2020 embedded vision summit

Eye Tracking For The Future: The Eyes Have It

Peter Milford, Parallel Rules Inc.

September 2020

with Parallel Rules Inc.

Outline

Eye Tracking Applications

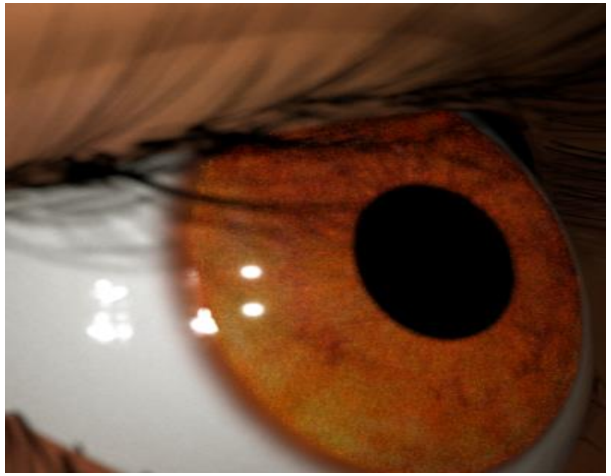
- Head Mounted Displays (HMDs) (Wearable)
- Remote Eye Tracking
- Eye Tracking User Cases: Vergence; Foveated Rendering. Assistive Technology

Eye Movement and Tracking Methods

- The Eye
- Eye tracking Methods
- Camera Sensors and Technology Suppliers

User Interfaces

- Dwell, Blink
- Saccades
- Smooth pursuit



Head Mounted Displays (HMDs) are Incomplete Without…

HMDs Incomplete Without Eye Interaction

Eye-Tracking & Control in HMDs:

Navigation
Activation
Reading
Paging
Searching
Zooming
Panning
Game Interaction
Multimodal Control
AR Control
VR Control

with Parallel Rules Inc.

Remote Eye Tracking

Computer monitors, TVs, cell phones

Sample uses:

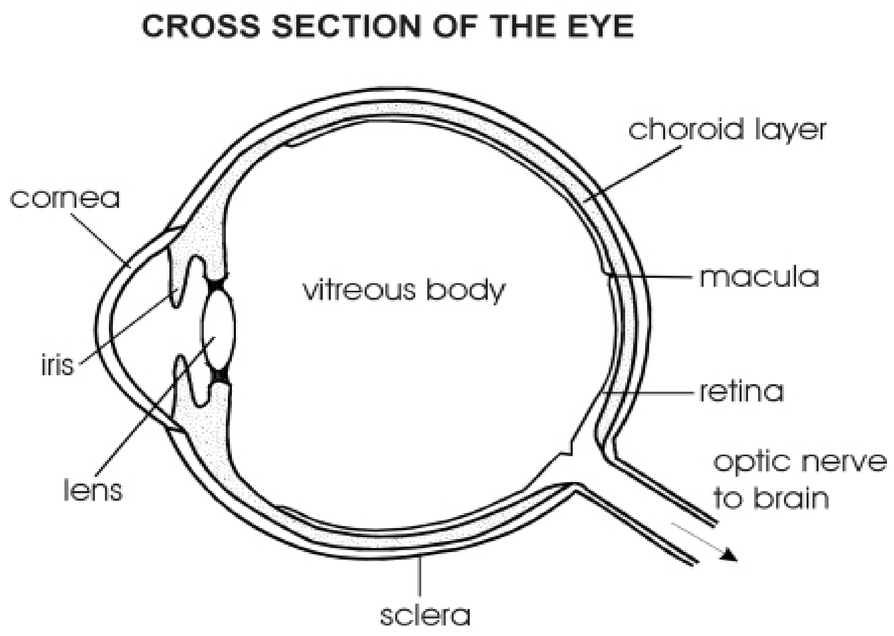
- Assistive Technology – For people who can only move their eyes
- Driver alertness – Safety for drivers
- Cell phone screen scrolling

Tobii Assistive Technology. Eye interaction system with remote eye tracking integrated into a tablet

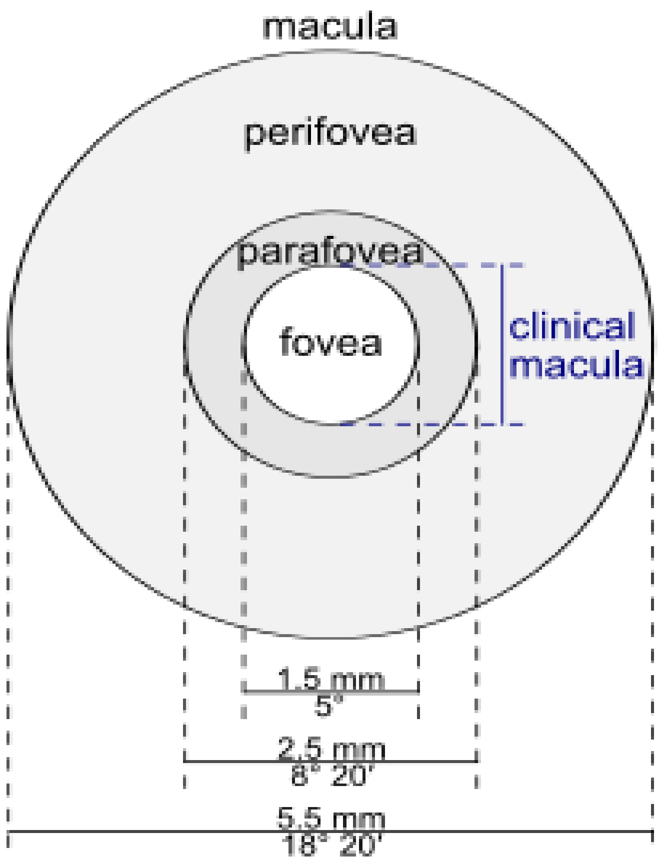
Remote eye tracking algorithms require: localizing heads and eyes; larger eye/head box (where we must track the eyes); camera with larger field of view and higher pixel count.

Schematic View Of Eye

- Cornea/lens form image on retina



• High resolution region of retina is called 'fovea' ~ few degrees of gaze view in diameter

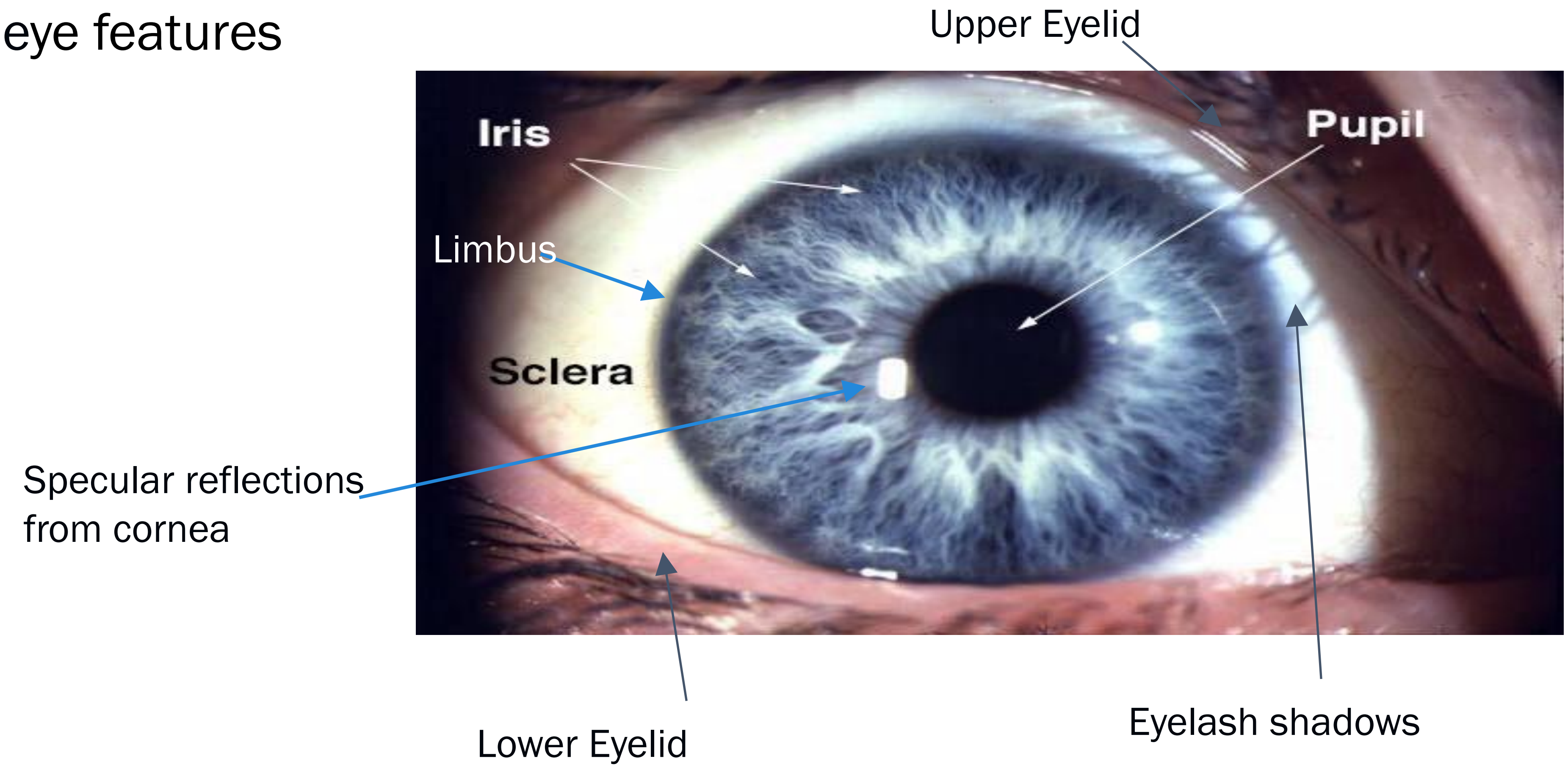


with Parallel Rules Inc.

Eye Features

2020 embedded vision summit

Prominent eye features

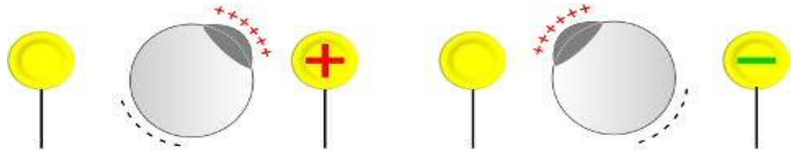


Eye Tracking History

Goal of eye tracking: measure where user is gazing – where is the 'fovea' looking

- First Eye tracking in 1800s by observation
- Corneal reflection photos 1d vs. time
- Mechanical eye tracking contact lens with pointers
- Oculography - monitor electric potential in eyeballs
  - can work with closed eyes
- Camera based eye tracking
- Collimated light based eye tracking

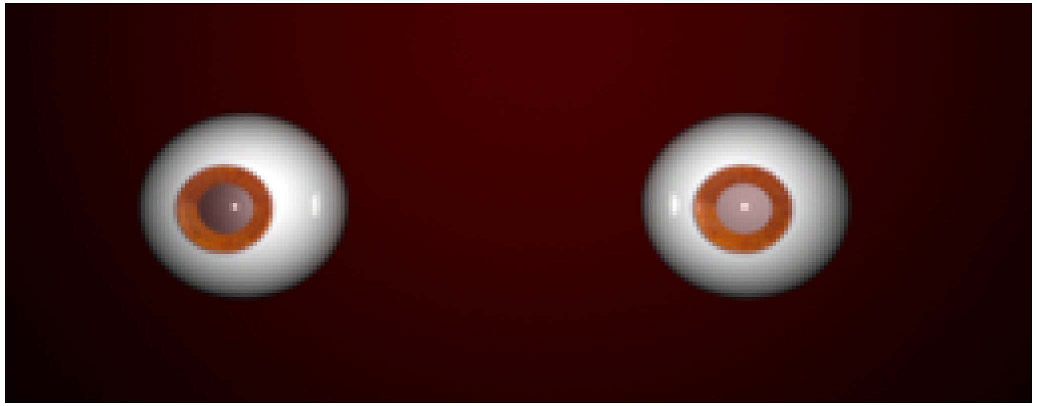
Jins Meme Oculography eye system



Eye Tracking Methods

Main Observables

- Purkinje Images (reflections from various eye surfaces)
- Dark/Bright Pupil
- Glints (1’st Purkinje reflection)

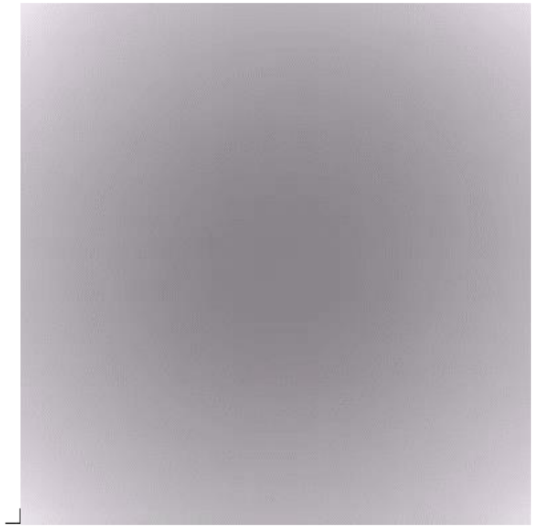


Red eye - bright and partial dark pupils. Single LED. Simulation.

Non-Camera based methods

- Mounting coils on eye or contact lens
- Oculography - measuring electric potentials

Frame 37



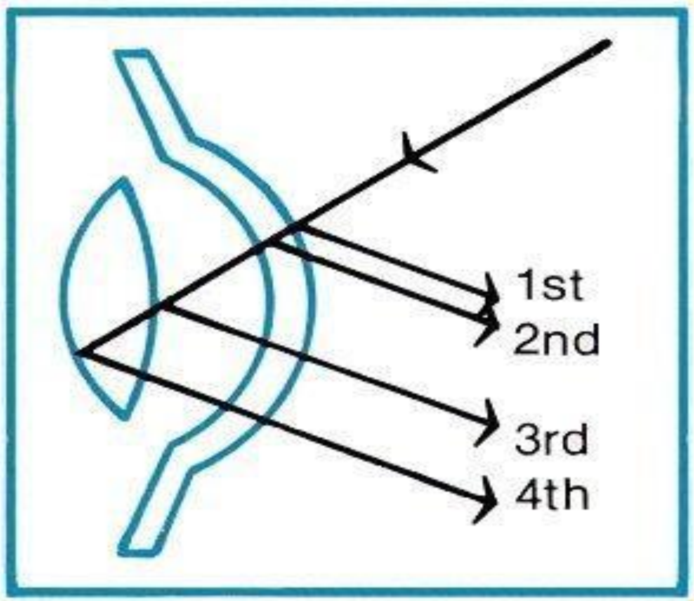
Algorithmic Approaches

- Pupil Center – Cornea Center – Example Geometric Approach
- Feature Based – Example Deep Learning Approach

with Parallel Rules Inc.

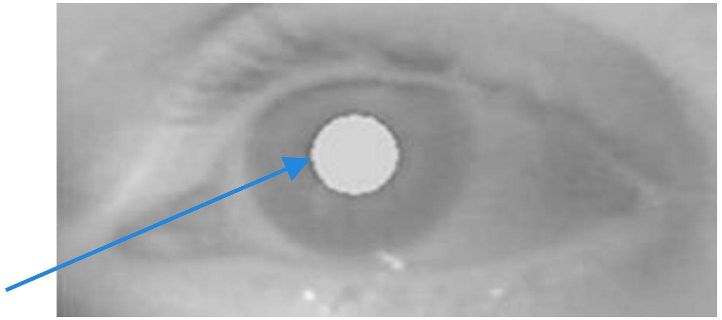
Eye Tracking Methods (Cont)

- Purkinje Images: Reflections from eye surfaces
  - 1’st - Anterior Cornea
  - 2’nd - Posterior Cornea
  - 3’rd - Anterior lens
  - 4’th - Posterior lens

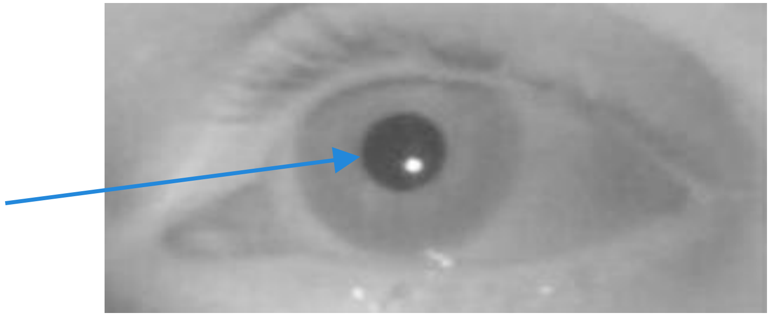


Eye Tracking Methods (Cont)

- Bright/Dark Pupil
  - Closely aligned light source and camera
  - Illuminates retina when light source on
  - Localizes pupil
  - Alternating illumination



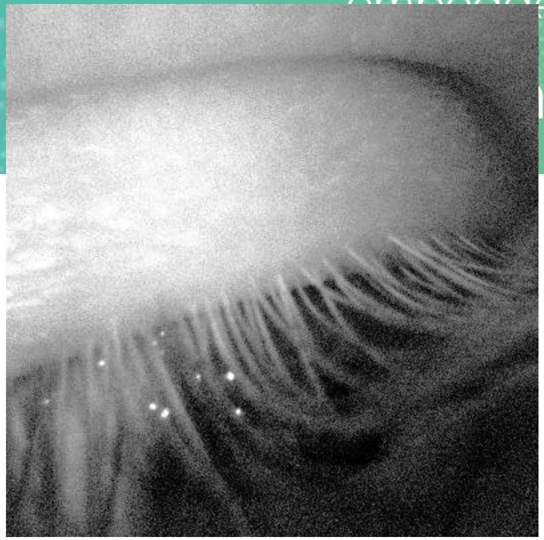
Bright pupil in IR - similar to Red eye in visible – camera aligned light source on



Dark pupil in IR
Camera aligned light source off
With visible glint

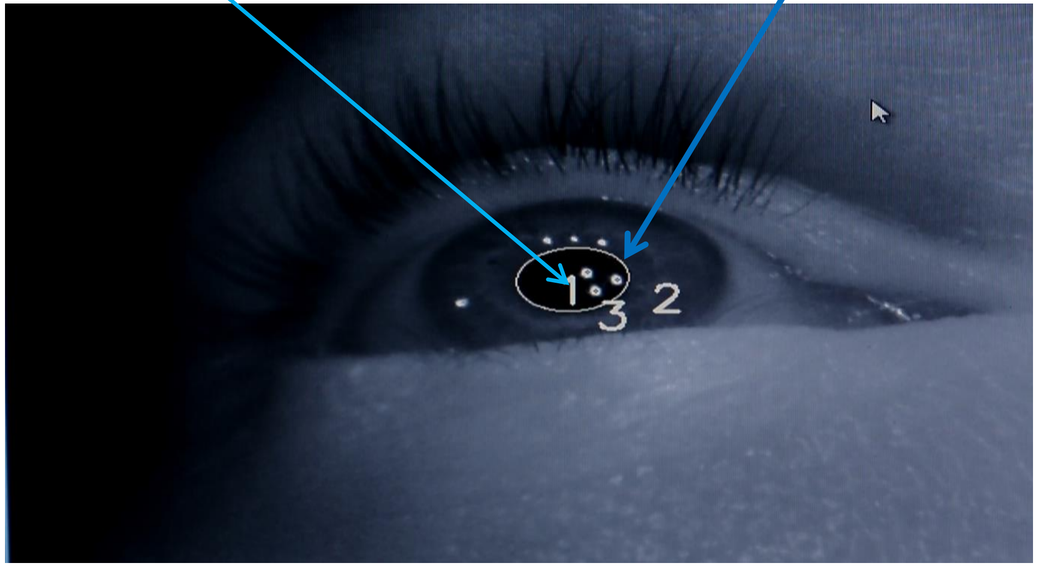
Eye Tracking Methods (Cont)

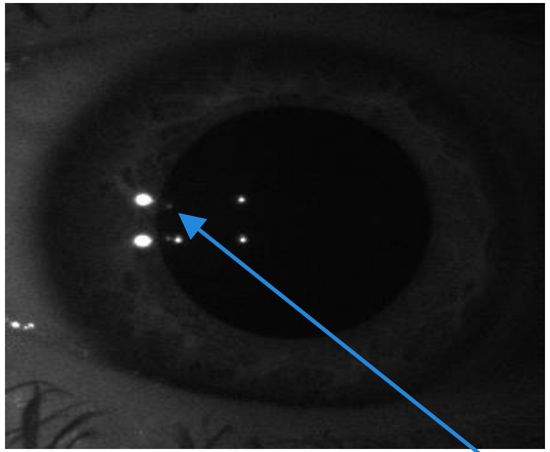
Glints - 1’st Purkinje reflection



Basis for pupil center – cornea center algorithms

3 tracked glints





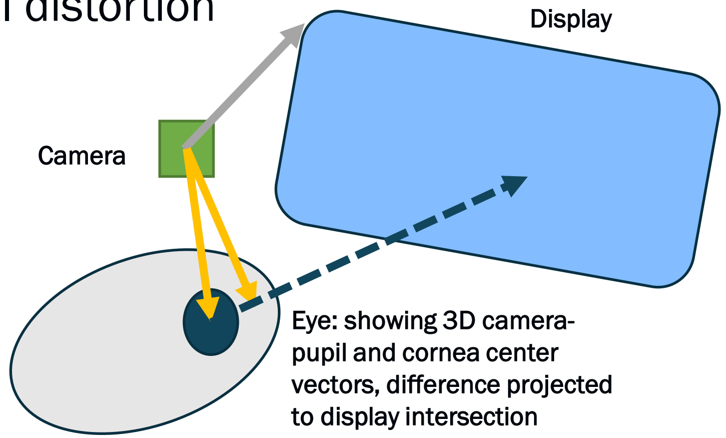
Large pupil, glints, secondary purkinje reflections

Pupil Center Cornea Center

<u>Algorithm basics:</u>
Find two points in 3D space on the eye in camera co-ordinates
Project a vector from the 2 points to where it intersects with the display in camera co-ordinates

Point 1: 3D Cornea Center
- Find glints on cornea
- Solve correspondence for which glint is from which IR-LED
- Project rays from the known location in camera co-ordinates of the LEDs. Glint reflections are equal angle from the incident ray, the normal ray passes through the center of a spherical cornea.
- Intersect the rays to estimate cornea center

Point 2: 3D Pupil center
- Find point in the pupil
- Find edges of pupil
- Fit ellipse or rotated circle to points with Ransac. Avoid eyelids and eye lashes
- Correct for corneal distortion



Eye: showing 3D camera-pupil and cornea center vectors, difference projected to display intersection

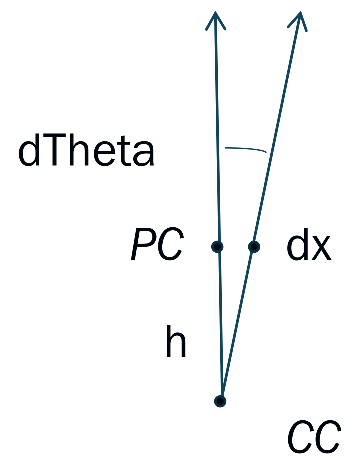
Pupil Center Cornea Center (Cont)

Approximate Error Tolerance

Consider one of the points as fixed, say the cornea center. *CC*

Perturb the second point, pupil center, *PC*, transversely by a small amount and measure the gaze error.

What perturbation, dx, leads to a 0.1 degree angular error?



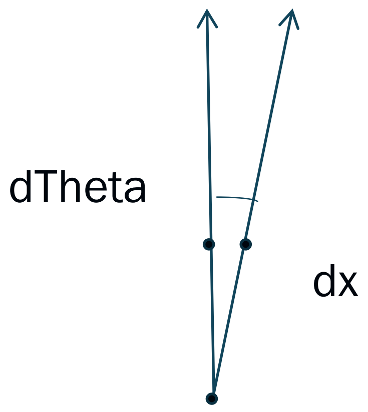
h is ~4.2 mm (cornea center to pupil center)
For a dTheta of 0.1 degrees, dx, the measurement error in pupil center is:

dx ~ h x dTheta radians
dx ~ 0.0042 x 0.1/180 x pi = 7 x 10-6 m or 7 um

Pupil Center Cornea Center (Cont)

System error sources

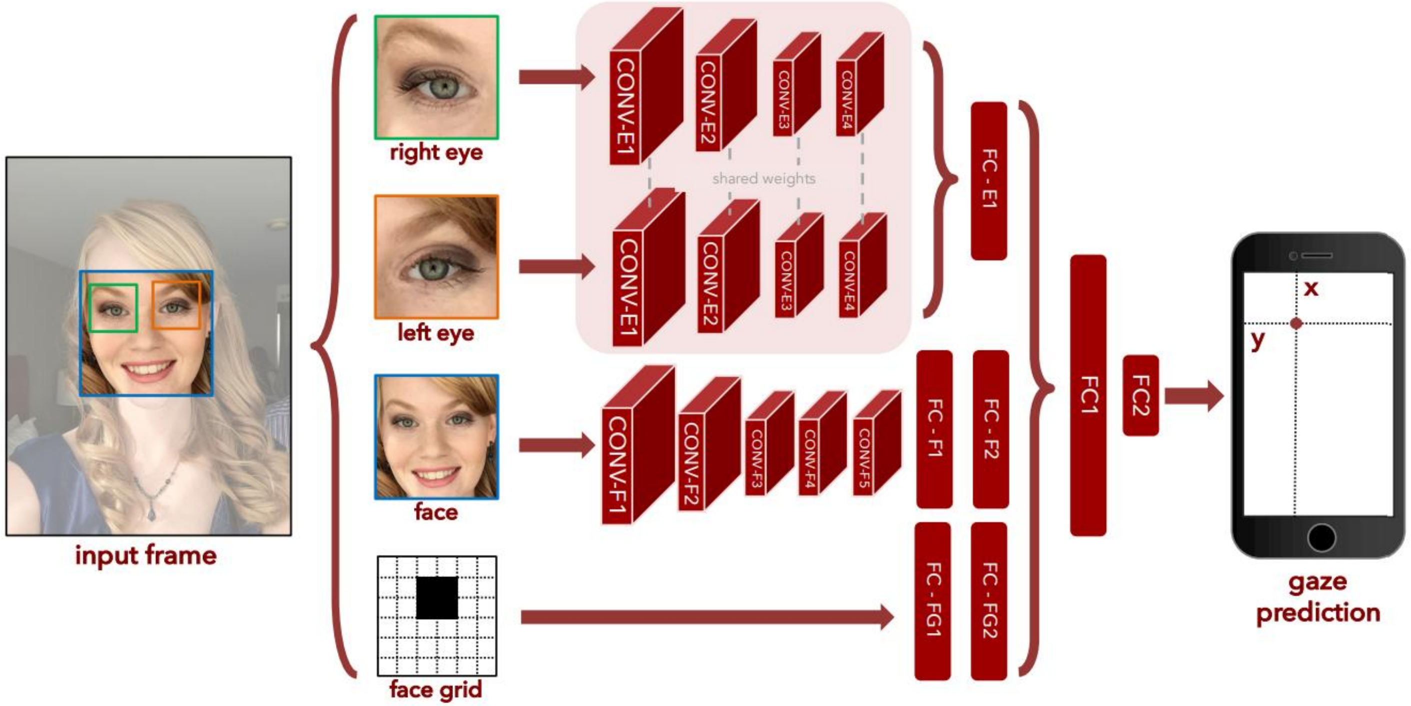
- Camera lens distortions/intrinsics – errors in all measured quantities
- LED pose – introduces error in cornea center
- Display pose – introduces gaze error
- Glint localization – introduces cornea center error
- Corneal distortion correction for pupil edge – pupil center error
- Pupil ellipse fitting errors – pupil center location
- Spherical cornea assumption - Cornea center location
- Camera-Camera pose - binocular gaze errors



Neural Network – Deep Learning Approaches

Sample Neural Network Architecture for Remote Eye Tracking

Training data from 1471 subjects
Accuracy reported as ~1.04 cm on cell phone screen and ~1.69 on tablet screens
(Estimate1.5 degrees average gaze error)

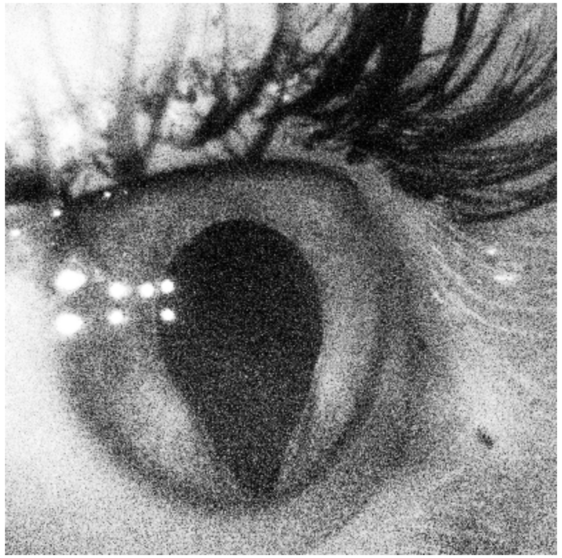


[Eye Tracking for Everyone K.Krafka*, A. Khosla*, P. Kellnhofer, H. Kannan, S. Bhandarkar, W. Matusik and A. Torralba](#)
[*IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2016*](#)

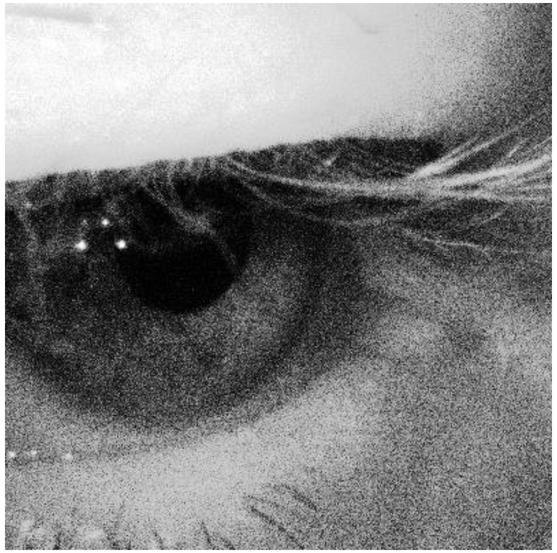
Note from paper:
Data preparation: First, from the 2,445,504 frames in GazeCapture, we select 1,490,959 frames that have both face and eye detections

with Parallel Rules Inc.

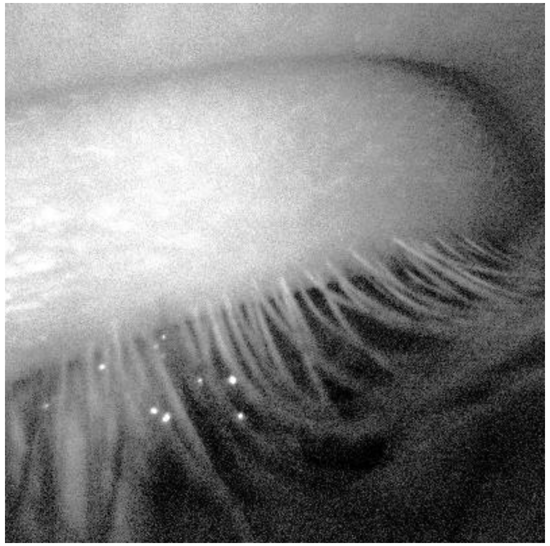
Some Challenging Situations…



Unusual Pupil - Rare



Partially Occluded Pupil and eyelash blocking pupil (both very common)



Very occluded pupil

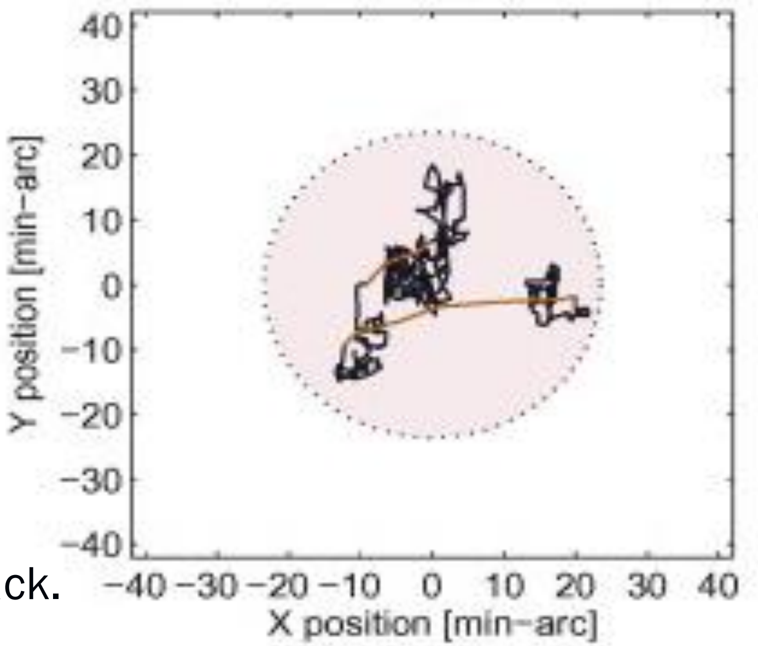
Eye Movement

Eye is fastest moving part of human body, up to 900 degrees/second for large saccades. Constrains measurement system

- At 30 Hz camera frame rate, eye moves up to 30 degrees between measurements
- 1 msec camera integration time, eye moves ~0.9 degrees, blurring the images

Eye constantly moving, typical ~0.5 degrees

- Microsaccades, drift and tremors



Microsaccade shown in red. Drift and tremors in black.
Typical amplitude ~ 0.5 degrees

Blinks

- Blinks - noise source for eye tracking
  - Inadvertent eyeball movement during pre/post blink
  - Partial pupil occulsions
- Blinks - interesting signal correlated with drowsiness
- Typical blink periods ~few hundred milliseconds, increasing with drowsiness
- Eye moves in socket during blink. Eye is blind around blink

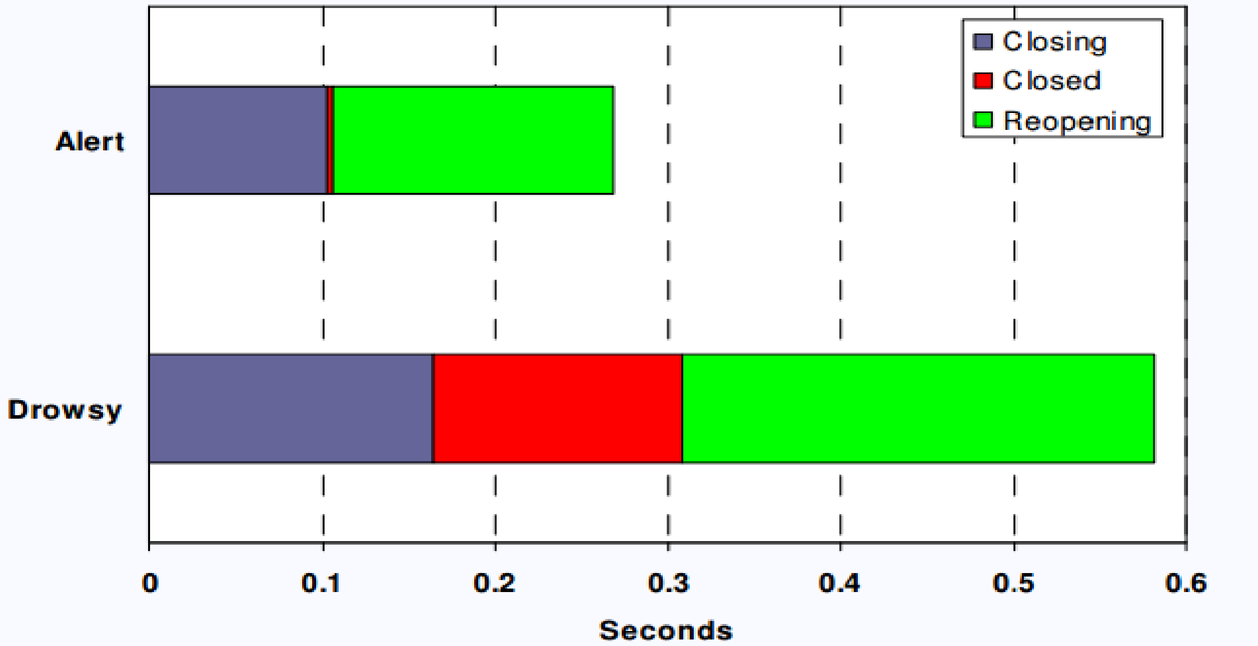


Fig. 4. The mean duration of each component of blinks in alert and drowsy subjects.

The duration of eyelid movements during blinks: changes with drowsiness
Tucker, A., & Johns, M. W.
Sleep, 2005; 28: A122.

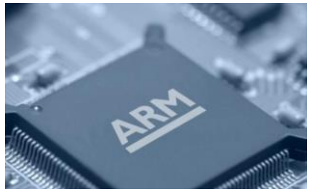
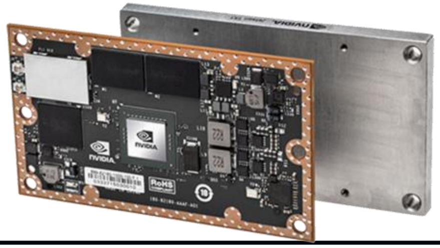
with Parallel Rules Inc.

Camera Requirements for AR/VR Eye Interaction

Specification	Value	Comments
Shutter	Global Shutter	Short exposure times. Short illumination time for power saving, eye safety, avoid motion blur
Frame Rate	100-200HZ (FR); 30+ (UI); 1+ (IPD, user recognition)	Most devices will have mixture of camera modes based on use cases
Eye spatial resolution	~0.05-0.1 mm/pixel	Resolve eye structures, eye tracking accuracy
Pixels	~QVGA	Depends on field of view of lens, HMD IPD adjustment, camera mounting locations
Illumination Wavelength	>840 nm	Illuminator not visible to users

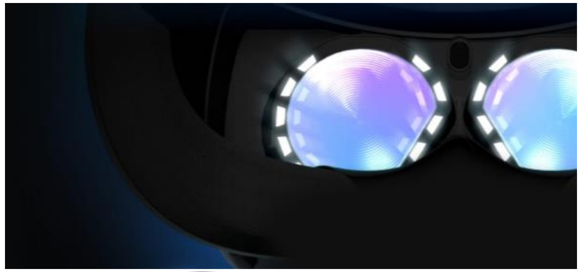
with Parallel Rules Inc.

Computational Requirements for AR/VR Eye Interaction

Specification	Geometric Algorithm	Deep Learning Algorithms	Comments
MIPs/Image	30 MIPS/Image	5000 MIPs/Image	Sample values from two different systems.
Memory	Megabytes	~Gigabyte	
Power use	GOPs ARM based embedded system 	TOPs Neural Network accelerator 	Geometric algorithms demonstrated on single core A9 processor. Neural Network algorithms demonstrated on Nvidia Jetson GPU. Other neural network algorithms demonstrated on cell phones

Technology Suppliers

Eye Tracking: 7Invensun, AdHawk, Argus, Ganzin, Tobii, Xperi, … others



Remote tracking Systems: Eyetech, Tobii, Eyeware, … others

HMDs: Microsoft, MagicLeap, HTC, … others

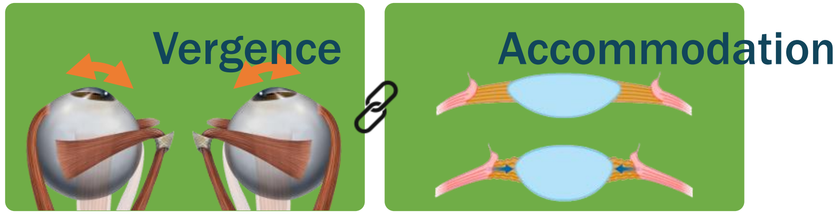
Use Cases: Vergence-Accommodation In HMDs

- Vergence-Accommodation display disparity can cause user problems, including headaches, in wearable display systems

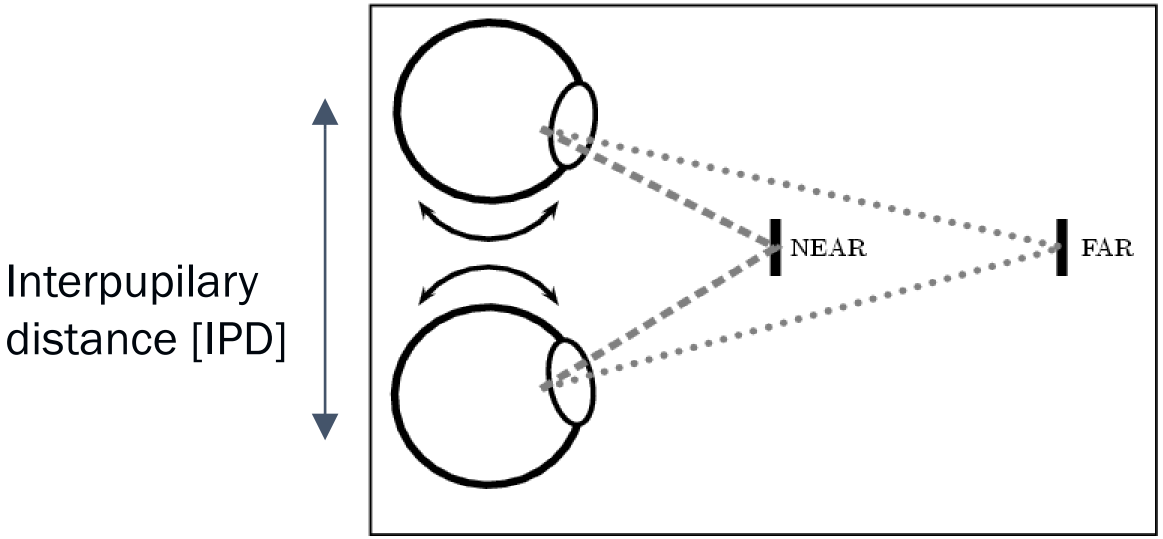
- Vergence can be measured by binocular gaze tracking systems and used to refocus display light from the point of gaze

Accommodation is the adjustment of the optics of the eye to keep an object in focus on the retina as its distance from the eye varies

Vergence is the simultaneous movement of both eyes in opposite directions to obtain or maintain single binocular vision

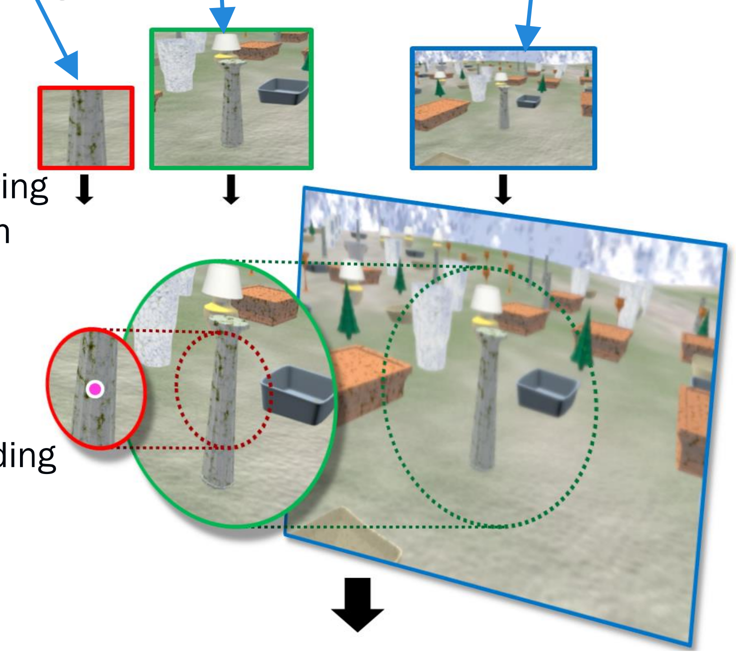


with Parallel Rules Inc.



Eye rotated to focus on near and far content. Eye lens changes shape/focus for real world content

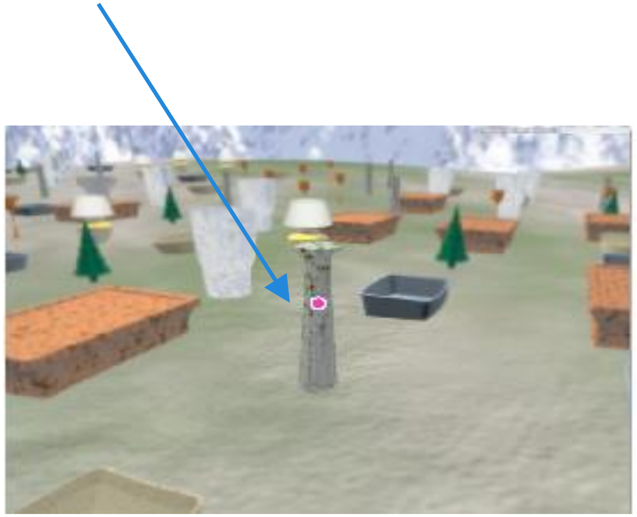
Use Case: Foveated Rendering (FR)



Save power and MIPS by rendering gaze target/foveal region at high resolution

Some display controllers will require foveated transport, sending 'compressed' FR data to the display panels

Rendered image is combination of high resolution rendering at gaze point (red) and lower resolution further from foveal region of eye

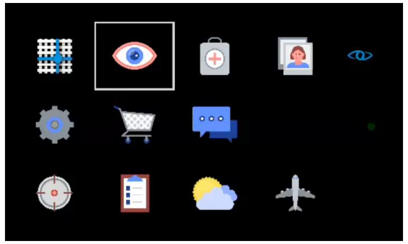


From Microsoft

Gaze measurement selects where to render image at highest quality. Low latency required to save rendering processing – smallest high resolution regions

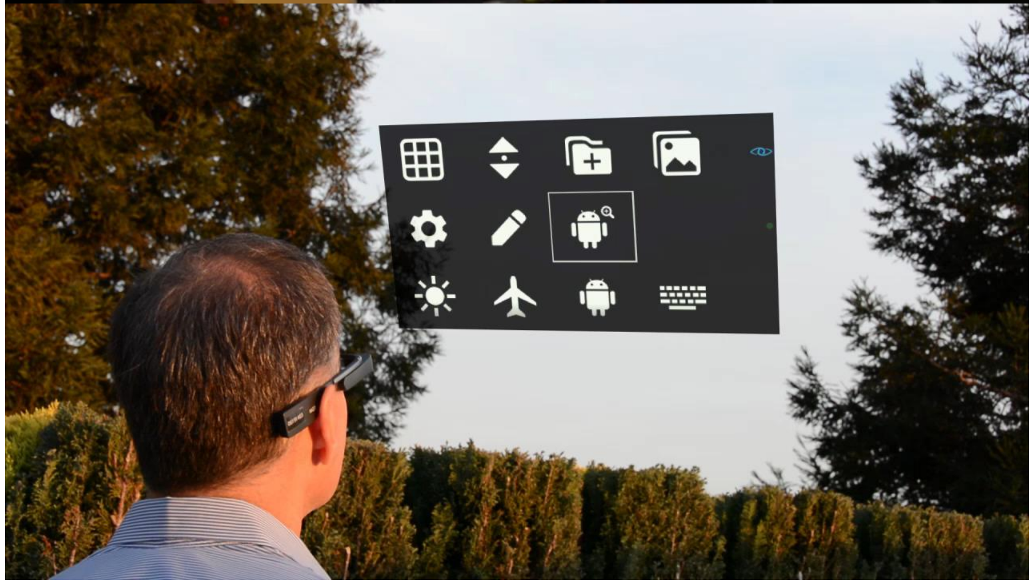
User Interfaces

- The eye is not a mouse, touch screen, hand or keyboard – it is an eye
    - For control of a user interface – let the eyes do what the eye do
    - Avoid cursors, dwell, blink
        - (Without a cursor, how do I know where I'm looking … you are looking there!)
    - Use subtle UI elements
    - Take advantage of saccadic blindness.
- Eyes are the fastest moving part of a human



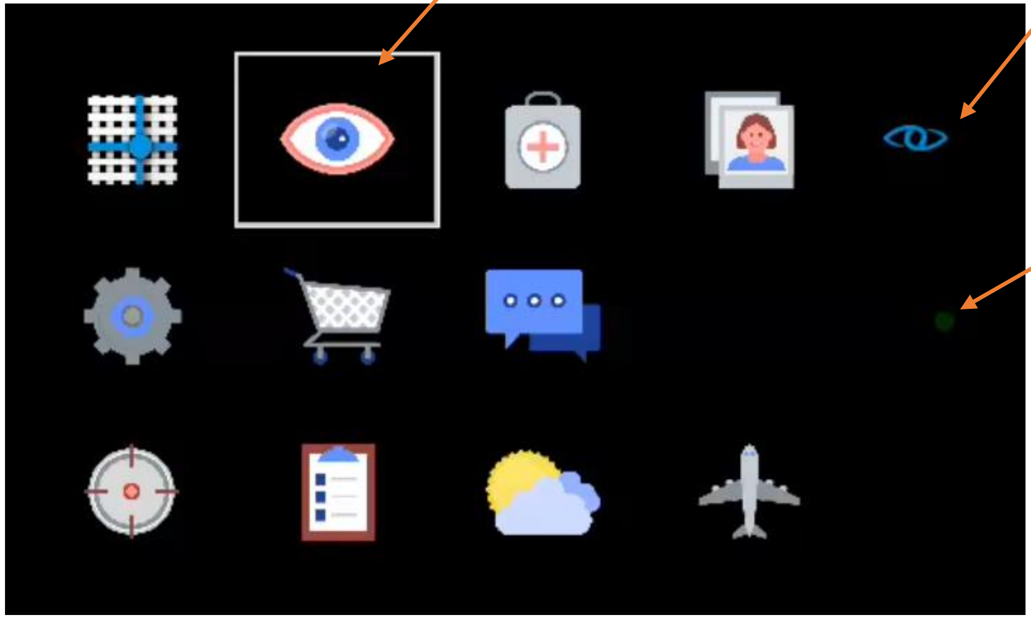
User Interfaces

- Pointing/Selecting
- Activating
- Saccades
- Smooth pursuit



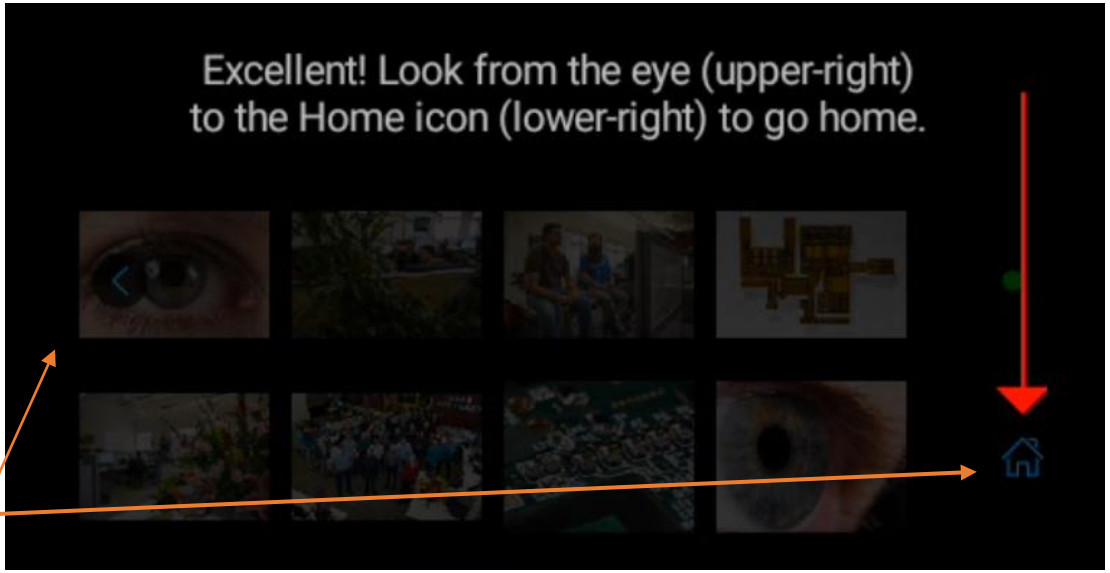
User Interfaces

Selection – Where you are looking



Main Reveal, with timeout to guide eye and avoid inadvertent activations

Activation – use memory guided saccades to activate

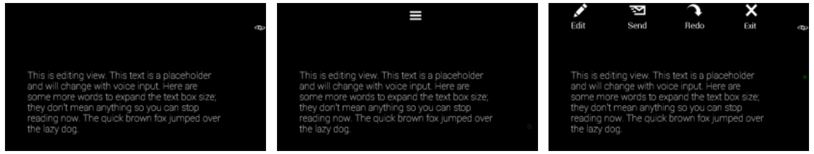


Main Reveal – shows faint home, back and menu items. Memory guided saccades activate them

with Parallel Rules Inc.

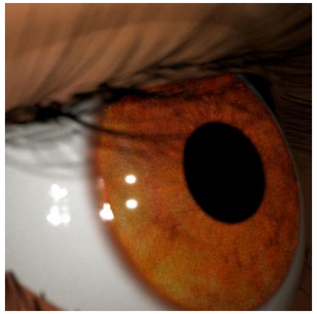
User Interfaces

- Augmented Reality User Interfaces
  - Avoid inadvertent activations by adding friction to irreversible actions
  - Sufficient contrast for visibility in real world environment
- Virtual Reality User Interfaces
  - Maximum Saccade length 15-20 degrees – larger is tiring, design likely requires dynamic placement of UI elements
  - Consider taking advantage of head movement in combination with eye movement
  - Consider using secondary activation device – a clicker for example



Conclusion

- Accurate robust eye tracking requires detailed system design and error/tolerance analysis
- Applications such as IPD measurement, foveated rendering appearing in shipping products
- Eyes can be used to control a user interface



Eye Tracking is NOT completely solved – room for new solutions!

Contact: Peter Milford pmilford@parallel-rules.com

Peter Milford, Parallel Rules Inc.

Ph.D in Astrophysics, University of Queensland, Brisbane Australia

Parallel Rules Inc., developing algorithms, sensors, image processing for customers in Silicon Valley and beyond

Advisor to Eyszlab: Eye based clinical monitoring for epilepsy

Advisor to Lemnis Technologies: solutions for vergence accommodation conflict in AR and VR Headsets

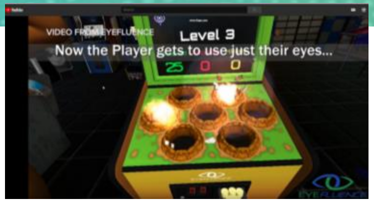
Advisor to Kura Technologies: Building the next generation AR HMD.

Contact: Peter Milford pmilford@parallel-rules.com

Resources

Contact: Peter Milford,
pmilford@parallel-rules.com

[Youtube demo of Eyefluence Eyetracking]



The duration of eyelid movements during blinks: changes with drowsiness
Tucker, A., & Johns, M. W.
Sleep, 2005; 28: A122.

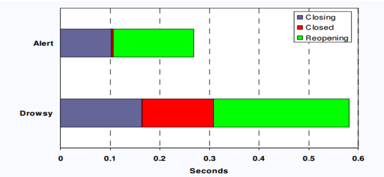


Fig. 4. The mean duration of each component of blinks in alert and drowsy subjects.

Microsoft Foveated Rendering Paper
NVIDIA Foveated Rendering Paper

Papers on Eye tracking:
- Eye tracking, general (paywall)
- Remote Eyetracking, geometric
- Cell Phone based deep learning

CES 2019
Consumer Technology Association LAS VEGAS JANUARY 08 - 11,2019

Lemnis Tech – Innovation award at CES 2019.
Vergence/Accommodation solutions

lemnistech

with Parallel Rules Inc.