Human Visual System – The Eye

- Extremely sophisticated multi-stage process:
  - light (information) enters through pupil
  - image is turned upside down
  - picked up by cones and rods on the retina
  - transduced into electrical signals
  - sent through optical nerve
  - visual cortex processes further

- Cones: sensitive to high spatial frequency
- Rods: sensitive to light

- Fovea:
  - <2° of visual field
  - cone-dense
  - prioritized in processing
  - 25% of cortex

- Cornea: important for eye tracking
Human Visual System – Temporal Vision

- Human visual response to motion

- Persistence of vision:
  - temporal sampling rate
  - at ~50-60 Hz flicker imperceivable
  - not fully explained

- Phi phenomenon:
  - threshold for apparent movement detection
  - fuses still images of movies

- Periphery sensitive to motion
  - Twice as sensitive to horizontal-axis movement as to vertical-axis movement
Human Visual System – Eye (Non-)Movements

- **Fixation**: where does the eye remain still

- **Micro-movements**:
  - Tremor
  - Microsaccade
  - Drifts

- **Saccade**: movement between fixations
  - fastest movement of the body
  - Blind for duration

- **Smooth pursuit**: following an object

- **Measurements in visual degrees (°) or minutes (′), with 1° = 60′**

### Table: Eye Movements

<table>
<thead>
<tr>
<th>Type</th>
<th>Duration (ms)</th>
<th>Amplitude</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixation</td>
<td>200–300</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Saccade</td>
<td>30–80</td>
<td>4–20°</td>
<td>30–500°/s</td>
</tr>
<tr>
<td>Glissade</td>
<td>10–40</td>
<td>0.5–2°</td>
<td>20–140°/s</td>
</tr>
<tr>
<td>Smooth pursuit</td>
<td>–</td>
<td>–</td>
<td>10–30°/s</td>
</tr>
<tr>
<td>Microsaccade</td>
<td>10–30</td>
<td>10–40′</td>
<td>15–50°/s</td>
</tr>
<tr>
<td>Tremor</td>
<td>–</td>
<td>&lt; 1′</td>
<td>20′/s (peak)</td>
</tr>
<tr>
<td>Drift</td>
<td>200–1000</td>
<td>1–60′</td>
<td>6–25′/s</td>
</tr>
</tbody>
</table>
Human Visual System – Eye (Non-)Movements

- Visual angle in stimulus space:
  - \( d \): viewing distance
  - \( \theta \): visual angle
  - \( x \): units in stimulus space

- In case of computer screen with:
  - \( M \times N \) mm screensize
  - \( r_x \times r_y \) px resolution
  - \( 1 \) mm = \( \frac{r_x}{M} \) px = \( \frac{r_y}{N} \) px

\[
\tan \frac{\theta}{2} = \frac{x}{d}
\]
Measuring the eye – Pupil/Corneal reflections

• Infrared light projected onto pupil

• Pupil can appear dark or bright

• Bright:
  • Tobii, ASL, etc
  • Infrared light reflected from retina
  • Works best with big pupil (less ambient light)

• Dark:
  • State-of-the-art
  • More robust

• Corneal reflection aids in calculating geometric centres

• Model-based vs. Feature-based
Measuring the eye – Sampling frequencies

• Nyquist-Shannon sampling theorem:
  • sampling frequency twice as large as movement

• Higher sampling frequency \(\leftrightarrow\) higher illumination needed

• 25-30 Hz
  • Slowest, typically record gaze-overlaid video

• 50-60 Hz
  • Remote/head-mounted systems

• 250 Hz
  • Low end of high speed tracking

• Above:
  • Too expensive
Measuring the eye – Sampling windows

- Intermediary no-sampling window:
  - 50 Hz tracker $\rightarrow$ 20ms
  - 500 Hz tracker $\rightarrow$ 2ms

- Allows much higher precision in on- and off-set of eye movements

- Probability of error:

  $$\tilde{\varepsilon} \sim N \left(0, \frac{1}{18nf_s^2} \right)$$

- $n$: number of datapoints
- $f_s$: sampling frequency
Measuring the eye – Common Factors

• Accuracy: true gaze vs. recorded gaze

• Precision: measurement reproduction

• Other factors:
  • Offset: angular distance accuracy
  • Spatial resolution: highest achievable precision
  • Jitter: tremor, microsaccades and drift
  • Resolution: smallest detectable movement
Measuring the eye – Precision

- Most important technical property of eye trackers

- Test with artificial eyes or steady gaze

- Calculation:
  - Standard deviation of data samples
    \[ s_x = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2} \]
  - Root mean square of inter-sample distances
    \[ \theta_{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \theta_i^2} \]
Measuring the eye – Precision Factors

- Eye camera resolution
- Spatial resolution of pupil and corneal reflection
- Head movement
- Movement in vicinity of eye tracker
- Eye color
Measuring the eye – Precision Error

- Left:
  - good precision
  - 7 fixations

- Right:
  - same data
  - precision error > 1°
  - 14 fixations
  - fixation spilling

- Raw scanpath of 50 Hz system
- 4-5 fixations
- Large movements in fixations
- RMS is 2.92°
Measuring the eye – Accuracy

• Most important for area of interest analysis

• Less important for eye movements

• Average angular distance $\theta_i$ between $n$ measurements and true location

  \[
  \theta_{\text{Offset}} = \frac{1}{n} \sum_{i=1}^{n} \theta_i
  \]

• Requires accurate fixation position
Measuring the eye – Accuracy Factors

• Calibration and Post-calibration:
  • Participants relax after an alert calibration phase

• Environmental factors:
  • Glasses
  • Contacts
  • Eye color
  • Tears
  • Etc

• Head movements

• Recalibration is useful!
Measuring the eye – Precision Error

• Top:
  • good accuracy
  • 7 fixations

• Bottom:
  • same data
  • precision error > 3°
  • fixation offset
Measuring the eye – Temporal Precision and Latencies

• Eye-Tracker Latency:
  • Delay between actual movement and recorded signal
  • Should be less than three samples

• Temporal Precision:
  • Standard deviation of latencies

• Stimulus-synchronization latencies:
  • Dissynchrony between stimulus presentation and recording
  • Particularly grievous with video stimuli
  • Very common, often overlooked
Measuring the eye – Filtering and Denoising

• Analysis software can introduce unwanted behaviour

• Filtering when calculating velocity and acceleration:
  • $\dot{\theta}$: velocity in °/s
  • $\theta$: angular distance between two samples
  • $f_s = \frac{1}{\Delta t}$: sampling frequency

$$\dot{\theta} = \frac{\theta}{\Delta t}$$

• Right:
  • Lowpass filtered raw signal
  • In use in common analysis software
Measuring the eye – Types of Eye Trackers

- Static:
  - Illumination and camera placed in front of participant

- Head-mounted:
  - A helmet, cap, or pair of glasses.
  - Commonly contains scene camera

- Head-tracker:
  - Calculate position of head in space as well

- Knowledge of position of head is crucial

- Recovery time

- Robustness
Some more inspiration
Some more inspiration
Some more inspiration