactive appliations

- If you want to roll your own...

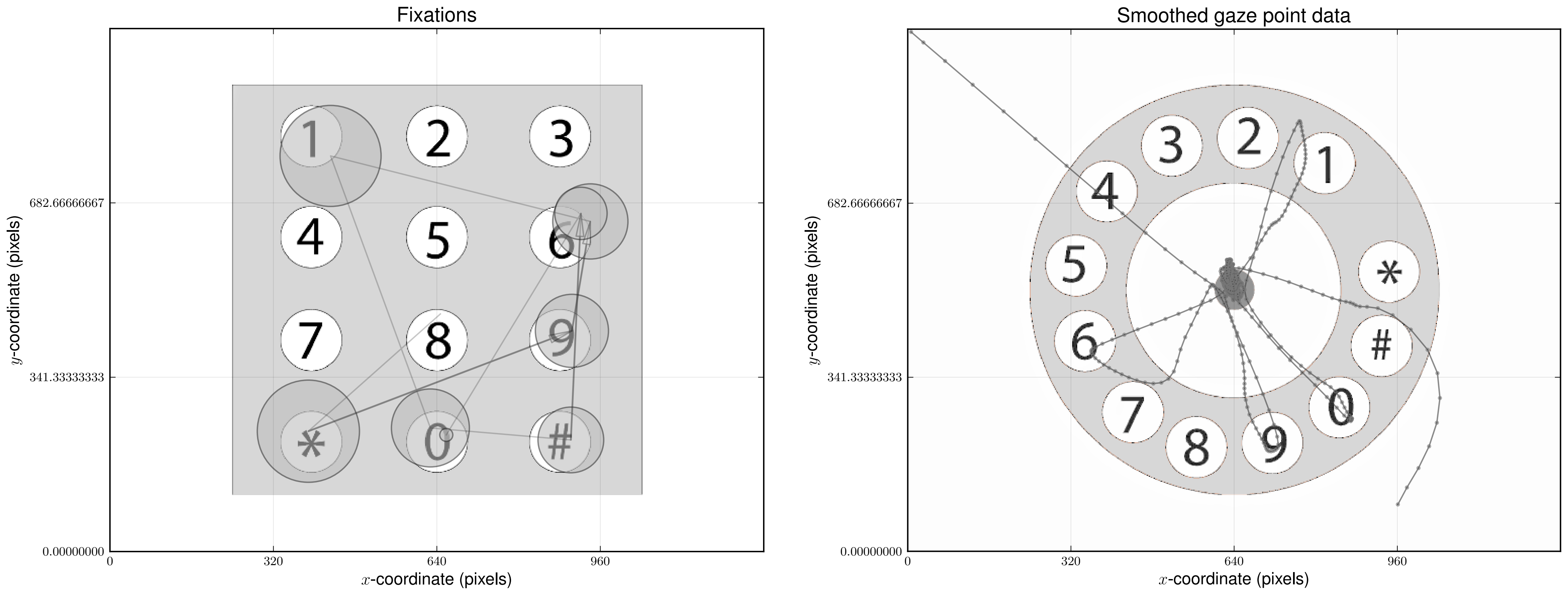


Example: designing for gaze interaction

- Using gaze for input: how best to exploit?
  - Midas touch problem known since Jacob (1990)
    - dwell time was established as method for gaze selection
  - Zhai et al.'s (1999) MAGIC pointing's key observation:
    - the eye is a perceptual organ, not meant for motor input (like hand)
  - What about gestures?

Example: designing for gaze interaction

- Example application: gaze-based PIN entry
- Problems with traditional approach:
  - dwell time selection of PIN numerals is slow
  - improve through thoughtful redesign



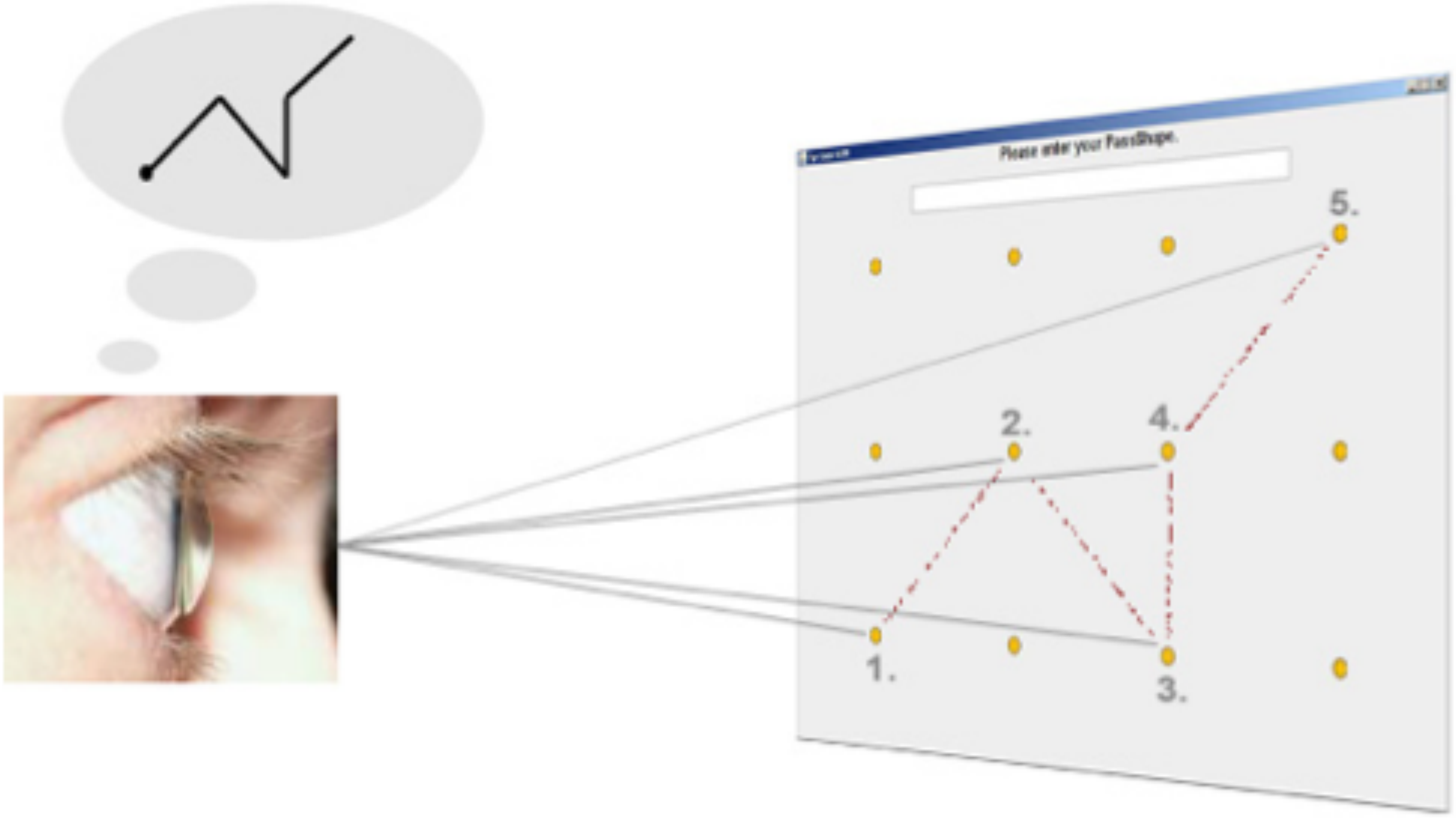
Background: Gaze-based authentication

- Background:
  - Hoanca and Mock’s (2006) PassFaces idea

  - immediate clear how password would work (intuitive)
  - based on dwell-time, however

Background: Gaze-based authentication

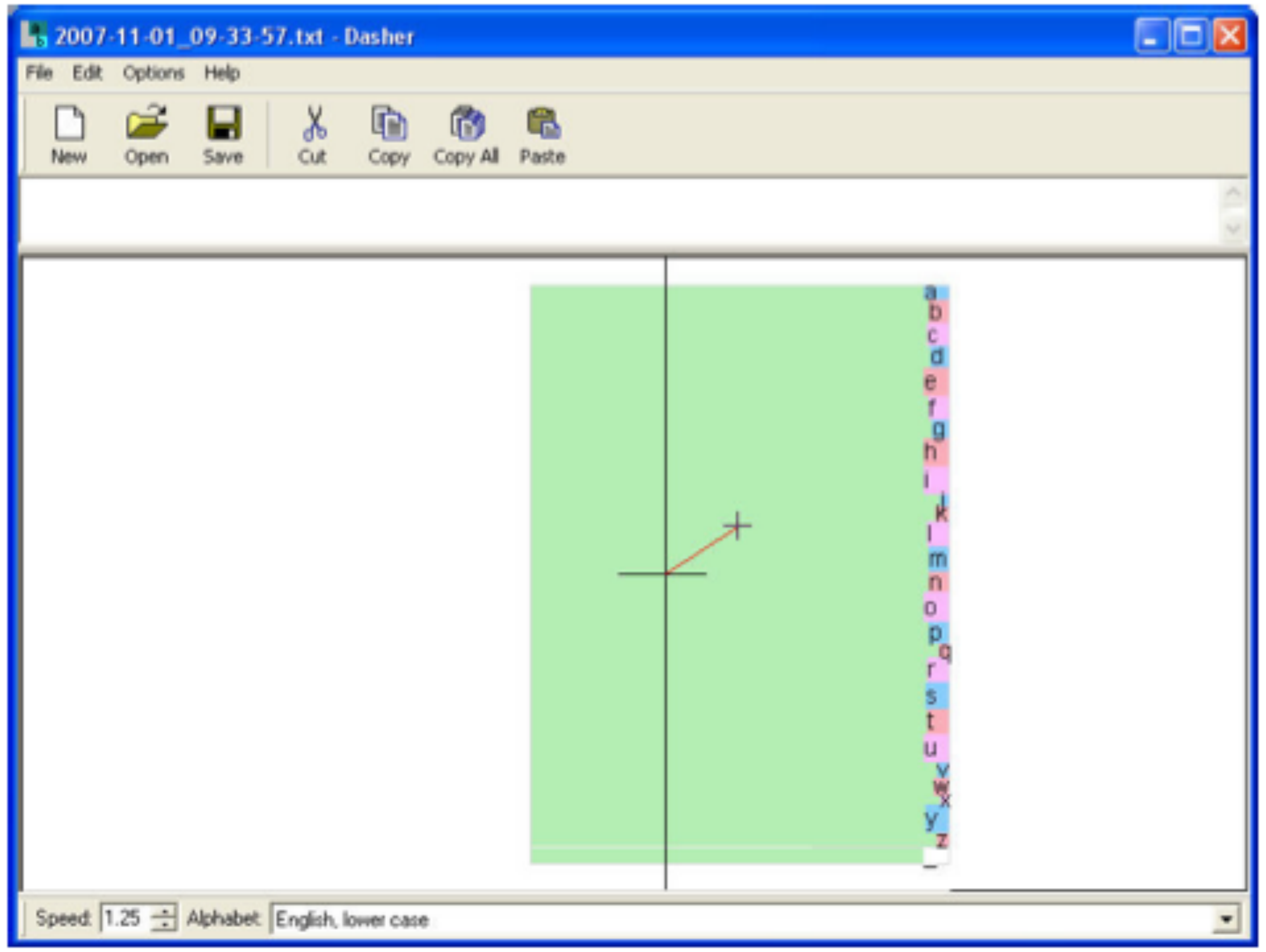
- Background:
  - De Luca et al. (2009) suggest gaze-based graphical password



  - idea is for user to remember shape
  - seems somewhat difficult...

Eye-typing

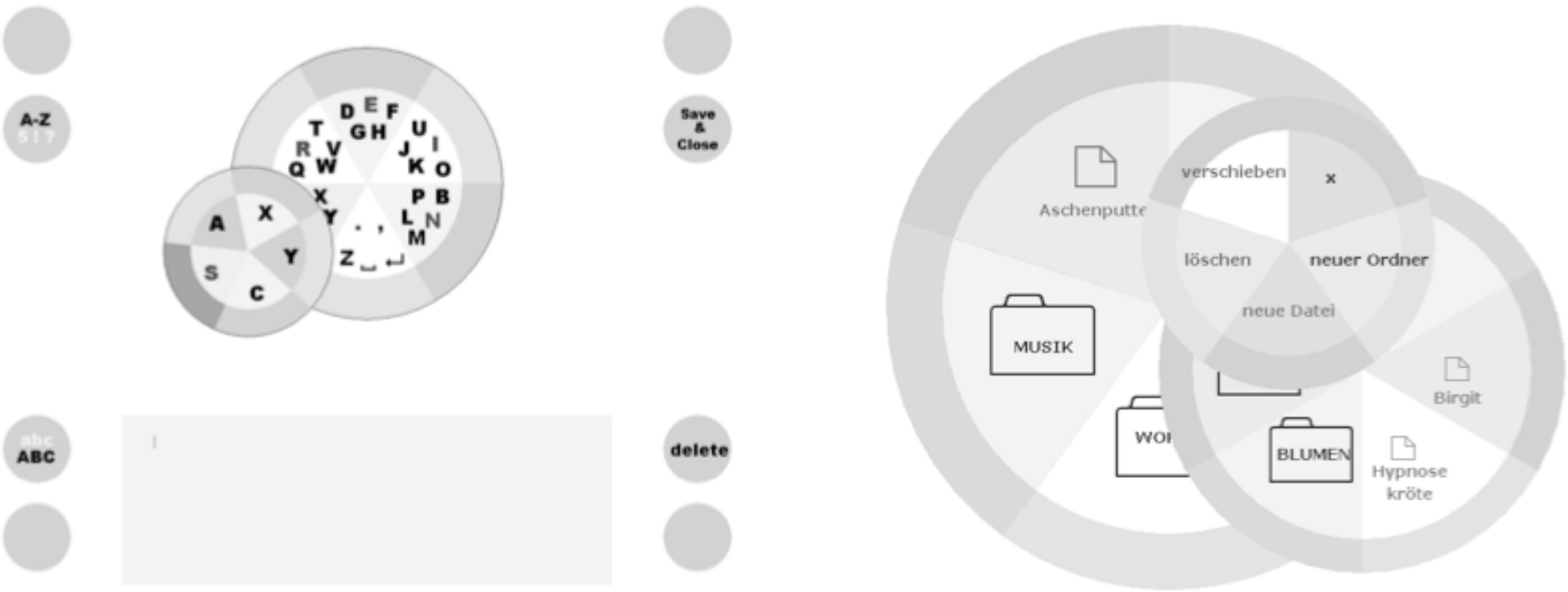
- Background:
  - would rather use eyes as in *Dasher's* eye-typing interface



  - reviewed by Tuisku et al. (2008)
  - uses boundary-crossing interface

Gaze-based menus

- Background:
  - following Huckauf and Urbina's (2008) pEYE menus

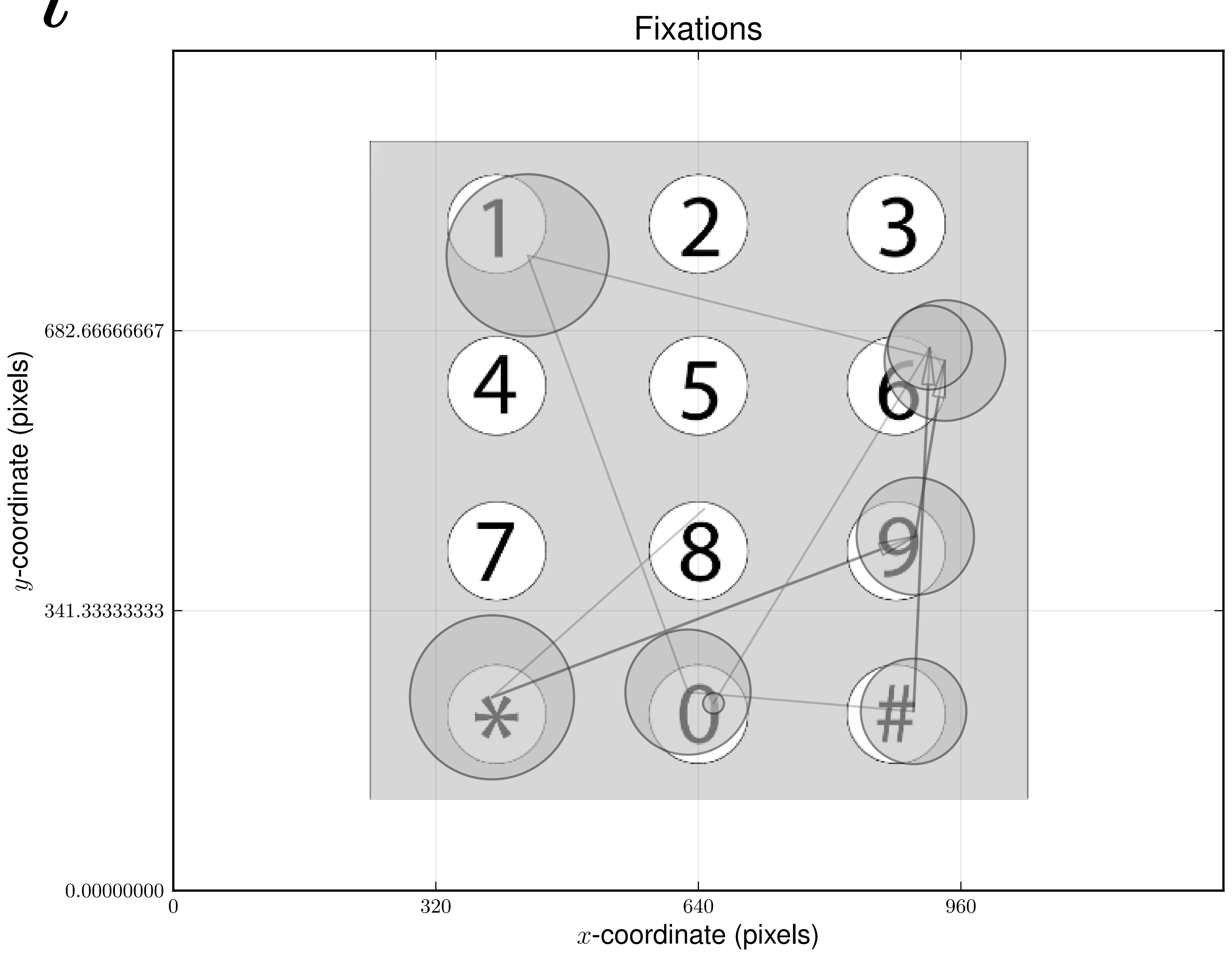


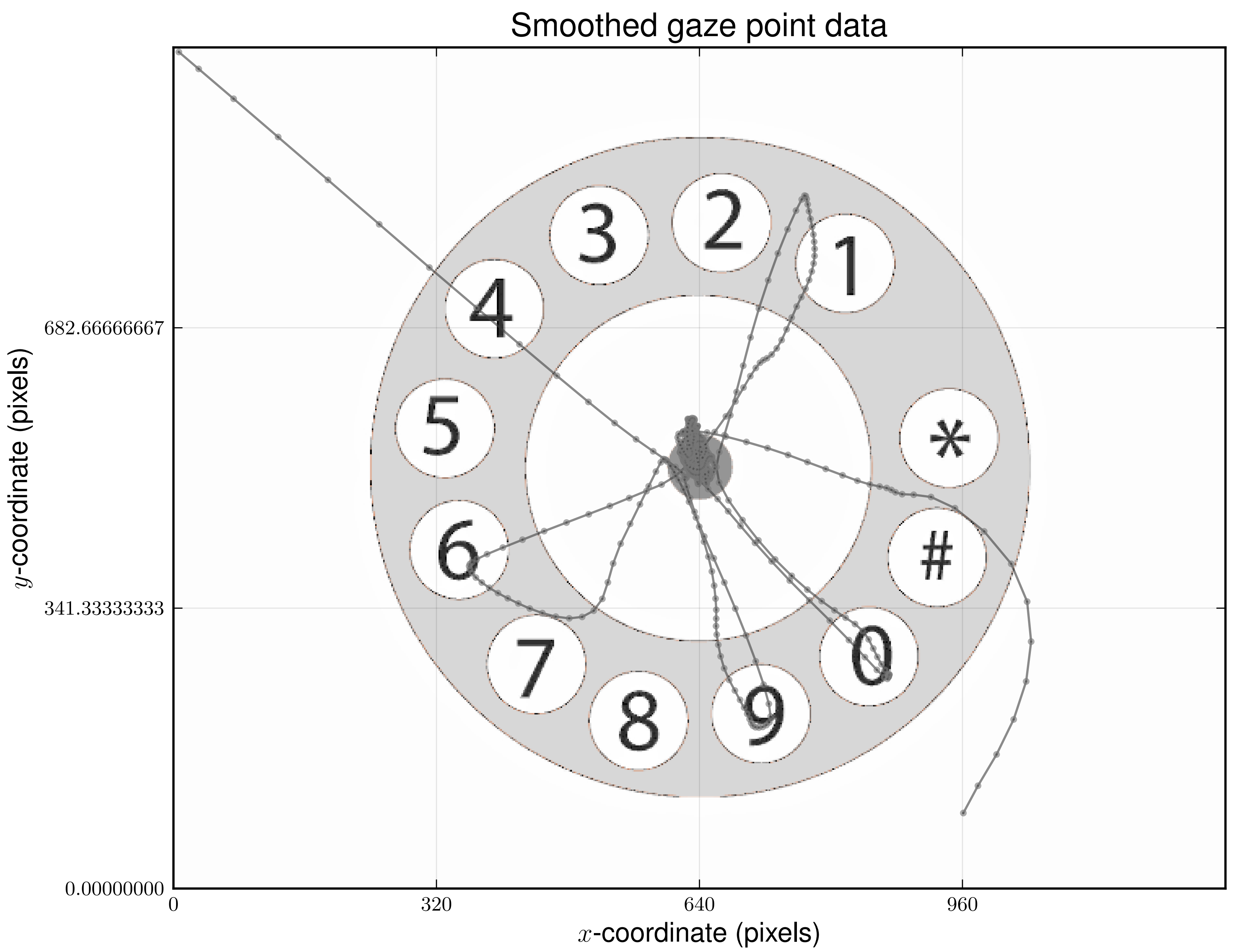
  - but add central fixation area to exploit center-bias

Modeling interaction

- Fitts' Law modeling:
  - each gaze transition modeled as Fitts' Law Movement Time:

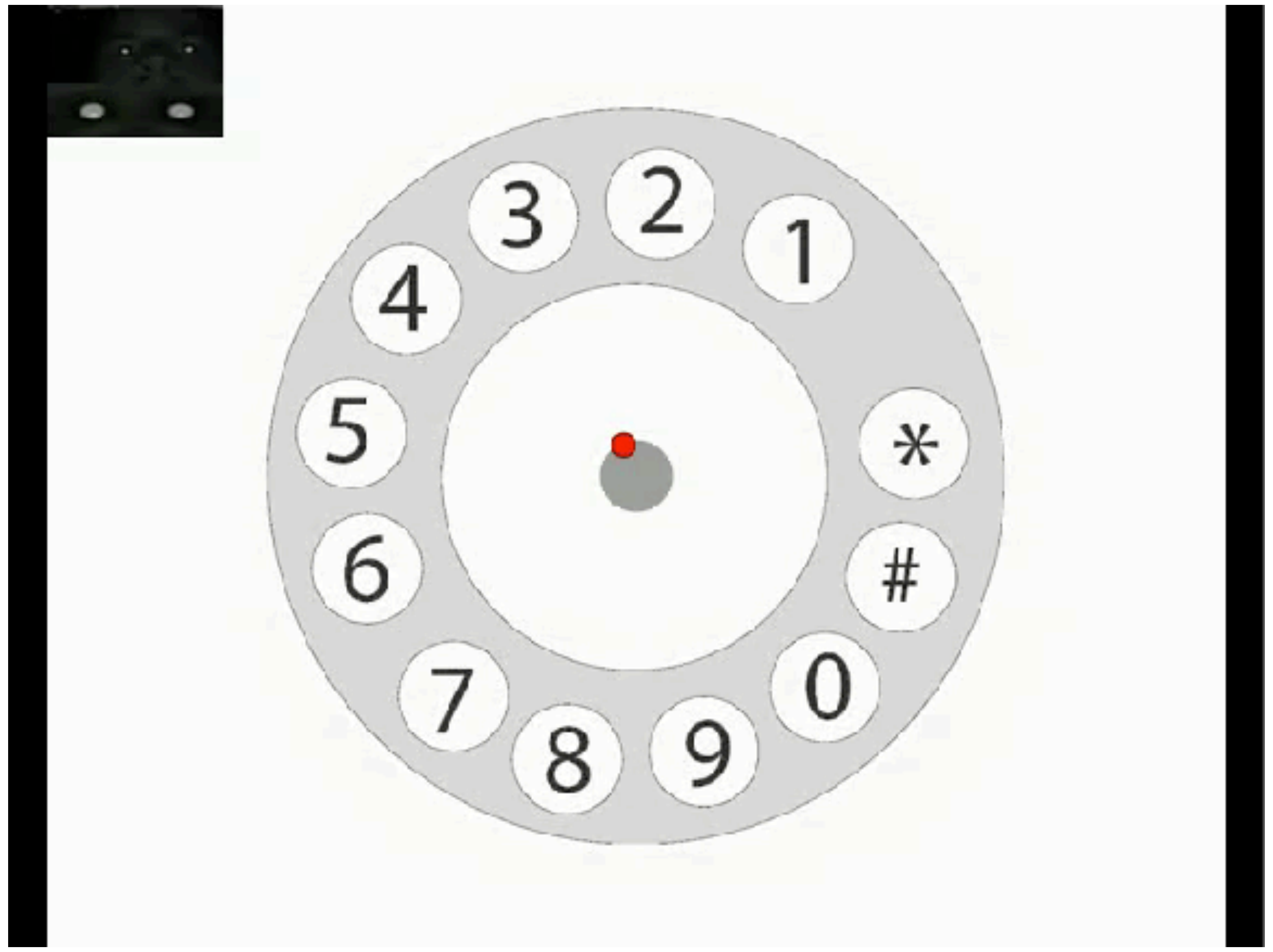
$$\sum_{i}^{|\mathrm{PIN}|} \mathrm{MT}_i \quad \text{with} \quad \mathrm{MT}_i = a + b\log_2(2A/W)$$





Modeling interaction

- Rotary interface:
  - equidistant targets (numeral *pads*)
  - no need to detect fixations (uses boundary crossings)
  - center-bias exploited with central dot target

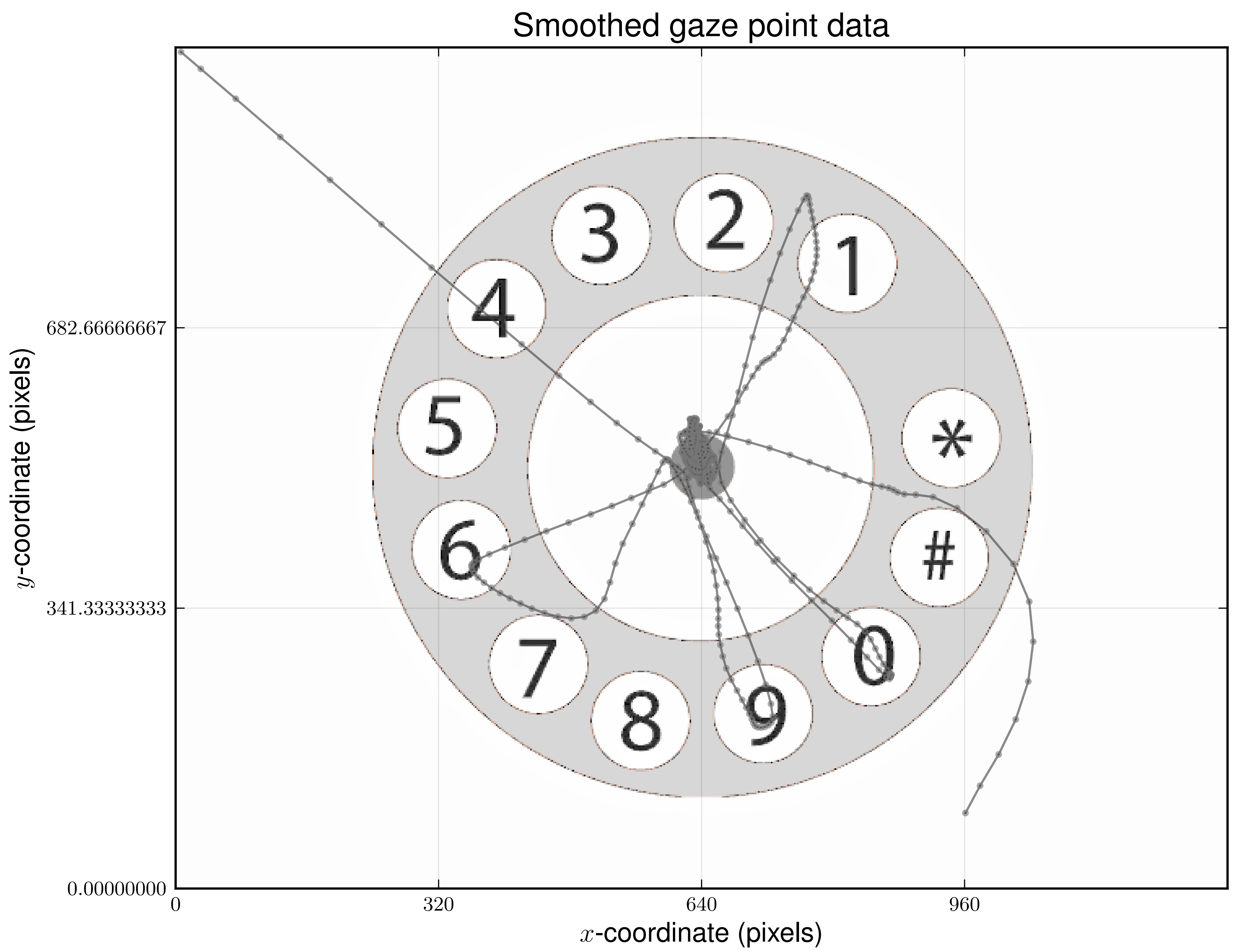


Implementation: rotary

- Smoothed boundary crossings yield character stream

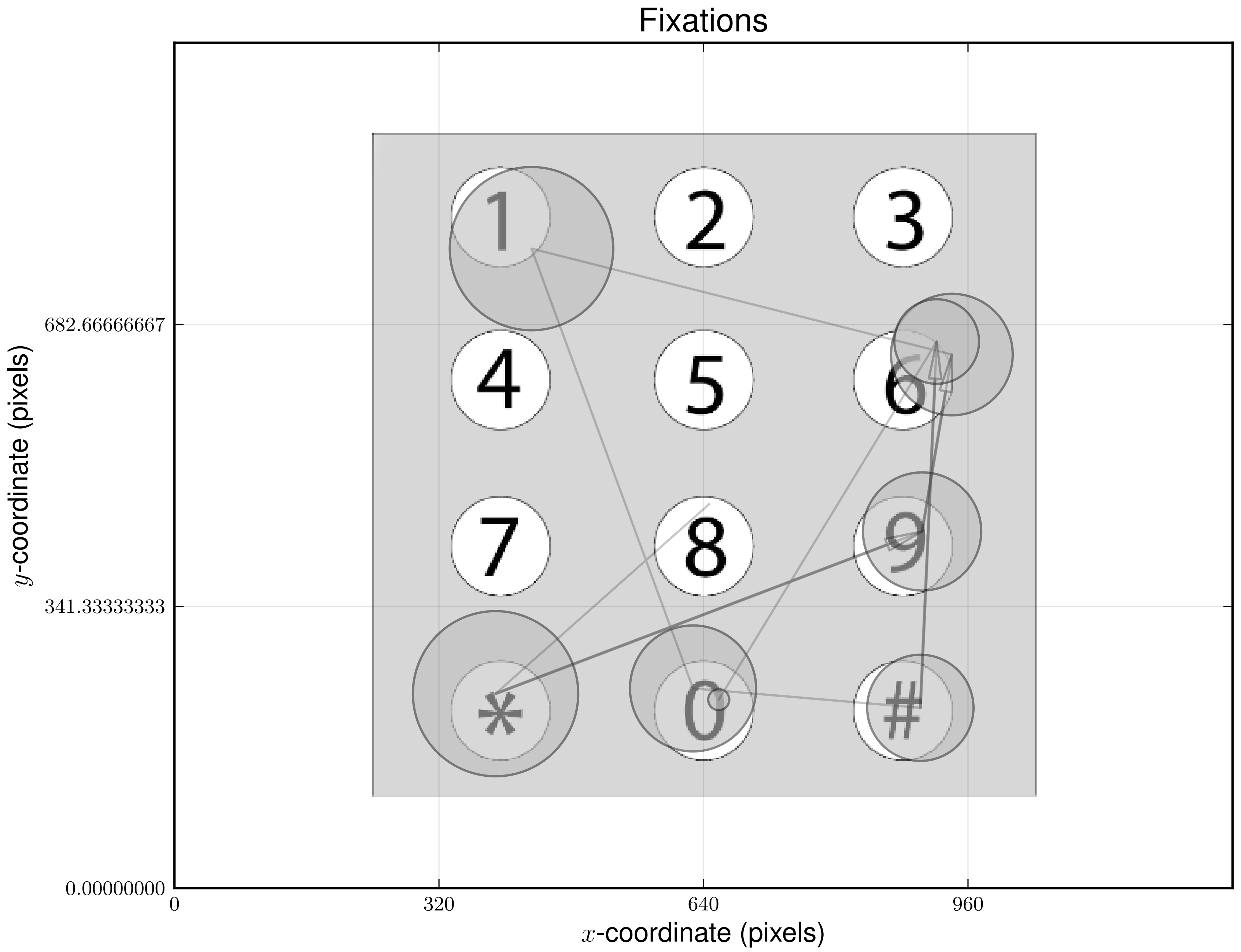
4444cccccc999999999cccccccc77776666cccccc11111111ccccc000000000cccccccccccc##

- needs to be further processed to give PIN entry code
- use a weighted voted scheme
- emphasize exiting pad
- side-effect:
  - allows correction of initial mass

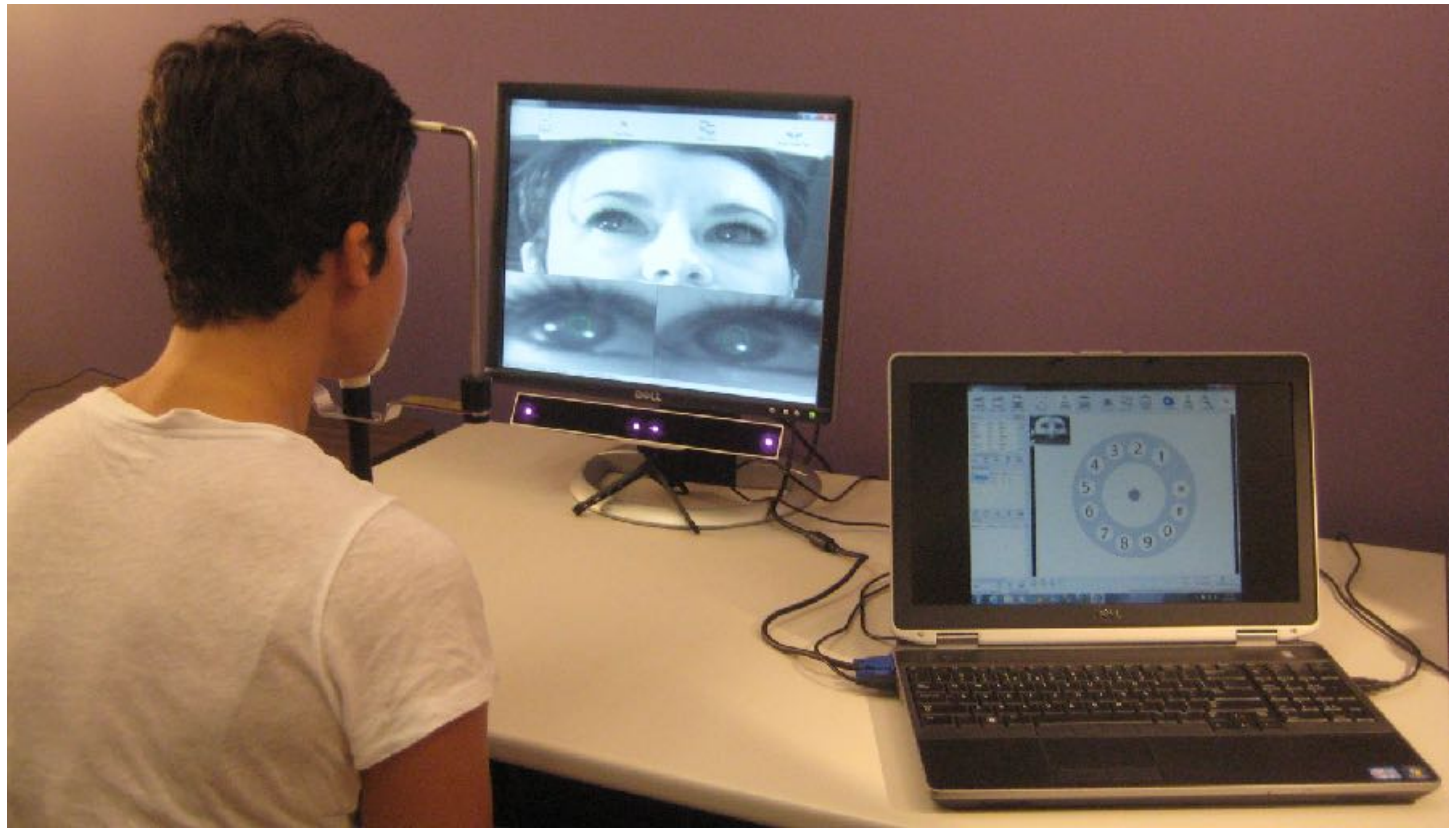


Implementation: keypad

- Fixation-based implementation striaghtforward, but…
  - needs start and end fixation ‘tokens’ (* and #)
  - dwell time is required:
    - necessary so that intermediate pads are not selected (Midas Touch)
  - fixation detection is required
  - use Savitzky-Golay filter
  - threshold on velocity
    - “saccade-picker”



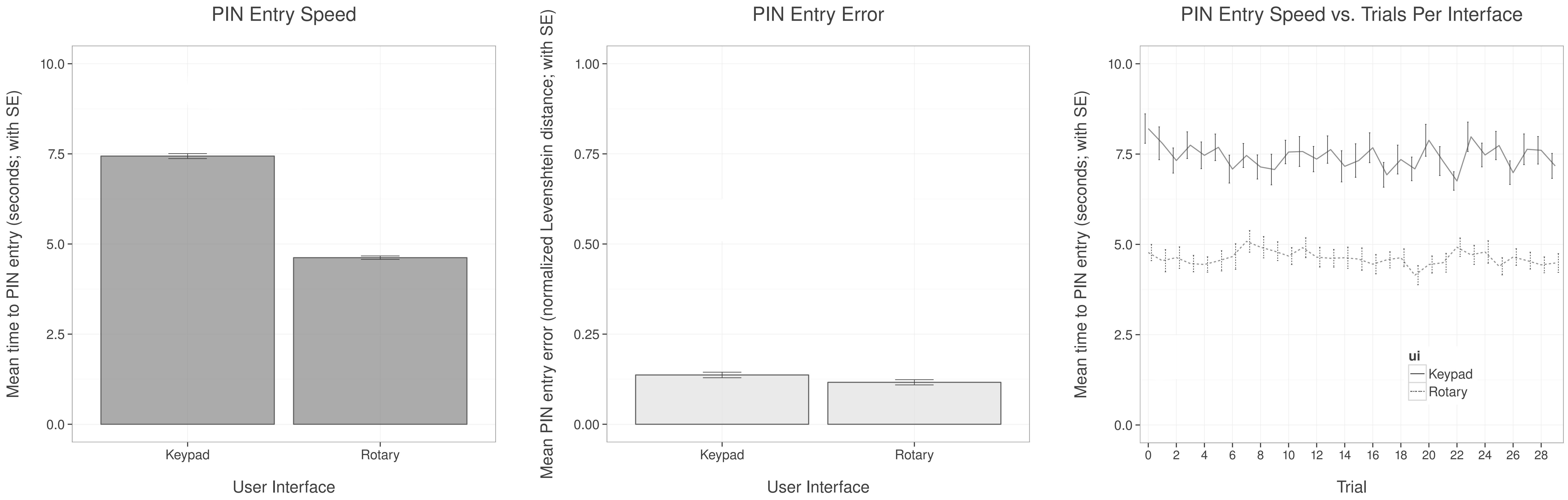
Evaluation: user study



- Participants:
  - 30 (24 M, 6 F)
  - ages 18-44
  - data from 3 excluded
- Apparatus:
  - Gazepoint GP3 eye tracker
    - 60 Hz, 1 deg accuracy (according to manufacturer)
  - chin-rest, sturdy (wooden) chair, Dell 19 inch monitor, laptop
- Procedure:
  - 9-point calibration followed by 30-second training
  - each interface tested with 30 trials (order counterbalanced)

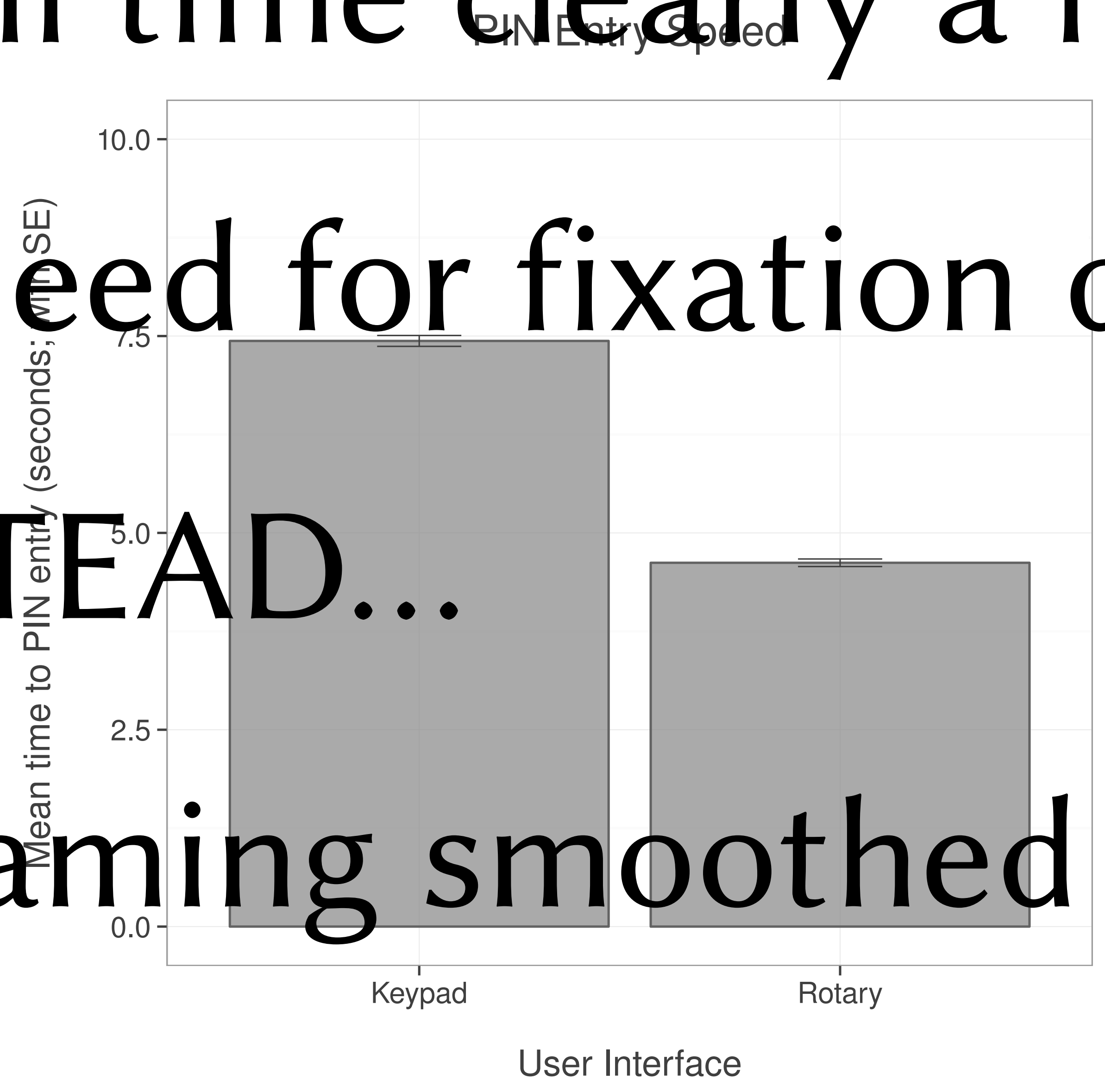
Results: speed, accuracy, trials

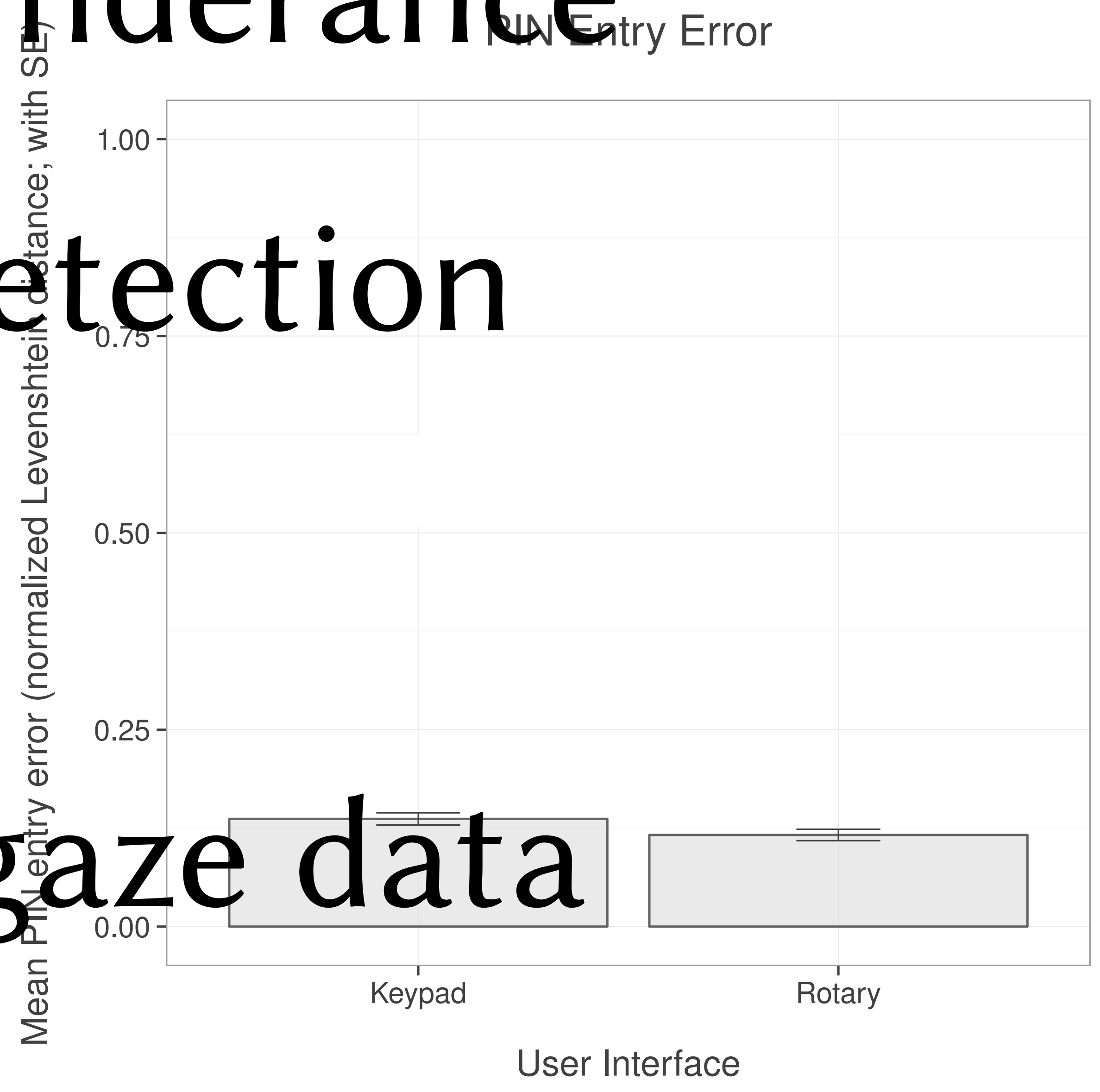
- Rotary interface: speed, accuracy, trials
  - faster input than keypad interface ($F(1,26) = 61.20$, $p < 0.01$)
  - average PIN error not sig. different ($F(1,26) = 1.16$, $p = 0.29$, n.s.)
  - learning effect sig. only for keypad ($F(29,754) = 1.96$, $p < 0.01$)

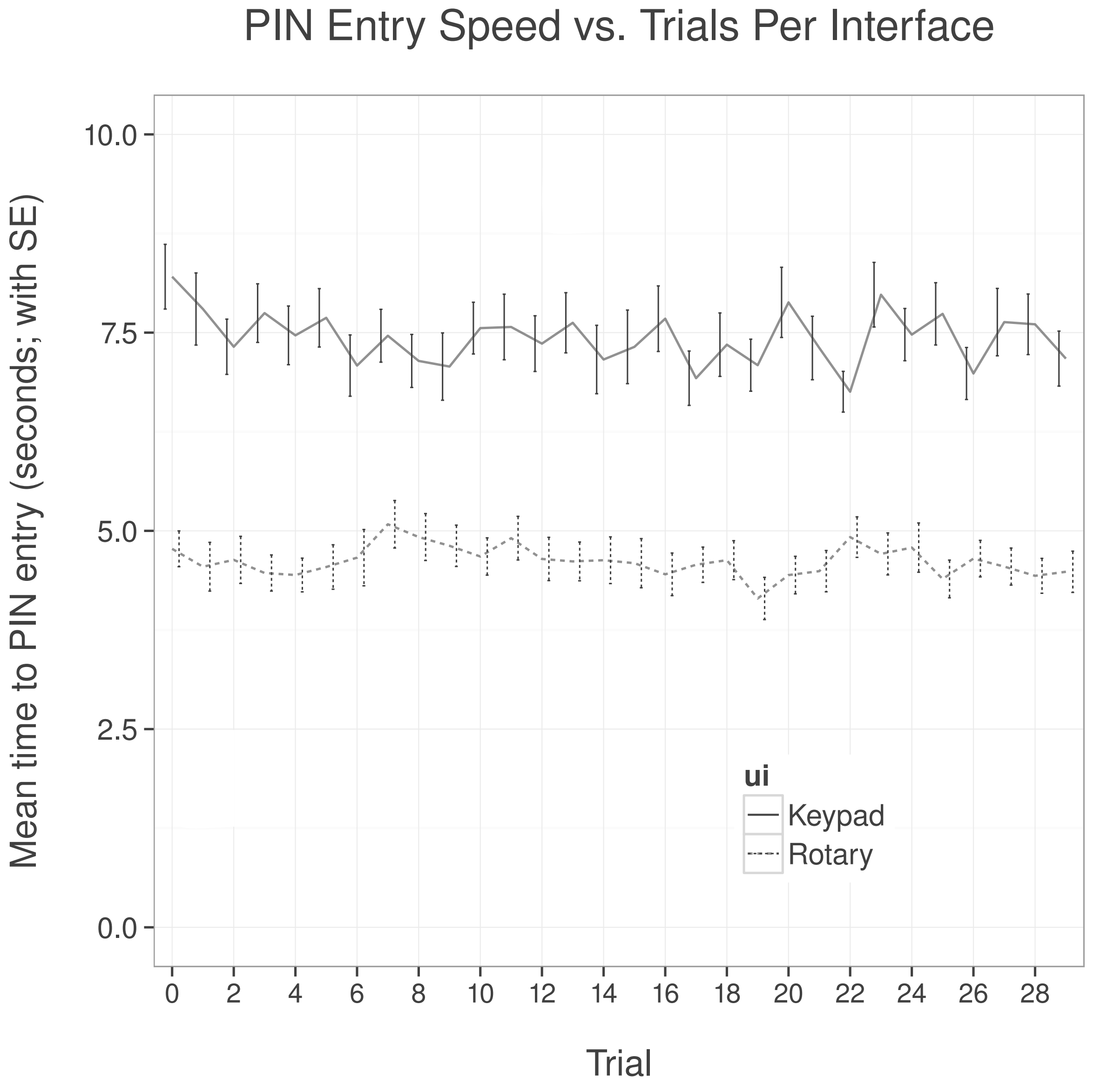


Results: speed, accuracy, trials

- Rotary interface: speed
  - faster input than keypad interface
    ($F(1,26) = 61.20$, $p < 0.01$)
  - as expected, following Fitts' Law
  - dwell time clearly a hinderance
  - no need for fixation detection
  - INSTEAD...
  - streaming smoothed gaze data

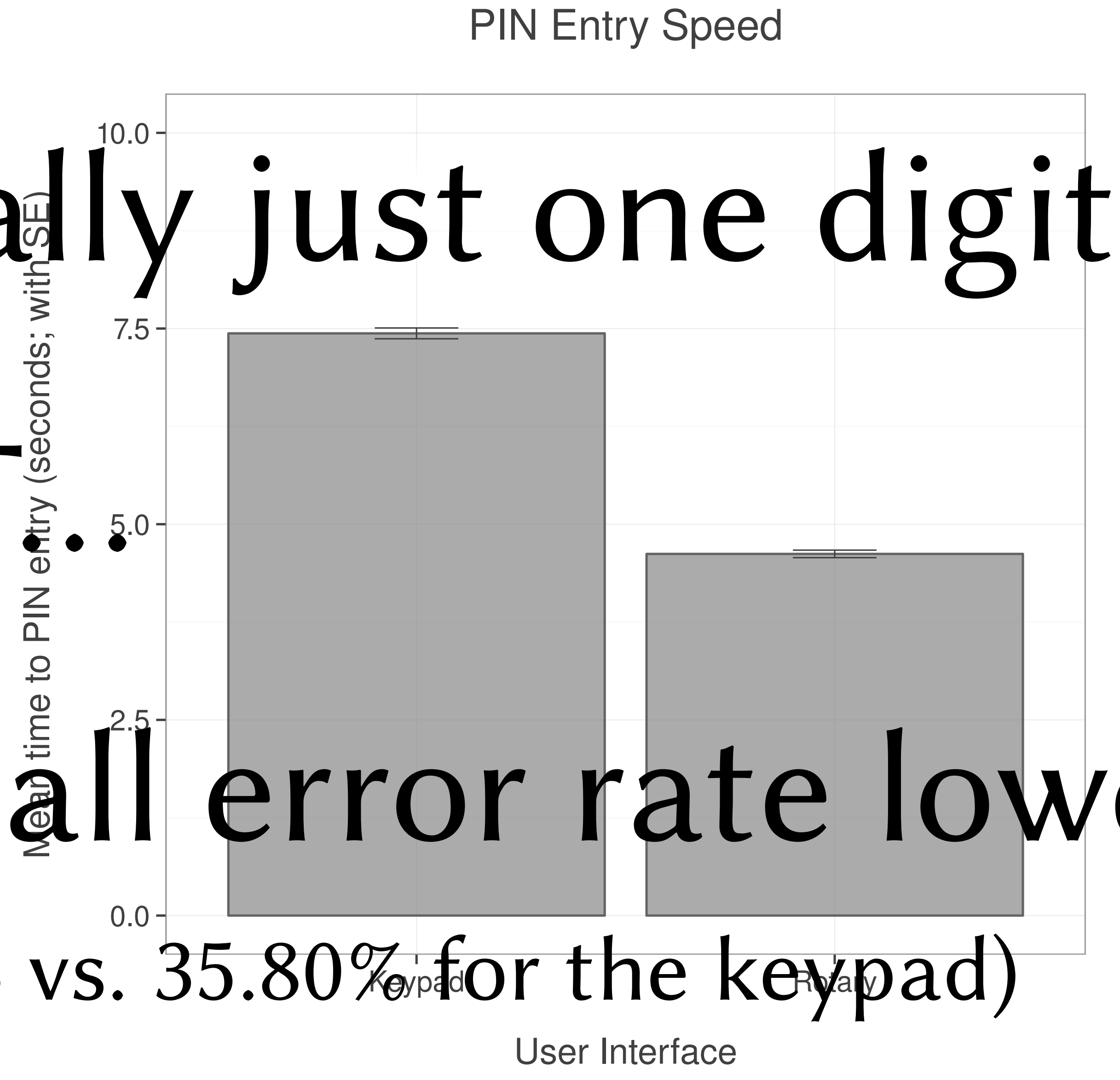


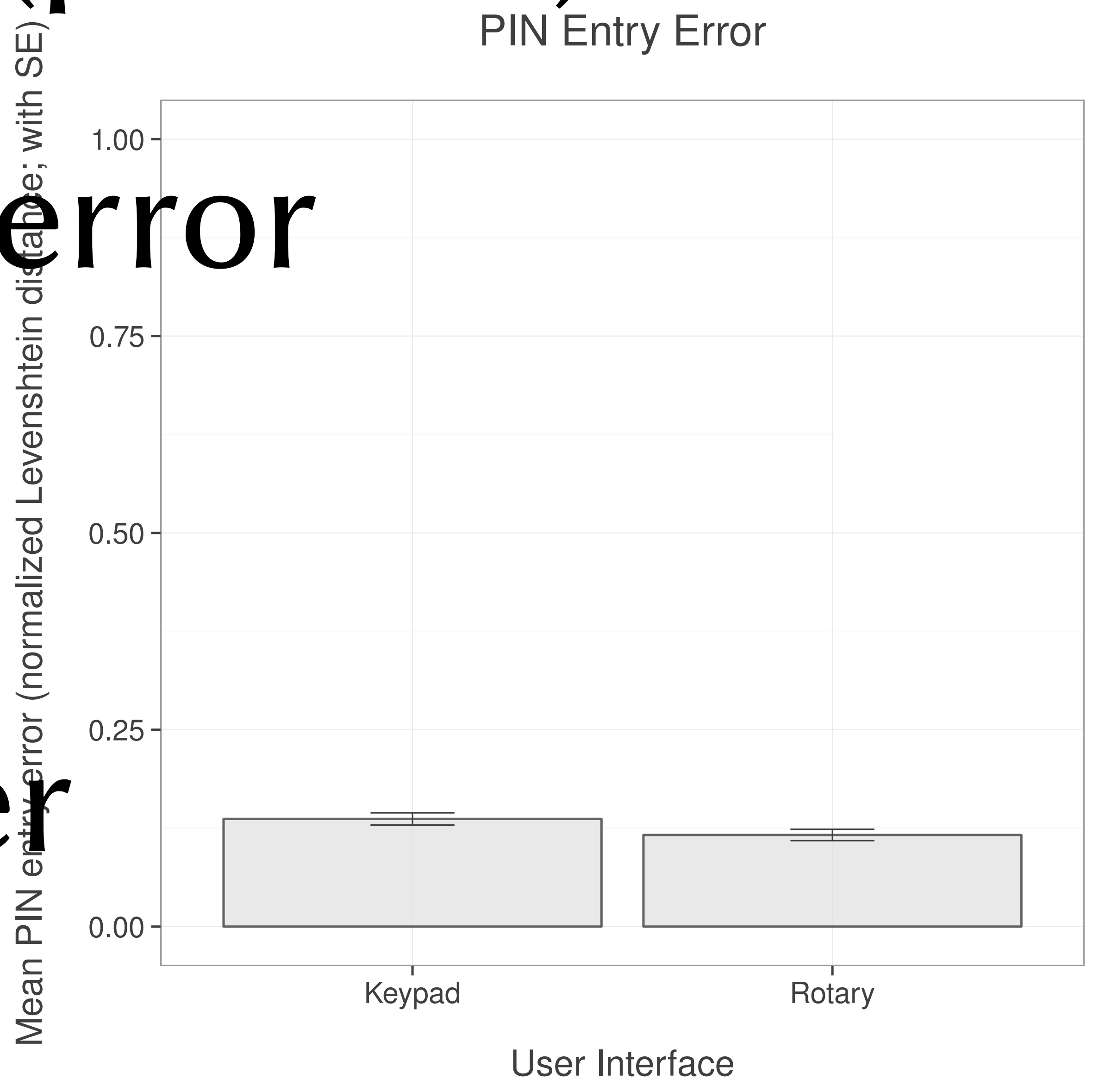


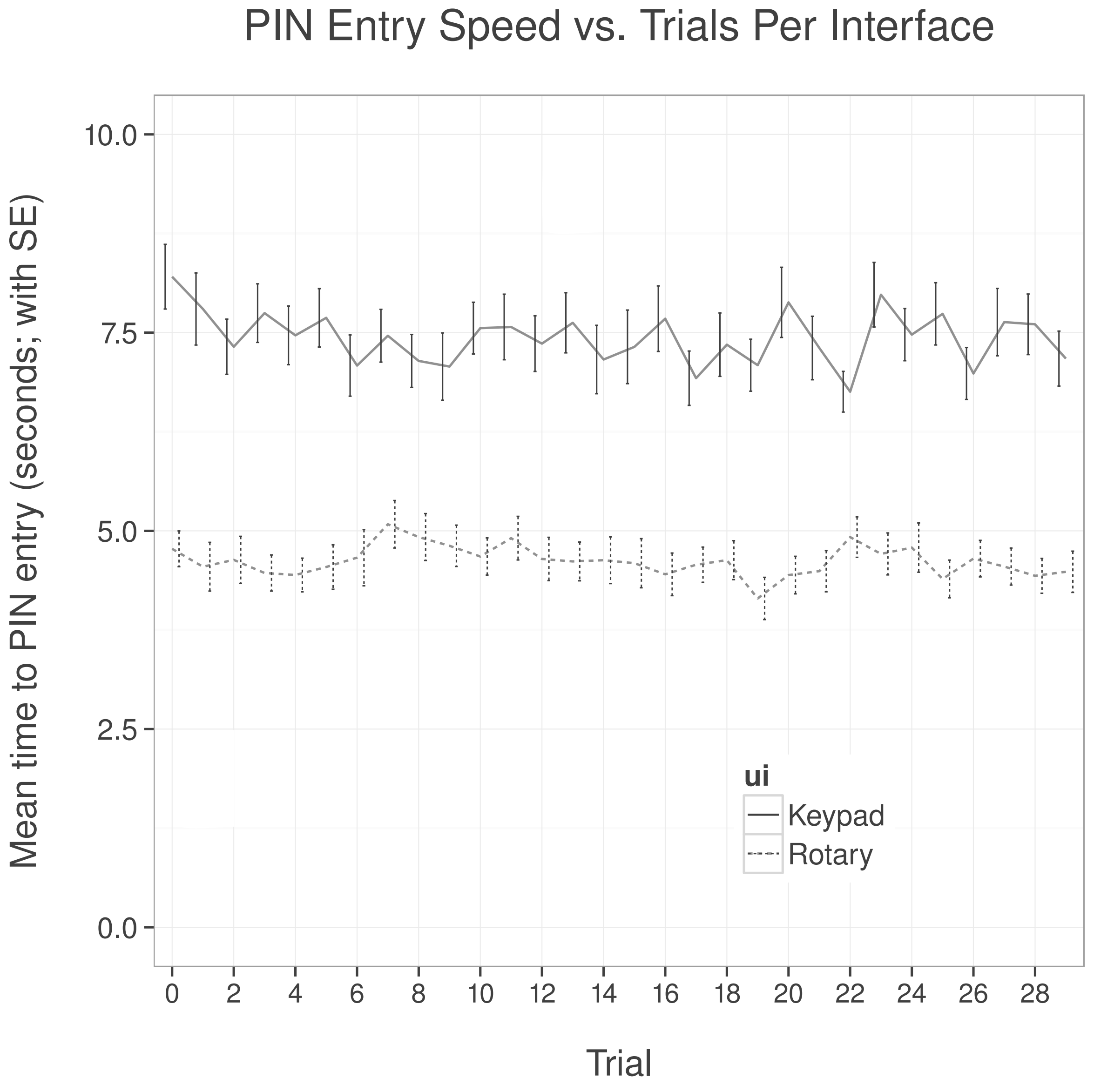


Results: speed, accuracy, trials

- Rotary interface: accuracy
  - average PIN error not sig. different
    (F(1,26) = 1.16, p = 0.29, n.s.)
  - error computed as normalized Levenshtein distance (per PIN)
  - usually just one digit error
  - BUT…
  - overall error rate lower
    (28.84% vs. 35.80% for the keypad)

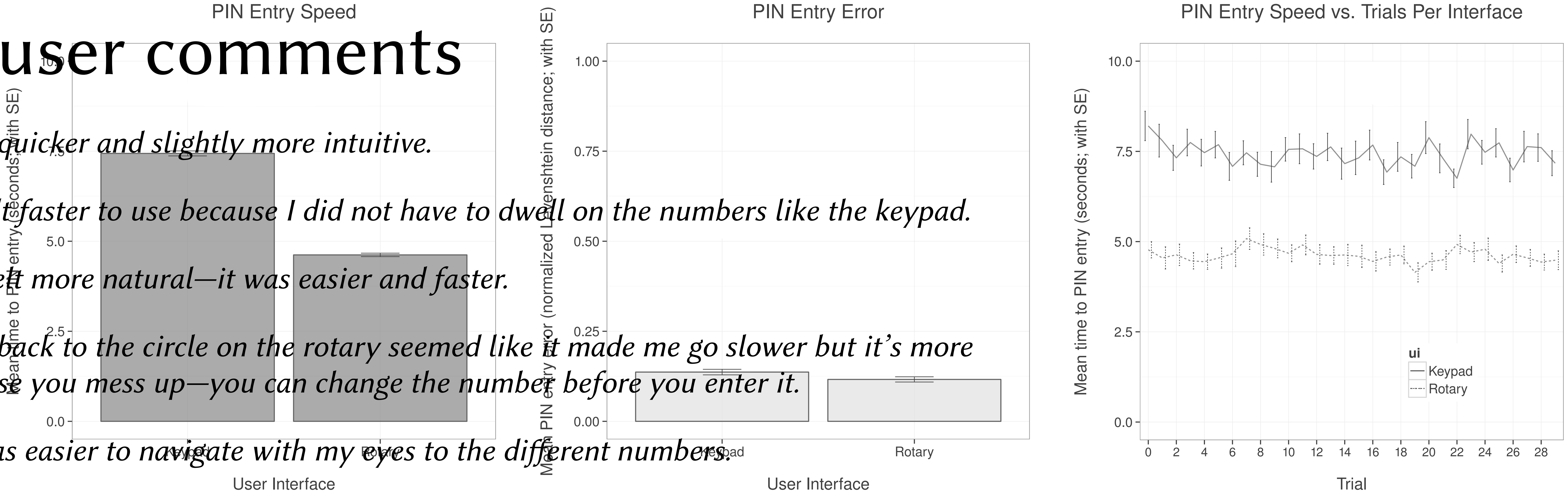






Results: speed, accuracy, trials

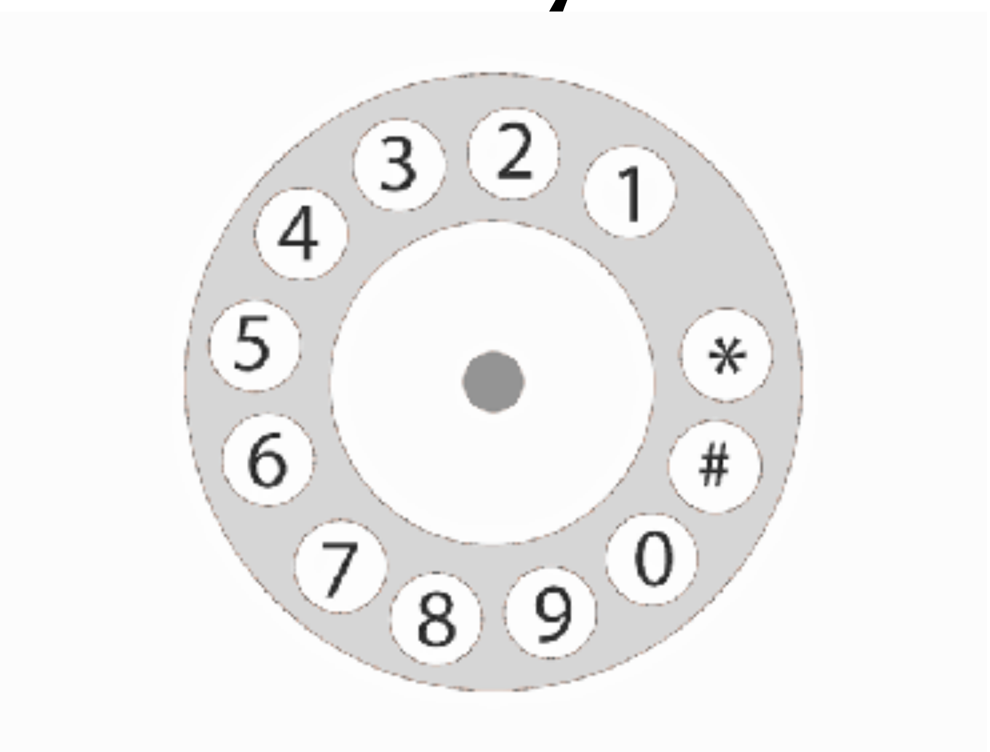
- Rotary interface: trials
  - learning effect sig. only for keypad
    (F(29,754) = 1.96, p < 0.01)
  - users found rotary UI intuitive
  - users preferred rotary interface
- Some user comments
  - *The rotary is quicker and slightly more intuitive.*
  - *The rotary felt faster to use because I did not have to dwell on the numbers like the keypad.*
  - *The keypad felt more natural—it was easier and faster.*
  - *Having to go back to the circle on the rotary seemed like it made me go slower but it's more efficient in case you mess up—you can change the number before you enter it.*
  - *The rotary was easier to navigate with my eyes to the different numbers.*



Results: keypad vs. rotary

- Similar error rates (no sig. difference; rotary's overall rate lower)
- Users grasped rotary operation immediately (no learning effect)
- Keypad showd steeper learning curve
- Rotary's speed entry follows Fitts' Law model, *by design*

- Rotrary is thus good gaze-based PIN entry candidate



Summary

- Start with good experimental design / hypothesis
- Re-instrument app to “talk” to eye tracker
- Calibrate, calibrate, calibrate (still)
- Analysis involves filtering of raw data to detect fixations
- Start with visualization (sanity check)
- Analyze data (find fixations, collate, stats)
- Write up report
- Automate as much as possible

Q & A

- Thank you!
- Questions?

Eye Tracking

Select References

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